Faculty of Electronic and Computer Technology and Engineering

DEVELOPMENT OF AN OPTICAL MICROFIBER SENSOR IN HONEY FOR DIFFERENT CONCENTRATIONS USING A TAPERING METHOD

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Bachelor of Electronics Engineering Technology with Honours

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DEDICATION

My special thanks go to my parents, siblings, and friends, who have always supported me and encouraged me to complete my final year project successfully. Meanwhile, I'm dedicating this thesis to my beloved supervisor, Dr. Aminah binti Ahmad, and co. supervisor Dr. Md Ashadi bin Md Johari who has given me a lot of guidance on how to achieve success for my final year project. Thank you very much. It means a lot to me. I am grateful for their inevitable sacrifice, tolerance, and consideration in making this effort feasible. I cannot provide the appropriate words that can accurately describe my appreciation for their loyalty, support, and belief in my ability to achieve my dreams.

ABSTRACT

Fiber optics, commonly referred to as optical fiber, is a medium and system for transmitting information as light pulses over a glass or plastic strand. When light signals are transmitted through fiber optic cable, they bounce off the core and cladding in a sequence of zig-zag bounces, a phenomenon known as total internal reflection. Recently, optical microfiber sensors have received considerable research efforts due to their high sensitivity, detection speed, and ability to use harsh environments. This project aimed to use microfiber optics as a liquid sensor to detect different honey concentrations using a tapering method. The single-mode fiber will be tapered using the tapering method, and the best size of microfiber optics will be used for further investigation as a liquid sensor. Furthermore, the three samples of different concentrations of honey will be tested. Before each test, the fiber would be dipped in the samples and measured. In a line graph, each measurement would have different results. The experiment's findings will be described in terms of sensitivity, correlation, and coefficient of determination of the graph, all of which are completely dependent on the honey concentration and light source.

ABSTRAK

Gentian optik, biasanya dirujuk sebagai gentian optik, ialah medium dan sistem untuk menghantar maklumat sebagai denyutan cahaya ke atas helai kaca atau plastik. Apabila isyarat cahaya dihantar melalui kabel gentian optik, ia melantun dari teras dan pelapisan dalam urutan lantunan zig-zag, fenomena yang dikenali sebagai pantulan dalaman lengkap. Baru-baru ini, penderia mikrofiber optik telah menerima banyak usaha penyelidikan kerana kepekaan yang tinggi, kelajuan pengesanan dan keupayaan untuk menggunakan persekitaran yang keras. Projek ini bertujuan untuk menggunakan optik mikrofiber sebagai sensor cecair untuk mengesan kepekatan madu yang berbeza menggunakan kaedah tirus. Gentian mod tunggal akan ditiruskan menggunakan kaedah tirus, dan saiz optik mikrofiber terbaik akan digunakan untuk penyiasatan lanjut sebagai penderia cecair. Tambahan pula, ketiga-tiga sampel kepekatan madu yang berbeza akan diuji. Sebelum setiap ujian, gentian akan dicelup ke dalam sampel dan diukur. Dalam graf garis, setiap ukuran akan mempunyai hasil yang berbeza. Penemuan eksperimen akan diterangkan dari segi kepekaan, korelasi, dan pekali penentuan graf, yang semuanya bergantung sepenuhnya pada kepekatan madu dan sumber cahaya.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

μm	-	Micrometer
θ_1	-	The incident angle between the light beam and the normal
θ_2	-	The refractive angle between the light ray and the normal
n_1	-	The refractive index of the medium the ligh is leaving
n_2	-	The refractive index of the material the light is entering
nm	-	Nanometer
dBm	-	Decibels per miliwatt
λ	-	Wavelength
ηEF	-	Fraction of power
$\frac{\lambda}{r}$	-	Normalized wavelength
$m\ell$	-	Milliliter
H_0	-	Make a decision to reject or fail to reject the H_0

LIST OF ABBREVIATIONS

SMF	-	Single Mode Fiber
MMF	-	Multimode Fiber
RIU	-	Refractive Index Unit
TIR	-	Total Internal Reflection
OMR	-	Optical Microfiber Resonator
NA	-	Numerical Aperture
OTDR	-	Optical Time Domain Reflectometer

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Optical microfiber sensors are fiber optic sensors that use thin fibers, typically with a diameter of a few micrometres, to detect changes in their environment. These highly sensitive sensors can detect temperature, pressure, refractive index changes, and other parameters. One interesting application of optical microfiber sensors is in monitoring the concentration of honey. The ingredients in honey are a mixture of sugar, enzymes, and a mixture of various compounds. The concentration of honey can also vary due to the factors of the type of flower used and also the method of processing the honey. Different concentrations of honey can also have a negative effect on the quality of honey and also on the nutritional value.

The refractive index of honey, which correlates with its concentration, can be determined using optical microfiber sensors. The light that passes through the microfiber sensor shifts as the honey concentration changes since the refractive index likewise varies. This change in light can be used as a measure of honey concentration. In the food industry, where the concentration of honey is crucial for quality assurance and legal compliance, this kind of sensor can be especially helpful. It can also be used in research and development to create new products and learn more about the characteristics of honey. Additionally, the application of optical microfiber sensors in honey at various concentrations offers an effective way for keeping track of the composition and quality of this significant dietary product.

The project aimed to create an optical microfiber sensor using a tapering method immersed in honey to detect sensitivity in different honey concentrations. The glass fiber was heated and stretched using the tapering method until it was thinner and tapered. Several sample sizes of tapered microfiber will develop, and the best size will be selected for further investigation. Different honey concentrations were added to the optical microfiber sensor, and as the honey's refractive index changed, so did the sensor's transmission spectrum. A spectrometer was used to find out how sensitive honey is by detecting these changes. The experiment demonstrated that the optical microfiber sensor had a detection limit of 3.64×10−4 RIU (refractive index unit), which was extremely sensitive to changes in sugar concentration. The outcomes showed how optical microfiber sensors might be used to monitor and regulate food quality applications.

In conclusion, the project's goal demonstrates how optical microfiber sensors may be used to monitor the concentration of sugar in honey using a tapering method. Optical microfiber sensors are a promising technology for detecting changes in their environment.

1.2 Problem Statement

The requirement for a quick, precise, and non-invasive way to assess various honey concentrations is the issue that is addressed by the use of an optical microfiber sensor in honey. Honey is a complex mixture of sugars, acids, and other ingredients, and the concentrations can vary greatly depending on the nectar's source, the hive's location, and the processing methods applied. Refractometry and hydrometry, two common procedures for measuring honey concentration, are invasive and may alter the material being analysed. A non-invasive solution that can deliver real-time measurements without affecting the sample is an optical microfiber sensor.

Using a tapered optical microfiber sensor in honey to increase the sensor's sensitivity and accuracy when measuring various honey concentrations. Traditional optical fiber sensors may have low sensitivity because of their size and the amount of light that can be linked to them. By tapering the fiber, the evanescent field around the fiber can be increased, which improves the sensitivity of the sensor to changes in the refractive index of the honey. The goal is to develop a method for creating a tapered optical microfiber sensor that can accurately and reliably measure a wide range of honey concentrations while minimizing interference from other components of the honey, such as sugars and acids, that could affect the accuracy of the measurements.

1.3 Project Objective

The project aim can be made as follows once the problem statement has been established:

a) To investigate microfiber optics as a liquid sensor using a tapering method.
b) To design microfiber optics as a liquid sensor to detect different concentrations of honey using a tapering method.
c) To analyse the performance of microfiber optics as a liquid sensor in detecting different concentrations of honey using a tapering method.

1.4 Scope of Project

The research project aims to investigate optical microfiber sensors and use microfiber optics as a liquid sensor to detect different concentration of honey using the tapering approach. Also, the effectiveness of the developed sensors will be assessed. The scope of the project for using a tapered optical microfiber sensor in honey to measure different concentrations of honey can include several stages.

Using the tapering method, the study seeks to investigate optical microfiber sensors and use microfiber optics as a liquid sensor to gauge honey concentration. Additionally, the effectiveness of the developed sensors will be assessed. Before the sensors are spliced, the fibres are cleaned with alcohol to eliminate any dust and then stripped to provide a clean end-uncoated fibre and a smooth cleavage surface. During testing, a 1550nm optical power source was used to gather the input wavelength, and an optical power metre was used to measure the output signal in (dBm) units.

The splicer then joins the sensors to form a connection between the two fiber optics. Then, to detect and examine various honey concentrations, an optical power supply and an optical power meter are linked to each fiber optic sensor. In this experiment, three (3) samples of honey in varying concentrations such as 100% concentration, approximately 70% concentration, and approximately 50% concentration will also be evaluated. Finally, the optical microfiber sensors with three (3) different sizes which are thick, medium, and thin created for this project and choose one for the best size to used and measure the honey concentration.

As a result, the experiment's results will be discussed in terms of the graph's sensitivity, correlation, and coefficient of determination, all of which are entirely reliant on the amount of honey present and the light source. The findings are converted to watts (dBm) using an optical power metre.

Table 1.1 The equipment used for this project

Equipment	Experiment Details

Fiber optic	Single-mode fiber and fiber optic pigtail
Size	125µm cladding glass
Liquid	Honey
Hardware	• Tapering Machine • Optical Power Meter • Optical Power Level/Source (1550nm) • Commercial Splicer Fujikura FSM-18R • Fujikura CT-30 Fiber Cleaver • Spectrophotometer

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Thin glass or plastic fibers with a diameter of less than one micron (μ) are known as microfiber optics. Numerous uses for these fibers can be found in a wide range of fields, including telecommunications, sensing, and biomedical imaging. This investigation of the literature will go over current research and developments in microfiber optics.

Researchers created a microfiber optic sensor for the detection of volatile organic compounds in a study that was published in the Journal of Lightwave Technology. A sensitive polymer coating was applied to the silica microfiber used to make the sensor. For the detection of several volatile organic chemicals, the sensor showed great sensitivity and selectivity [1].

The use of microfiber optics for the detection of changes in refractive indices was the subject of another study that was published in the Journal of Optics. The researchers tapered a regular single-mode fiber to create a microfiber optic. The sensor was discovered to be extremely sensitive to changes in refractive index, making it appropriate for a variety of sensing applications [2].

Researchers demonstrated the application of microfiber optics for biological imaging in a work that appeared in Optics Express. The researchers created a microfiber optic probe and utilised it to image biological samples in high resolution. As a result of the probe's excellent sensitivity and resolution, it can be used for a variety of biological imaging applications [3].

Researchers looked at the usage of microfiber optics for the detection of magnetic fields in another work that was published in the Journal of Applied Physics. The researchers created a microfiber optic that was covered in a magnetically sensitive substance. As a result of the sensor's high magnetic field sensitivity, it can be used for a variety of magnetic sensing applications [4].

In conclusion, there are many uses for microfiber optics in a variety of fields, such as sensing, imaging, and telecommunications. The creation of high-sensitivity and high-resolution sensors and probes for many purposes has been the focus of recent research. With further research, it's anticipated that the applications of microfiber optics are going to expand.

2.2 Optical Microfiber

A form of optical fiber with an extremely small diameter is known as optical microfiber. Its high refractive index and material, either glass or plastic, enable effective light transmission and confinement within the fiber. Since optical microfibers are so flexible, it can be easily bent and shaped without significantly reducing the amount of light that can transmit. It is therefore perfect for a variety of uses, such as sensing, communication, and biological imaging.

Optical microfibers' capacity to improve light-matter interactions is one of its main advantages. It has been utilised in many sensing applications, including temperature, pressure, and chemical sensing, due to its small size, which enables it to probe minuscule quantities. In telecommunications, optical microfibers are also utilised to send high-bandwidth signals over great distances. Couplers, splitters, and filters that separate or combine signals and block particular light wavelengths can all be created using it [5].

Optical microfibers are probed into biological tissues and cells in biomedical imaging to produce high-resolution photographs of objects that are invisible to the human eye. It has been utilised for intracellular imaging, which allows for the visualisation of individual cells, as well as endoscopy, which involves inserting a microfiber into the body to view interior organs. In conclusion, optical microfibers are incredibly adaptable optical fibers with a wide range of uses in fields like sensing, telecommunications, and biomedical imaging. It is suited for a variety of applications due to its tiny size, flexibility, and capacity to improve light-matter interactions. Future research is anticipated to find many more possibilities for these fibers.

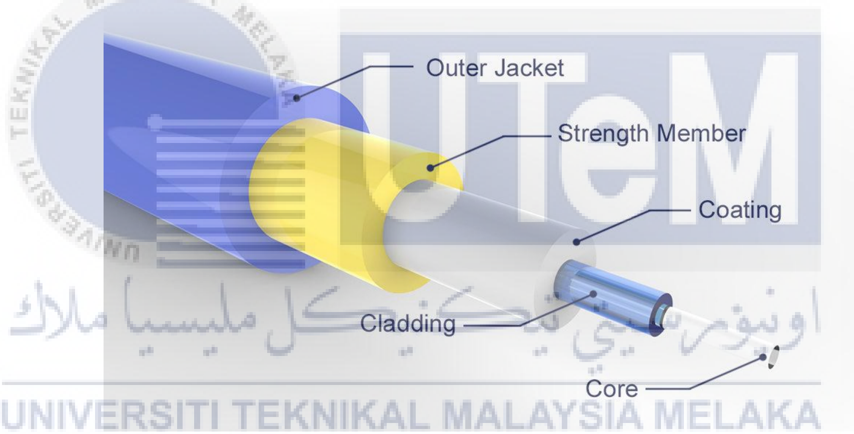


Figure 2.1 The basic structure of optical fiber

2.2.1 Single-Mode Fiber

A single mode or ray of light at a time can be carried by a single-mode fiber, a type of optical fiber. It is used to transport data over long distances with high bandwidth and little signal loss in telecommunication and data communication applications. Figure 2.2 shows the core diameter of a single-mode fiber, which is significantly smaller than the core diameter of a multimode fiber and normally ranges between 8 and 10 micrometres (μm). Compared to multimode fibers, single-mode fibers offer a greater bandwidth and a greater transmission range [6]. Additionally, they are resistant to the sort of signal distortion known as modal dispersion, which can happen in multimode fibers.

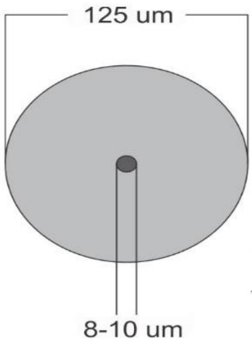


Figure 2.2 Measurement of the cladding and single-mode core

Single-mode fibers are frequently used in high-speed data transfer applications like data centers as well as long-distance telecommunications such as transoceanic cables. Additionally, it's utilised in specialised applications such as fiber optic sensors. Despite being more expensive than multimode fiber optic cables, single-mode fiber optic cables provide a number of benefits, including fast data speeds over greater distances with minimal signal loss. It is perfect for applications that need high reliability, low latency, and fast data transmission [7].

Despite being more expensive than multimode fiber optic cables, single-mode fiber optic cables have a number of benefits, including:

1) Higher bandwidth: Compared to multimode fiber optic cables, single-mode fiber optic cables can transfer more data over longer distances.

2) Greater data transmission range: Compared to multimode fiber optic cables, single-mode fiber optic cables have a substantially greater data transmission range.

3) Less attenuation: Single-mode fiber optic cables exhibit lower attenuation (signal loss) than multimode fiber optic cables, allowing for greater signal transmission distances without the use of signal amplification.

4) Immunity to modal dispersion: Single-mode fibers are suitable for applications that need high data rates and minimal latency since they have no modal dispersion.

Single-mode fiber optic technology is an excellent option for a variety of communication applications because it can transmit high-speed data over long distances with little signal loss and a lot of bandwidth.

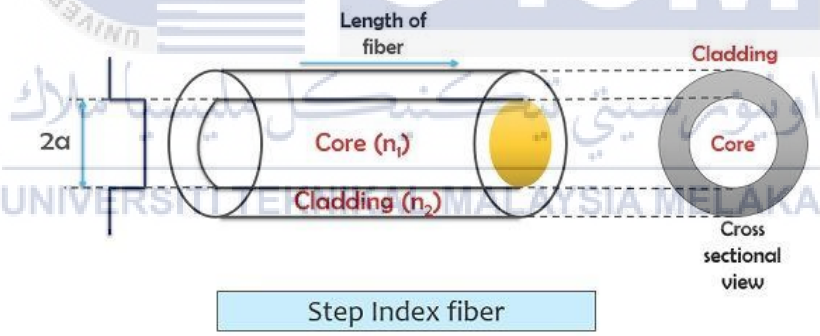


Figure 2.3 Single-mode step-index fiber

2.3 Properties of Optical Microfiber

An optical microfiber is a thin strand of glass or other transparent material with a diameter less than the wavelength of light. The optical properties of microfibers are highly sensitive to changes in their geometry and refractive index, making them useful for a variety of sensing and communication applications [5]. Here are some of the key properties of optical microfibers:

1) High sensitivity: Optical microfibers are highly sensitive to changes in their surrounding environment, including temperature, pressure, and refractive index. This sensitivity is due to the strong evanescent field that extends beyond the fiber's core and interacts with the surrounding medium.
2) Low loss: Microfibers can be fabricated with extremely low loss, allowing light to propagate over long distances without significant attenuation. This makes them ideal for use in optical communication and sensing systems.
3) Small size: Optical microfibers have diameters that are typically less than 10 microns, which allows them to be easily integrated into complex optical systems and devices.
4) Nonlinear properties: Microfibers exhibit a variety of nonlinear optical effects, including four-wave mixing and Raman scattering, which can be exploited for signal processing and wavelength conversion.

5) High surface-to-volume ratio: The large surface area of microfibers relative to their volume makes them ideal for chemical and biological sensing applications. When coated with sensitive material, the fiber can detect trace amounts of specific chemicals or biological agents.
6) Flexible and bendable: Microfibers can be bent into small radii without significant loss, allowing them to be woven into intricate patterns or conform to the contours of the surface they are applied.

Overall, optical microfibers are highly versatile optical components with a wide range of applications in sensing, communication, and signal processing.

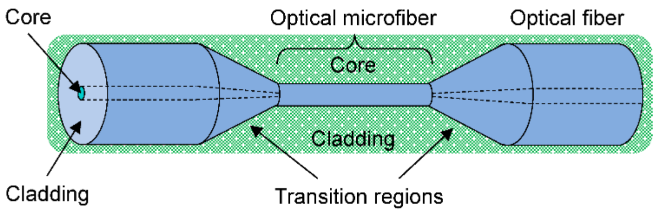


Figure 2.4 A considerable amount of power propagation interacts with optical microfiber, which is a sensitive area

2.3.1 How an Optical Microfiber Works

A normal optical fiber functions similarly to an optical microfiber, but on a much smaller size. It is a thin filament having a diameter that is less than the wavelength of light, typically constructed of glass or another transparent material. Due to the optical microfiber's high surface area to volume ratio, light beams that enter the fiber interact with the material that are passing through. The evanescent field that extends beyond the core of the fiber interacts with the surrounding medium as the light beam travels through the fiber's core.

Optical microfibers can be utilised as sensors due to their high sensitivity to changes in their geometry and refractive index. Changes in the transmitted light signal can be seen when the fiber is coated with a sensitive substance, such as a biological or chemical agent. This interaction between the substance and the fiber's evanescent field can be measured. To ascertain the existence and concentration of the target chemical, these variations can be analysed.

Optical microfibers can be utilised for signal processing and communication in addition to sensing. Microfibers' small size makes it simple to incorporate into intricate optical devices and systems, and microfiber low loss makes it perfect for transmitting light signals over great distances [5].

In microfibers, nonlinear optical processes like four-wave mixing can be used to process signals and change wavelengths. These effects are brought on by the interaction of the fiber's substance and the powerful light beam. Optical microfibers are adaptable optical parts with numerous uses in signal processing, communication, and sensing.

2.4 Fabrication of Microfiber by Using a Tapering Method

2.4.1 The Flame Brushing Technique

A quick and efficient process for creating optical fibers and microfibers from glass or other transparent materials is flame brushing. With this method, the material is softened by heating a glass rod or performing with a high-temperature flame and then being drawn into a fine fiber or microfiber. A glass rod or other piece of equipment used to start the process is often constructed of silica or another type of high-purity glass. A high-temperature flame, such as a hydrogen-oxygen flame, is used to hold the rod or preform, softening and making the material viscous.

Two mechanical "brushes" that are operated by a computer programme progressively pull apart the softened glass material as it does so. The material is stretched and made thinner into a fiber or microfiber as the brushes move apart from one another at a controlled speed. The resulting fiber or microfiber is then chilled and given a protective coating to shield it from harm and boost its functionality. To produce fibers with various sizes or characteristics, the procedure can be done numerous times.

The fabrication of high-quality optical fibers and microfibers with low loss and high strength frequently uses the flame brushing technique. Depending on the needs of the application, the process can be utilised to produce fibers with diameters ranging from a few microns to tens of microns [8]. The procedure is popular for small-scale manufacture of optical fibers and microfibers since it is rather straightforward and can be carried out using affordable equipment.

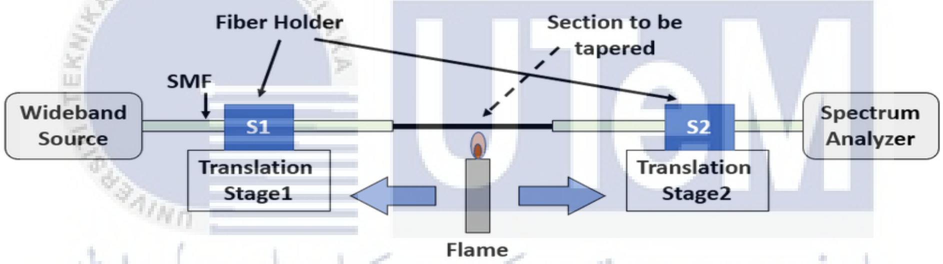


Figure 2.5 Flame brushing technique schematic

2.5 Adiabaticity Criteria

Similar to tapered optical fibers, but with a much smaller diameter of only a few micrometres, are tapered microfibers. Due to their smaller size and greater susceptibility to external conditions, tapered microfibers' adiabaticity criteria differ from those for tapered fibers in some ways. The taper angle of tapered microfibers must be short enough to guarantee that light is adequately coupled to the fiber core throughout the taper zone. As a result, the taper angle must be less than a critical angle that is based on the microfiber's size and the light's wavelength. The efficiency will decrease if the taper angle is too steep since the light may be lost or scattered.

The taper of tapered microfibers must be long enough to allow light to adiabatically follow changes in the fiber's refractive index. This is a crucial requirement. In order for the light to adapt to the shifting circumstances without being lost or scattered, the rate of change in the fiber's refractive index must be slow enough. The wavelength of the light, the microfiber's diameter, and the fiber's refractive index profile all affect how long of a taper is necessary for adiabaticity [5].

In addition to these criteria, other elements including the microfiber's material characteristics and the environment around it can also have an impact on the adiabaticity of tapered microfibers. For instance, the presence of contaminants or flaws in the fiber may cause light to be scattered or absorbed, which may lower the effectiveness of the taper. The refractive index of the fiber can also fluctuate in response to variations in temperature or humidity, which can have an impact on the adiabaticity of the taper [9].

As a result, the adiabaticity requirements for tapered microfibers are comparable to those for tapered fibers, with a few more parameters to take into account because of it smaller size and greater susceptibility to external influences. Tapered microfibers can be employed in a variety of cutting-edge optical systems and devices by carefully planning and optimising the taper geometry and taking environmental considerations into account.

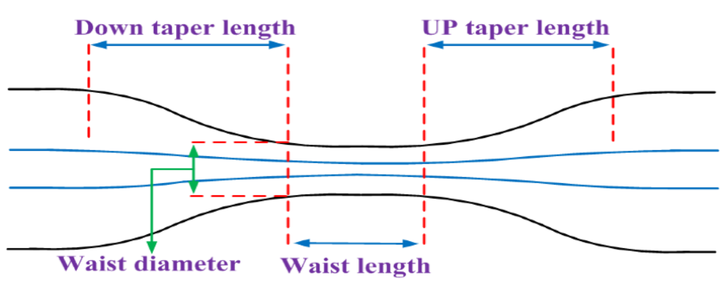


Figure 2.6 Refractive index sensor with high sensitivity based on adiabatically tapered microfibre

2.6 Optical Microfiber Devices

With sizes on the order of micrometres or sub-micrometers, optical microfiber devices are extremely thin strands of dielectric material, such glass or silica, that allow for precise control and manipulation of light at the nanoscale. Using the device's distinctive optical characteristics, low-cost, miniaturized, all-fiber optical devices can be created for a number of uses. As a result, some researchers have concentrated their efforts on creating microfiber-based optical resonators, which have several applications in optical communication, laser systems, and sensors. These devices can also function as optical filters and the most popular type of photonic device constructed from microfibers is lithographic planar waveguides [5] [10].

Optical microfiber as a sensor also has various methods for measured liquid, gas, temperature and so on. The method used in this study is the tapering method. Meanwhile, other methods are known as straight fiber method and D-shape method. These methods have different processes to form fiber optic as a sensor and each method has its own way to determine sensitivity and accurate value for measured concentration of liquid.

2.6.1 Straight Fiber Method

Straight fiber method is a method that is categorized as a relatively simple method compared to other methods. Straight fiber method only uses single-mode fiber optic which is 125 µm in size and single-mode fiber connector (pigtail) for connection. This method does not need to make a stripping process, in fact this method continues to make a connector between the single-mode fiber (125μm) and the single-mode fiber connector (pigtail) through the splicing process. Splicing process that uses commercial splicer Fujikura FSM-18R that will connect both single-mode fiber and single-mode connector (pigtail) into a sensor [11].

However, this straight fiber sensor has a shortcoming which is that it has low sensitivity and the measured value is not accurate due to the thick size of the single-mode fiber making it difficult to get a good output value and sensitivity. The figure below shows an example of a fiber optic sensor that uses the straight fiber method.

Figure 2.7 Straight fiber sensor

2.6.2 D-shaped Fiber Method

The sensor is constructed from 125 μm single-mode fiber. To create a D-shaped fiber, a wheel-style side polishing mechanism must be developed in the first phase.

Sandpaper with an 800-grit rating is placed on the grinding wheel. A certain amount of stress is delivered to the optical fiber along the Y direction by manually regulating the translation stage, which is fixed on two exact three-dimensional Y-axis adjustable translation stages. The prepared D-shaped optical fiber is then installed in the system in order to complete the discharge fusion taper processing of the optical fiber using an optical fiber fusion splicer (Fujikura FSM-18R) [12].

The process to make D-shaped on single-mode fiber will take a long time to get high sensitivity by producing a thin D curve. If you get a thin D curve, to test the concentration of a liquid you will get a high accurate value just like the tapering method.

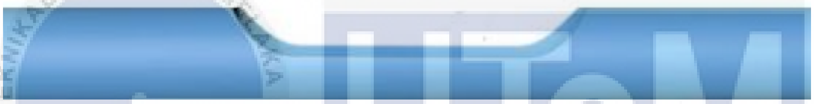


Figure 2.8 D-shaped fiber sensor

2.7 Optical Sensor using Microfiber

In an optical sensor made of microfibers, the microfiber interacts with the target analyte or the physical characteristic being measured and acts as a transducer. The interaction may result from modifications to the refractive index, absorption, fluorescence, or other optical properties. It is possible to functionalize or modify the microfiber with specific coatings or substances in order to improve its sensitivity to the target analyte. For instance, a microfiber that has been coated with a selective liquid (chemical) layer can be used to detect gases. As the gas molecules interact with the coating, the optical properties of the microfiber change [13].

Changes in the transmitted or reflected light result from the target analyte's interaction with the microfiber. Different optical measurement methods, such as intensity-based measurements, interferometry, or spectroscopy, can be used to identify and quantify these changes. The high sensitivity and small size of microfibers enable the detection of very low concentrations of analytes or small changes in physical parameters. Additionally, the flexibility and compactness of microfibers make them suitable for integration into portable or miniaturized sensing systems [5].

2.7.1 Evanescent Wave

An optical fiber or waveguide is an example of two media with different refractive indices that are separated by an electromagnetic wave known as an evanescent wave. It is produced when a wave that is in motion collides with a boundary at an angle that is greater than the critical angle, resulting in total internal reflection (TIR) [5]. When there is total internal reflection, a component of the incident wave enters the second medium to create the evanescent wave rather than being transmitted across the boundary. As it moves away from the interface, the evanescent wave's intensity exponentially decays with increasing distance from the boundary.

Even though the evanescent wave's strength rapidly declines, it still carries energy and knowledge about the characteristics of the nearby medium. Its evanescent field, which persists outside of the waveguide or fiber but does not propagate like a regular traveling wave, is what distinguishes it. The evanescent wave is important in many applications, but it is especially important in sensing and near-field optics. To detect changes in the surrounding medium's refractive index or other qualities, for instance, evanescent wave sensing uses a wave to probe the area. Highly sensitive detection or analysis can be achieved by taking advantage of the interaction between the evanescent wave and analytes or molecules that are around the waveguide or fiber [5] [14].

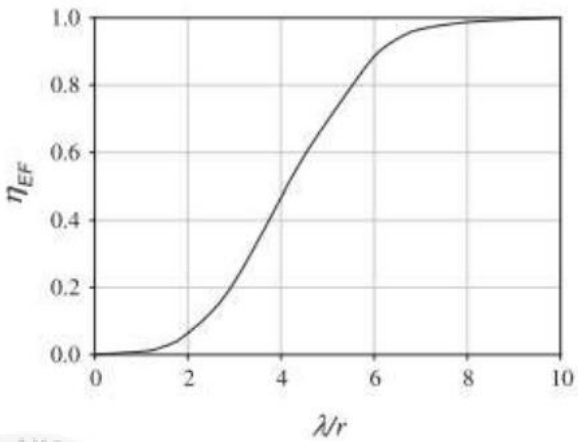


Figure 2.9 Relationship between the normalized wavelength (ƛ/r) and the silica microfiber's power (ηEF) fraction [5]

2.7.1.1 Total Internal Reflection

Total internal reflection is an optical phenomenon that occurs when a light ray traveling through a medium with a higher refractive index encounters a boundary with a medium of lower refractive index at an angle of incidence greater than the critical angle. The light ray completely reflects back into the first medium rather than being refracted and entering the second medium. The difference in light speed between the two media is what causes this phenomenon. The refracted angle would be larger than 90 degrees, which is not physically conceivable when the angle of incidence is greater than the critical angle [15]. Total internal reflection thus takes place, keeping the light contained within the initial medium. Particularly in fiber optics and optical communications, total internal reflection has many real-world uses. Total internal reflection is used by optical fibers, which have a high-refractive-index core and a lower-refractive-index cladding, to direct and transmit light signals across long distances with little loss.

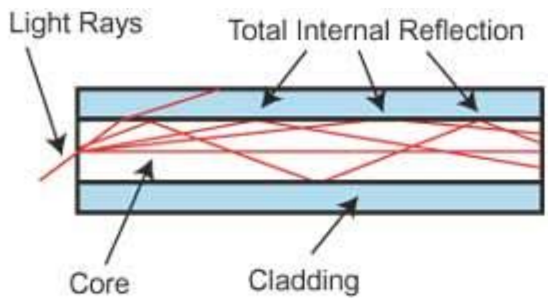


Figure 2.10 Total internal reflection inside the core

Devices like prisms, optical reflectors, and reflective coatings also use total internal reflection. To reroute, concentrate, or improve the propagation of light beams, these applications rely on the controlled reflection of light. The refractive indices of the two media involved affect the critical angle, which decides whether total internal reflection occurs [16]. Snell's law specifies the mathematical connection between the critical angle and the refractive indices.

2.7.1.2 Snell's Law Concept

Snell's Law, commonly referred to as the law of refraction, is a fundamental idea in optics that defines how light behaves as it crosses the boundary between two distinct transparent substances, such as air and water or glass. According to the law, there is a continuous relationship between the sine of the angle of incidence and the sine of the angle of refraction. The angle of incidence is the angle between the incident ray and the surface normal. Snell's Law can be expressed mathematically as:

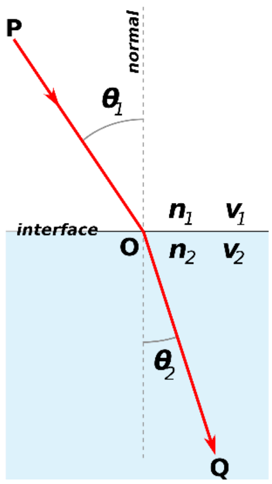


Figure 2.11 Snell's law concept

According to Figure 2.12, Snell's law can be stated as follows:

$$\frac{Sin\theta_1}{Sin\theta_2} = \frac{n_1}{n_2} \; or \; \frac{Sin\theta_1}{Sin\theta_2} = \frac{v_1}{v_2} \tag{2.1}$$

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 states that light waves change direction as they cross the boundary between two media with different refractive indices. When light enters a medium with a higher refractive index, it bends towards the normal, or the line perpendicular to the surface, resulting in a smaller angle of refraction [5]. On the other hand, if light enters a medium with a lower refractive index, it will deviate from the normal and arc away from the normal, increasing the angle of refraction. comprehension different optical phenomena including light bending in lenses, rainbow production, and light behaviour in prisms requires a comprehension of this equation. It provides a mathematical relationship that allows for the prediction and analysis of how light propagates through different media and how it interacts with boundaries between them.

2.7.2 Optical Microfiber Resonators (OMRs)

Microfiber can be used to create resonant structures like micro-loops, micro-knots, and micro-coils. This would lead to the propagation of modes across two adjacent large evanescent field sections. The element of quality's most crucial resonator parameter is Q. It can be estimated by subtracting the wavelength from the transmission spectrum resonance bandwidth (FWHM) [5].

$$Q = \frac{\lambda}{FWHM} \tag{2.2}$$

The use of loop and knot resonators as refractometric sensors that make use of a sizable percentage of the microfiber mode that transmits in the fluidic channel was also mentioned by Vienna et al. (2008). Every variation in the analyte's refractive index results in a shift in the resonance wavelength [5], as shown in Figure 2.13.

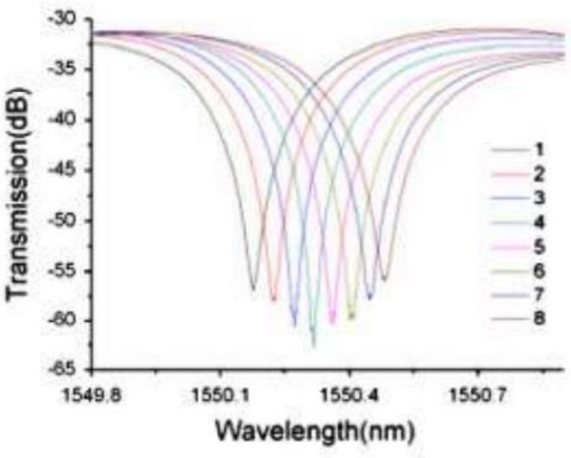


Figure 2.12 Refractometric sensors based on loop and knot resonators' resonant wavelength change [5]

For microfluidic applications, Xu et al. created a refractometric sensor by utilizing a micro-coil resonator with an intrinsic channel. The same procedure is applied to a sensor with a refractometric loop resonator. It functions similarly to a sensor with a refractometric loop resonator. The overlapping of the evanescent wave and the analyte during mode propagation in the microfiber is the cause of this. The resonant wavelength alters as the refractive index varies. The resonance wavelength shifts to a longer wavelength when the analyte’s refractive index rises. These high-Q resonators are appropriate for evanescent sensing for chemical and biological detection due to their enormous resonator surface [5].

2.8 Fiber Optic Sensors for Measured concentration of Liquid (Honey)

The relative amount of dissolved solids, primarily sugars, that are present in honey is referred to as its concentration. Bees make honey from floral nectar, which is a naturally occurring blend of sugars and water. Bees transform the nectar into honey by evaporation and regurgitation. The proportion of dissolved solids (mostly sugars) to the honey's overall bulk or volume determines its concentration. Honey's main sugars are fructose and glucose, which together account for the majority of its carbohydrates. Various elements, including the type of flowers from which the nectar was gathered, the environment, and beekeeping techniques, might affect the concentration of these sugars in honey.

Fiber optic sensors can be utilized for measuring the concentration of liquids, including honey. These sensors offer advantages such as high sensitivity, immunity to electromagnetic interference, and the ability to perform remote and distributed measurements [17]. The refractive index of the liquid, which is directly related to its concentration, can be measured by fiber optic sensors. Honey is a good candidate for use as a concentration measuring parameter since its refractive index fluctuates with its sugar content. Changes in the refractive index can be seen and related to concentration by submerging or flowing the liquid honey over a fiber optic probe or within a fiber-optic-based sensor device [18] [19].

For measuring concentrations, fiber optic interferometric sensors can also be utilized. These sensors make use of the collisions between two or more light waves that are traveling along distinct routes. The concentration-induced changes in the refractive index can be identified as variations in the interference pattern by putting the honey sample in the optical path of an interferometric apparatus. This makes it possible to gauge the concentration of the honey [18]. For concentration measurements, fiber optic sensors based on the idea of evanescent wave absorption can be used. The liquid honey is exposed to a section of the fiber core in these sensors. When light passes through the fiber, a portion of its energy is released as an evanescent wave. The concentration of the honey can be determined and measured by the honey's concentration-dependent evanescent wave absorption [5].

Fiber optic sensors can calculate the concentration of liquid honey using Raman spectroscopy. Raman scattering occurs when light contacts the sample's molecules, producing a unique spectral fingerprint that can be used for identification and concentration calculations. By analysing the Raman spectrum produced by a fiber optic probe immersed in honey, the concentration can be determined based on specific spectral features [17]. These fiber optic sensing methods allow for non-intrusive, real-time monitoring of the concentration of liquid honey. For the purpose of ensuring the precision and uniformity of honey products, they can be integrated into business procedures, quality assurance programmes, or laboratory setups. The correlation between the sensor output and the actual concentration may require calibration methods, taking into account elements like temperature, contaminants, and fluctuations in the composition of the honey [19].

In this project, honey will be measured with three (3) concentrations which are 100% concentration, approximately 70% concentration, and approximately 50% concentration. These three honey samples will be measured by using the best size of fiber optic sensor. Each size for this fiber optic will measure the three concentrations of honey to find out which fiber optic size can get a more accurate honey concentration reading. Accurate measurement of honey concentration is vital for quality control, ensuring compliance with regulatory standards, and meeting consumer expectations. Various methods, including refractometry, spectrophotometry, and hydrometry, can be employed to measure the concentration of honey and determine its quality.

2.9 Microfiber Optic’s Application

Microfiber optics, also known as optical microfibers, are extremely thin and flexible optical fibers with diameters typically in the range of a few micrometers to a few hundred nanometers. Microfibers are exceptional materials that are perfect for functionalizing fiber-optic circuits on a micro or nano scale because of their tight optical confinement, high fractional evanescent fields, and large tunable waveguide dispersion. Research over the past decade has created prospects for fiber optics' renewal and growth. Based on current developments in micro or nanofibers, it emphasizes waveguide and near-field optics. Additionally, nonlinear optics, quantum, and atomic optics, as well as micro or nanofiber applications, can be utilized [20]. Microfiber optic sensors offer advantages such as high sensitivity, fast response time, immunity to electromagnetic interference, and the ability to perform distributed and remote measurements. Their small size and flexibility enable their integration into various devices, systems, and structures. With ongoing research and development, microfiber optic sensors continue to advance and find new applications in diverse fields.

2.10 Summary

The methods used to create tapered microfibers are covered in this chapter. In this part, the flame-brushing method for creating microfiber is covered. So, this chapter has covered the different methods to make fiber optic as a sensor. As of now, must have been a lot of studies done on optical microfiber in terms of fabrication methods, properties, and applications. These tiny fibers have provided a number of advantageous qualities for controlling light on the micro or nanoscale, as well as a new platform for both scientific research and technological applications by shrinking optical fiber widths to the wavelength scale. Numerous new applications of optical micro or nano in atom optics have recently been demonstrated, which may open up new possibilities for using light in ways other than optics and pave the way for a bright future for fiber optics and technology. These capabilities include the ability to waveguide tightly confined evanescent fields with low losses, strong near-field interaction, and miniaturized sizes.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter provides an introduction to the design process of a liquid sensor based on microfiber optics, including thorough information on the tools and components utilized, the production process of the sensor, prototypes, and other topics. With the aid of a tapering strategy, the suggested study seeks to develop a sensor that can recognize honey as a liquid at various concentrations.

For sensing and quantifying the characteristics of liquids such as honey, microfiber optics provide a special methodology. These sensors make use of optical fibers that have extremely small (micrometer-scale) diameters. The microfiber's small size increases its sensitivity to changes in the liquid and allows for accurate measurements. It is possible to detect interactions with the honey, such as changes in refractive index, absorption, or fluorescence, by including a sensing device or coating on the microfiber. The qualities of the liquid can be precisely measured by analyzing these variations in the light passed through the microfiber, which can reveal important details about the parameters of honey samples.

3.2 Project Flow Chart

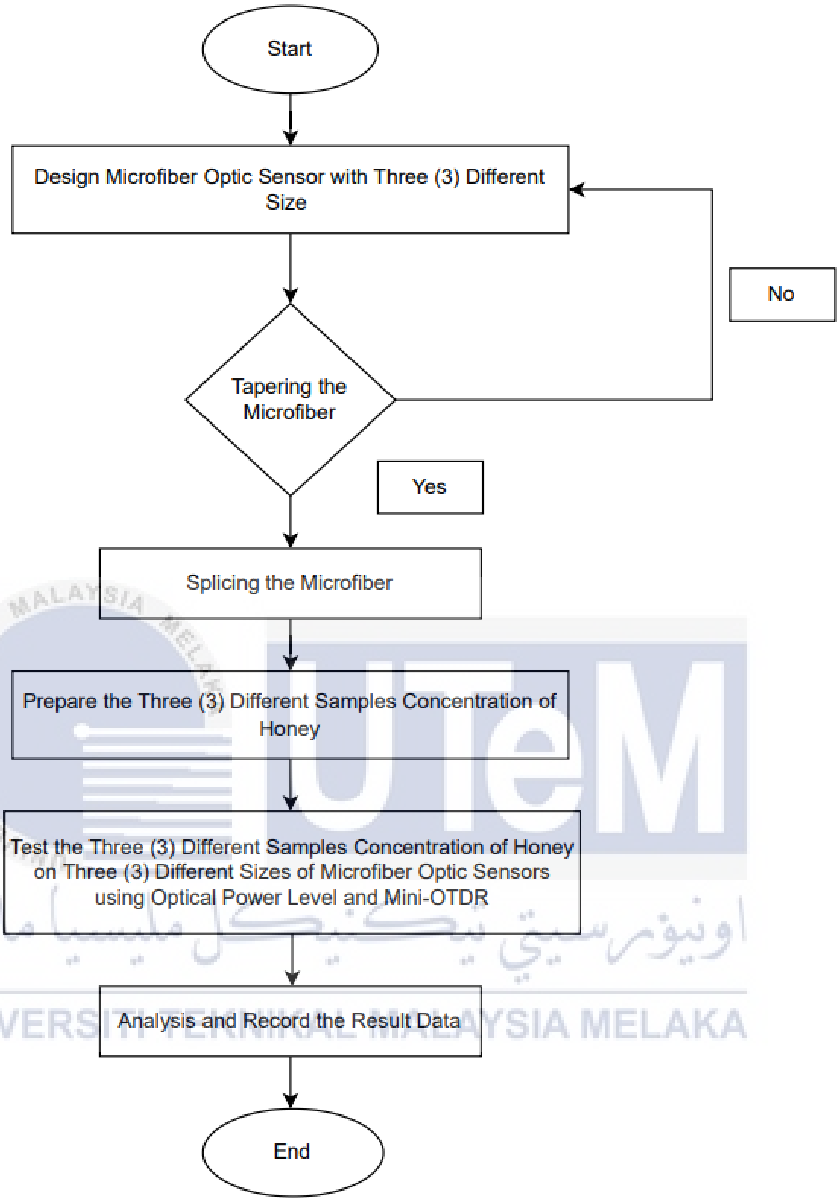


Figure 3.1 Project's workflow process

According to Figure 3.1, the research began with the development of a microfiber optic sensor that uses a tapering method to detect liquid (in this case, honey). Three samples (100% concentration), (approximately 70% concentration), and (approximately 50% concentration) of honey in various quantities will be examined with the best one size of microfiber optic. Each measurement would yield a different result in a line graph. To minimize losses throughout the experiment, the 125micrometer single-mode fiber was first cut to the same length. The preparation of the three samples of honey with various concentrations came next. Throughout the experiment, the honey will be kept in a plastic container.

Each fiber will be examined and tracked when the setup is complete in order to derive an average measurement. Following the results, the experiment's findings which are entirely dependent on the honey concentration and light source will be discussed in terms of sensitivity, correlation, and the graph's coefficient of determination.

3.3 Method of Project

The methodology requires the use of complementing models, facility and equipment-specific procedures, throughout each stage of project development. A methodology is made up of many approaches that are individually used to address different aspects of the methodology as a whole. The sensor structure can be expanded using a variety of techniques. The steps listed below can be used to accomplish these.

3.3.1 Tapering the Microfiber Process

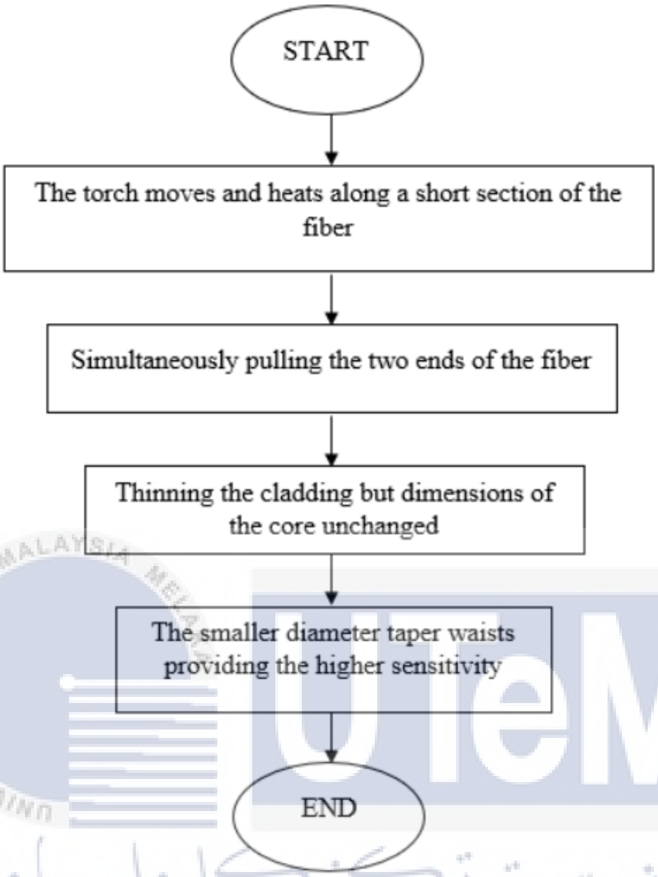


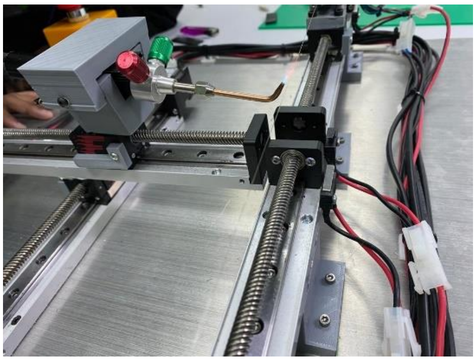
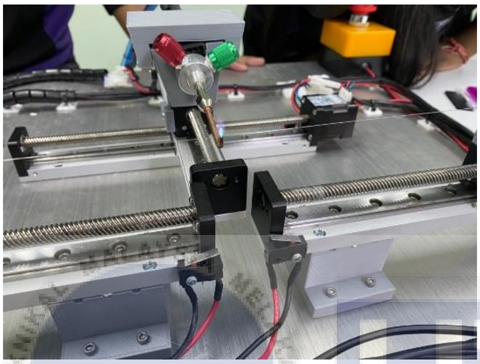
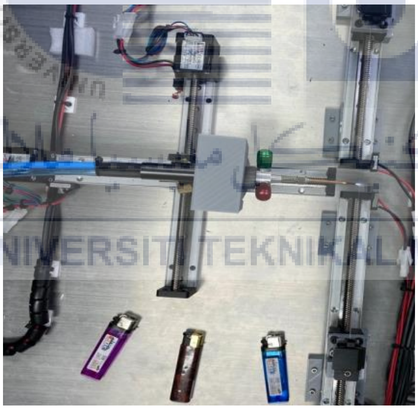
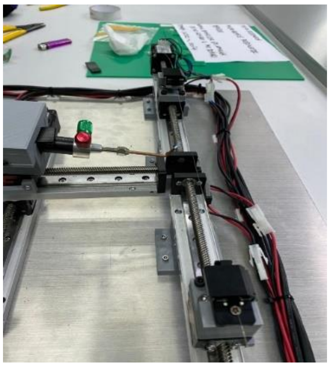
Figure 3.2 Flowchart of the tapering process

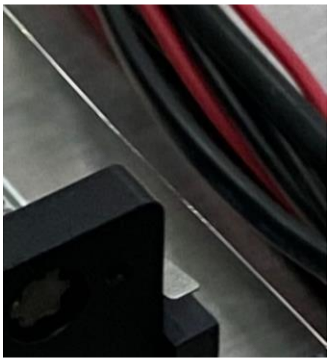
To create tapered microfiber, a coating length of several centimetres is first removed from the SMF. After that, the SMF is supported by two fibre holders and positioned horizontally on the translation stage. As seen in Figure 3.2, the torch pulls the two ends of the fiber while moving and heating a brief segment of the fiber. Oxygen and the flame of a gas hob provide the heat. The rig has two stepper motors that are used to regulate the translation stage and torch movement. The waist diameter of a heated glass fiber decreases upon stretching. The tapered fiber is created with good homogeneity along the heat region.

The core and cladding diameters are lowered by the same amount during the tapering process. Light is linked from the untapered fiber's basic mode to the tapered section's modes so that they can interact with the process's surrounding medium. Thinnelling the optical microfiber's cladding while maintaining its core dimensions is another method to improve the interaction of light travelling within the fiber with the surrounding medium. Its sensor's performance depends on the tapered microfiber; higher sensitivity is produced by taper waists with smaller diameters. Table 3.1 provides a detailed flowchart of the tapering process.

Table 3.1 Complete steps on tapering process

No	Procedure	Description
1		Using a stripping tool, cut and remove the second layer (cladding) from the centre of the optical cable.
2		Using tissue and alcohol to remove the dust.

3		Place the stripped fiber optic in the middle of the tapering machine holder.
4		Adjust the two tapered holders until the optical fiber is taut.
5		Adjust oxygen and gas to ignite the flame and obtain a perfect flame before burning the optical fiber.
6		Move the flame nozzle forward until the flame hits the fiber optic to create combustion and move the flame nozzle to the left and also to the right until it is finished.

7		Finally, look at the results of the optical fiber after burning using the tapering method.

3.3.2 Splicing Process

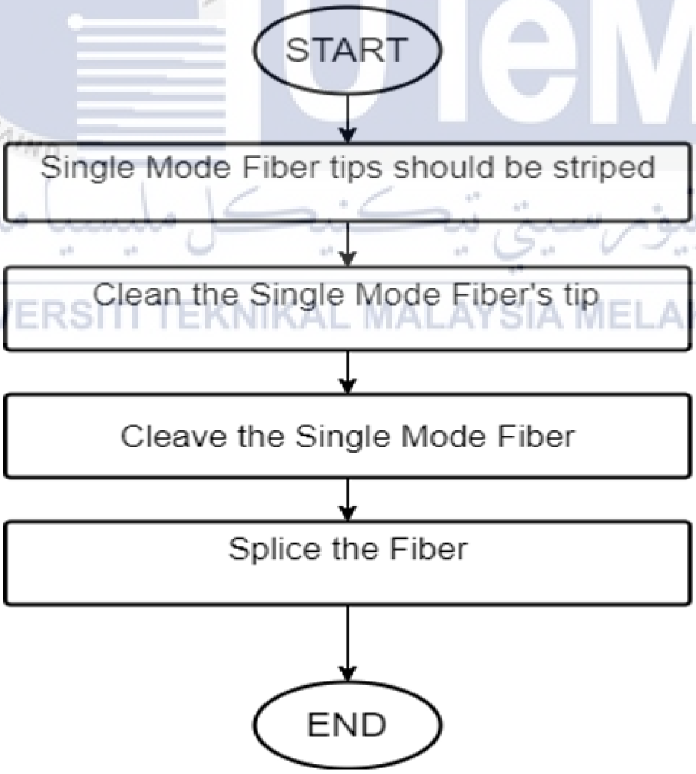


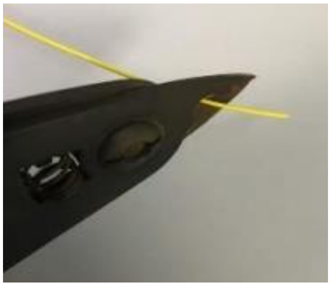
Figure 3.3 Flowchart of splicing process

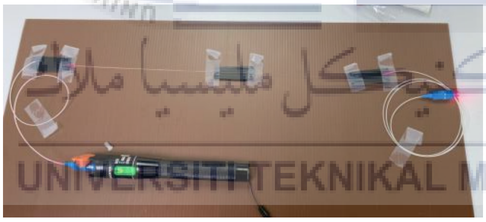
The Single Mode Fiber's coating layer is first removed using a fiber optic cable remover. After that, alcohol is used to clean the fibers and remove any leftover coating or dust. The fiber is then cut off using a Fujikura CT-30 high-quality cleaver to produce a flat, and perpendicular end face on each fiber.

The joining of two fibers after they have been cleaned and stripped of their cladding is accomplished using the Fujikura FSM-18R splicing tool. The fiber will then be mounted on the splicer with the fibers positioned parallel to one another. In order to give the joint mechanical strength and protection, the fusion splicer frequently adds a protective sleeve or heat shrink tube over the spliced area.

Table 3.2 Detailed procedure for using the Fujikura FSM-18R to splice

No.	Procedure	Description
1.		List of splicing equipment that will be used throughout the splicing process.
2.		Need to switch on Fujikura FSM-18R first to get ready before using it.

3.		Cut the optical cable's outermost layer.
4.		The optical cable's second (cladding) layer should be removed.
5.		Using tissue and alcohol to remove the dust.
6.		Use a high-precision cutter to cut the optical cable.

7.		Make sure the cable is in the same position when want to place it on the divider.
9.		Once press "start," wait for the connection to establish itself.
10.		After completing the connection between the two cables, the connection cable is placed on the 27" x 30" Impra board.

3.3.3 Process of Determining Concentration

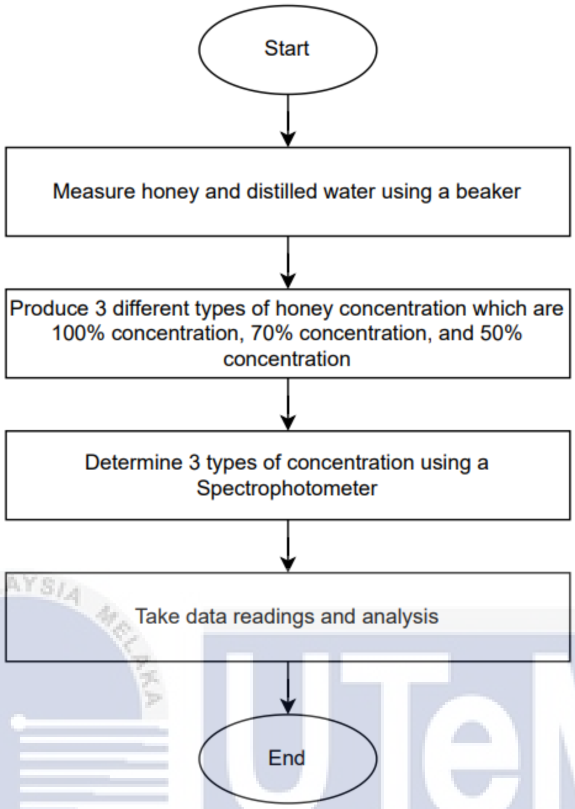


Figure 3.4 Flowchart process to determine the percentage concentration of honey

A spectrophotometer is an equipment used to determine the concentration of a liquid. In addition, this equipment will also give values of transmittance, absorption, factor (set by itself), and concentration for a certain liquid concentration. For this analysis, the concentration of honey must be accurately determined to avoid any errors in the final results. The concentration of honey that needs to be determined is 100% concentration, 70% concentration and 50% concentration.

Figure 3.5 Spectrophotometer (Spectrumlab 721s)

The concentration wavelength used to determine the concentration of honey is 550nm and the factor value is set at 1000. Before determining this concentration, honey must be mixed with distilled water according to the measurement to distinguish each concentration's percentage difference. The figure below shows honey and distilled water being measured using a beaker before mixing.

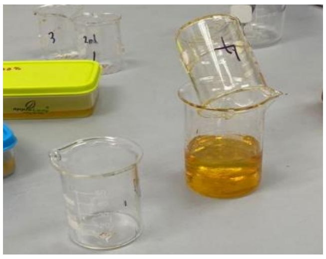
Figure 3.6 Honey and distilled water are measured using a beaker

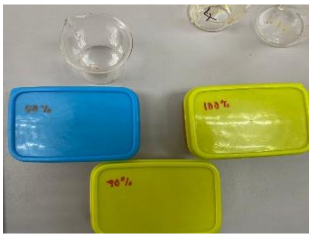
After the honey and distilled water have been measured, separate each of the estimated honey concentrations of 100% concentration, 70% concentration, and 50% concentration and place the honey in a plastic container. After that, put each condition of honey that has been separated into the curvettes before placing the curvettes into the spectrophotometer as shown in the diagram below.

Figure 3.7 Curvettes (containing honey inside) are placed into the Spectrophotometer

The spectrophotometer will determine the value of transmittance, absorption, factor, and concentration for each concentration of honey. Record the concentration reading value for each honey condition as an analysis. The table below shows each type of equipment used to determine the honey concentration:

Table 3.3 Equipment used to determine the concentration of honey

Equipment	Description
 Beaker	• A beaker measures the quantity of honey and distilled water before mixing.

 Plastic Container	• A plastic container is used to put a mixture of honey and distilled water that has been measured.
 Cuvettes	• Put the measured honey into the cuvettes. • Cuvettes are inserted into the Spectrophotometer to determine the honey concentration value.
 Spectrophotometer (Spectrumlab 721s)	• Set the wavelength concentration to 550nm. • Determine the concentration of the liquid (Transmittance, Absorption, Factor, and Concentration). • The laser light will penetrate the cuvettes and directly get the liquid value.

3.3.4 Experimental Setup Process

Preparing and arranging of the tools, materials, and equipment needed to carry out a scientific experiment or research is part of the experimental setup procedure. The experiment's goal and the variables that will be assessed or controlled are often the first things to be determined. It also entails adhering to certain guidelines, making required modifications, and making sure safety measures are taken. The experimental setup procedure is essential for scientific research to provide dependable and precise results. To fulfil the goal of this project, the experiment procedure process will be continued in this section.

3.3.4.1 Preparations of Tapered Microfiber Optic Sensor

The tapered microfiber optical sensor for the preparation process is provided in Table 3.1 and these are some a samples of tapered microfiber fabrication based on the tapering method, as illustrated in Figure 3.8.

Figure 3.8 The microfiber optic has been tapered

3.3.4.2 Dropper Feeder to Dripping Liquid (Honey)

A dropper feeder drips liquid (honey) on the microfiber optic sensor and measures the sensitivity, linearity, and repeatability of various liquid (honey) concentrations. After splicing the fiber optic, Figure 3.9 shows a picture of the dropper feeder that will be used to drip honey on the microfiber optic sensor with just a few drops. The Dropper feeder makes it very easy to drip honey on the microfiber optic sensor to get a more accurate sensitivity value.

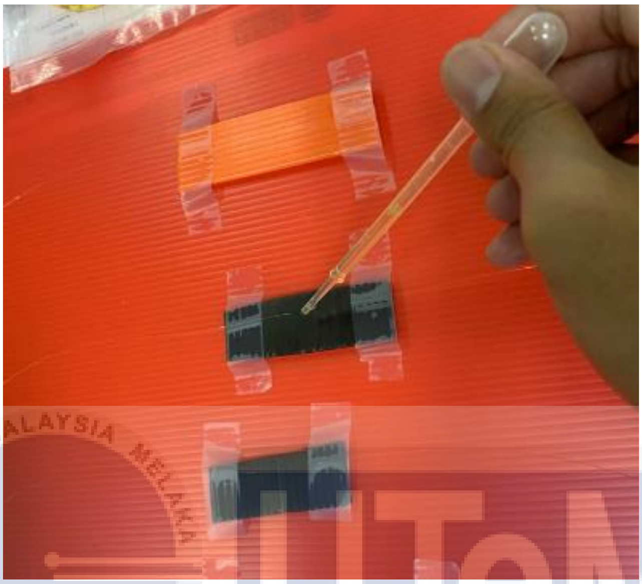


Figure 3.9 Dropper feeder

3.3.4.3 Procedure Material and Equipment Setup

For the first step, we must set the wavelength of the optical power level and mini-OTDR to 1550 nm and plug the fiber optic pigtail shown in Figure 3.10. The concentration of the liquid (honey) will then be tested and put through its paces by making readings for sensitivity, linearity and repeatability taken with an optical power level mini-OTDR for various concentrations of honey shown in Figure 3.11. Lastly, the output can then be measured in decibels (dBm) and taken every three minutes at a wavelength of 1550 nm using the Optical Power Level and Mini-OTDR five (5) times take for each varied concentration of honey.

Figure 3.10 Optical Power Level and Mini-OTDR

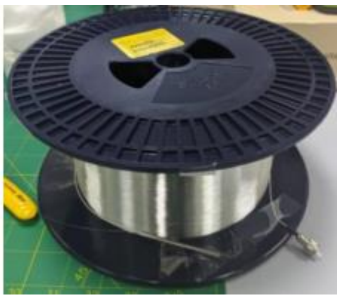
Figure 3.11 Tapered microfiber sensor in different concentrations of honey

3.4 Tools and Materials

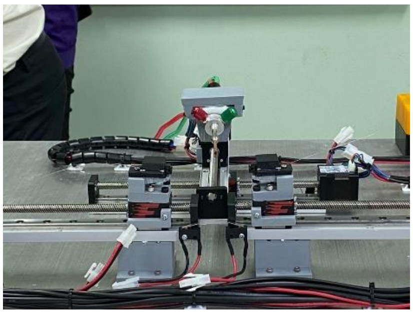
The complete equipment and materials used for this project are shown in Table 3.4.

Table 3.4 All equipment and materials used for this project

Equipment and Material	Description
 SimpliFiber Pro (Optical Power Level)	At 850 nm, 1300 nm, 1310 nm, 1490 nm, 1550 nm, and 1625 nm, the SimpliFiber Pro optical power meter is accurately calibrated. The meter has a reference power level saving feature that enables a clear display of fiber loss.
 Mini-OTDR Optical Power Meter	Produce a waveform and also a value for the concentration of a liquid as an output. The wavelength is 1550nm.
 Tape Dispenser	Used to secure the tapered microfiber on the impra board.
 Commercial Splicer Fujikura FSM-18R	Similar in versatility and toughness to the Fujikura 12-fiber ribbon splicer, the FSM-18R fusion splicer is a 4-fiber ribbon splicer. The FSM-18R fusion splicer can splice up to 4 fibers as well as single

	fibers, making it ideal for FTTx or LAN applications. The improved robust features endure a 30" drop test and offer resistance to stress, dust, and rain to save downtime and increase operating effectiveness.
 Cleaver Fujikura CT-30	A unique cb-16 blade made of extremely resilient steel is used by the Fujikura CT-30A to split fiber. At least 1000 cleaving operations are intended to be performed at each blade position. The blade can be fixed at 16 distinct rotational positions.
 Fiber Optic Stripper	An instrument used to remove closely packed optical fibers is called an optical fiber stripper. It is frequently used to remove tightly packed optical fibers before splicing them.
 Single-mode fiber	Used in the creation of sensors and the size of fiber optics that we use is 125nm.

 Single mode connector (pigtail)	A fiber optic cable is terminated with a factory-installed connector on one end, leaving the other end unterminated, to form a fiber optic pigtail. As a result, the connector side can be connected to machinery while the other side is melted using optical fiber cables. The 99% of single-mode applications that employ optical fiber can be joined in the best possible way with a fiber optic pigtail.
 Isopropyl Alcohol	It resolves numerous problems with fiber optics after splitting and before connecting by simply removing the harmful dirt, residue, and dust.
 Tissue	When cleaning end faces using the wet-to-dry approach, low-lint and non-woven wipes can be utilized. These materials can be used to clean fiber optic connectors because they are very absorbent.

 Tapering Machine	Tapering of optical fibers has been employed for modifying the light propagation conditions in fibers, and further allowing for the guided light to interact with other structures or materials.
 Dropper Feeder	A dropper feeder is used to drip liquid (honey) on the microfiber optic sensor and measure the sensitivity, linearity, and repeatability of various liquid (honey) concentrations.
 Impra board 27” x 30”	Used as the main supply point for experiments, the fiber is laid once it has been spliced.
 Honey	This project uses honey to measure concentration in 3 conditions which are 100% concentration, approximately 70% concentration, and approximately 50% concentration.

 Spectrophotometers	Spectrophotometers measure intensity in relation to the light source's wavelength.

3.5 Experimental Setup Project

The microfiber optic sensor setup will demonstrate the connection of the equipment and components with their functions in this part. Also, this part has shown the specific demonstration of tapered fiber fabrication using a flame in Figure 3.11 and a microfiber optics sensor to detect liquid (honey) in Figure 3.12.

3.5.1 Tapered Microfiber Optic using a Tapering Method

Biconical tapered fibers can be created using this method and connected to single-mode fiber (SMF) at both ends. Low-loss microfiber-based devices can also be created using these biconical tapered fibers. Biconical tapered fibers provide a versatile framework for the creation of several photonic devices. Researchers can quickly incorporate these fibers into current optical setups by connecting both ends of the tapered fiber to SMFs.

The potential of biconical tapered fibers to increase light coupling efficiency is one of their key benefits. A greater numerical aperture (NA) and a smaller mode field diameter are the results of the steady reduction in fiber diameter during the tapering process. Due to their low-loss properties, microfiber-based devices made with biconical tapered fibers have attracted a lot of attention. Strong light confinement and decreased scattering losses are produced by the tapering process, which produces microfibers with diameters typically in the submicron range.

Techniques for making biconical tapered fibers are compatible with a range of optical fibers, including photonic crystal, specialised, and silica fibers. This flexibility makes it possible to combine many fiber types into a single device, which makes it easier to realise intricate and multifaceted photonic systems. Biconical tapered fiber production can be simply scaled up to create several devices with reliable performance. Figure 3.11 illustrates a schematic of the flame-brushing method's use in the production of tapered fibers. In order to create tapered fiber, the SMF had a coating length of several cm removed (see Figure 3.12). The SMF is then positioned horizontally on the stage and secured with two fiber holders.

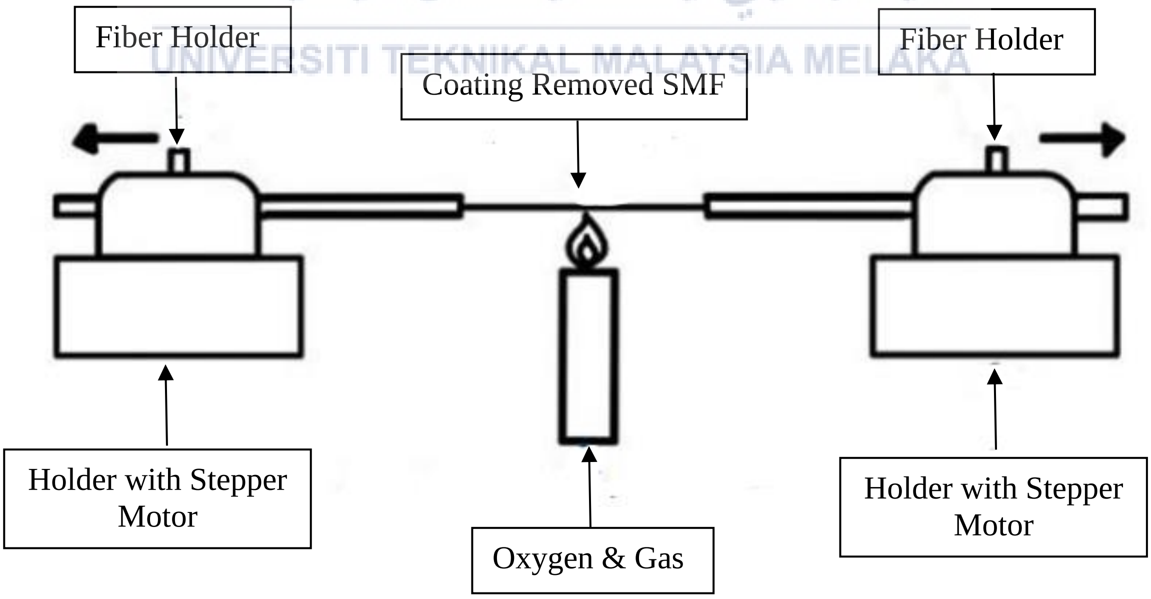


Figure 3.12 Setup for a flame-blushing experiment to create tapered microfiber

3.5.2 Microfiber Optics Sensor to Measured Liquid (Honey)

Single-mode fiber optic sensors are connected to an Optical Power Level at the input to assess the various liquid (honey) concentrations. The wavelength that the optical power level emits to the fiber is 1550 nm. The mini-OTDR then records the outcome in dBm, as seen in Figure 3.13 below.

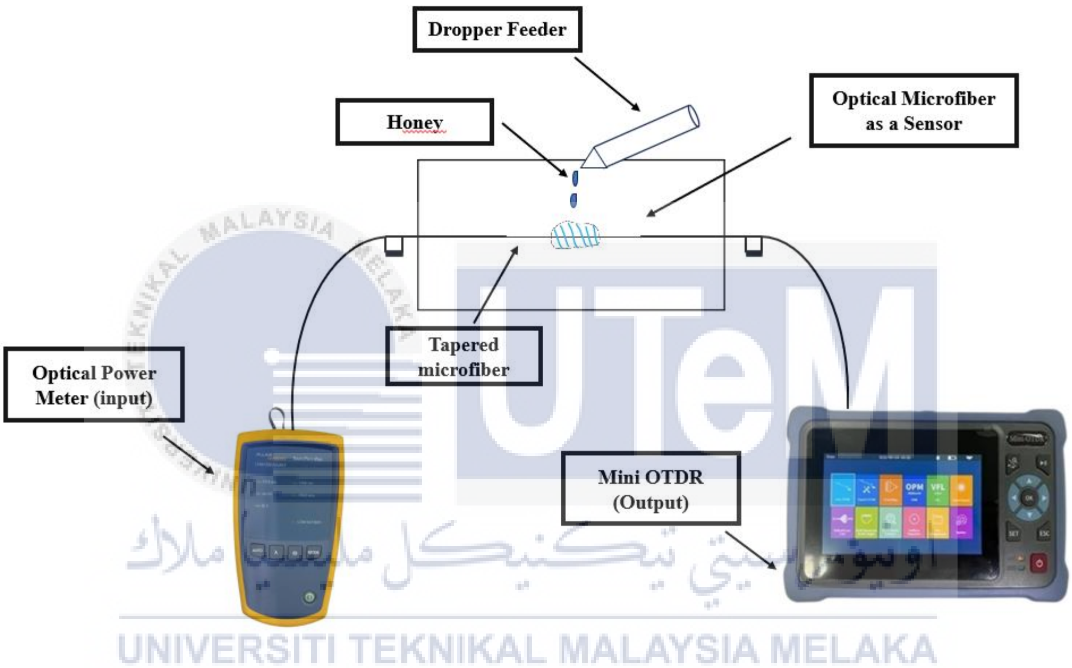


Figure 3.13 Experiment setup of optical microfiber sensor to measure liquid (honey) in different concentrations

Three samples of various honey concentrations will be evaluated, as well as three variations in the thickness of the optical microfiber size that will be employed to do so. Every measurement will yield a different result in a line graph. The optical microfiber will function as a sensor to find various concentrations of honey. Three drops of honey will be applied to the microfiber optic sensor. Approximately 100% of the honey is dripped for the first time.

Next comes a 70% and a 50% transition on the optical microfiber. As a result, the various honey concentrations, will affect the reading's value.

The experimental findings will be discussed in terms of sensitivity, correlation, and coefficient of determination graphs, all fully dependent on honey concentration and light source. The results of the analysis will be shown.

3.6 Limitation of the Proposed Methodology

One of the project’s limits is the difficulty in creating dependable and repeatable devices for applications requiring tapered microfiber optic sensors. It should be mentioned that, in their most basic configuration, tapered devices lack selective sensitivity and necessitate specificity coating. In addition, technical concerns about the intricate treatment of microfiber throughout the procedure and keeping their performance affordable. Next, because of inadequate and restricted equipment, students will use the laboratory at the FTKE building.

3.7 Summary

This chapter outlines the suggested process for creating an optical microfiber sensor for liquid (honey) in various concentrations utilizing a tapering method. The primary objective of the suggested methodology is to increase the optical power level and the mini-OTDR waveform output value. Instead of achieving the highest level of accuracy, the technique's ultimate goal is to maximize the effectiveness, simplicity of use and manipulation, and usefulness of microfiber optic sensors.

CHAPTER 4

RESULTS & DISCUSSIONS

4.1 Introduction

This chapter presents the results and analyses of developing a microfiber optic sensor for measuring liquid (honey). A case study was carried out to show the sensitivity of optical microfiber cables. Three distinct samples of the concentration of honey will be evaluated such as 100% concentration, approximately 70% concentration, and approximately 50% concentration, as well as three samples of the three different sizes (thick, medium, and thin) of the microfiber optical sensor must choose the best one size that was used to measure the concentration of honey. A dropper feeder will dribble honey on the fibers before each test, and the fibers will then be measured. Every measurement will yield a different result in a line graph. To determine the sensitivity, linearity, and repeatability of the graph all of which depend totally on the honey concentration and the light source experimental results will be presented in a case study. It should be mentioned that this case study aims to demonstrate the suggested methods for testing various honey concentrations. The proposed procedure involves testing five (5) times because of the percentage value for each distinct concentration of honey.

4.2 Results and Analysis

This chapter analyses test findings from three samples of liquid (honey) at various concentrations using the best-tapered microfiber optic as a sensors. These analyses are broken down into many pieces of data, including the number of tests, the best one-size of microfiber optic sensors, the linearity, and indications of high sensitivity, consistency, repeatability, and steady execution tests.

4.2.1 The Best Size of Microfiber Optic Sensor

The microfiber optic sensor's dimensions are determined by the needs and particular application. Because microfiber optic sensors are small and flexible, they can be used for a wide range of tasks, including detecting changes in temperature, pressure, humidity, liquid, and refractive index. The ideal size will depend on several variables, including the desired level of sensitivity, the material to be detected, and the environment in which the sensor will be utilised.

Table 4.1 Comparison of the Experiment's Data Collection

Output Power 100% Honey Concentration (dBm)			
	Wavelength 1550nm		
Time	Size A	Size B	Size C
1	-37.59	-42	-42.61
2	-39.78	-43.55	-42.99
3	-39.93	-43.81	-43.37
4	-40.42	-43.9	-43.46
5	-40.61	-43.99	-43.51
6	-40.61	-43.99	-43.58

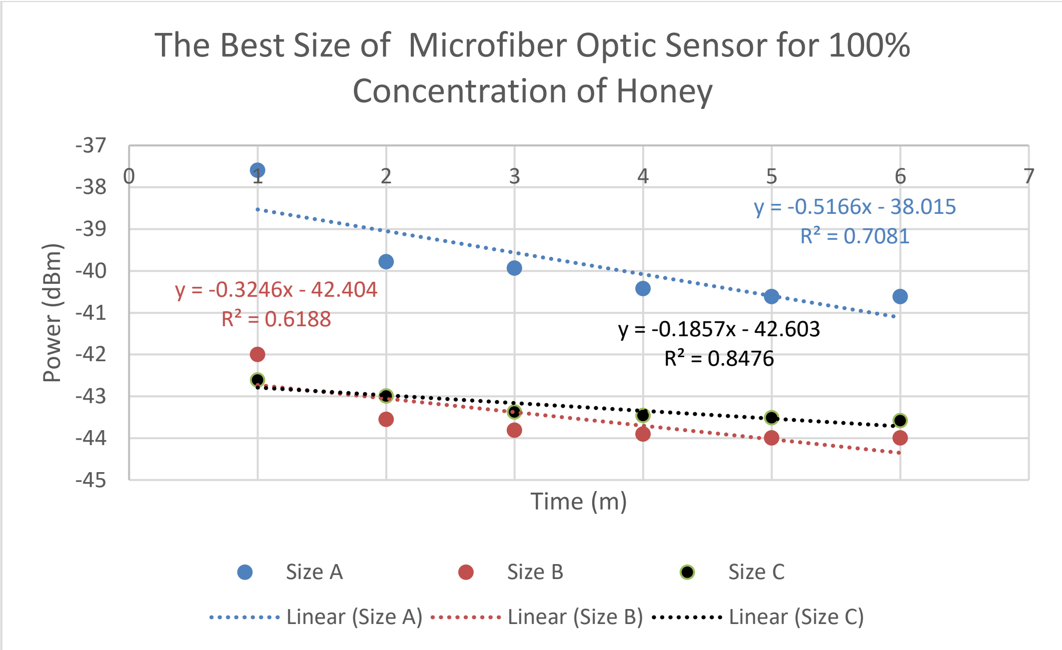


Figure 4.1 Power Transmitted Graph for 100% Concentration of Honey

Table 4.1 above shows the reading of the output power values for 100% honey concentration (dBm) using a wavelength of 1550nm for size A, size B, and size C tapered microfiber. To determine the best microfiber optic sensor must look at the sensitivity value. The graph in Figure 4.1 shows that microfiber optics sizes A, B, and C have different sensitivity values. Without considering the sign value, the sensitivity value for size A is 0.5166, the sensitivity value for size B is 0.3246, and the sensitivity value for size C is 0.1857. The sensitivity value for size A is higher compared to the sensitivity value of microfiber optic sensor size B and also size C. It shows that microfiber optic sensor size A is the best size for measuring the concentration of honey.

To further confirm the sensitivity of this microfiber optic sensor, we need to know the size of its thickness. If the size of the microfiber optic sensor is thin, then the sensitivity of the microfiber optic sensor is high. Here , it shows the size of the microfiber optical sensor determined by using a microscope, as shown in Figure 4.2. To assess the microfiber's sensitivity level, it is crucial to ascertain its size. Sizes 12.6 µm (size A), 26.5 µm (size B), and 30.3 µm (size C) were discovered. The range of axis-y is measured to investigate sizes.

Figure 4.2 Determining the size of microfiber using a Microscope

Figures 4.3, 4.4, and 4.5 below show the size thickness value and size thickness difference on each tapered microfiber.

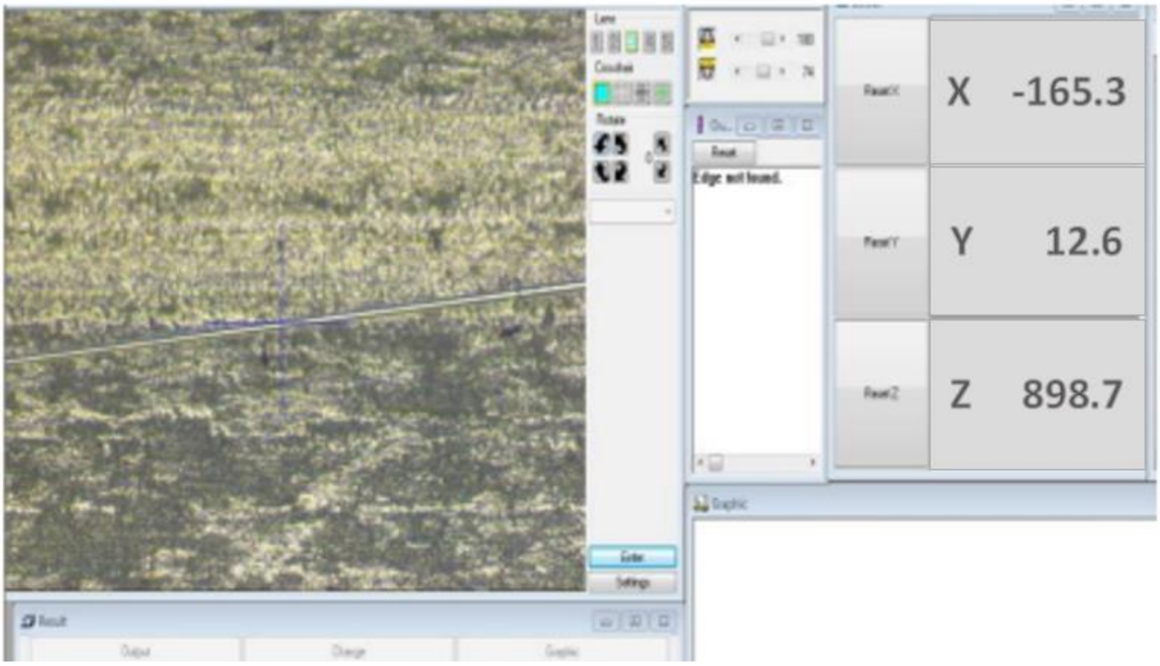


Figure 4.3 Microfiber Optic size A (12.6 μm)

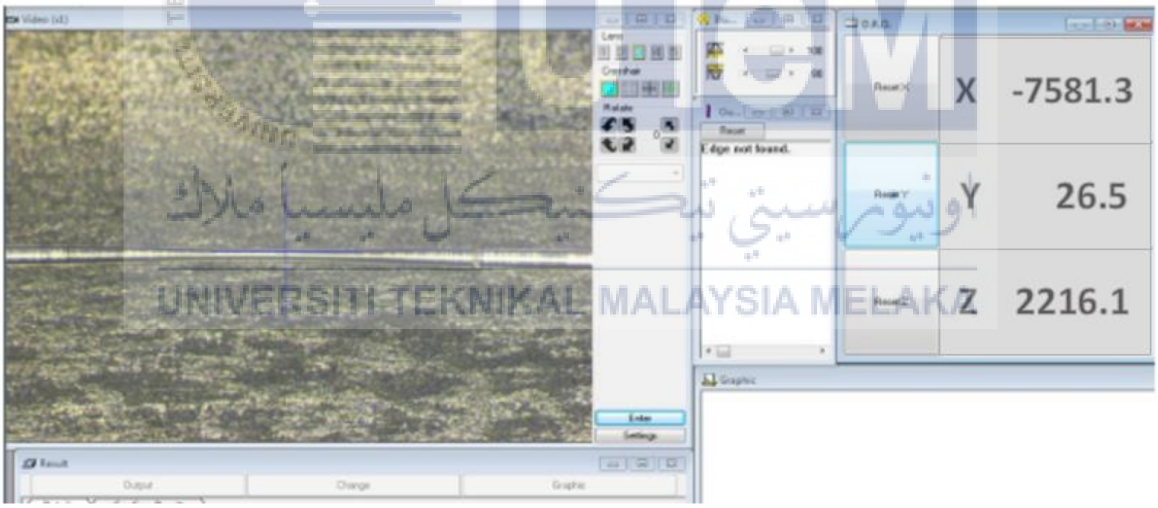


Figure 4.4 Microfiber Optic size B (26.5 μm)

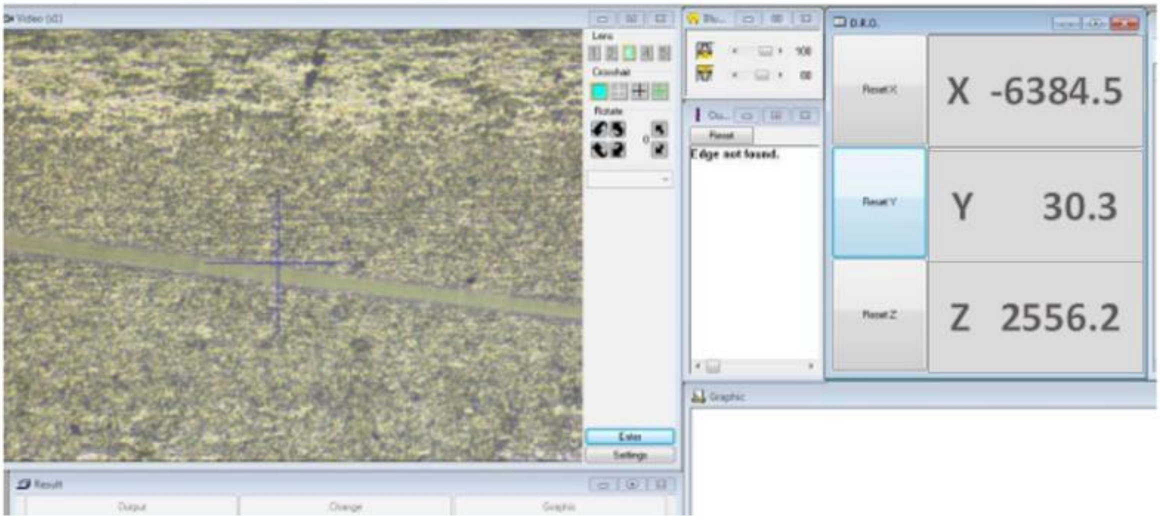


Figure 4.5 Microfiber Optic size C (30.3 µm)

In comparison to the other two tapered microfibers, size A demonstrated the best-tapered microfiber with the smallest size, yielding the highest sensitivity. The microfiber's tiniest size could make it extremely sensitive. The diameter of the microfiber optic size B has narrowed to approximately 26.5 µm. The second-smallest tapered sample in terms of size is this one. Of the three tapering sample sizes, the microfibre optic size C's diameter along axis Y displays the largest size. Consequently, of the two microfiber optics, microfiber optic size C will have the lowest sensitivity.

Table 4.2 Sensitivity and linearity of microfiber optic sensors

Optical Microfiber Sensor	Sizing	Sensitivity (dBm)	Linearity
Size A	12.6 µm	0.5166	84.15
Size B	26.6 µm	0.3246	78.66
Size C	30.3 µm	0.1857	92.07

Table 4.2 above shows each tapered microfiber size's sizing, sensitivity, and linearity values. A discussed, the sensitivity value for microfiber optic size A (-0.5166 (dBm)) is higher than the other sizes. The sensitivity values for each type of fiber shown in the table are taken from the slope value of the regression line by omitting the value sign. For the linearity value, the linearity value for microfiber optic sensor size A is 0.841, for microfiber optic sensor size B is 0.787, and for microfiber optic sensor size C is 0.921. All three linearity values for each size are strong negative linear correlations. Furthermore, the linearity value indicates that the data have a good fit.

4.2.2 Difference Results For Each Concentration Of Honey

For this analysis, the concentration of honey to be tested is 100%, 70%, and 50%. To determine the percentage value of the honey concentration by using a spectrophotometer (Spectrumlab 721s). Before using the spectrophotometer, the honey must be mixed with distilled water to reduce the concentration for concentration percentages such as 70% concentration and 50% concentration. Table 4.3 below shows the quantity of honey and also the quantity of distilled water measured using a beaker and will be mixed.

Table 4.3 Measured value of honey and distilled water

Concentration	Honey	Distilled Water
50%	30mℓ	30mℓ
70%	30mℓ	20mℓ
100%	30mℓ	0mℓ

After preparing the three (3) different concentrations of honey mixed with honey and distilled water, separate each type of honey concentration in a plastic container. After that, put each type of honey concentration in the cuvettes and when finished, put the cuvettes into the spectrophotometer to get the reading value for each honey concentration.

Set the wavelength concentration value which is 550nm and set the factor value which is 1000. The laser light will penetrate the cuvettes and will directly get the liquid value (transmittance, absorption, factor, and concentration) for each concentration as shown in table 4.4 below.

Table 4.4 The concentration value for 3 conditions of honey by using a spectrophotometer

Condition of Honey	Transmittance Value	Absorption Value	Factor Value	Concentration Value
50%	74.0	0.131	1000	131
70%	72.8	0.138	1000	138
100%	55.5	0.255	1000	255

Referring to Table 4.4, the honey concentration value for the 50% condition is 131, the honey concentration value for the 70% condition is 138, and the honey concentration value for the 100% condition is 255. The absorption value for each condition is increased because the amount of distilled water mixed into the honey is accurate. The honey concentration value for each condition is accurate. Calculation to obtain the concentration value:

$$\boxed{Absorption \times Factor = Concentration}$$

The factor value for each condition is set to the same value which is 1000. This is because if the factor value is set below 1000, the concentration value will become unstable and get a decimal point. In this case, the factor value is set to 1000 in each condition to obtain an accurate and stable concentration value.

4.2.3 Sensitivity of Microfiber Optics Sensor on 50%Honey Concentration

Based on the performance of microfiber optics as a liquid sensor in various honey concentrations that were tested, the analysis is based on the sensitivity and linearity % of the data. As indicated in Table 4.5, this investigation has seen and recorded the output power for 50% concentration of honey at 1550 nm wavelengths. About 50% of the honey concentration was tested initially, and then 70% and 100% of the honey concentration.

Table 4.5 Comparison of Data Collected for 50% Honey Concentration

Output Power 50% Honey Concentration (dBm)			
	Wavelength 1550nm		
Time	Size A	Size B	Size C
1	-38.63	-39.7	-39.55
2	-39.46	-40.34	-39.96
3	-40.05	-40.35	-40.03
4	-40.26	-40.38	-40.08
5	-40.26	-40.4	-40.15

6	-40.39	-40.43	-40.15

Table 4.6 Sensitivity and linearity of 50% honey concentration

Size of Microfiber Optic Sensor	Sensitivity (dBm)	Linearity
Size A	0.326	0.898
Size B	0.1103	0.738
Size C	0.1034	0.856

According to Table 4.6, the 50% concentration of honey had a greater sensitivity value at microfiber optic sensor size A, managing to have 0.326 dBm. This cycle was repeated five times for each concentration, which lessened random error when observing the results. In contrast, we can observe that the value linearity at the microfiber optic size A has the maximum linearity which is strong negative linear correlation, leading to the data fitting in the linear graph. This indicates that microfiber optics will function at the maximum value of a liquid sensor. With a linearity of 0.898 of the 50% honey concentration interacting with the light source passing through it, the microfiber optic sensor size A exhibits a significant linear connection in comparison to the microfiber optic sensors size B and size C. Compared to microfiber optic sensors of sizes B and C, the sensitivity value of microfiber optic sensor size A is higher.

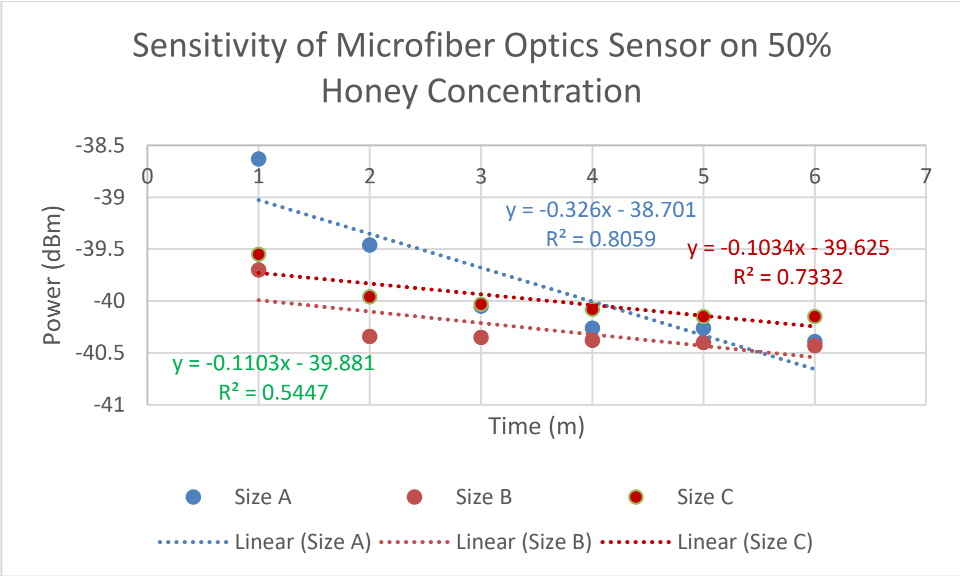


Figure 4.6 Sensitivity of microfiber sensor on 50% honey concentration

Three distinct lines for sensitivity are displayed in Figure 4.6, with the overall result percentage being 50% honey concentration at 1550 nm wavelength. With various sizes of optical microfiber sensors, the optical microfiber functions as a sensor to measure the concentration of honey and perform in concentration sensitivity. The parameters under observation were sensitivity and linearity. The cycle has a clear tendency to rise and fall before levelling off and reaching its starting point. Based on the factors, the analysis indicates that an optical microfiber sensor size A will demonstrate the superior performance of the optical microfiber sensor. Time and power (dBm) have a significant positive linear correlation. This experiment also establishes that the sensitivity is sensed using microfiber optics as a liquid sensor.

4.2.4 Sensitivity of Microfiber Optics Sensor on 70%Honey Concentration

The second investigation is based on the test's results regarding the sensitivity and linearity of microfiber optics' performance as a liquid sensor in honey concentrations of

70%. Using an optical microfiber sensor of varying sizes, the output power has been measured and documented for each concentration through this investigation, as indicated in Table 4.7.

Table 4.7 Comparison of data collected for 70% honey concentration

Output Power 70% Honey Concentration (dBm)			
	Wavelength 1550nm		
Time	Size A	Size B	Size C
1	-38.63	-39.24	-40.25
2	-40.34	-40.68	-40.37
3	-41.27	-40.71	-40.79
4	-41.78	-40.74	-40.84
5	-42	-40.75	-40.86
6	-42.2	-40.76	-40.86

Table 4.8 Sensitivity and linearity of 70% honey concentration

Size of Microfiber Optic Sensor	Sensitivity (dBm)	Linearity
Size A	0.6669	0.921
Size B	0.224	0.7
Size C	0.1306	0.884

According to Table 4.8, the 70% concentration of honey had a greater sensitivity value at microfiber optic sensor size A, managing to have 0.6669 dBm. This cycle was repeated five times for each concentration, which lessened random error when observing the results. In contrast, we can observe that the value linearity at the microfiber optic size A has the maximum linearity which is strong negative linear correlation, leading to the data fitting in the linear graph. This indicates that microfiber optics will function at the maximum value of a liquid sensor. With a linearity of 0.921 of the 70% honey concentration interacting with the light source passing through it, the microfiber optic sensor size A exhibits a significant linear connection in comparison to the microfiber optic sensors size B and size C. Compared to microfiber optic sensors of sizes B and C, the sensitivity value of microfiber optic sensor size A is higher.

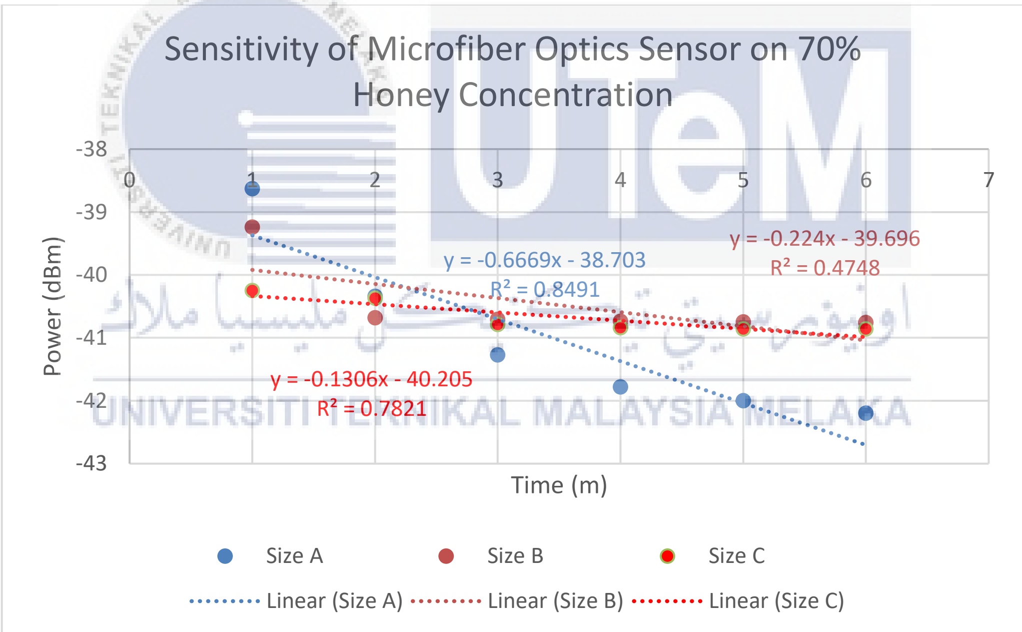


Figure 4.7 Sensitivity of microfiber sensor on 70% honey concentration

Three distinct lines for sensitivity are displayed in Figure 4.7, with the overall result percentage being 70% honey concentration at 1550 nm wavelength. With various sizes of optical microfiber sensors, the optical microfiber functions as a sensor to measure the concentration of honey and perform in concentration sensitivity. The parameters under observation were sensitivity and linearity. The cycle has a clear tendency to rise and fall before levelling off and reaching its starting point. Based on the factors, the analysis indicates that an optical microfibre sensor size A will demonstrate the superior performance of the optical microfiber sensor. Time and power (dBm) have a significant positive linear correlation. This experiment also establishes that the sensitivity is sensed using microfiber optics as a liquid sensor.

4.2.5 Sensitivity of Microfiber Optics Sensor on 100%Honey Concentration

The third investigation is based on the test's results regarding the sensitivity and linearity of microfiber optics' performance as a liquid sensor in honey concentrations of 100%. Using an optical microfiber sensor of varying sizes, the output power has been measured and documented for each concentration through this investigation, as indicated in Table 4.9.

Table 4.9 Comparison of data collected for 100% honey concentration

Output Power 100% Honey Concentration (dBm)			
	Wavelength 1550nm		
Time	Size A	Size B	Size C
1	-37.59	-42	-40.08
2	-39.78	-43.55	-41.02
3	-39.93	-43.81	-41.17
4	-40.42	-43.9	-41.17
5	-40.61	-43.99	-41.22

6	-40.61	-43.99	-41.25

Table 4.10 Sensitivity and linearity of 100% honey concentration

Size of Microfiber Optic Sensor	Sensitivity (dBm)	Linearity
Size A	0.5166	0.841
Size B	0.3246	0.787
Size C	0.1843	0.766

According to Table 4.10, the 100% concentration of honey had a greater sensitivity value at microfiber optic sensor size A, managing to have 0.5166 dBm. This cycle was repeated five times for each concentration, which lessened random error when observing the results. In contrast, we can observe that the value linearity at the microfiber optic sensor size A has the maximum linearity which is strong negative linear correlation, leading to the data fitting in the linear graph. This indicates that microfiber optics will function at the maximum value of a liquid sensor. With a linearity of 0.841 of the 100% honey concentration interacting with the light source passing through it, the microfiber optic sensor size A exhibits a significant linear connection in comparison to the microfiber optic sensors size B and size C. Compared to microfiber optic sensors of sizes B and C, the sensitivity value of microfiber optic sensor size A is higher.

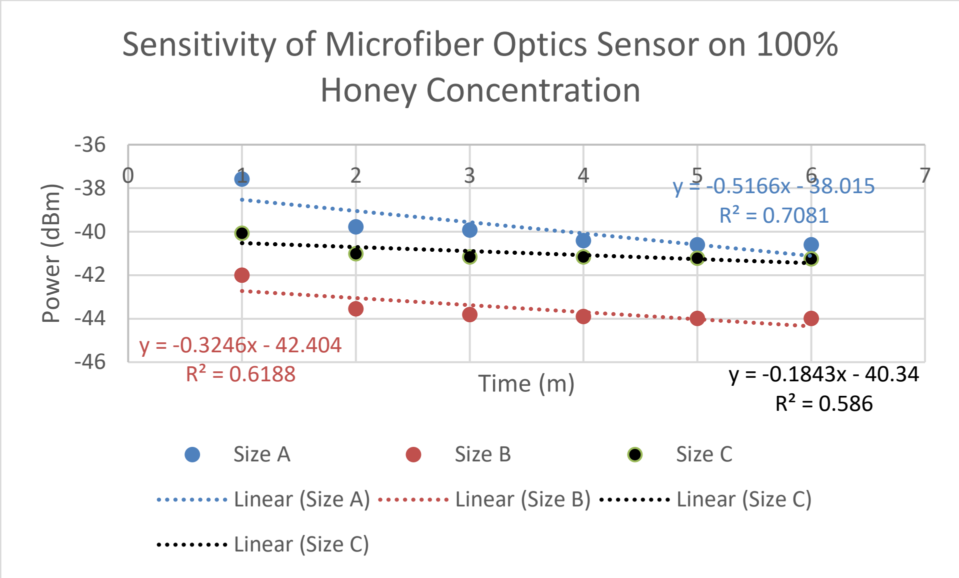


Figure 4.8 Sensitivity of microfiber sensor on 100% honey concentration

Three distinct lines for sensitivity are displayed in Figure 4.8, with the overall result percentage being 100% honey concentration at a wavelength of 1550 nm. With various sizes of optical microfiber sensors, the optical microfiber functions as a sensor to measure the concentration of honey and perform in concentration sensitivity. The parameters under observation were sensitivity and linearity. The cycle has a clear tendency to rise and fall before levelling off and reaching its starting point. Based on the factors, the analysis indicates that an optical microfiber sensor size A will demonstrate the superior performance of the optical microfiber sensor. Time and power (dBm) have a significant positive linear correlation. This experiment also establishes that the sensitivity is sensed using microfiber optics as a liquid sensor.

4.2.6 Repeatability of Microfiber Optic Sensor Size A on 100% Concentration

Repeatability in concentration analysis refers to the consistency or reproducibility of measurements taken in the same way each time. It describes the extent to which repeated experiments or measurements produce comparable outcomes. Analysis of Variance, or ANOVA, is a statistical method for examining how group means in a sample differ from one another. ANOVA and repeatability are related in that ANOVA can be used to evaluate measurement variability among various groups or conditions in an experiment. To be more precise, ANOVA breaks down the overall variability seen in a set of data into two main parts the variation within groups and the variance across groups.

The repeatability of microfiber optic sensor size A at 100% concentrations was examined in this investigation. Using statistical analysis and an ANOVA technique, the analysis utilise the 100% concentrations with microfiber optic sensor size A based on the results for all concentrations to demonstrate that the repeatability obtained almost the same value as shown in Table 4.11. This analysis also applies the ANOVA hypothesis testing procedure. Analysis of variance (ANOVA) is used to compare the variations between two or more population means. Statistically, the result was the same several times. It is necessary to state the null and alternative hypotheses as a result.

Table 4.11 Value of five readings for microfiber optic sensor size A at 100% honey concentration

Time	The 1st Reading Value	The 2nd Reading Value	The 3rd Reading Value	The 4th Reading Value	The 5th Reading Value
1	-37.59	-38.51	-40.21	-38.35	-38.88
2	-39.78	-40.17	-40.21	-39.19	-39.05
3	-39.93	-40.17	-40.4	-39.34	-39.37
4	-40.42	-40.41	-40.4	-39.34	-39.55
5	-40.61	-40.51	-40.49	-39.44	-39.55

6	-40.61	-40.51	-40.49	-40.29	-39.61

Table 4.12 The output from the table above

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
1st	6	-238.94	-39.8233	1.318947
2nd	6	-240.28	-40.0467	0.590627
3rd	6	-242.2	-40.3667	0.016347
4th	6	-235.95	-39.325	0.38275
5th	6	-236.01	-39.335	0.09151

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4.933287	4	1.233322	2.569227	0.062702	2.75871
Within Groups	12.0009	25	0.480036			
Total	16.93419	29				

$$H_0 : \mu_1 = \mu_2 = \ldots = \mu_k \quad , \; k = 5$$

$$H_1 : \mu_i \neq \mu_j$$

Decision:

Failed to reject H_0. Its because the value of F_{test} is low compared to the value of $F_{critical}$.

Conclusion:

At a 95% confidence interval, there is no difference between the means of repeated experiment. Even though the experiment is repeated many times, the mean value will remain the same.

All things considered, repeatability is a notion associated with measurement consistency, and ANOVA is a statistical technique employed to examine variability both within and across groups. The within-group variability component of an ANOVA is influenced by repeatability, and the accurate interpretation of ANOVA results depends on paying close attention to repeatability.

4.3 Summary

The case studies in this chapter used a tapering method to show how the suggested microfiber optic sensor development system may be used in a range of honey concentrations. Three sizing of microfiber optic sensors, which are size A, size B, and size C and three samples of honey with varying concentrations of 100% concentration, 70% concentration, and 50% concentration, serve as the basis for the case study. Using an input wavelength of 1550 nm, the output power has been seen and recorded for each concentration using this analysis. Analyses of the sensitivity and linearity of the microfiber optics liquid sensor's performance at 1550 nm wavelengths were found to be satisfactory. However, the sensitivity value in various honey concentrations was found to be the linear graph slope. The experiment was conducted five times in order to minimize random reading errors and ensure accurate data collection.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This thesis presents the technique for creating microfiber optic sensors for honey in various concentrations utilising a tapering process. The suggested approach is reliable and efficient for producing good results with only accurate data and little network measurement information. The suggested analytical technique combines linearity and sensitivity to determine the correlation for every sample in honey at varying concentrations. The sensor's analysis during the test revealed that, the measurement is stable even at modest concentration variations. Furthermore, because of the small size and large fractional evanescent fields, microfiber optic sensors have demonstrated unique advantages over conventional optical fibre sensors, such as high sensitivity for refractive index measurement. In addition, the microfiber's surface enhancement and tight confinement allow for the achievement of high sensitivity with minimal optical power a highly sought-after feature for numerous applications.

In general, the research presented in this thesis has advanced knowledge of sensor significance in microfiber optics. The method given is efficient in utilising limited data, both in quantity and type, and requires less complex mathematical operations and computations to yield prompt, convincing, insightful, and precise outcomes. The objective of the project was to create strategies that would support the creation of inexpensive sensors that rely only on optical microfibre sensing. It so provides the way for the suggested additional investigation.

5.2 Future Works

There are several suggestions and opportunities for microfiber optical sensing advancements in the future, such as:

a) Microfiber optical sensors can be connected to the Internet of Things for even easier and more convenient sensor output monitoring (IoT). Because authorised users may access the system from anywhere in the world, IoT makes remote monitoring possible. Furthermore, increasing the detecting zone may increase the sensitivity of the sensors and increase their resonant output when an optical signal flows through them.

b) Provide methods for employing microfiber sensors to monitor in real time. Applications including industrial operations, healthcare, and environmental monitoring may benefit greatly from this.

c) When combined with new materials and microfiber, these optical microfiber liquid sensors which use a tapering method and have demonstrated promising uses in highly sensitive liquid sensing.

d) To increase the accessibility of microfiber sensing technologies, assist in their commercialization. This could entail collaborations with business, programmed for knowledge transfer, and attempts to cut production costs.

e) Microfiber optical sensors can be shaped into any shape, including micro bottle resonators and D-shaped sensors. as intrinsic benefits, namely as resilience to electromagnetic interference, compact size, and lightweight, make them both cost-effective and attractive.

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APPENDICES

Appendix A: Gantt Chart for BDP 1

PROJECT ACTIVITIES		(PSM 1) SEM 2 2022/2023													
NO.	TITLE	WEEK 1	WEEK 2	WEEK 3	WEEK 4	WEEK 5	WEEK 6	WEEK 7	WEEK 8	WEEK 9	WEEK 10	WEEK 11	WEEK 12	WEEK 13	WEEK 14
1	Title selection and BDP Registration														
2	Background study: Search for papers related to the project														
3	Evaluate of Work Progress 1														
4	Complete report for Chapter 1 (Introduction)														
5	Complete report for Chapter 2 (LiteratureReview)														
6	Complete report for Chapter 3 (Methodology)														
7	Evaluate of Work Progress 2														
8	Submit report with Turnitin < 30%														
9	Submission and Evaluation of BDP Final Report														
10	PSM 1 Presentation														

Appendix B: Gantt Chart for BDP 2

PROJECT ACTIVITIES		(BDP 2) SEM 1 2023/2024													
NO.	TITLE	WEEK 1	WEEK 2	WEEK 3	WEEK 4	WEEK 5	WEEK 6	WEEK 7	WEEK 8	WEEK 9	WEEK 10	WEEK 11	WEEK 12	WEEK 13	WEEK 14
1	Continue to study and understand the concept/procedure for this project														
2	Evaluate of work progress 1														
3	Start doing this project: Stripping, Tapering, and Splicing the fiber														
4	Complete report for Chapter 4 (Results and Analysis)														
5	Collect data results, conclusion, and draft report														
6	Evaluate of work progress 2														
7	Submit the first draft report to SV for approval														
8	Submit a report with Turnitin <30%														
9	BDP 2 presentation														
10	Submission and evaluation of BDP 2 final report on ePSM														