# DEVELOPMENT OF OPTICAL MICROFIBER SENSOR FOR DETECTING CONCENTRATIONS OF ACIDIC SOLUTIONS

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**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

# DEVELOPMENT OF OPTICAL MICROFIBER SENSOR FOR DETECTING CONCENTRATIONS OF ACIDIC SOLUTIONS

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**This report is submitted in partial fulfilment of the requirements for the degree of Bachelor of Electronics Engineering Technology (Industrial Electronics) with Honours**

**Faculty of Electronics and Computer Technology and Engineering**
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**DEDICATION**

*I dedicate this report to my beloved family, whose unwavering support and love have been the cornerstone of my academic journey, particularly to my parents. Zuli Arman bin Ali and Haffizal binti Ismail. To my dedicated supervisors, Ir. Ts. Dr. Mohd Fauzi Bin Ab Rahman and Dr. Md Ashadi Bin Md Johari, your guidance and inspiration propelled me to successfully complete this Bachelor project. My heartfelt thanks also extend to my friends for their camaraderie and shared insights, making this academic journey enjoyable. A special dedication to my bestfriends, Siti Fatimah, Najwa Syazwani and Nur Aisyah Sofia for their enduring support, patience, and belief in my abilities throughout the challenges of report writing. This work is a collective dedication to all those who have played vital roles in shaping my academic path, and I am deeply grateful for their contributions.*

## ABSTRACT

The development of optical microfiber sensors tailored for detecting concentrations of acidic solutions, specifically vinegar, addressed the need for precise and versatile sensing solutions in various industries. This study presented a comprehensive investigation focusing on fabricating functional single-mode fibers using the flame brushing technique, designing a measurement setup utilizing 1310 nm and 1550 nm input laser sources for acidic concentration detection, and evaluating the performance of microfiber sensors in detecting various concentrations of acidic solutions in vinegar. Through systematic evaluation of sensor performance metrics such as sensitivity, response time, and resolution, this research provided insights into optimizing sensor design and operation for enhanced efficiency in quantifying acidic solution concentrations. The objectives included fabricating optimized single-mode fibers, designing a versatile measurement setup for accurate assessment of acidic concentrations in vinegar, and systematically evaluating sensor performance metrics. Its stability and effectiveness in a variety of applications, such as chemical analysis, environmental monitoring, and food processing, were validated by experimental results. This study contributes to better quality control and process optimisation by developing optical sensing technology, which offers a workable and dependable option for companies needing continuous and accurate acidity detection.

## *ABSTRAK*

Pembangunan sensor mikrofiber optik yang direka untuk mengesan kepekatan larutan berasid, khususnya cuka, telah memenuhi keperluan untuk penyelesaian pengesanan yang tepat dan serba boleh dalam pelbagai industri. Kajian ini membentangkan penyiasatan yang komprehensif dengan menumpukan pada penghasilan gentian mod tunggal menggunakan teknik *flame brushing*, mereka bentuk sistem pengukuran yang menggunakan sumber laser input 1310 nm dan 1550 nm untuk pengesanan kepekatan asid, serta menilai prestasi sensor mikrofiber dalam mengesan pelbagai kepekatan larutan berasid dalam cuka. Melalui penilaian sistematik terhadap metrik prestasi sensor seperti sensitiviti, masa tindak balas, dan resolusi, kajian ini memberikan pandangan untuk mengoptimumkan reka bentuk dan operasi sensor bagi meningkatkan keberkesanan dalam mengukur kepekatan larutan berasid. Objektif kajian ini termasuk penghasilan gentian mod tunggal yang dioptimumkan, mereka bentuk sistem pengukuran yang serba boleh untuk penilaian tepat kepekatan asid dalam cuka, serta penilaian sistematik terhadap metrik prestasi sensor. Penemuan kajian ini menyumbang kepada kemajuan teknologi penderiaan optik dan menawarkan penyelesaian praktikal untuk aplikasi yang memerlukan pemantauan kepekatan cecair yang tepat, dengan implikasi yang meluas ke pelbagai industri termasuk pemprosesan makanan, pemantauan alam sekitar, dan analisis kimia.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background

The development of optical microfiber sensors for liquid concentration detection plays an important role in the research area that has emerged from the field of optical fiber sensors [1]. Due to their great sensitivity, accuracy, and reliability, optical fiber sensors have been intensively studied and used in a variety of fields. Using a microfiber, a form of optical fiber with a diameter of a few micrometers to detect changes in the refractive index of a liquid around the microfiber is the fundamental idea behind an optical microfiber sensor for liquid concentration measurement. The concentration of the liquid being tested is directly correlated with this change in refractive index. The requirement for more precise and sensitive sensing technologies in a variety of industries, including environmental monitoring, biomedical diagnostics, and the food business, has fueled the development of optical microfiber sensors for liquid concentration measurement [2][3].



Conventional sensing approaches, such chromatography techniques and electrochemical sensors, have drawbacks like high sample preparation costs and low sensitivity. Because optical fibers can send large volumes of data over long distances with little signal loss, they are extremely important in our daily lives. The inner core and the outer cladding are the two fundamental components of these fibers. The inner core has a diameter of around 9 μm and is usually made of silica that has been doped with germanium. It acts as a conduit for light signals to go through. The outer cladding, which has a greater diameter of around 125 μm and is composed of pure silica, surrounds the core [4]. By keeping light inside the core and reducing signal loss through reflection and dispersion, the cladding serves

as a protective coating. Because of the carefully considered core and cladding parameters, optical fibers can provide dependable, high-performance communication solutions for a wide range of applications.

An optical microfiber has a diameter of around ≤ 12 μm, low roughness, and strong index contrast with the surrounding medium [4]. It is created by heating and drawing bulk glass or a conventional optical fiber. Because of its sub-wavelength cross-section, an optical microfiber has many novel properties, including large manageable waveguide dispersion, high fractional evanescent fields, and tight optical confinement, all of which are highly desirable for functionalizing fiber-optic circuits on the micro/nano scale [5]. Comparing optical microfiber sensors to conventional sensing techniques reveals a number of benefits. They need little sample preparation, are very sensitive, and are simple to integrate into current systems. They are also inexpensive, portable, and suitable for real-time monitoring.

Using a microheater, a single-mode optical fiber is pulled to a few micrometers in diameter in order to fabricate optical microfiber sensors [6]. To improve the sensor's sensitivity, a small coating of cladding material is applied to the resultant microfiber. After that, the microfiber is placed into a liquid sample, and light is directed through it. The transmission spectrum shifts in response to changes in the refractive index of the liquid surrounding the microfiber; this shift can be identified and examined to ascertain the liquid's concentration.

It has been successfully possible to measure the concentration of several acidic substances, such as organic acid and mineral acid, using optical microfiber sensors. They have also been used to measure blood glucose levels and the presence of contaminants in water [7]. By functionalizing the surface of the microfiber with particular molecules that have the ability to bind to the target analyte selectively, the performance of optical microfiber sensors can be further improved. The goal of this project is to construct optical microfiber

sensors for liquid concentration detection, which will offer a sensitive and accurate way to determine the concentration of various liquids. Because optical microfiber sensors can detect changes in the surrounding medium's refractive index, they are useful for measuring liquid concentrations. By functionalizing the surface of the microfiber with a material that interacts with the target analyte in a specific way, the selectivity and sensitivity of the sensor can be increased. The businesses that stand to gain from the development of optical microfiber sensors for liquid concentration measurement include the food industry, medical diagnostics, and environmental monitoring.

## 1.2 Global Issues

The development of optical microfiber sensors to measure acidic solution concentrations resolves several of global issues related to manufacturing, public health and environmental monitoring. Although acidic solutions are essential to many industries, they are handled incorrectly, they can have serious negative effects on the environment and human health. Acid containing industrial discharges, for example can contaminate soil and water, harming human populations as well as ecosystems. Reducing these risks and ensures adherence to environmental rules depend on the sensitive and accurate detection of acidic concentrations.

In the field of public health, it is essential to keep an eye on the acidity levels in drinks and food items to ensure consumer safety and preserve product quality. Furthermore, measuring differences in the acidity of body fluids and treat diagnose and treat diseases as well as offer significant health insights.

Moreover, accurate control of acid concentrations is necessary for efficient and high-quality manufacturing in industrial processes. Optical microfibers sensors are a non-invasive, extremely sensitive and small technology for monitoring acidic solutions in real-

time. This helps to promote environmentally friendly and sustainable management practices in variety of industries. Global efforts to preserve the environment, safeguard public health and promote industrial sustainability have been easier by this technology.

## 1.3 Problem Statement

Dependable and sensitive sensors that can precisely measure the concentrations of acidic solutions are essential in sectors including chemical processing, environmental monitoring, and medicines. Many times, the sensitivity, reaction time, and environmental compatibility of conventional pH sensors and other analytical procedures are limited. The unique qualities of optical microfiber sensors such as their high sensitivity, quick reaction times, and suitability for a variety of chemical environments, make them a promising alternative.

However, there are a number of difficulties in creating an optical microfiber sensor that is especially meant to detect acidic solution concentrations. These difficulties include validating the sensor's performance over a range of acidic concentrations, assuring long-term stability and reliability in corrosive environments, and optimizing the sensor design for maximum sensitivity. As a result, the problem statement attempts to solve these issues and create a novel optical microfiber sensor that can precisely and consistently detect acidic solution concentrations, meeting the increasing need for cutting-edge sensing technologies in applications for monitoring acidic solutions.



## 1.4 Project Objective

The project aim is to develop a sensitive, accurate, and cost-effective method for liquid concentration detection using optical microfiber sensors, with the potential to provide real-time monitoring and enable on-site measurements in various fields. Specifically, the

objectives are as follows:

a) To fabricate a functional single mode microfiber using flame brushing technique.
b) To develop a measurement set-up for acidic (vinegar) liquid concentration detection based on 1310 nm and 1550 nm input laser sources.
c) To evaluate the performance of microfiber sensor in detecting various acidic (vinegar) liquid concentration, in terms of sensitivity, responsivity, resolution, linearity, standard deviation, linear range.

## 1.5 Scope of Project

The project scope of developing an optical microfiber sensor for liquid concentration detection is as follows:

a) Develop an optical microfiber sensor with enhanced sensitivity and specificity for real-time liquid concentration detection, focusing on applications in biomedical, environmental, and industrial settings.
b) Testing with an acidic (vinegar) solution.
c) Using two input laser sources, 1310 and 1550 nm in the solution measurement.
d) The experiment is conducted in a controlled lab environment.



## 1.6 Outline report

The motivation and importance of creating optical microfiber sensors for liquid concentration detection are discussed in the introduction, which also highlights the sensors' potential for high sensitivity and dependability in a variety of applications, such as industrial processes, biomedical diagnostics, and environmental monitoring. It talks about how the basis for sensor operation is the idea that refractive index varies in response to liquid concentrations. Global concerns are emphasized, including the necessity of accurate acidic

solution measurement to address public health, industrial efficiency, and environmental damage. The problem statement highlights the difficulties in creating reliable microfiber sensors for acidic solutions and points out the drawbacks of conventional sensors, such as their low sensitivity and sluggish reaction times. The chapter ends by outlining the project's goals, which include designing a measurement setup with laser sources at 1310 nm and 1550 nm, fabricating a single-mode microfiber using the flame brushing technique, and assessing the sensor's sensitivity, resolution, and linearity. The project scope highlights the key features, applications, and controlled experimental environment to ensure precise results.

The theoretical underpinnings and developments in optical microfiber sensor technology are reviewed in this chapter. An overview of optical microfibers is given at the outset, including information on their special qualities, including their capacity to detect changes in the refractive index of nearby liquids, intense light confinement, and evanescent fields. The chapter also examines the various uses of microfibers in photonics, telecommunications, and sensing, as well as their production methods, such as flame brushing. Performance-affecting loss mechanisms are discussed together with important attributes like sensitivity, resolution, and response time. When contrasting optical microfiber sensors' capabilities with those of conventional sensing methods, it also emphasizes the benefits of these sensors, such as their small size, affordability, and low sample preparation needs. An analysis of prior research on the design, functionality, and use of microfiber sensors offers valuable information about current shortcomings and areas for development. A summary of the results is provided at the end of the chapter, highlighting the importance of the suggested project in furthering the development of optical microfiber sensor technology.

The methodology chapter outlines the methodical steps taken to accomplish the

project's goals. Using the flame brushing technique, a functional single-mode microfiber is first created. This process entails stripping, cleaving, and cleaning the fiber to produce a tapered structure with exact measurements. Clarity and reproducibility are ensured by thorough explanations of the tools and methods utilized. An Optical Time-Domain Reflectometer (OTDR), a microfiber sensor placed in a controlled environment, and laser sources with wavelengths of 1310 nm and 1550 nm are used in the experimental setup for liquid concentration monitoring. The steps for calibrating the apparatus and making acidic (vinegar) solutions at different concentrations are described. In order to provide accurate and trustworthy results, the evaluation procedure comprises techniques for evaluating the sensor's sensitivity, resolution, and response time. Additionally, by highlighting the project's contribution to innovation and sustainable industrial practices, the chapter argues for its alignment with the Sustainable Development Goals, especially SDG 9. The chapter is concluded with a summary that emphasizes the methodology's contribution to the project's objectives.

Chapter 4 presents the findings and comments from the creation of an optical microfiber sensor of liquid (acidic) concentration measurement, with an emphasis on the sensor’s possible uses in lab environments. This chapter explores the range of tests that were performed to assess the performance of the sensor, such as sensitivity, resolution and response time. A crucial step in ensuring low-loss connections within the optical microfiber, which is fusion splicing, yielded positive results with minimal loss of 0.02 dB. The experimentation with different vinegar concentrations, ranging from 0% to 50%.

Chapter 5, The project's main conclusions and results are outlined in the conclusion, which also considers how well the goals were met. It focusses on the successful creation of a single-mode microfiber sensor through the use of the flame brushing technique, the design of an operational experimental setup, and the assessment of the sensor's ability to detect

concentrations of acidic liquid. The chapter emphasizes the sensor’s sensitivity, resolution, and linearity as key indicators of its efficacy. Future research is advised to investigate different materials for increased resilience, increase the variety of liquids that may be detected, and improve the sensor's design for field use. By tackling these issues, the research establishes the foundation for future developments in optical microfiber sensor technology, which could find use in a variety of sectors including as food processing, biomedical diagnostics, and environmental monitoring.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

Optical microfiber sensors have emerged as a pivotal technology in the field of sensing, offering unique advantages due to their minuscule size and exceptional optical properties. Defined by their diameters ranging from tens of nanometers to several micrometers, optical microfibers provide high flexibility, strong light confinement, and significant evanescent fields [8]. These attributes make them particularly suitable for a wide array of applications, including environmental monitoring, biomedical sensing, and industrial process control.

In recent decades, the miniaturization trend driven by advances in microtechnology and nanotechnology has significantly impacted the field of optical sensors. Optical microfibers, with their enhanced sensitivity and spatial resolution, have become critical components in the development of high-performance sensors. These sensors are capable of detecting various physical, chemical, and biological parameters with high precision, making them indispensable in numerous scientific and technological domains [9].

The purpose of this literature review is to provide a comprehensive overview of the advancements in optical microfiber sensors. It will explore the fundamental properties and fabrication techniques of optical microfibers, examine their diverse sensing applications, and discuss the challenges and opportunities in this rapidly evolving field. By synthesizing key findings from recent research, this review aims to highlight the significant contributions of optical microfiber sensors and their potential to revolutionize modern sensing technologies.

## 2.2 Optical microfiber

Throughout the previous century, optical fibers found extensive application in the telecommunications industry because of their unique characteristics, which included low transmission loss, large bandwidth, and multiplexing ability [10]. Due to its unique properties, optical fiber application has recently expanded to various fields, such as sensing. By taking use of their special qualities, optical sensors may be able to find the intended application, even when the price of their better established electronic sensor cousin is more competitive. Among its distinctive qualities are its low losses, remote sensing capabilities, immunity to electromagnetic interference, capacity to guide light without the need for electrical biassing, and suitability for usage in environments where explosions are a possibility [11].

Glass microfiber optics are minuscule, ultra-clean glass strands with a diameter roughly equivalent to that of human hair. While the optical microfibers are grouped together, sending light signals over great distances. The three layers that make up the jacket., the outside covering of the cable that shields the bundles are buffer coating, cladding, and core [12]. The microfiber is coated with a plastic buffer to keep it safe from moisture and harm. Cloaking is the term for the outer optical substance that envelops the core and reflects light into it. The core of a microfiber optic cable is the thin glass center of the microfiber that allows light to be sent and received.

There are two types of microfiber optics: single-mode and multi-mode. With a smaller core, the single-mode communication system can send infrared laser light over long distances [4]. Larger cores are found in multi-mode transmissions, which are frequently employed over short distances. **Figure 2.1** shows the cross-section of fiber optic cable.

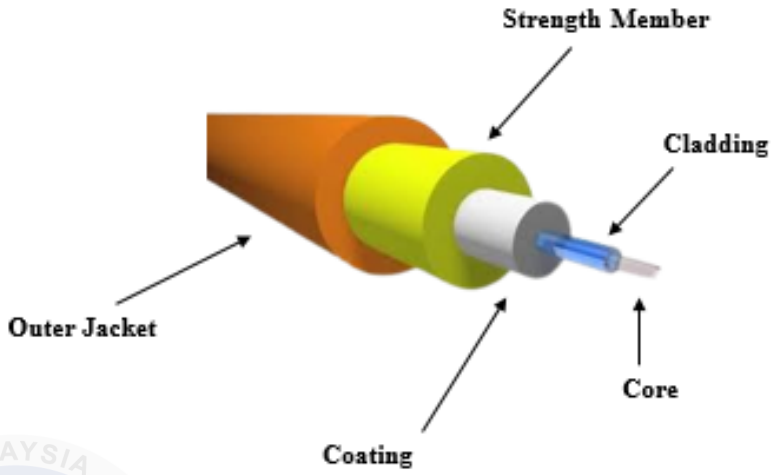


Figure 2.1 Cross-section of fiber optic cable.

Although fiber optics and copper wires are interchangeable, fiber optics are progressively taking the place of copper wires as a dependable method of signal delivery in several applications, including communication systems. Fiber optics outperform copper in a number of ways, including lower costs, thinner structure, and more carrying capacity. The most effective method for transporting digital data is via optical fibers. The explanation is because there was no electricity in the gearbox, which reduces the likelihood of fire sparking. Cables made with fiber optics are more compact, lightweight, and flexible.

An optical microfiber is a specialized optical waveguide created by heating and pulling a standard optical fiber to reduce its diameter to a few hundred nanometers to a few microns, especially in the microfiber waist region [13]. It is also referred to as a tapered fiber, subwavelength fiber, microwire, or photonic microfiber. This portion is down-tapped and spans many millimeters. Because of their small size, optical microfibers have special qualities that allow for effective coupling with micro- and nanoscale structures, strong light confinement, and significant evanescent field interaction [14]. Their capacities to propagate

and interact with light make them useful instruments in a variety of industries, such as photonics, telecommunications, optoelectronics, and sensing.

Over the past 20 years, optical microfibers have drawn a lot of attention from researchers because of their remarkable mechanical and optical properties. These include their compact size, affordability, capacity to produce substantial evanescent fields, and good confinement of light propagation. Because of these benefits, optical microfibers are very appealing for lasing and sensing applications. Although silica fibers are frequently utilized in the creation of optical microfibers, various materials such as lead silicate, bismuthate, phosphate, tellurite glasses, chalcogenide glasses, and various polymers have also been investigated. This wide variety of materials makes it possible to customize the optical characteristics of microfibers to meet the needs of certain applications and creates opportunities for a wide range of technical breakthroughs [15].

Developments in the field of optical fibers attempted to link the HE11 and HE12 modes, two propagating light modes, in the early 1970s [16]. The objective of these endeavors was to investigate the potential of employing optical fibers to enable the conveyance and modification of light signals among these modes. There are several drawbacks to optical microfibers, such as high loss rates and difficulties creating fibers with a diameter of about 5 μm. Nonetheless, a noteworthy advancement occurred in 2003 when an optical microfiber with a diameter of roughly 50 nm and an output power loss of less than 0.1 dB/mm was successfully fabricated. This accomplishment represented a significant development in the field [17].

Comparing optical microfiber structures to waveguides made using lithography reveals two important benefits. First off, they show reduced losses, which means that light is transmitted more effectively. Second, they make it simple to fabricate three-dimensional elements like knots, rings, and loops. Because of these qualities, optical microfibers are a

viable choice for a number of photonics and optical communication system applications [18].

An optical microfiber's usual structure consists of three primary regions: the waist area, which has a tighter diameter, the final transition region, which tapers up, and the beginning transition region, which tapers down. Such optical microfibers have ends that work similarly to regular single-mode fibers. A number of variables, like the temperature of the flame employed during production and the speed at which the fiber is stretched, have a substantial impact on how much the diameter of an optical microfiber is reduced. The ultimate dimensions and properties of the microfiber are determined in large part by these parameters. **Figure 2.2** shows the different structural regions of an optical microfiber. These regions are the waist region, which has a narrower diameter, the final transition zone, where the fibre tapers up, and the initial transition region, when the fiber tapers down in diameter.

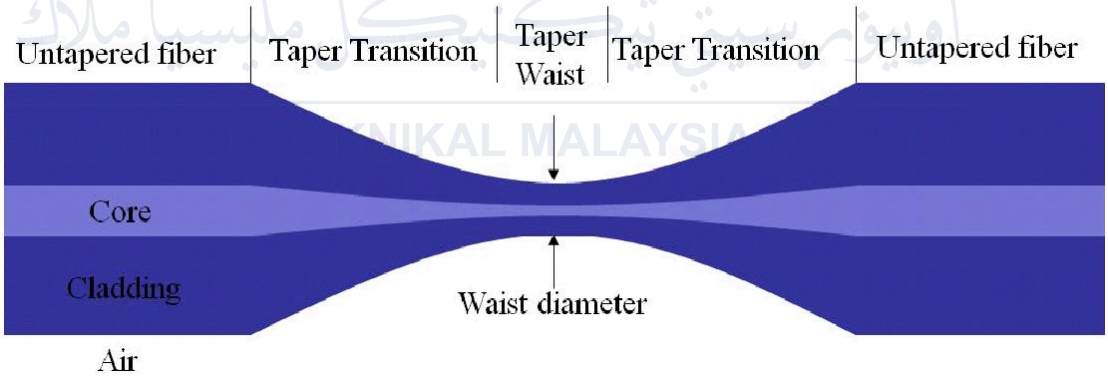


Figure 2.2 Structural region of an optical microfiber [18].

## 2.3 Characteristics of optical microfiber

Depending on how the microfiber functions inside the experimental system, the many uses for optical microfibers can be roughly divided into two groups. These classifications are based on the distinct tasks that the optical microfiber completes, making it possible to apply it to a wide range of scientific and technological domains.

### 2.3.1 Evanescent field

A substance known for its remarkable transparency, silica glass, is widely used in the manufacturing of optical fibers. These fibers are made up of two primary layers: the cladding, which is the outer layer, and the core, which is the inner cylinder. Because the core's refractive index is marginally higher than the cladding's, $nCO < nCl$, light can propagate through it [19]. When light meets the contact between the core and cladding, it causes a phenomenon known as complete internal reflection due to the difference in refractive index. Consequently, the light is essentially contained inside the fiber's core, because they can facilitate the transmission of a single mode or route of light, optical fibers having this feature are frequently referred to as step-index fibers or, more precisely, single mode fibers.

Graded-index fibers, on the other hand, have a refractive index profile that steadily drops from the core towards the cladding. Multiple modes of light can propagate simultaneously through these kinds of fibers, also known as multimode fibers. **Figure 2.3** shows the diameters of optical fiber core.



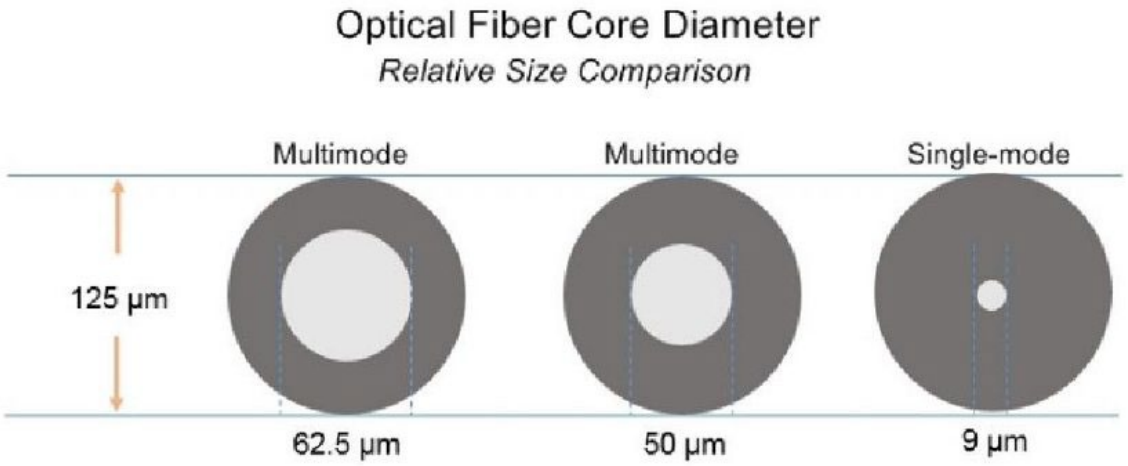


Figure 2.3 Diameter of optical fiber

The term "core mode" refers to the light that travels through the optical fiber's core.

Even though it has an evanescent field, it is unable to approach the cladding region very far. These fibers are made up of two primary layers: the cladding, which is the outer layer, and the core, which is the inner cylinder. Because the core's refractive index is marginally higher than the cladding's, $nCO < nCl$, light can propagate through it. [20] As a result, the exterior medium surrounding the fiber cannot be penetrated by the core mode's evanescent field. This property makes the evanescent field irrelevant for sensing purposes because it is unable to penetrate the fiber's surrounding medium [21]. The phenomenon of light propagation within an optical fiber through total internal reflection illustrates in **Figure 2.4**

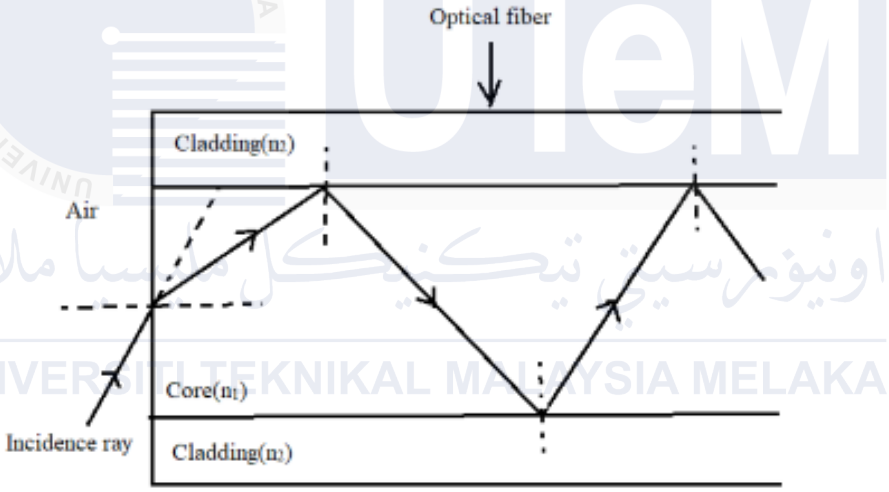


Figure 2.4 The phenomenon of light propagation within an optical fiber through total internal reflection [1].

A cylindrical waveguide composed of a dielectric substance is called an optical microfiber. A fiber is stretched in a specific area to a small diameter, usually a few microns, during the creation of optical microfibers. The fiber core and cladding are gradually reduced in size while maintaining their chemical structure during this tapering process. The strength of evanescent field radiation is significantly amplified when the fiber is tapered to a waist diameter less than the wavelength (λ) of the light. This improved evanescent field creates opportunities for the realization of sensing applications [22].

Furthermore, a microfiber's evanescent field shows a deeper penetration as the microfiber's waist diameter gets smaller. The evanescent wave intensity outside the optical microfiber is amplified quickly as a result of this decrease in the core-cladding interactions inside the microfiber [23]. The Z-direction Poynting vectors for an optical microfiber with a 200 nm diameter and a 600 nm wavelength are shown graphically in **Figure 2.5** A two-dimensional (2-D) and a three-dimensional (3-D) view are both included in the illustration [24].

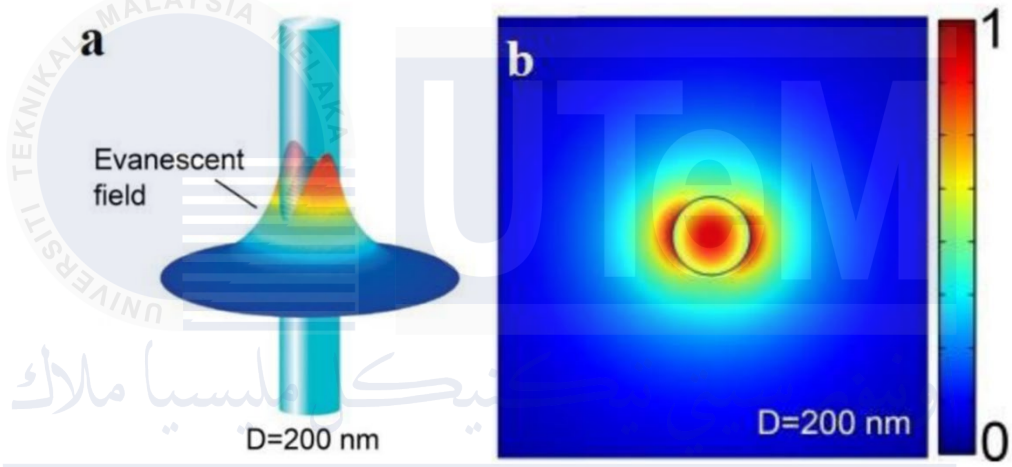


Figure 2.5 The Z-direction Poynting vectors for an optical microfibre with a 200 nm diameter and a 600 nm wavelength [24].

The evanescent field of an optical fiber follows an exponential decay pattern, as described by the following **Equation 2.1** [24] :

$$E(z) = E0\ exp(-z/dp) \qquad (2.1)$$

The absorption and dispersion of the evanescent field within an optical microfiber can be characterized by the Beer-Lambert Law, which can be represented by the following **Equation 2.2** [24].

$$ln\ I/I_0 = -c\alpha\chi \qquad (2.2)$$

In this equation, $I$ represents the output power in milliwatts (mW), $i_0$ is the input

power in mW, $\alpha$ is a microfiber-specific characteristic constant, $c$ is the cell concentration, and $\chi$ is the fiber interaction length. The equation quantifies the relationship between input and output power, taking into account the absorption and dispersion properties of the evanescent field within the optical microfiber

### 2.3.2 Optical microfiber loss

Achieving excellent transmission is a crucial need for optical microfibers in a variety of applications [25]. Two aspects contribute to the propagation loss in optical microfibers: the microfiber's increased surface area and decreased diameter as a result of the tapering and drawing process. The overall loss is influenced by this decrease in diameter and increase in surface area. Furthermore, it has been noted that elevated microfiber loss can also be caused by the external environment, frequently as a result of particle attachment on the microfiber surface [26].

According to experimental tests, silica-based optical microfibers have a transmission loss of about 1 dB/m, which is twice as much as that of state-of-the-art telecommunication fibers. In spite of this, optical microfibers nevertheless have a far lower transmission loss than flat photonic circuits made via lithography. The microfiber surface can be cleaned using distilled water, acetone, methanol, and isopropanol, among other chemical solutions, to lessen the effect of dust and microparticles on microfiber loss and restore its transmission qualities [27]. Alternatively, optical microfibers can be treated with post-processing methods such as heating. Interestingly, a larger microfiber diameter results in a significant reduction in the contamination effect on the microfiber surface .

Variations in the microfiber diameter have a significant impact on the propagation loss (α) in optical microfibers, and this relationship can be quantitatively stated by the following **Equation 2.3** [27].

$$\alpha = \frac{1}{4\gamma}\sqrt{\frac{k}{LF}}\exp\left(-\frac{\pi L f \gamma^2}{x}\right) \qquad (2.3)$$

where $k$ is the propagation constant, $\gamma$ is the absolute value of the transverse component of the propagation constant, and $L_f$ is the characteristic length of the diameter fluctuations.

## 2.4 Application of optical microfiber

Depending on how the microfiber functions inside the experimental system, the many uses for optical microfibers can be roughly divided into two groups. These classifications are based on the distinct tasks that the optical microfiber completes, making it possible to apply it to a wide range of scientific and technological domains.

### 2.4.1 Optical microfiber sensing

Microfiber has special qualities that can make it an attractive option for sensing applications. These include strong evanescent field, large anomalous waveguide dispersion, configurability and visible field amplification. Microfiber also shows notable near-field interaction with its surrounding and high evanescent coupling with other waveguides such as metal, semiconductors and substrates. For sensing applications where a sizable power fraction is required to interact with the surrounding refractive index medium, a large evanescent field is necessary need [1].

As previously noted, optical fiber sensors offer a number of benefits over conventional sensor technologies for a wide range of applications, including vast possibilities for sensing applications. Small size, no need for electrical power at the remote location, and the ability to multiplex numerous sensors along the fiber's length by applying light wavelength shift to each sensor or by measuring the time delay as light travels through

each sensor are some benefits of optical fibers for sensing [28].

## 2.5 Sensing parameters

For the best results in the realm of sensing physical, chemical, and biological fluctuations, a number of important parameters are taken into account. The sensitivity, response time, and resolution are some of these factors.

### 2.5.1 Sensitivity

Sensitivity in sensing is a critical parameter that defines the effectiveness of a sensor in detecting and responding to minimal changes in the measured quantity, known as the measurement. It represents the sensor's ability to discern even minute variations in the input signal, thereby providing precise and accurate readings. Sensitivity is often quantified by calculating the ratio of the sensor's resolution to its responsivity. Resolution refers to the smallest detectable change in the measured quantity that the sensor can reliably discern. Responsivity, on the other hand, is the measure of the output signal produced by the sensor per unit change in the input signal. A high sensitivity indicates that the sensor can detect very small changes in the measured quantity, producing a significant output signal even for minimal variations [29].

This is particularly important in applications where precise measurement is crucial, such as in medical diagnostics, environmental monitoring, and high-precision manufacturing. The ability to achieve high sensitivity depends on various factors including the design of the sensor, the materials used, and the specific technology employed. Enhancing sensitivity often involves optimizing these factors to reduce noise, improve signal amplification, and ensure that even the slightest changes in the input are accurately captured and reflected in the sensor's output. High sensitivity sensors are essential for applications

requiring detailed and accurate monitoring, enabling effective detection and analysis of subtle changes in the measured environment or substance.

### 2.5.2 Resolution

Resolution is a fundamental aspect of any detection system, representing the smallest increment or change in the measured value that can be reliably distinguished [30]. It serves as a critical indicator of the system's ability to accurately quantify variations in the quantity being measured. Various factors contribute to the determination of a system's resolution, including its architecture, components, and measurement methods. A system with lower resolution may struggle to identify finer details or subtle changes in the measured quantity, potentially leading to inaccuracies or loss of valuable information.

Conversely, a higher-resolution system can discern even minute variations with greater accuracy and detail, providing more precise and reliable measurements. Optimizing and determining the resolution of a detection system is essential to ensure its effectiveness and trustworthiness across a wide range of applications. By carefully assessing and adjusting the system's design, components, and measurement techniques, engineers and researchers can enhance its resolution capabilities, enabling it to deliver accurate and meaningful results in various scientific, industrial, and technological fields. Ultimately, a well-optimized resolution contributes to the system's overall performance, facilitating more informed decision-making and advancing knowledge and understanding in diverse areas of research and application.

### 2.5.3 Responsivity

Responsivity in the context of optical microfiber sensors for detecting acidic solutions refers to the sensor's ability to produce a measurable output change in response to

variations in pH levels. It is quantitatively defined as the ratio of the change in output (such as wavelength shift or intensity change) to the corresponding change in pH, typically expressed in units like nanometers per pH unit (nm/pH). A high responsivity indicates that even minor changes in acidity will result in significant shifts in the sensor's output, making it highly sensitive to pH variations. This characteristic is crucial for applications that require precise monitoring of acidity, as it enhances the sensor's capability to detect subtle differences in pH, ensuring accurate measurements. Responsivity can vary across the sensor's operational range, and understanding this parameter helps in optimizing the sensor for specific applications, as it directly influences the reliability and effectiveness of pH detection in real-world environments [31].

### 2.5.4 Linearity

Linearity in the context of optical microfiber sensors for pH detection refers to the degree to which the sensor's output corresponds directly and proportionally to changes in the input variable, specifically the pH level of the solution. A linear relationship means that if the pH increases or decreases by a specific amount, the sensor output will change by a consistent and predictable amount, which can be represented by a straight line on a graph plotting output against pH. This linearity is crucial for ensuring accurate and reliable measurements, as it simplifies the calibration process and enhances the interpretability of results. In practical applications, maintaining linearity over a defined range of pH values allows users to confidently determine the acidity of a solution based on the sensor's output without needing complex adjustments or calculations. When the sensor operates outside its linear range, it may exhibit non-linear responses, leading to potential inaccuracies in pH measurement, underscoring the importance of understanding and establishing the linearity of the sensor for effective performance [32].



### 2.5.5 Standard deviation

Standard deviation is a statistical measure that quantifies the amount of variation or dispersion in a set of data points. In the context of optical microfiber sensors for pH detection, standard deviation is used to assess the consistency and reliability of the sensor's output when exposed to the same pH conditions repeatedly. A low standard deviation indicates that the sensor's measurements are closely clustered around the mean (average) value, suggesting high precision and reliability in its readings [33]. Conversely, a high standard deviation reflects greater variability in the output, which can lead to uncertainty in pH measurements and may signal issues with the sensor's performance or stability.

Calculating the standard deviation involves taking the square root of the variance, which is the average of the squared differences from the mean. Understanding standard deviation is crucial for evaluating the quality of the sensor's measurements, as it provides insights into the sensor's repeatability and overall performance, helping users make informed decisions based on the precision of the pH readings obtained from the device.

### 2.5.6 Linear Range

The range of acidic concentrations where the sensor's output varies predictably and proportionately to the concentration being measured is known as the "linear range" in the context of developing optical microfiber sensors for detecting acidic solutions. Consider it the "sweet spot" where the sensor performs most consistently and accurately. For example, if the linear range is 0% to 50% concentration, it means the sensor produces consistent and exact readings within this range. The sensor's accuracy may decrease and its response may not exhibit a linear relationship outside of this range. Because it enables the sensor to measure a wider range of concentrations efficiently, a wide linear range is preferred. This makes the sensor more adaptable and helpful for a variety of applications, such as environmental studies or monitoring acidity levels in food preparation. [34]

## 2.6 Comparison of previous studies related to the project

It is helpful to compare earlier studies on the creation of optical microfiber sensors for liquid concentration detection in order to get understanding of the field's progress and enduring difficulties. The production processes, sensitivity improvements, and application ranges of optical microfibers have all been thoroughly investigated in earlier research. A critical analysis if these works aids in determining the advantages and disadvantages of different strategies, such as the employment of varied wavelength light sources for increased detection accuracy and the flame brushing technique for the manufacturing of microfibers. This project seeks to improve the performance and applicability of optical microfiber sensors in industrial and biomedical settings by analyzing the approaches and results of previous research filling in knowledge gaps and suggesting novel solutions. In order to develop sensing technologies that are more effective, dependable and affordable, it is crucial.

Table 2.1 Comparison of Previous Work Related to the Project

| Author | Aim | Advantages | Disadvantages |
|---|---|---|---|
| [5] | The study aims to explore recent advancements in optical fiber sensors, with a specific focus on the application of microfibers in biochemical and physical sensing. It underscores how optical fibers' unique attributes have expanded their utility beyond telecommunications to sensing domains, citing advantages like low transmission loss, remote sensing capabilities, and suitability for challenging environments. The review emphasizes the benefits of microfibers, including their large optical confinement, flexibility, and high sensitivity to environmental changes. Furthermore, it discusses how advancements in micro/nanotechnology enable sensor miniaturization without compromising | • High bandwidth and multiplexing capability<br>• Remote sensing<br>• Immunity to electromagnetic interference | • Packaging and integration issues<br>• Cost<br>• Material limitations |

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| | performance metrics. The study also highlights tapered microfibers' role in enhancing interaction with surrounding analytes, thereby improving detection capabilities for diverse chemical and physical parameters. | | |
| [6] | Biochemical sensors with high sensitivity are essential for food safety, environmental monitoring and medical diagnostics. Sub-wavelength diameter optical microfibers are now necessary for fiber-optic biochemical sensors because of their strong optical nonlinearity, broad evanescent field and small size. With an emphasis silicabased microfiber production techniques, this article examines current developments in microfiber biochemical sensors. Based on demodulation techniques, microfiber | • High sensitivity<br>• Compact size (miniaturization)<br>• Diverse sensing capabilities<br>• Precision measurement | • Mechanical weakness<br>• Susceptibility to external factor<br>• Application-specific limitations<br>• Complex fabrication for special structures |

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| | structures are divided into optical intensity-modulated sensors. After a discussion of the basis mechanics of sensing, an outline of the applications in chemical detection, biosensing, gas sensing and environmental monitoring is given. An overview of upcoming potential and difficulties in microfiber biochemical sensors is provided in the paper's conclusion. | | |
| [7] | This paper provides a thorough analysis of the substrates, microbial species, and processing techniques related to the manufacture of vinegar. During alcoholic and acetic fermentation, Acetobacter predominantly converts ethanol (C2H5OH) to acetic acid (CH3CO2H), which is how vinegar is made. The article talks about diverse | • Provides detailed insights into the traditional and modern methods of vinegar production.<br>• Discusses the diversity of substrates and | • May be technical and detailed, potentially requiring prior knowledge of fermentation process.<br>• Focuses primarily on production methods and |

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| | microbial species that cause fermentation and covers a variety of agricultural substrates utilised in the manufacturing of vinegar, like fruits and grains. It also looks at the ageing processes, fermentation methods, and acetic acid bacteria species that affect vinegar quality. | microbial species used, highlighting the versatility of vinegar production.<br>• Offers comprehensive overview of factors affecting vinegar quality, aiding in the understanding of its flavor and aroma profiles. | micro bial aspects, which might limit coverage if broader socio-economic or environmental aspects related to vinegar production.<br>• Could be extensive, requiring time and effort to digest all the information provided. |
| [8] | This study focuses on optical microfiber, which are amorphous material-made cylindrical optical waveguides with a diameter of around 1µm. Before 2003, uneven profiles and substantial optical losses | • High sensitivity due to their small size and large evanescent field.<br>• Compact size. | • Requires precise control over the manufacturing process.<br>• Higher transmission loss. |

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| | made constructing long, low-loss optical microfiber's challenging, diameters smaller than 5µm. A two-step fabrication procedure that involved drawing an optical fiber taper into nanowire by wrapping it around a heated glass was significant breakthrough. Despite having greater transmission losses, this approach sparked a lot of research and produced a number devices for optical microfiber based sensing, communications and laser applications. | • Useful in nonlinear optics and various advanced photonic applications. | • Challenging to handle and integrate into larger systems. |
| [1] | The development of Raman distributed optical fiber sensing (RDOS) is reviewed in this article, emphasizing its applicability and efficiency for distributed temperature measurements across a range of engineering domains. The four main challenges facing traditional RDOS, despite its wide | • Excellent efficacy and adaptability for measuring temperature.<br>• Broad range of uses, spanning from industrial manufacture to scientific | • Limited precision in temperature measurement as a result of several technical issues.<br>• Challenges in striking a |

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| | applicability and maturity, are: variations in Raman optical attenuation, low signal-to-noise ratio (SNR), and fixed errors in the demodulation equation that limit the accuracy of temperature measurement; the inability to balance spatial resolution and sensing distance; the trade-off between SNR and measurement time; and the incapacity to perform dual-parameter detection. The study suggests that merging RDOS with knowledge-based technologies, including sophisticated demodulation, can greatly improve accuracy and performance. It also outlines typical applications and performance benefits. | research.<br>• Complex and advanced technology. | balance between spatial resolution and sensing distance.<br>• Alternatives between measurement time and SNR. |
| [9] | With an emphasis on the classification, distribution, | • Offers a comprehensive | • Readers who are not |

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| | and generation mechanisms of vinegar volatile organic compounds (VVOCs), this paper offers a thorough analysis of vinegar. Fruit and cereal varieties are the primary categories for vinegar; its raw materials include a variety of fruits (such as grape, apple, and pineapple) and starchy cereals (such as sorghum, rice, and wheat). The article discusses how the various basic ingredients, microbes, and production methods of vinegars from around the world affect their distinct flavors and fragrances. It also emphasizes the health advantages of vinegar, particularly conventional varieties because of its advantageous components. The paper explores the mechanics underlying the creation of VVOCs and talks about developments in analytical | summary of vinegar's classification and distribution throughout the world.<br>• Draw attention to the health advantages of vinegar and elevates its intake above that of a simple condiment.<br>• Explain developments in VVOC analysis methods and provides insights into contemporary scientific methods. | familiar with food science or chemistry may find the complex scientific and technical content difficult to understand.<br>• In addition to the review's probable concentration on volatile organic compounds (VVOCs), it may miss other significant facets of vinegar production and consumption.<br>• Practical considerations |

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| | techniques for their detection. Lastly, it looks at potential avenues for future research to learn more about VVOCs and how they are made. | | in the production and consumption of vinegar may not be fully addressed by the study due to its emphasis on analytical methods and mechanisms. |
| [10] | This study uses Cite Space software and Web of Science Core Collection (WoSCC) data to do a thorough bibliometric analysis of vinegar research from 1998 to 2019. By highlighting key themes, new trends, and potential areas for future research, it seeks to visualize the knowledge map of vinegar research. The analysis divides the major issues into | • Outlines major themes and patterns in the comprehensive examination of vinegar research as a whole.<br>• Makes the knowledge map easier to understand | • For scholars who are not familiar with these techniques, using sophisticated tools like Cite Space and bibliometric analysis may be challenging. |

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| | six categories: bacteria, chemicals, health functions, production technologies, adjuvant medications, and vinegar residues. It covers 883 original research and review articles and has 19,663 references. The study also makes use of Shneider's four-stage paradigm to comprehend how vinegar research has evolved over time. | by using bibliometric methods to visualize the field's intellectual structure.<br>• Assists in the identification of new trends and possible study topics. | • Since only publications indexed in the WoSCC are included in the study, pertinent studies published elsewhere may be missed.<br>• Although thorough, the wide breadth may miss important features or subtleties within each of the six themes that have been found. |
| [11] | This paper examines the most recent developments in optical microfibers produced from standard fibers | • Ultrafast fiber laser performance is enhanced | • The production of consistent, high-quality |

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| | for application in ultrafast fiber lasers. It discusses the special qualities and production processes of optical microfibers and emphasizes how crucial they are to ultrafast fiber lasers. Significant evanescent field, adjustable dispersion, great optical nonlinearity, low optical loss, and complete compatibility with traditional fibers are some of the important characteristics. This paper reviews current developments in ultrafast fiber lasers with particular emphasis on high optical nonlinearity, dispersion control, and fast saturable absorbers fabricated from microfiber-supported nanomaterials. The article wraps off by going over potential uses for these lasers in the future, including enhanced dispersion and nonlinearity control and sensing and measuring | by optical microfibers, which provide very low optical loss and high optical nonlinearity.<br>• Laser characteristics can be precisely controlled by tailoring the dispersion properties of optical microfibers.<br>• Fast saturable absorbers and other applications benefit from the efficient interaction that a significant amount of the evanescent field allows | optical microfibers may pose technological challenges and need for specialized equipment.<br>• Optical microfibers have limited practical usage in some conditions due to their delicate nature and susceptibility to damage.<br>• There may be challenges in producing ultrafast fiber lasers based on microfibers on a larger scale for industrial use. |

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| | applications. | with surrounding materials. | |
| [3] | This paper reviews materials, techniques, and applications of optical sensors for pH measurement. It covers historical methods, influencing factors like temperature and ionic strength, and optical techniques such as luminescence, reflectometry, and absorptiometry. Innovative sensor designs for extreme pH values, dye-free methods, and polymeric hosts are discussed. Applications span bioprocess monitoring, oceanography, and medicine, with insights into future advancements and challenges in the field. | • Comprehensive coverage of optical pH sensing methods and materials.<br>• Detailed discussion on a wide range if optical techniques sensing.<br>• Highlights diverse applications in various fields, providing a broad perspective. | • Complexity and length of the review may be overwhelming for readers new to the topic.<br>• Required specialized knowledge and equipment, limiting accessibility.<br>• Integration and practical application of these sensors can be challenging. |

| | | | |
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| [12] | With an emphasis on industrial and medical applications, this paper investigates developments in laser micro/nano processing technologies for the fabrication of complex optical fibre sensors. It focusses on several laser-processed transducing structures, such as fibre Bragg gratings, cladding waveguides, and microcavities. These structures provide up new sensing options by improving sensing capabilities in applications like optofluidic biphotonic devices and improved Rayleigh backscattering fibres. | • Enables advanced and complex sensing applications.<br>• Applicable to a wide range of fields, particularly industrial and medical.<br>• Direct writing techniques and laser inscription configurations improve the versatility and functionality of fiber sensors. | • Complexity in fabrication and potential high costs associated with laser processing technologies.<br>• Requires precise control and expertise to achieve the desired structures and functionalities.<br>• Potential challenges in integrating these advanced structures into existing systems and ensuring their reliability in practical applications. |

## 2.7 Summary

Optical microfibers, characterized by their small diameter comparable to or smaller than the wavelength of guided light, offer unique properties that make them valuable in various applications, particularly sensing. One key feature is the evanescent field, which extends beyond the fiber's core, enabling interaction with the surrounding medium. This property allows optical microfiber detect changes in parameters such as refractive index, temperature and chemical concentration through evanescent field sensing mechanisms.

Despite their small size, optical microfibers can maintain low optical loss, ensuring efficient light transmission and enabling sensitive detection of small changes in the surrounding environment. In sensing applications, optical microfibers demonstrate high sensitivity, providing precise measurement capabilities, along with high resolution to distinguish subtle variations in the sensed parameters. Additionally optical microfiber exhibit fast response times, facilitating real-time monitoring and detection of dynamic events. Overall, optical microfibers offer a versatile platform for sensing application, leveraging their evanescent field properties, low loss and high sensitivity to enable accurate and rapid measurement of various physical and chemical parameters in diverse environments.

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

This chapter will detail the methodology for achieving the stated objectives: fabricating a functional single-mode fiber using the flame brushing technique, designing a measurement setup for liquid concentration detection using 1310 nm and 1550 nm input laser sources, and evaluating the performance of the microfiber sensor in detecting various liquid concentrations, focusing on sensitivity, response time, and resolution. The methodology section covers the step-by-step process of creating the single-mode fiber, the design considerations for the measurement setup, including the selection of components and calibration procedures, and the experimental protocols for testing the microfiber sensor's performance. This comprehensive approach ensures a thorough understanding of the techniques and tools necessary to meet the research goals effectively.



## 3.2 Methodology

This project focuses on the development of an optical microfiber sensor for liquid concentration detection. Accordingly, this chapter delineates the methodologies and strategies employed to achieve the project's objectives. The project was systematically divided into three primary phases: the fabrication of a functional silica glass microfiber using the flame brushing technique; the design of an optimized experimental setup for liquid concentration detection, incorporating input laser sources with wavelengths of 1310 nm and 1550 nm; and the evaluation of the microfiber sensor's performance in detecting varying

liquid concentrations.

### 3.2.1 Fabrication of microfiber sensor using flame brushing technique.

The flame brushing technique enables the fabrication of optical microfibers with micrometer-scale diameters, offering ultra-thin structures with precise control. This method employs a small, adjustable flame commonly from an oxy-hydrogen or butane torch to heat conventional optical fibers. To ensure stability, the fiber is positioned horizontally and securely fastened at both ends. While the flame is applied, the fiber is drawn simultaneously and at a controlled rate from both ends, allowing the softened glass to be shaped into a fine, tapered form.

The ability to precisely control the diameter of the resulting microfiber by adjusting parameters such as flame temperature, pulling speed, and applied tension is fundamental to the flame brushing process. By meticulously optimizing these factors, microfibers with consistent diameters and minimal surface roughness can be fabricated, which is critical for maintaining low optical loss and ensuring high sensitivity in sensing applications.

The method offers several advantages, including the production of long, uniform microfibers with excellent optical properties, making it well-suited for various applications, such as photonic devices, optical sensors, and telecommunications. Additionally, the flame brushing approach is highly appealing for both research and industrial use due to its simplicity, cost-effectiveness, and practicality compared to alternative techniques like chemical etching or laser ablation.

#### 3.2.1.1 Stripping Process.

By using the fiber cutter, the jacket and cladding of the optical fiber cable were stripped away as shown in **Figure 3.1**. The triple hole design allowed for various cable

diameters and offered adaptability. Measurements like 0.25 um, 0.9 um, and 3 mm were usually used to identify the three holes, signifying the diameter of the wires that could be removed through each one.

**Figure 3.1** Stripping the jacket and cladding of the optical fiber.

Entails removing the covering from the fiber optic in order to make it ready for fusion splicing. Typically, the laser was used to precisely cut the holes in the stripper blade. The stripper could cut through the gap without shattering the glass fiber since it was big enough. Following the stripping procedure, an assessment was conducted to ascertain the effectiveness of the stripping. In the event that it worked, the procedure moved on to the following stage. If not, the stripping procedure was carried out once again until it was effective.

### 3.2.1.2 Cleaning Process.


**Figure 3.2** Clean the optical fibre with alcohol.

The bare fiber was cleaned with a piece of free-lint tissue soaked in 99.9% isopropyl alcohol till it made a squeaky sound after the plastic cladding was removed from the fiber optic wires as shown in **Figure 3.2**. This prevented contaminants from remaining inside a fiber optic line after splicing and leading to splice loss. In **Figure 3.3** represented the types of alcohol used.


**Figure 3.3** Type of alcohol used

### 3.2.1.3 Cleaving Process.

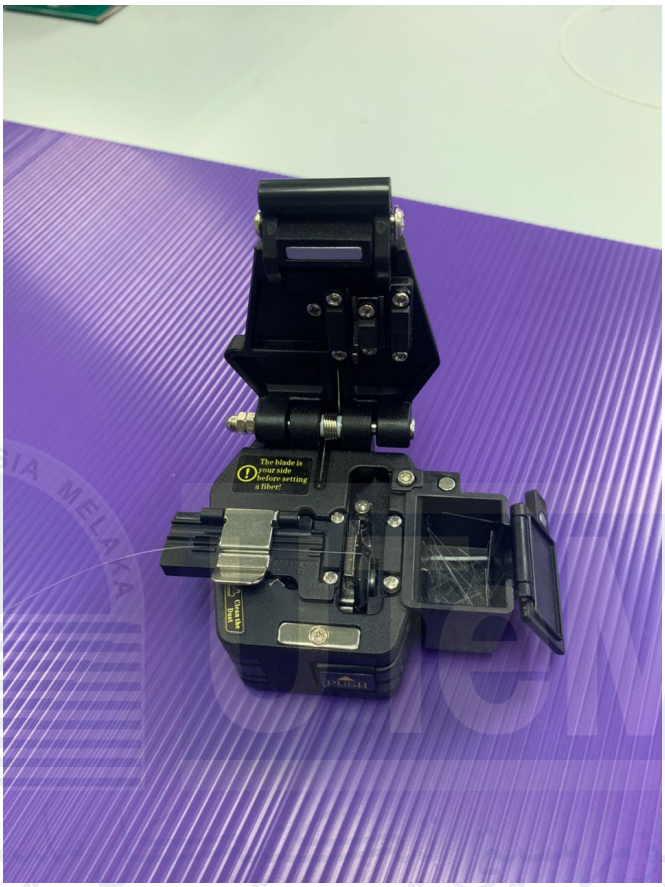


**Figure 3.4** Cleave the middle and both ends of the optical fiber.



Next, a hand cleaver was used to sever the Single Mode (SM) pigtails, and both ends of the fiber optic cable that was being tested. It is possible that during the fiber-cutting procedure, the surface of the fiber tips was not perfectly flat. To ensure a seamless connection, a good cleaver has to be used to produce a clean break on the ends of two fiber optic cables before splicing them together. A visual inspection and testing of the stripped fiber ends were done to assess the success of the stripping procedure. The end product of a good stripping procedure would be clean, undamaged fiber ends free of any dirt or leftover coating. If flaws were found, the stripping procedure was carried out again until the intended outcome was obtained. Likewise, an examination was carried out to guarantee the effectiveness of the cleaving procedure. The procedure moved on to the following phase if

the cleaving was successful; if not, it was repeated until it was.

### 3.2.1.4 Splicing Process.


**Figure 3.5** Splicing machine

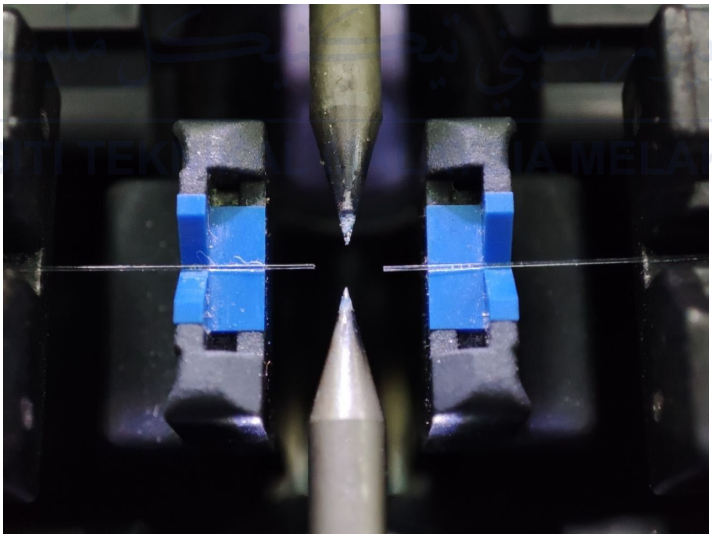

**Figure 3.6** A fusion splicer to fuse two fiber together.

The optical fiber's exposed fiber tips were tested once the cleaving was finished, and the SM pigtails were then loaded and spliced using a fusion splicer. Splicing was the process of joining two stripped fiber optic wires with a splicing equipment (**Figure 3.5**). An electric arc was employed by a fiber optic fusion splicer to fuse two fibers together as shown in

**Figure 3.6.**

For correct splicing, the distance between the electrode and the two fiber ends was essential. It was crucial to follow the important guidelines in order to prevent incorrect splicing. To achieve the highest transmission rate, the total loss along the cable, including splice loss, had to be as low as possible. By using the fusion splicing process, fiber cores were fused together with the least amount of attenuation and insertion loss possible usually less than 0.01 dB.

A fusion splicer using specialized equipment was used to precisely align the two ends of the fiber. The fiber ends were fused or welded together during the fusion splicing process using an electric arc or another type of heat source. Consequently, there was less light loss because the fibers were joined in a transparent, non-reflective, and continuous way. The two strands were correctly aligned before starting. Second, to splice single-mode and multimode fiber cables, a tiny electric arc was created to melt the fiber and fuse them together.

A few advantages of fusion splicing were decreased back reflection and splicing loss (around 0.1 dB). a number of things, such as the surrounding heat sources, the light that is present, and the weather. After the splicing procedure was verified to be successful, it was deemed finished. The splicing procedure was repeated until it was successful if not. The splicing process was represented visually by the flowchart, which highlighted decision points where each step's success was assessed before moving on to the next. This made sure that the splicing procedure was done precisely and quickly.

### 3.2.1.5 An overview of fabrication optical microfiber using flame brushing technique

**Figure 3.7** illustrates the overall process of microfiber fabrication using the flame brushing technique, highlighting the meticulous execution required for optimal results. Initially, the fiber was thoroughly cleaned to eliminate contaminants that could compromise

tapering quality, a critical step for ensuring high sensitivity and performance in sensing applications. The cleaned fiber was then securely positioned in the flame brushing equipment to prevent any movement during the process, ensuring uniform tapering.

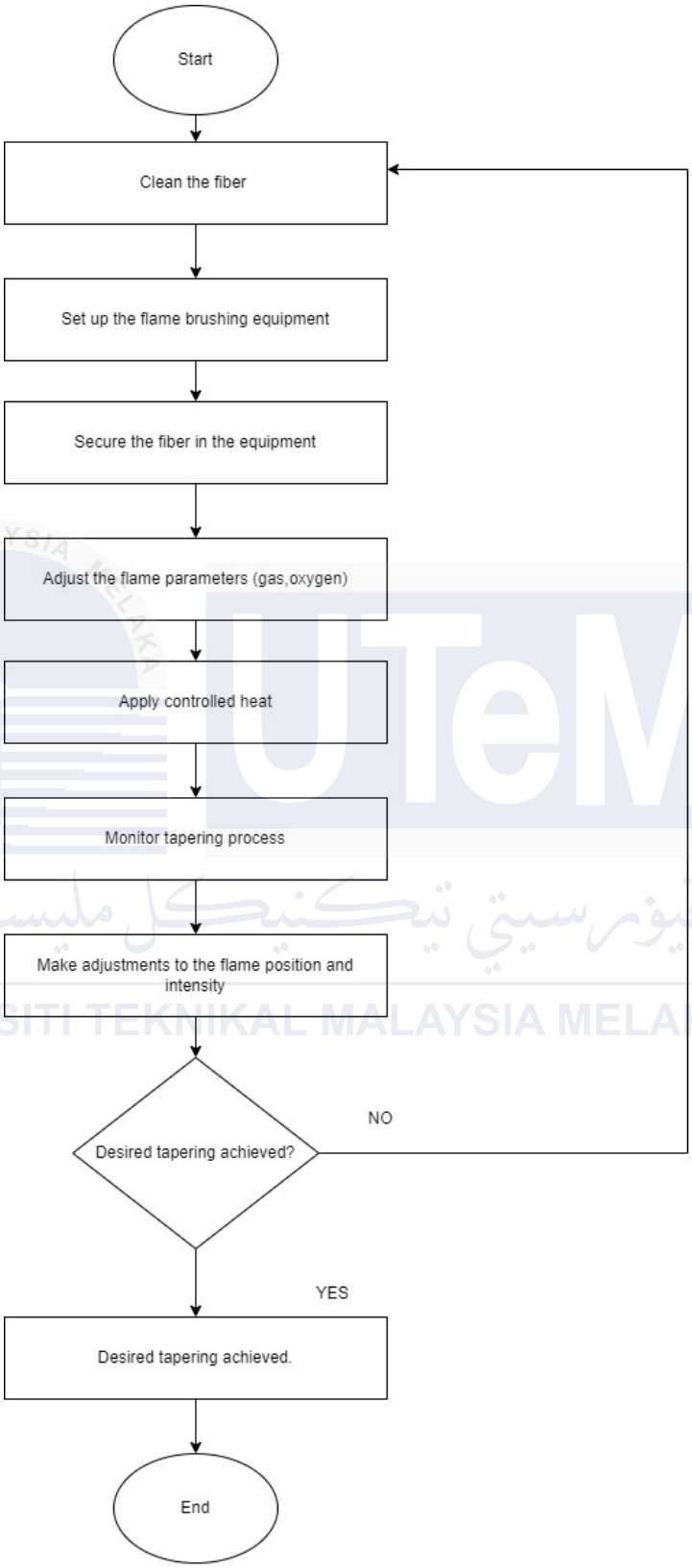


**Figure 3.7** Process flow-chart of microfiber fabrication using the flame brushing technique

The flame parameters, such as gas and oxygen levels, were precisely adjusted to achieve controlled heat, crucial for maintaining the fiber's structural integrity and achieving

a target waist diameter of approximately 7-8 microns. Throughout the heating process **(Figure 3.8),** constant monitoring and adjustments were necessary to maintain the desired tapering profile, ensuring the microfiber's robustness and reliability. This iterative adjustment cycle was vital to detect and correct any deviations, ensuring the final tapering met the stringent specifications required for high-performance sensing. The process concluded successfully upon achieving the desired tapering, reflecting the precision and care taken to fabricate a high-quality microfiber sensor suitable for advanced applications. . The fiber was securely positioned in the apparatus, ensuring it was held firmly and correctly aligned, as shown in **Figure 3.8.**

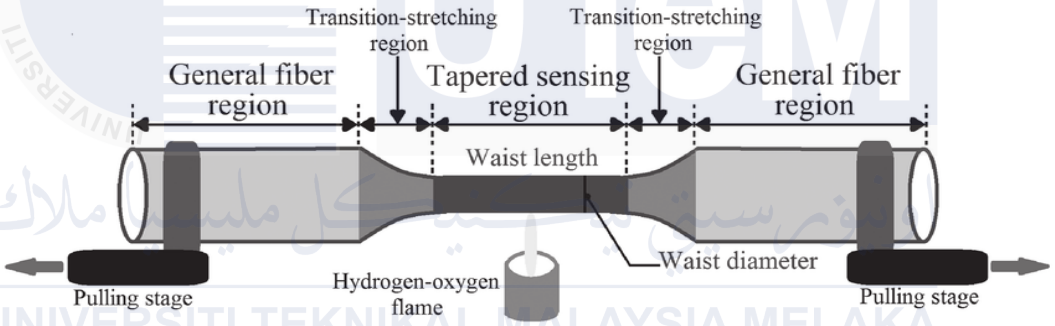


**Figure 3.8** Microfiber fabrication using flame brushing technique

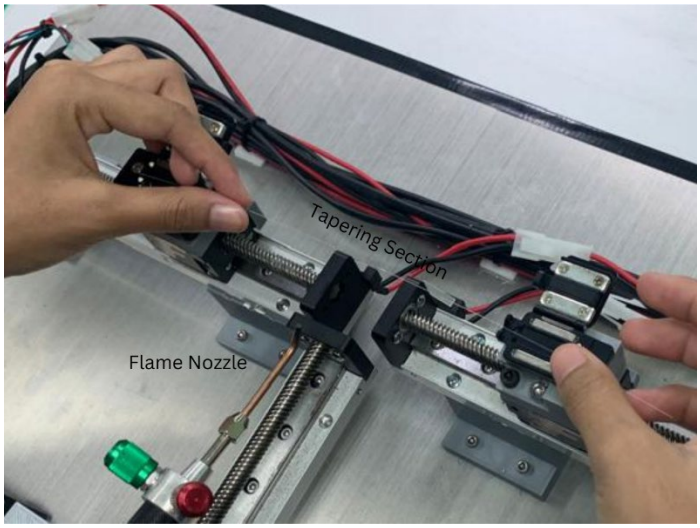


**Figure 3.9** The secure position of the fiber in the apparatus


**Figure 3.10** Adjust flame parameters (gas flow rate, intensity)

**Figure 3.10** shows the adjustment of the flame parameters, including the gas flow rate and flame intensity, to achieve the desired tapering effect. It also depicts the apparatus prepared, applying controlled heat to the fiber using a sweeping motion. The process was continuously monitored to ensure proper tapering and prevent any damage to the fiber. Throughout the procedure, necessary adjustments were made to the flame position and intensity to achieve the desired tapering profile.

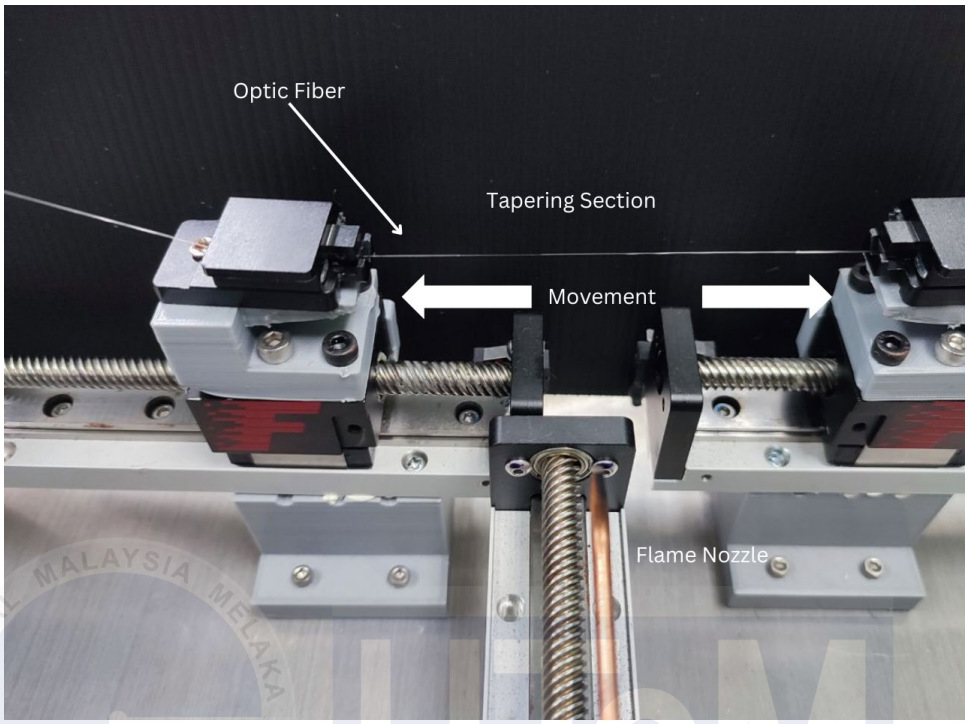


**Figure 3.11** Burning the fiber with the tapering technique

Once the desired tapering was achieved, the fiber was removed from the apparatus, as represented in **Figure 3.11**. The tapered microfiber was inspected for defects, and quality checks were performed. The microfiber was cleaned to remove any residual particles or contaminants. The fabricated tapered microfiber was now ready for further use or experimentation.

### 3.2.1.6 Flowchart representation of the steps involved in determining power loss using an Optical Time Domain Reflectometer

The flowchart illustrating the calculation of sensor power loss using an optical time-domain reflectometer (OTDR) is presented in **Figure 3.12**, while the role of the OTDR is depicted in **Figures 3.13** and **3.14**. To initiate the process, the OTDR was powered on and allowed to complete its initialization. Subsequently, the OTDR was connected to the sensor under test using an appropriate optical connector or adapter. The OTDR parameters such as

wavelength, pulse width, and measurement range were then configured based on the sensor's characteristics and the required measurement precision.

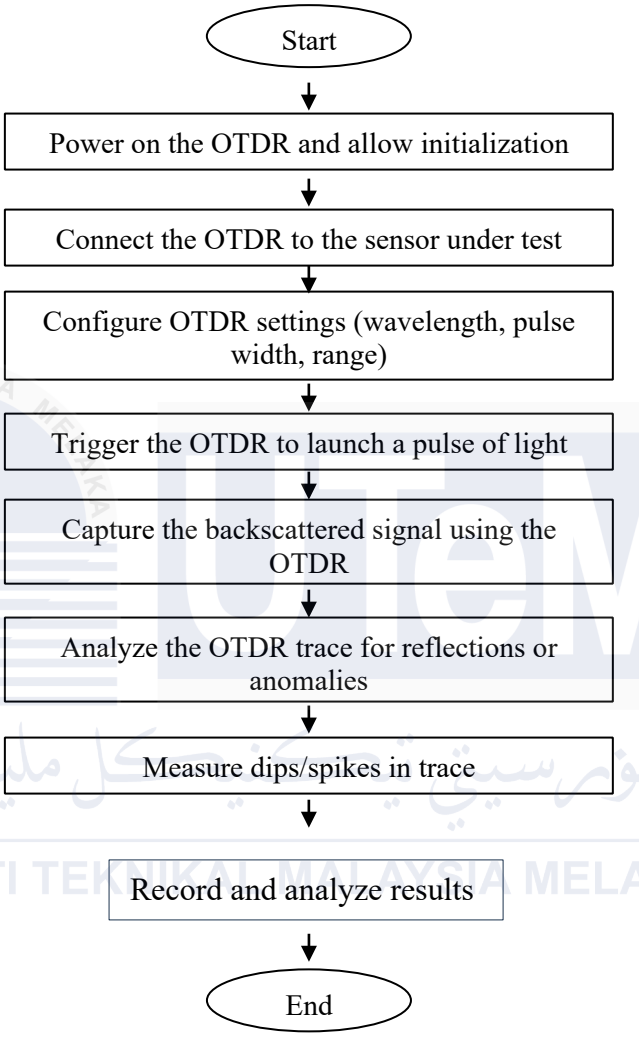


**Figure 3.12** Determine the sensor power loss using an Optical Time Domain Reflectometer (OTDR)




**Figure 3.13** Function of OTDR


**Figure 3.14** Optical Time Domain Reflectometer (OTDR)

Once the OTDR setup was complete, it was activated to transmit a light pulse into the sensor. The backscattered signal reflected from the sensor was recorded by the OTDR, containing critical information about the sensor's power loss.

The analysis of the OTDR trace obtained from the measurement is illustrated in **Figure 3.15**. This trace was carefully examined to identify significant reflections or irregularities indicative of power loss within the sensor. Specific attention was given to dips or spikes on the trace corresponding to the tested sensor, as these features provided valuable insights into the sensor's performance.

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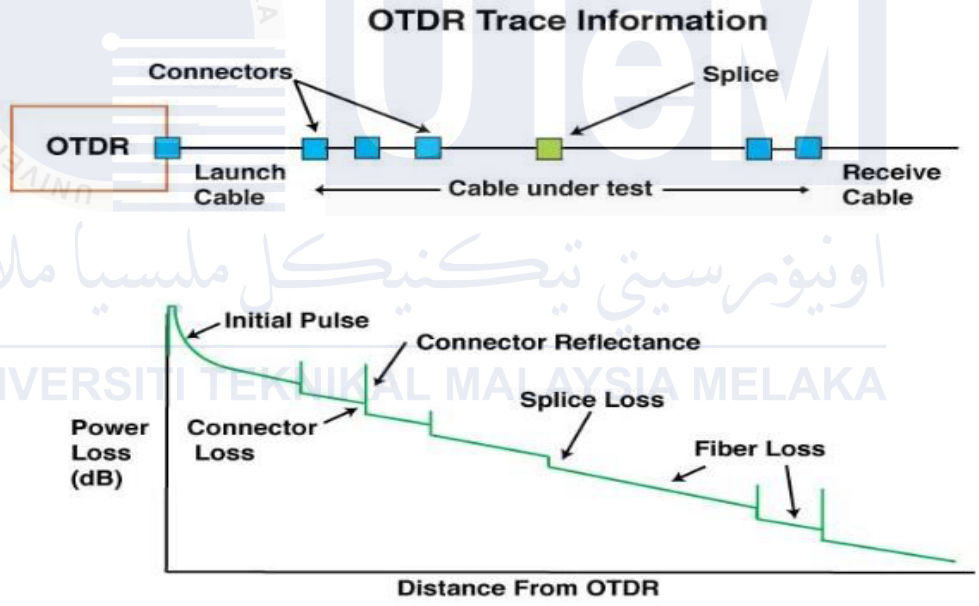



**Figure 3.15** The analyse the OTDR trace

The depth or amplitude of the occurrences on the OTDR trace was analyzed to determine the sensor's power loss. Appropriate algorithms and calibration parameters specific to the tested sensor were applied to calculate the power loss based on the observed depths or magnitudes of the dips or spikes. The power loss measurement results, presented in **Figure 3.16**, were recorded and analyzed for future comparison and study. To assess the

sensor's performance and ensure compliance with required specifications, the measured power loss was compared against the sensor's design criteria or relevant industry standards.

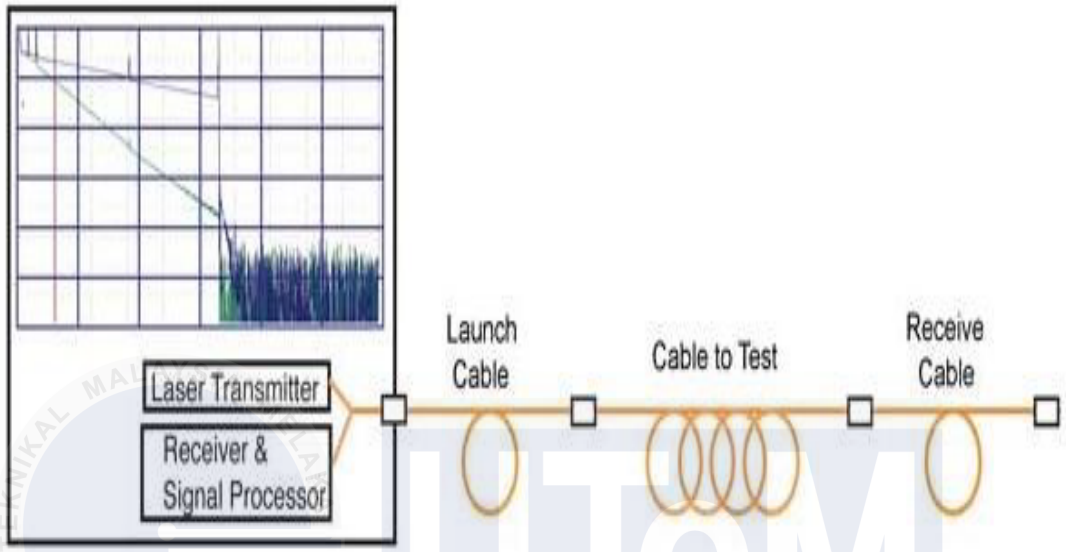



**Figure 3.16** Record and analyze the results of the power loss measurement

If required, the measurement procedure was repeated using different measurement ranges, pulse widths, or wavelengths to gain a comprehensive understanding of the sensor's power loss characteristics under varying conditions. Upon completion of the measurements, the Optical Time-Domain Reflectometer (OTDR) was powered down and disconnected from the sensor to finalize the power loss analysis. The recorded results were subsequently utilized for documentation, troubleshooting, or further analysis.



### 3.2.2 Measurement set-up for acidic liquid concentration detection

There are numerous crucial phases involved in designing a measurement setup for liquid concentration detection using 1310 nm and 1550 nm input laser sources. An optical microfiber sensor is first created by aligning and coupling two laser sources that emit light at the correct wavelengths. These microfiber sensors placed within a transparent container

containing liquid sample. It was created utilizing a flame brushing technique. For consistent reading, the container provides a steady environment.

Through microfiber, the laser light travels and interacts with the liquid through the evanescent field. The transmitter light is captured by photodetectors positioned at the microfiber's output end, and an optical power meter is used to measure it. A data acquisition system is used to record and analyze the power meter's data. This arrangement provides an accurate and dependable way to measure liquid concentration by allowing the detection of changes in liquid concentration based on differences in transmitted light intensity at the various wavelengths.

#### 3.2.2.1 Preparation of acidic (vinegar) solutions with various concentrations.

The preparation of acidic (vinegar) solutions with varying concentrations begins with a stock vinegar solution at a known acidity level. A precise volume of the concentrated vinegar is measured, followed by the addition of a calculated amount of distilled water. For example, mixing equal parts of vinegar and water produces a solution with half the concentration of the original vinegar. By adjusting the vinegar-to-water ratio, solutions with specific concentrations can be achieved. These diluted solutions are thoroughly mixed to ensure uniformity. This method enables precise control of acidity levels, which is critical for applications such as cleaning agents, culinary recipes, and experimental calibrations.

#### 3.2.2.2 Designing experimental setup

**Figure 3.17** illustrates the designing experimental setup involving 1310 nm and 1550 nm input laser sources for liquid concentration detection. The input laser sources at 1310 nm and 1550 nm wavelength are comprehensive investigation into liquid concentration sensing is fueled.

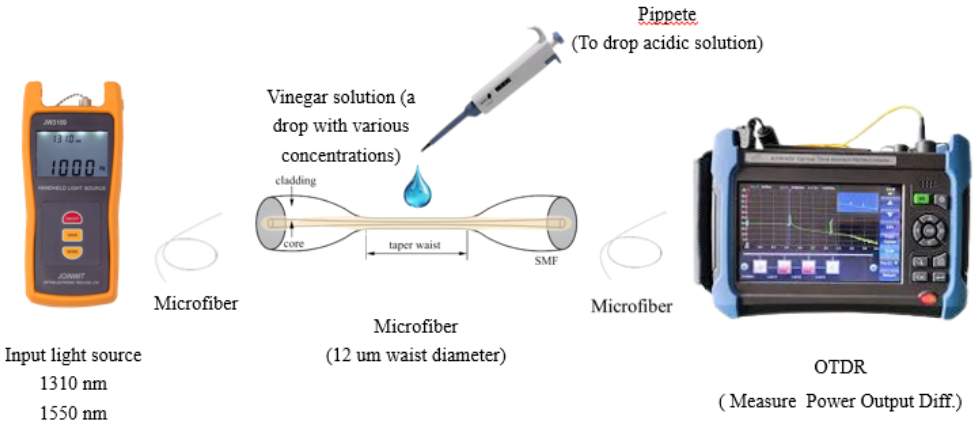



**Figure 3.17** Designing experimental setup involves utilizing 1310 nm and 1550 nm input laser sources for liquid concentration detection.

As transmitters, these laser sources provided regulated light pulses that pass through a precisely constructed tapered fiber. One of the setup's key components, this tapered fiber, interacts uniquely with a vinegar solution that comes in different ratios. The interaction offers a refined understanding of the solution's optical characteristics, as the tapered fiber functions as a sensitive medium to identify concentration-related alterations.

In this experimental setup, the input laser sources acted as a transmitter, emitting the light pulses at both wavelengths, 1310 nm and 1550 nm. The input power in dBm was simultaneously measured by the Optical Domain Time Reflectometer (OTDR). The tapered silica fiber sensor was ensured to be cleaned and fabricated while the optical microfiber was tested in the middle. With the apparatus set up, the six different vinegar concentrations (0-50%). As seen in Figure 3.20, the experimental apparatus which included the OTDR, input laser sources, and tapered silica fiber sensor was assembled in order to carry out the experiment.

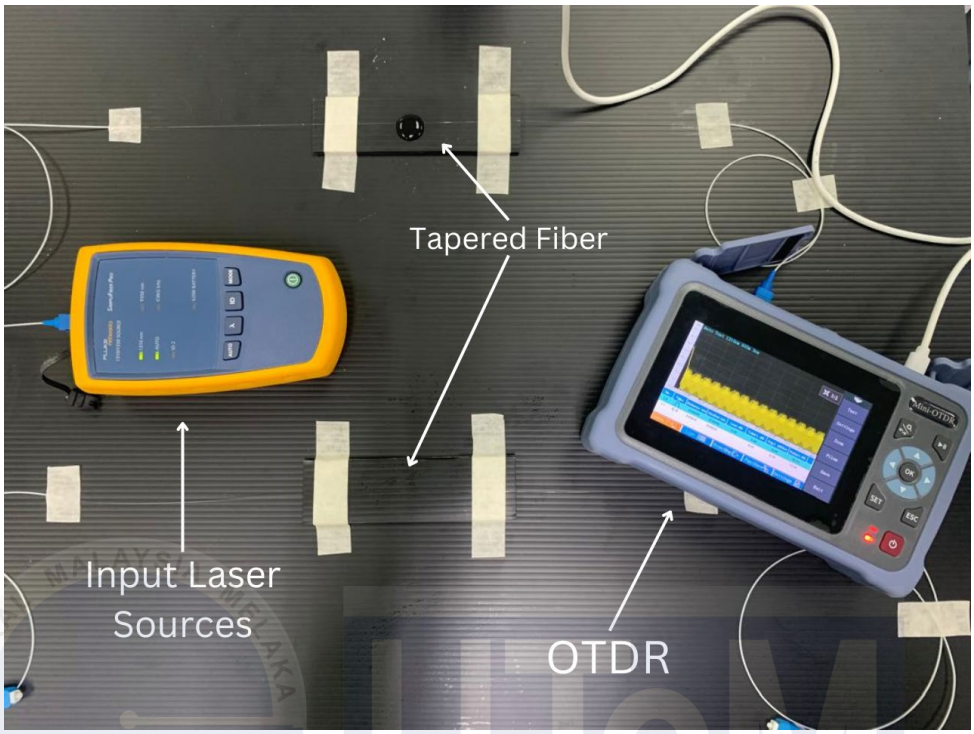



**Figure 3.18** Design of optical microfiber sensor experiment setup at the development phase.

The input laser sources in the experimental setup served as the transmitter, sending out light pulses with wavelengths of both 1550 nm and 1310 nm. The output power was simultaneously measured in dBm by the OTDR (Optical Time-Domain Reflectometer), which also functioned as the receiver. The tapered silica fiber sensor was checked for cleanliness and calibration, and the optical microfiber was tested in the middle. After setting up the equipment, the six vinegar concentrations 50%, 40%, 30%, 20%, 10%, and 0% were made in accordance with the established technical protocols and the liquid concentration calculation, as shown in **Table 3.1.**

**Table 3.1** Acidic liquid concentration calculation

| Vinegar Concentration | Calculation |
|---|---|
| 0% (0ml Vinegar) | $\frac{Amount\ of\ vinegar}{Amount\ of\ Vinegar + DI\ Water} \times 100$ $\frac{0ml}{0ml + 1ml} \times 100 = 0\%$ |
| 10% (1ml Vinegar + 1ml DI Water) | $\frac{Amount\ of\ vinegar}{Amount\ of\ Vinegar + DI\ Water} \times 100$ $\frac{1ml}{1ml + 9ml} \times 100 = 10\%$ |
| 20% (2ml Vinegar + 8ml DI Water) | $\frac{Amount\ of\ vinegar}{Amount\ of\ Vinegar + DI\ Water} \times 100$ $\frac{2ml}{2ml + 8ml} \times 100 = 20\%$ |
| 30% (3ml Vinegar + 7ml DI Water) | $\frac{Amount\ of\ vinegar}{Amount\ of\ Vinegar + DI\ Water} \times 100$ $\frac{3ml}{3ml + 7ml} \times 100 = 30\%$ |
| 40% (4ml Vinegar + 6ml DI Water) | $\frac{Amount\ of\ vinegar}{Amount\ of\ Vinegar + DI\ Water} \times 100$ $\frac{4ml}{4ml + 6ml} \times 100 = 40\%$ |
| 50% (5ml Vinegar + 5ml DI Water) | $\frac{Amount\ of\ vinegar}{Amount\ of\ Vinegar + DI\ Water} \times 100$ $\frac{5ml}{5ml + 5ml} \times 100 = 50\%$ |

The table shows how to use a dilution process with vinegar and distilled (DI) water to create vinegar solutions with different concentrations, from 0% to 50%. The volume ratio of vinegar to the entire solution, stated as a percentage, is used to calculate each concentration. At the 0% concentration, DI water makes up the entire solution and no vinegar

is added. The vinegar component makes up 10% of the solution when 1 mL of vinegar is combined with 9 mL of DI water to make a total of 10 mL. Similarly, for 20%, 2 mL of vinegar is combined with 8 mL of DI water; for 30%, 3 mL of vinegar is mixed with 7 mL of DI water; for 40%, 4 mL of vinegar is added to 6 mL of DI water; and for the final 50% concentration, equal volumes of vinegar and DI water, 5 mL each, are used.

The following formula (**Equation 3.1**) is routinely used to calculate each concentration:

$$Concentration(\%) = \frac{Amount\ of\ Vinegar}{Amount\ of\ Vinegar + DI\ Water} \times 100 \quad (3.1)$$

For experiments that need reliable and repeatable results, this guarantees exact control and accuracy in solution preparation. A systematic assessment of the sensor's performance in a variety of acidic conditions is made possible by the methodical methodology, which offers a clear development of vinegar concentrations. The sensitivity, linear range, and overall response of the sensor to different acidity levels may be determined thanks to this gradient of concentrations, which is crucial for its validation and optimization in practical applications. The table successfully illustrates the regularity and dependability of the dilution process by preserving proportionate concentration increments, providing a strong basis for the experimental studies.

Furthermore, the experimental process should employ distilled water (DI water). The first concentration, designated as 50%, entails using pure shampoo without any DI water added. By adding more DI water to the solution, the vinegar concentration is adjusted and diluted, as shown in **Table 3.1**. For instance, as shown in **Figure 3.19**, to reach 50% concentration, 5 ml of vinegar and 5 ml of DI water are combined and constantly swirled for 5 minutes to guarantee complete mixing and blending. This painstaking preparation

procedure ensures that the six distinct vinegar concentrations utilized in the experiment are correct and consistent, upholding the integrity of the scientific inquiry throughout the experiment to retain the purity necessary for precise and trustworthy results. **Figure 3.20** shows the procedure to drop the acidic liquid on the tapered fiber.

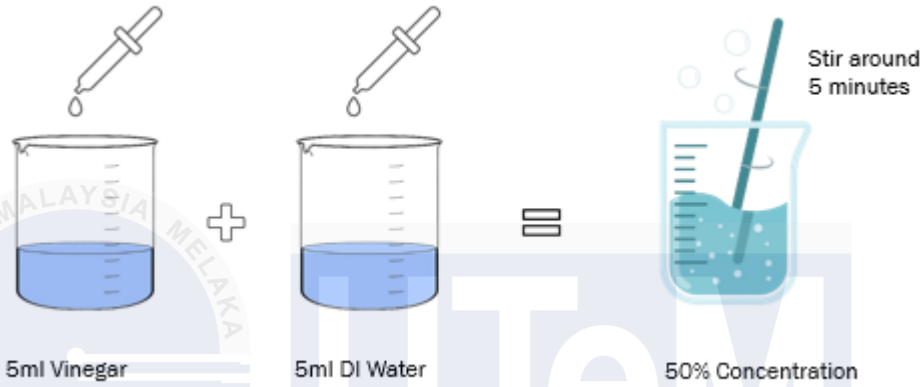



**Figure 3.19** The 50% concentration solution

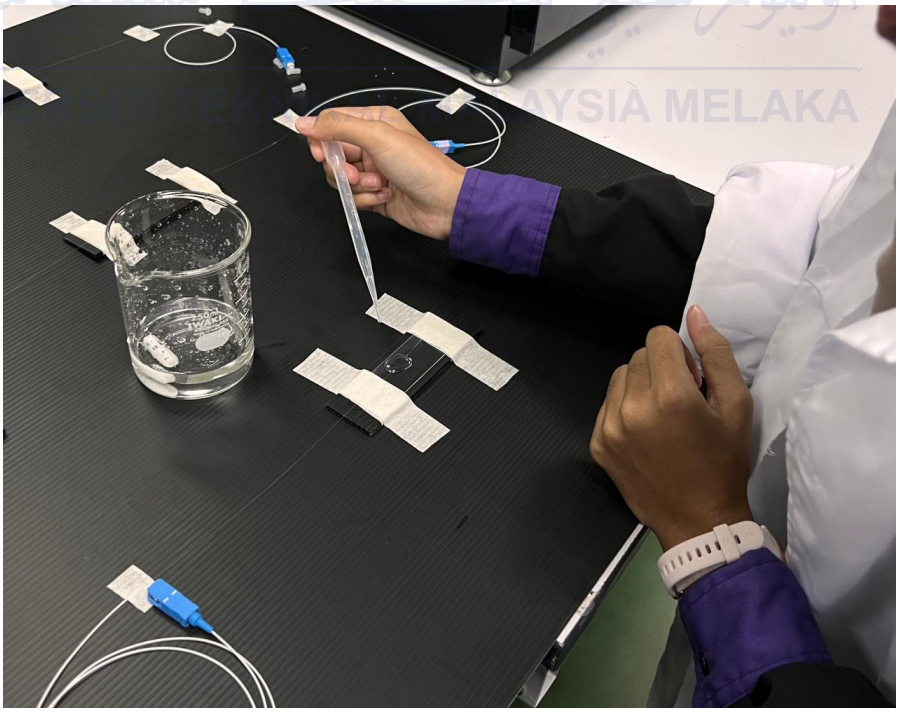


**Figure 3.20** Immersed the tapered fiber sensor into each vinegar concentration solution one drop at a time.

### 3.2.3 Microfiber sensor evaluation procedures

A number of methodical techniques are used in the evaluation of microfiber sensors in order to guarantee their sensitivity, resolution and response time in a range of applications. These procedures are essential to ascertain the sensor's performance in various scenarios and to confirm their suitability for practical uses including environmental monitoring, biochemical detection and medical diagnostics. Testing the sensor's sensitivity, resolution and response time in identifying particular compounds or environmental changes is one of the most important evaluation processes. In order to make sure the microfiber sensors can survive real-world use scenarios; several stress tests are also used to evaluate the stability and endurance of the sensor. The genuine capabilities and potential limitations of microfiber sensors are thoroughly studied and comprehended through these extensive evaluation techniques.



#### 3.2.3.1 Evaluating the microfiber sensor's performance in detecting various liquid concentrations.

Stabilization was given enough time to establish equilibrium when the tapered silica fiber sensor was submerged in each vinegar concentration solution, usually a few minutes. During this waiting time, the sensor was guaranteed to stabilize and adapt to its surroundings. After stabilization, the output power for each vinegar concentration was recorded using the OTDR (Optical Time-Domain Reflectometer). **Figure 3.21** displayed the output power values recorded for each vinegar concentration, while **Figure 3.22** displayed the output power measured using OTDR. For precise and trustworthy data on the sensor's reaction to various concentrations, this step was essential. The experiment's goal was to examine how different vinegar concentrations affected the tapered silica fiber sensor's optical characteristics by methodically recording the output power at equilibrium.


**Figure 3.21** Output power measured using OTDR


**Figure 3.22** Collect the recorded output power values for each vinegar concentration.



Following data analysis, a graph was created with output power on the y-axis and concentration on the x-axis, using the recorded output power values for each vinegar concentration. The data points were subjected to linear regression analysis in order to get the regression line's equation and linear coefficient ($R$). To evaluate how well the regression line fit the data, the coefficient of determination ($R^2$) was computed. The change in output power per unit change in concentration was represented by the regression line's slope. In order to comprehend the link between concentration and output power, the data were interpreted by taking into account the linear coefficient, coefficient of determination, and slope.

## 3.3 Justification for sustainable development goals (SDG)

This project advances **SDG 9:** Industry, Innovation, Infrastructure, which is essential for many industrial uses, such as environmental monitoring and quality control in the food industry by developing sensor technology. By improving process monitoring and control, the invention of an extremely sensitive and dependable optical microfiber sensor for identifying acidic liquids, such as vinegar, showcases innovation in sensor fabrication and measurement methodologies and advances sustainable industrial practices.

By accomplishing the aforementioned goals, this research creativity and adds to the larger context of industrial growth and environmental stewardship, while also demonstrating technical breakthroughs and ensures alignment with sustainable development goals.

## 3.4 Summary

This chapter outlines the methodologies employed to achieve the project's objectives. First, a functional single-mode microfiber was fabricated using the flame brushing technique, ensuring precise control over the microfiber's dimensions to minimize optical loss and maximize sensitivity. Next, a measurement setup was designed for detecting acidic (vinegar) liquid concentrations using 1310 nm and 1550 nm input laser sources. Finally, the microfiber sensor's performance was evaluated based on key parameters, including sensitivity, responsivity, resolution, linearity, standard deviation, and linear range, to assess its effectiveness in detecting varying liquid concentrations. These methods collectively ensured the successful fabrication, implementation, and evaluation of the proposed sensor system.

# CHAPTER 4

# RESULTS

## 4.1 Introduction

This chapter presents the results of the experiments conducted to achieve the objectives outlined in the methodology. The primary goal was to fabricate a functional single-mode microfiber using the flame brushing technique, design a measurement setup for acidic (vinegar) liquid concentration detection, and evaluate the performance of the microfiber sensor. The results are discussed in terms of the sensor's sensitivity, responsivity, resolution, linearity, standard deviation, and linear range, which are crucial for assessing its capability in detecting varying concentrations of acidic liquids. The findings are analyzed and compared to the expected outcomes, providing insights into the effectiveness of the microfiber sensor and its potential applications in real-world scenarios. Additionally, the discussion highlights any challenges encountered during the experiments and offers suggestions for further improvements in sensor design and performance.



## 4.2 Fabricated silica glass microfiber

In order to create tapered microfibers using the flame brushing process, the right fiber material had to be chosen and cleaned to guarantee its purity. With careful attention to safety precautions and exact fiber alignment, the equipment was set up safely. To achieve the best tapering effects, flame characteristics were adjusted. A sweeping motion was used to apply controlled heat, which was constantly checked to avoid damage and adjusted as needed. The

fiber was taken out after tapering, and the tapered microfiber was examined for flaws. Cleaning was done to get rid of any remaining particles, and quality checks were carried out. The resulting tapered microfiber was then prepared for experimentation or additional application.

The assessment of the effect of tapering on optical power levels at both 1310 nm and 1550 nm wavelengths was shown in **Table 4.1**. Comparative investigation showed some interesting patterns. The optical power without tapering was recorded at -42.46 dBm at 1310 nm, and with tapering, it dropped to -41.34 dBm. This led to a drop of 1.02 dBm, indicating that the tapering strategy reduced optical power. Likewise, the optical power without tapering started at -38.41 dBm at 1550 nm, whereas the tapered counterpart started at -41.46 dBm. This resulted in a 3.05 dBm reduction, suggesting that the addition of tapering significantly reduced optical power. Subsequent analysis at 1310 nm revealed a 1.12 dBm drop from -43.45 dBm without tapering to -42.33 dBm with tapering. The reduction was 2.58 dBm at 1550 nm, going from -40.14 dBm without tapering to -42.72 dBm with tapering. These findings demonstrated the efficiency of the tapering procedure, particularly at 1550 nm, where the optical power decrease was more noticeable, pointing to a possible wavelength-dependent effect on the tapering result.

The material's intrinsic qualities or the unique features of the optical fiber at that wavelength may be responsible for the more notable decrease in optical power at the 1550 nm wavelength. The tapering process may have a greater effect on lowering optical power at 1550 nm since the material used in the experiment may have stronger absorption or scattering effects at this wavelength. Furthermore, the optical fiber's characteristics and design could behave differently at different wavelengths, affecting the tapering result differently at 1550 nm and 1310 nm. A more thorough knowledge of this phenomenon would come from additional research and study into the fiber characteristics and material properties

at various wavelengths.

**Table 4.1** The evaluating the impact of tapering

| INPUT LASER SOURCE 1310nm | | |
|---|---|---|
| MINUTES | WITHOUT TAPERED | WITH TAPERED |
| 1 | -41.34 | -42.46 |
| 2 | -42.33 | -43.45 |
| 3 | -42.98 | -43.98 |
| 4 | -42.98 | -43.98 |
| 5 | -42.98 | -43.98 |
| INPUT LASER SOURCE 1550nm | | |
| MINUTES | WITHOUT TAPERED | WITH TAPERED |
| 1 | -41.46 | -38.41 |
| 2 | -42.72 | -40.14 |
| 3 | -42.80 | -40.59 |
| 4 | -42.80 | -40.59 |
| 5 | -42.80 | -40.59 |

### 4.2.1 Minimizing losses in fiber splicing.

Fusion splicing was used in our project to join optical microfibers with a loss of 0.00 dB, as shown in **Figure 4.1**. The proposed microfiber sensor is made up of sets A, B, and C. The middle part of each set was tapered using a flame brushing technique and tested for various liquid concentrations. This showed that the fusion splicing was successful and that the spliced fibers achieved a near-perfect connection with minimal signal loss. The achieved loss value of 0.02 dB suggested that the splicing process was accurate and produced a highly efficient connection between the fibers. These results showed how effective the fusion splicing technique was in our project.

For the optical microfiber sensor to have dependable and low-loss connections, the splicing procedure had to be completed successfully. It made it possible for light signals to be transmitted with little to no attenuation, which was necessary for precise measurement and detection. A crucial stage in the creation of our optical microfiber sensor was the splicing

procedure, which gave us a strong platform on which to test and assess the sensor's performance in liquid concentration detection.


**Figure 4.1** Positive results with a loss of 0.02dB

### 4.2.2 Size of optical microfiber

The microfiber that was tested under a microscope was shown graphically in **Figure 4.2**. A microscope fitted with a micrometer scale was used to carefully measure the exact size of the microfiber optic sensor.

**Figure 4.2** Observing the size of microfiber

This microfiber sensor was successfully fabricated using a tapered method and a controlled combustion procedure. After being refined, the initial size of 125 µm was significantly reduced, resulting in an outstanding final size of 7.5 µm, as shown in **Figure 4.3.**



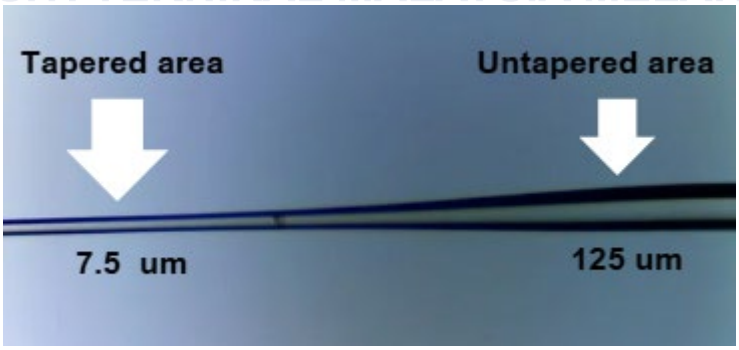



**Figure 4.3** Size of tapered and untapered microfiber.

## 4.3 Experimental result using 1310nm and 1550nm input laser sources

**Table 4.2** shows the results for various liquid (vinegar) concentration percentages of laser sources at 1310 nm. Furthermore, **Table 4.3** shows the outcomes for the laser sources

at 1550 nm for different liquid concentrations. The presented data revealed a sophisticated understanding of the optical properties of laser sources at 1310 nm across different liquid contents. A similar pattern emerged, showing that lower average optical power was associated with higher concentrations. When the average optical power was -44.966 dBm, the concentration of 0% once more stood out. Precision was demonstrated by the low standard deviation readings at 0% concentration, which stayed at 0.0423.

A 1310nm input laser source's performance at various liquid concentrations, ranging from 0% to 50%, is shown in the table. The standard deviation, sensitivity, linearity at each concentration level, and average output power in dBm are the main metrics that are examined. With results ranging from -44.966 dBm at 0% concentration to -39.784 dBm at 50% concentration, the data indicates that the average power (dBm) rises with concentration. This pattern implies that larger signal responses are the outcome of higher concentrations. With very low values across the concentrations, the standard deviation values show the consistency of the data. The 20% concentration, on the other hand, has the largest standard deviation of 0.1547, showing increased variability in the measurements at this level.

Sensitivity varies with concentration and quantifies the change in output power in relation to concentration variations. With a value of 0.1391 dBm at 40% concentration, the sensitivity is highest; at 50% concentration, it is lowest, at 0.0649 dBm. This suggests that the laser source responds best to variations in concentration of about 40%.

The percentage of measured data that follows a linear trend, or linearity, ranges from 72.7% to 99.77%. While the lowest linearity of 72.7% at 20% concentration indicates some departure from linear behaviour at this point, the highest linearity of 99.77% is shown at 50% concentration, suggesting a significant correlation with the expected trend. All things considered, the table sheds light on how well the 1310 nm laser source performs at various liquid concentrations, demonstrating that the system is very sensitive and linear at the

majority of concentrations, with some variability at particular concentration levels.

**Table 4.2** The different liquid (vinegar) concentration percentages of laser sources at 1310nm

| Input laser sources, 1310nm | | | | |
|---|---|---|---|---|
| **liquid concentration (%)** | **Average (dBm)** | **Std Dev** | **Sensitivity (dBm)** | **Linearity (%)** |
| 0% | -44.966 | 0.0423 | 0.0613 | 99.41 |
| 10% | -44.176 | 0.054 | 0.0754 | 99.11 |
| 20% | -43.176 | 0.1547 | 0.1049 | 72.7 |
| 30% | -41.811 | 0.0472 | 0.1348 | 99.89 |
| 40% | -40.429 | 0.0985 | 0.1391 | 98.14 |
| 50% | -39.784 | 0.2003 | 0.0649 | 99.77 |

**Table 4.3** The different liquid (vinegar) concentration percentages of laser sources at 1550nm

| Input laser sources, 1550nm | | | | |
|---|---|---|---|---|
| **Liquid concentration (%)** | **Average (dBm)** | **Std Dev** | **Sensitivity (dBm)** | **Linearity (%)** |
| 0% | -40.935 | 0.0692 | 0.0022 | 98.75 |
| 10% | -39.9 | 0.1137 | 0.1021 | 98.9 |
| 20% | -39.733 | 0.14 | 0.0201 | 97.2 |
| 30% | -39.107 | 0.1712 | 0.065 | 99 |
| 40% | -38.415 | 0.048 | 0.0621 | 98.5 |
| 50% | -37.605 | 0.1776 | 0.0762 | 99.8 |

The performance characteristics of a laser-based measurement system operating at a wavelength of 1550 nm for different liquid concentrations are summarized in **Table 4.3**.It displays information on the percentage of liquid concentration, average power in decibels (dBm), measurement standard deviation, sensitivity in dBm, and linearity percentage. Each row in the liquid concentration percentage column represents a specific measurement for a certain concentration level, with values ranging from 0% to 50% in increments of 10%. A direct correlation between concentration and system response is suggested by the average power (dBm) column, which displays the detected power level in respect to 1 milliwatt and

shows an upward trend (becoming less negative) as concentration increases. The average power, for example, is -40.935 dBm at 0% concentration and rises to -37.605 dBm at 50%. The measurements' consistency or variability is shown in the standard deviation column; lower numbers denote more stable results.

The standard deviation shows that measurement variability tends to rise at greater concentrations, ranging from 0.048 at 40% to 0.1776 at 50%. The system's sensitivity, expressed in decibels per milliwatt (dBm), indicates how responsive it is to variations in liquid concentration. The system is more sensitive to changes in concentration at specific levels, as seen by the sensitivity, which is 0.0022 dBm at 0% and 0.065 dBm at 30%. The system's output's ability to follow a linear trend with variations in liquid concentration is evaluated by the linearity column.

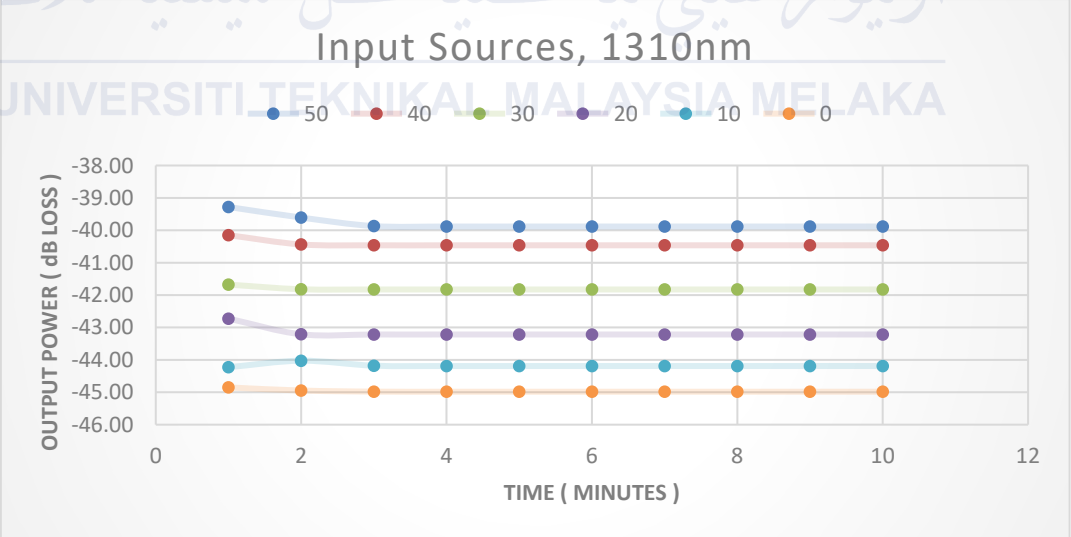
With values at or over 98% for all concentrations, the data shows a high degree of linearity. The accuracy and dependability of the system are demonstrated by the highest linearity, which is recorded at 50% concentration (99.8%), and the lowest at 20% concentration (97.2%). Overall, the table shows how the measurement system behaves at various liquid concentrations, emphasizing its excellent linearity, sensitivity variations at different concentrations, consistent performance, and rising power levels, which make it a good choice for precise and accurate liquid concentration measurements.

The 1310 nm system often shows somewhat more linearity across concentrations when compared to the two wavelengths, which could make it more dependable for extremely precise applications. But for applications that need constant responsiveness, the 1550 nm system shows a more balanced sensitivity response across various concentration levels, which might be useful. Overall, both wavelengths work well, exhibiting good sensitivity and linearity, which qualifies the system for very accurate and minimally deviant liquid concentration measurements.

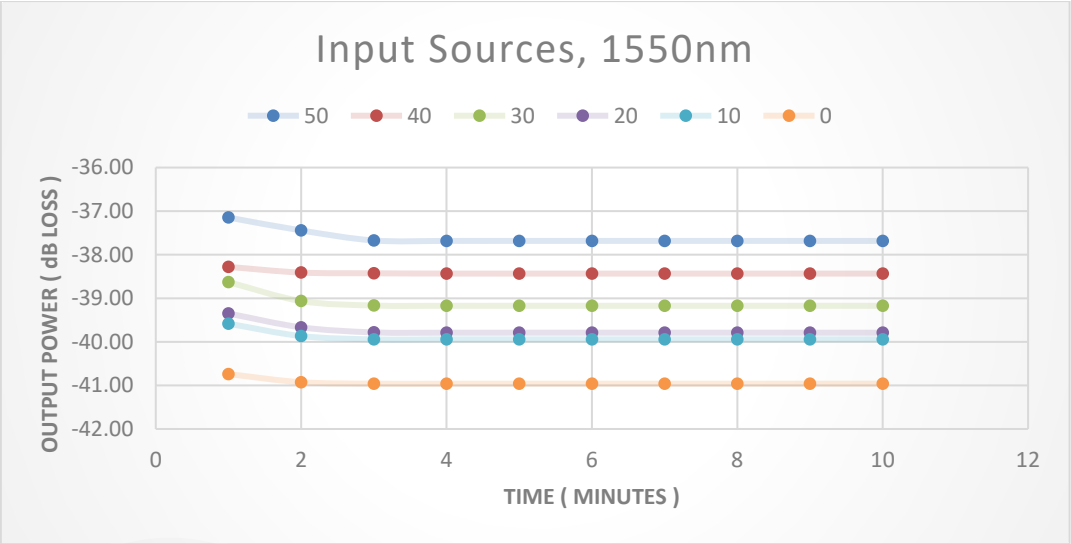
The stability of the suggested sensor was carefully examined in the final evaluation by gathering data every second for ten minutes. The graphs showing the connection between output power and time at the 1550 nm and 1310 nm wavelengths, respectively, for liquid concentration sensing ranging from 50% to 0% are shown in Figure 4.4 (a) and (b). The results showed that the output power measured at 1550 nm was continuously constant for the course of the observation. However, at the same period, there was some variation in the output power at the 1310 nm wavelength.

These results highlight the suggested sensor's improved stability at the 1550 nm wavelength, indicating that it is appropriate for long-term and dependable liquid concentration detecting applications. The sensor's wavelength-specific performance nuances are highlighted by the comparison with the 1310 nm wavelength, which is crucial for maximizing its application in a variety of sensing settings.






**(a)**




**(b)**

**Figure 4.4** Stability of the proposed sensor incorporating (a) 1310nm and (b) 1550nm wavelength in liquid concentration.

## 4.4 Evaluation on the performance of microfiber sensor

This experiment uses two single-mode fiber pigtails linked at the splice, with an unclad section in the middle, to transmit modulated light through an optical time domain reflectometer (OTDR). The evaporation of light particles from the optical cable's core affects the transmission. Data is gathered at one-minute intervals using wavelengths of 1310 nm and 1550 nm throughout a ten-minute period. The experiment starts with a 50% shampoo concentration in the first liquid, turning the attention to liquid concentration—more especially, vinegar. Throughout the ten-minute experiment, subsequent liquids add increasing amounts of DI water, resulting in concentrations of 40%, 30%, 20%, 10%, and 0%, respectively, at one-minute intervals. This method enables a thorough examination of the changes in vinegar concentration over the course of the investigation.

**Figure 4.5** shows the meticulously documented real-time responses of the applied optical microfiber sensor for liquid concentration detection at both the 1550 nm and 1310

nm wavelengths, spanning from 50% to 0%. The dynamic behaviour of the microfiber sensors as they interact with different liquid concentrations is depicted in these figures. The findings of the experiment showed that when the microfiber sensor was subjected to different liquid concentrations, the output power decreased linearly. Interestingly, when compared to its counterpart on the 1310 nm wavelength, the sensor built with the microfiber placed on the 1550 nm wavelength showed better linearity and sensitivity. The greater refractive index of the 1550 nm wavelength, which is affected by changes in liquid content, is responsible for this improved performance.

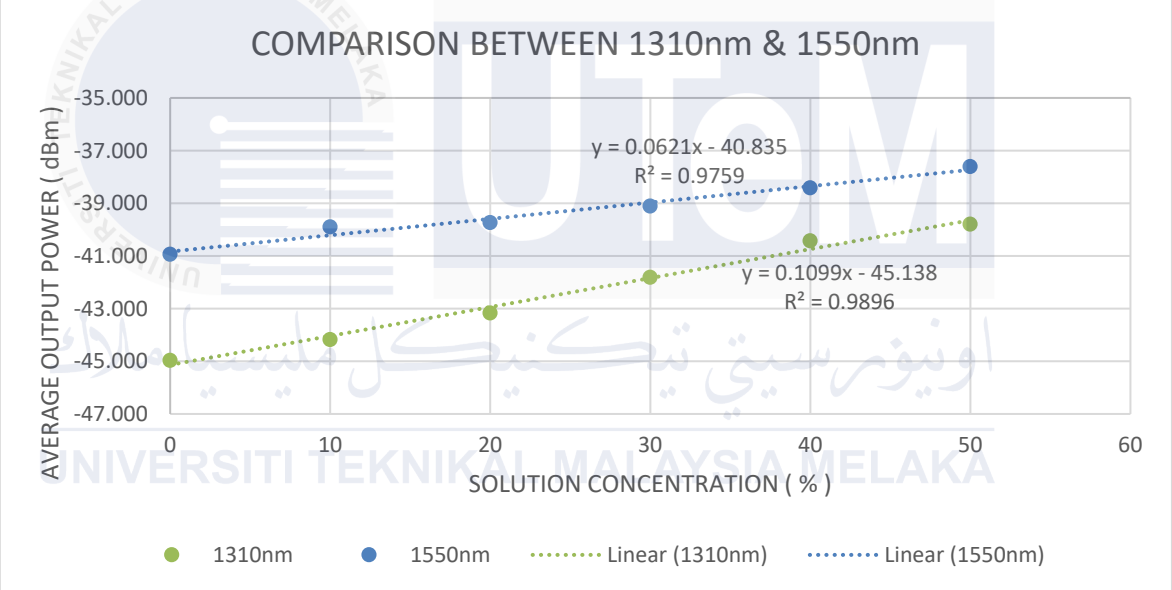



**Figure 4.5** Optical microfiber sensor responses at both wavelength

An important factor in this situation is the well-known fact that the wavelength of 1550 nm has a greater refractive index than the microfiber core. The amount of light absorbed by the medium rises as the directed light from the microfiber interacts with the liquid concentration at a wavelength of 1550 nm. As a result, the directed light intensity inside the microfiber is more strongly impacted, providing increased linearity and sensitivity to variations in liquid concentration. This result emphasizes how crucial wavelength selection is to maximizing microfiber sensor performance for certain sensing applications.

The temperature sensors' sensing performance data, including their accuracy,

sensitivity, and response time, is shown in **Table 4.4.**

**Table 4.4** Sensing performance of the temperature sensors.

| Parameters | 1310nm | 1550nm | Legend |
|---|---|---|---|
| Average standard deviation | 0.0995 | 0.1200 | Lower is better |
| Resolution | 1.6022 | 1.0919 | Lower is better |
| Sensitivity | 0.0621 | 0.1099 | Higher is better |
| Linearity | 98.98% | 97.59% | Higher is better |
| Dynamic range | 0-50% | 0-50% | Relevance |
| $R^2$ | 0.9896 | 0.9759 | Higher is better |

The accuracy, sensitivity, and dependability of laser-based measuring systems operating at 1310 nm and 1550 nm wavelengths are compared in the table based on a number of important factors. The coefficient of determination ($R^2$), linearity, sensitivity, resolution, average standard deviation, and dynamic range are among the criteria taken into account. Guidelines for interpreting the results are provided in the "Legend" column, which also indicates whether lower or higher values are desired for each parameter.

Lower values of the "Average standard deviation" indicate more steady readings and serve as a gauge of the measures' consistency. The standard deviation of the 1310 nm system is lower (0.0995) than that of the 1550 nm system (0.1200), indicating that the 1310 nm system produces more reliable findings. Similar to this, the 1550 nm system has a better "Resolution," which gauges the system's capacity to pick up on minute changes, at 1.0919 as opposed to 1.6022 for the 1310 nm system, where a lower value is desirable.

Regarding "Sensitivity," which measures the system's capacity to identify concentration changes, the 1550 nm system is more sensitive to concentration variations than

the 1310 nm system (0.0621 dBm), with a sensitivity of 0.1099 dBm. Though greater values are preferred for both, "Linearity," which measures how well the system's reaction follows a predictable pattern, is marginally higher for the 1310 nm system (98.98%) than for the 1550 nm system (97.59%).

Both methods may measure concentrations within the same range because they have the same "Dynamic range" of 0–50%. Last but not least, the 1310 nm system has a marginally higher "R2" value (0.9896) than the 1550 nm system, which indicates that the 1310 nm system offers a better linear fit. R2 is a measure of how well the data fits a linear regression model.

In summary, the 1310 nm system offers better consistency and linearity, while the 1550 nm system excels in resolution and sensitivity. The choice between the two systems depends on the specific application requirements, balancing precision, sensitivity, and measurement stability.



## 4.5 Summary

The study effectively accomplished two main goals first, optimizing sensor geometry for maximum acidic ion sensitivity and mechanical stability by precise flame brushing; and second, developing an advanced acidic concentration measurement setup that uses particular optical wavelengths (1310 nm and 1550 nm) to precisely measure changes in acidity content. Robust sensor performance and accurate measurement capabilities over a range of concentrations were assured by the careful control of fabrication factors and the integration of sophisticated optical elements such couplers, filters, and detectors. These accomplishments signify important advances in sensor technology and open the door to more advanced environmental monitoring and analytical applications across a range of academic and professional fields.

# CHAPTER 5

## 5.1 Introduction

In conclusion, the results of this experiment offer significant perspectives and emphasize the accomplishments of the study goals. The finding demonstrates important developments and contributions to the regulation, providing a solid basis for further research and useful applications. The study's thorough analysis and thorough testing have produced convincing data that confirms initial theories and provide path for future research and innovation.

## 5.2 Conclusion

In this study, the primary objective was to fabricate a functional single-mode microfiber using the flame brushing technique, aiming for a waist diameter of 7 µm. This report documents the accomplishments of this goal. Through meticulous fabrication processes, a microfiber with the desired specifications have been fabricated, marking a significant milestone in our research.

Another key objective was the design of a measurement set-up tailored for detecting concentrations of acidic liquids, specifically vinegar, utilizing 1310 nm and 1550 nm input laser sources. Important parts of the experimental setup are the Optical Time-Domain Reflectometer (OTDR), input laser sources, and the tapered silica fiber sensor. The OTDR is the receiver that measures output power, and the input laser sources act as the transmitter that emits light pulses at both 1310 nm and 1550 nm wavelengths. The cleanliness and correct calibration of the tapered silica fiber sensor are carefully monitored. To ensure

accuracy and consistency, six distinct vinegar concentrations are prepared using precise scientific processes listed in **Table 3.1**. Controlled and reliable conditions are made possible by immersing the tapered silica fiber sensor, one drop at a time, in each vinegar concentration solution. The information required to examine the sensor's reaction to changing vinegar concentrations is obtained by subsequently recording output power using the OTDR at equilibrium. The experimental setup's effective design lays the groundwork for a thorough examination of liquid concentration sensing.

We have made substantial progress in this area by demonstrating the feasibility of the measurement set-up. This achievement underscores our commitment to developing precise and effective tools for liquid concentration detection using advanced optical techniques.

The final goal, which was to assess how well the optical microfiber sensor performed in identifying different liquid concentrations, has been achieved. The sensor's real-time reactions to various vinegar concentrations were methodically recorded and examined through painstaking experimentation. The results showed a distinct and linear correlation between variations in liquid concentration and the sensor's output power. The greater sensitivity and linearity of the 1550 nm sensor were shown by the thorough comparison of its performance at the 1310 nm and 1550 nm wavelengths, highlighting its effectiveness in identifying and differentiating changes in liquid concentration. The suggested sensor's stability throughout the course of the 10-minute observation period especially at the 1550 nm wavelength further confirms its ability to detect and react to varying liquid amounts. All things considered, the successful assessment of the microfiber sensor's performance in liquid concentration detection represents a significant turning point in accomplishing the project's goals and offers insightful information for further advancements and applications.

Using 1310 nm and 1550 nm laser sources, this study successfully created a single-

mode microfiber with a 12 μm waist diameter using the flame brushing technique, created a dependable measuring setup for detecting the concentrations of acidic liquids, and assessed the sensor's functionality. Six different vinegar concentrations were used to calibrate and test important parts, such as an optical time-domain reflectometer (OTDR) and a tapered silica fiber sensor. The findings showed a linear relationship between sensor output power and liquid concentration, with the 1550 nm sensor exhibiting higher stability and sensitivity over the course of the 10-minute observation period. These accomplishments represent a critical turning point in the development of optical microfiber sensors for accurate liquid concentration measurement.

## 5.3 Future Works

Enhancing the sensitivity, stability, and adaptability of optical microfiber sensors for the detection of acidic solutions may be the main goal of future research. Investigating cutting-edge fabrication methods like chemical etching or femtosecond laser writing is one way to get even finer microfiber dimensions and more robust evanescent field interactions. Furthermore, real-time remote monitoring and data analysis for applications in industrial and environmental contexts may be made possible by integrating the sensor with Internet of Things (IoT) systems.

The application of the sensor would be further expanded by extending the range of detected acidic solutions, including stronger acids or complicated combinations. To increase the sensor's robustness and resilience to challenging conditions, researchers could potentially look at the application of novel materials like polymer coatings or nanomaterials. Lastly, creating hybrid or multi-wavelength sensing systems may improve precision and allow for the simultaneous detection of several parameters, opening the door for more sophisticated and multipurpose optical sensing technologies.

## 5.4 Project commercialization

In order to commercialize an optical microfiber sensor for detecting acidic liquids, the study must be turned into a workable, marketable product that meets actual demands. The first stage is to improve the sensor's design to guarantee cost-effectiveness, dependability, and user-friendliness. This may entail developing a small, portable gadget that combines the microfiber sensor with user-friendly software for real-time data visualization and analysis, which would appeal to sectors like biomedical diagnostics, environmental monitoring, and food processing. When it comes to monitoring acidic food preservatives, identifying contaminants in water, or determining the pH of biological fluids, it is essential to identify specific target markets. Advanced manufacturing methods, including automated microfiber fabrication, should be developed to reduce production costs and guarantee scalability. Production could also be streamlined by working with seasoned optical component manufacturers. Gaining a competitive edge would be facilitated by patent protection for the sensor's design, manufacturing method, and applications.



Another crucial stage is regulatory compliance, which calls for following guidelines like FDA approvals for medicinal purposes or ISO certifications for industrial use. Pilot studies with prospective customers can be used for market testing and yield insightful input that helps the product be further improved to better suit user needs. Effective distribution channels and easier market access can be achieved through collaborations with software developers, optical manufacturers, and industry-specific associations. Offering a variety of models to meet the needs of different clientele, a strategic pricing approach should strike a balance between affordability and profitability. To draw in potential customers, marketing initiatives such as trade exhibitions, online advertisements, and trade journals might emphasize the sensor's precision, sensitivity, and cutting-edge technology.

Sustainability, which highlights the sensor's contribution to waste reduction and environmental initiatives, can also be a major selling feature. To stay relevant in a cutthroat market, long-term strategies could involve improving the sensor's capabilities, including multi-parameter sensing or integration with Internet of Things (IoT) platforms. The optical microfiber sensor can effectively move from research to a commercially viable device that offers substantial value across several industries if these issues are addressed in their entirety.

## REFERENCES


[1] Jali, M. H., Rahim, H. R. A., Md Johari, M. A., Baharom, M. F., Ahmad, A., Yusof, H. H. M., & Harun, S. W. (2021). Optical Microfiber Sensor: A Review. *Journal of Physics: Conference Series*, *2075*(1).

[2] Li, Y., Xu, Z., Tan, S., Fang, F., Yang, L., Yuan, B., & Sun, Q. (2019). Recent advances in microfiber sensors for highly sensitive biochemical detection. *Journal of Physics D: Applied Physics*, *52*(49), 493002.

[3] Chen, J.-H., Li, D.-R., & Xu, F. (2019). Optical microfiber sensors: sensing mechanisms, and recent advances. *Journal of Lightwave Technology*, *37*(11), 2577–2589.

[4] Ismaeel, R., Lee, T., Ding, M., Belal, M., & Brambilla, G. (n.d.). (2019) *Optical microfiber passive components*.

[5] Li, K., Wang, J., & Guo, T. (2020). Optical Microfiber Sensors. In L. Wei (Ed.), *Advanced Fiber Sensing Technologies* (pp. 59–80). Springer Singapore.

[6] Ward, J. M., O'shea, D. G., Shortt, B. J., Morrissey, M. J., Deasy, K., & Nic Chormaic, S. G. (n.d.). (2020) *A heat-and-pull rig for fiber taper fabrication*.

[7] Dai, M., Chen, Z., Zhao, Y., Gandhi, M. S. A., Li, Q., & Fu, H. (2020). State-of-the-Art Optical Microfiber Coupler Sensors for Physical and Biochemical Sensing Applications. In *Biosensors* (Vol. 10, Issue 11). MDPI.

[8] Wei, L., & Tjin, S. C. (2020). Special issue "fiber optic sensors and applications": An overview. In *Sensors (Switzerland)* (Vol. 20, Issue 12, pp. 1–4). MDPI AG.

[9] Pendão, C., & Silva, I. (2022). Optical Fiber Sensors and Sensing Networks: Overview of the Main Principles and Applications. In *Sensors* (Vol. 22, Issue 19). MDPI.

[10] Zhang, L., Tang, Y., & Tong, L. (2020). Micro-/Nanofiber Optics: Merging Photonics and Material Science on Nanoscale for Advanced Sensing Technology. *ISCIENCE*, *23*, 100810.

[11] Chen, H., Luo, B., Wu, D., Shi, S., Li, Y., Zou, X., & Zhao, M. (2022). Sensitive enhanced refractive index sensor based on series tapered thin-core microfiber with Vernier effect. *ICOCN 2022 - 20th International Conference on Optical Communications and Networks*.

[12] Sun, D., Xu, S., Liu, S., Fu, Y., & Ma, J. (2021). A fiber-optic ultraviolet sensor based on the evanescent field: Enhanced effects of black phosphorous film. *Optical Fiber Technology*, *67*.

[13] Latif, A. A., Mohamad, F., Bakar, M. H. A., Mustapa, M. A., Awang, N. A., & Zakaria, Z. (2019). Curvature sensor utilizing evanescent field propagation via microfibers. *Journal of Physics: Conference Series*, *1151*(1).

[14] Liu, Z., Wang, Y., Guo, S., Liu, J., & Zhu, P. (2024). Preparation and characterization of bacterial cellulose synthesized by kombucha from vinegar residue. *International Journal of Biological Macromolecules*, *258*.

[15] Zhu, L., Lin, Q., Yao, K., Zhao, N., Yang, P., & Jiang, Z. (2022). Intensity-demodulated fiber-optic vector magnetic field sensor based on fiber-optic evanescent field. *Optics and Laser Technology*, *152*.

[16] Li, Y., Wang, L., Li, L., & Tong, L. (2019). Optical microfiber-based ultrafast fiber lasers. *Applied Physics B: Lasers and Optics*, *125*(10).

[17] Li, J., & Zhang, M. (2022). Physics and applications of Raman distributed optical fiber sensing. In *Light: Science and Applications* (Vol. 11, Issue 1). Springer Nature.

[18] Chen, F. H., Biria, S., Li, H., & Hosein, I. D. (2019). Microfiber Optic Arrays as Top Coatings for Front-Contact Solar Cells toward Mitigation of Shading Loss. *ACS Applied Materials and Interfaces*, *11*(50), 47422–47427.

[19] Leal-Junior, A. G., Diaz, C. A. R., Avellar, L. M., Pontes, M. J., Marques, C., & Frizera, A. (2019). Polymer optical fiber sensors in healthcare applications: A comprehensive review. In *Sensors (Switzerland)* (Vol. 19, Issue 14). MDPI AG.

[20] Li, J., & Zhang, M. (2022). Physics and applications of Raman distributed optical fiber sensing. In *Light: Science and Applications* (Vol. 11, Issue 1). Springer Nature.

[21] Liu, S., Huang, H., Lu, J., Xu, N., Qu, J., & Wen, Q. (2022). Liquid-Phase Exfoliation of Ta2NiS5 and Its Application in Near-Infrared Mode-Locked Fiber Lasers with Evanescent Field Interactions and Passively Q-Switched Bulk Laser. *Nanomaterials*, *12*(4).

[22] Pallarés-Aldeiturriaga, D., Roldán-Varona, P., Rodríguez-Cobo, L., & López-Higuera, J. M. (2020). Optical fiber sensors by direct laser processing: A review. In *Sensors (Switzerland)* (Vol. 20, Issue 23, pp. 1–37). MDPI AG.

# APPENDICES

| ACTIVITY | PLAN START | PLAN DURATION | ACTUAL START | ACTUAL DURATION | ACADEMIC WEEK | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| DESIGNING THE FINAL VERSION AND FABRICATING THE EXPERIMENTAL SETUP | 1 | 2 | 1 | 2 | | | | | | | | | | | | | | |
| PREPARATION OF MICROFIBER SENSORS ( 3 SETS ) | 2 | 4 | 2 | 4 | | | | | | | | | | | | | | |
| RUN THE EXPERIMENT WITH VARIOUS SOLUTION | 4 | 2 | 4 | 2 | | | | | | | | | | | | | | |
| TROUBLESHOOTING ERROR DURING EXPERIMENTS | 5 | 2 | 5 | 2 | | | | | | | | | | | | | | |
| OBSERVE AND TABULATING DATA INTO EXCEL | 3 | 3 | 3 | 3 | | | | | | | | | | | | | | |
| FINAL CHECKING OF DATA COLLECTED IN EXCEL AND CREATING GRAPH | 4 | 5 | 4 | 5 | | | | | | | | | | | | | | |
| CORRECTION OF CHAPTER 1 | 7 | 5 | 7 | 5 | | | | | | | | | | | | | | |
| CORRECTION OF CHAPTER 2 | 4 | 3 | 4 | 3 | | | | | | | | | | | | | | |
| CORRECTION OF CHAPTER 3 | 7 | 5 | 7 | 5 | | | | | | | | | | | | | | |
| REPORT WRITING ON CHAPTER 4 & 5 | 7 | 5 | 7 | 5 | | | | | | | | | | | | | | |
| CORRECTION OF CHAPTER 4 & 5 | 1 | 14 | 1 | 14 | | | | | | | | | | | | | | |
| FIRST FINAL REPORT DRAFT SUBMISSION | 11 | 3 | 11 | 3 | | | | | | | | | | | | | | |
| SECOND FINAL REPORT DRAFT SUBMISSION | 12 | 2 | 12 | 2 | | | | | | | | | | | | | | |

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LOGBOOK WRITING | 14 | 1 | 14 | 1 | | | | | | | | | | | | | | | |
| SUBMIT REPORT VIA EPSM | 14 | 1 | 14 | 1 | | | | | | | | | | | | | | | |
| BDP PRESENTATION | 14 | 1 | 14 | 1 | | | | | | | | | | | | | | | |