OPTIMIZATION OF D-SHAPE OPTICAL FIBER STRUCTURES WITH A LOW INSERTION LOSS

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UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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This report is submitted in partial fulfilment of the requirements for the degree of Bachelor of Electronic Engineering with Honours

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I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Bachelor of Electronic Engineering with Honours.

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Supervisor Name : Ir. Dr. Anas bin Abdul Latiff

Date : 24-JAN-2024

DEDICATION

This research is dedicated to my family and friends who are never missed to give attention and love throughout my research journey.

This research also dedicated to my supervisor, Ir. Dr. Anas bin Abdul Latiff who have guided me with great attention and motivated me to set a higher goal to produce a better research.

Finally, I dedicated this research to all UTeM lecturers and staff who involved in giving cooperation for this study.

ABSTRACT

The demand for high-performance optical communication systems has fueled the exploration of innovative optical fiber structures. This final year project focuses on the optimization of D-shaped optical fiber structures with the overarching goal of achieving low insertion loss. The unique geometry of D-shaped fibers offers promising advantages, motivating our investigation into the optimization parameters that can enhance their performance. The study begins with an in-depth exploration of D-shaped optical fiber structures, investigating their design principles and inherent characteristics. Building upon existing literature, we identify key areas for improvement and embark on a comprehensive optimization process. This optimization spans various facets, including geometry, materials, and fabrication processes. A crucial aspect of our investigation is the evaluation of insertion loss, a critical parameter in optical communication. We delve into the factors influencing insertion loss and propose strategies to minimize this loss through the optimized D-shaped optical fiber structures. Numerical simulations and modeling techniques are employed to assess the efficacy of our optimization efforts. The experimental validation phase involves the fabrication of the optimized D-shaped optical fibers and rigorous testing to measure insertion loss. Results obtained from experiments are compared with

theoretical expectations, providing insights into the practical viability of our optimized structures. Furthermore, we discuss potential applications of the optimized D-shaped optical fibers in real-world scenarios, considering the impact of low insertion loss on overall system performance. A comparative analysis with existing optical fiber structures highlights the advantages and practical considerations of our optimized design. The project concludes with reflections on the outcomes, limitations, and implications of the research. We propose avenues for future exploration and development, envisioning the continued evolution of D-shaped optical fiber as integral components of advanced optical communication systems. This final year report encapsulates a comprehensive exploration of D-shaped optical fiber structures, offering valuable insights for researchers and practitioners in the field of optical communications. The optimization strategies developed in this study contribute to the ongoing efforts to enhance the efficiency and reliability of optical fiber-based communication networks.

ABSTRAK

Permintaan untuk sistem komunikasi optik berprestasi tinggi telah mendorong penerokaan struktur gentian optik yang inovatif. Projek tahun akhir ini memberi tumpuan kepada pengoptimuman struktur gentian optik berbentuk D dengan matlamat menyeluruh untuk mencapai kehilangan sisipan yang rendah. Geometri unik gentian berbentuk D menawarkan kelebihan yang menjanjikan, mendorong penyiasatan kami terhadap parameter pengoptimuman yang boleh meningkatkan prestasinya.Kajian ini bermula dengan penerokaan mendalam struktur gentian optik berbentuk D, menyiasat prinsip reka bentuk dan ciri-ciri yang wujud. Berdasarkan literatur sedia ada, kami mengenal pasti bidang utama untuk penambahbaikan dan memulakan proses pengoptimuman yang komprehensif. Pengoptimuman ini merangkumi pelbagai aspek, termasuk geometri, bahan dan proses fabrikasi.Aspek penting dalam penyiasatan kami ialah penilaian kehilangan sisipan, parameter kritikal dalam komunikasi optik. Kami menyelidiki faktor-faktor yang mempengaruhi kehilangan sisipan dan mencadangkan strategi untuk meminimumkan kehilangan ini melalui struktur gentian optik berbentuk D yang dioptimumkan. Simulasi berangka dan teknik pemodelan digunakan untuk menilai keberkesanan usaha pengoptimuman kami.Fasa pengesahan eksperimen melibatkan fabrikasi gentian optik berbentuk D yang dioptimumkan dan ujian yang ketat untuk mengukur kehilangan sisipan. Keputusan yang diperoleh daripada eksperimen dibandingkan dengan jangkaan teori, memberikan pandangan tentang daya maju praktikal struktur kami yang dioptimumkan.Tambahan pula, kami membincangkan potensi aplikasi gentian optik berbentuk D yang dioptimumkan dalam senario dunia sebenar, dengan mengambil kira kesan kehilangan sisipan yang rendah terhadap prestasi sistem keseluruhan. Analisis perbandingan dengan struktur gentian optik sedia ada menyerlahkan kelebihan dan pertimbangan praktikal reka bentuk kami yang dioptimumkan.Projek ini diakhiri dengan refleksi tentang hasil, batasan, dan implikasi penyelidikan. Kami mencadangkan jalan untuk penerokaan dan pembangunan masa hadapan, membayangkan evolusi berterusan gentian optik berbentuk D sebagai komponen penting sistem komunikasi optik termaju.Laporan tahun akhir ini merangkumi penerokaan menyeluruh struktur gentian optik berbentuk D, menawarkan pandangan berharga untuk penyelidik dan pengamal dalam bidang komunikasi optik. Strategi pengoptimuman yang dibangunkan dalam kajian ini menyumbang kepada usaha berterusan untuk meningkatkan kecekapan dan kebolehpercayaan rangkaian komunikasi berasaskan gentian optik.

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LIST OF SYMBOLS AND ABBREVIATIONS

SMF	:	Single-mode Fiber
MMF	:	Multi-mode Fiber
OSA	:	Optical Spectrum Analyzer
PMF	:	Polarization-maintaining optical fiber
TLS	:	Tunable Laser Source
FS	:	Full Spectrum Laser

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In the dynamic landscape of modern communication systems, the relentless pursuit of higher data rates, increased bandwidth, and lower signal losses has led to a continuous exploration of innovative technologies. Optical fibers stand at the forefront of this evolution, serving as the backbone for high-speed data transmission. Among the diverse array of optical fiber structures, D-shaped optical fibers have emerged as promising candidates, offering unique geometric advantages that can potentially revolutionize the landscape of optical.

This final year project endeavors to address a critical aspect of optical fiber performance—insertion loss—through the optimization of D-shaped optical fiber structures. Insertion loss, the reduction of signal power as light traverses through a fiber, remains a pivotal consideration in the design and implementation of optical communication systems. The distinctive geometry of D-shaped fibers presents an intriguing opportunity for enhancement, propelling our investigation into the realms of geometry, materials, and fabrication processes to unlock their full potential.

The initial chapters of this report provide a comprehensive exploration of D-shaped optical fiber structures, delving into their design principles, manufacturing techniques, and existing applications. Drawing from an extensive review of the literature, we identify areas for improvement and set the stage for a systematic optimization process.

The primary objective of this study is to optimize D-shaped optical fiber structures with the overarching goal of achieving low insertion loss. The optimization process involves a meticulous examination of key parameters, including the geometric configuration of the fiber, the choice of materials, and the fabrication methods employed.

As we progress, the project transitions into the experimental phase, wherein the theoretical concepts are translated into tangible structures. The fabricated D-shaped optical fibers undergo rigorous testing to quantify and analyze insertion loss. The results obtained from these experiments are compared with theoretical expectations, providing valuable insights into the effectiveness of the optimization strategies.

This report not only presents the outcomes of our research but also explores the broader implications of the optimized D-shaped optical fibers in real-world scenarios. Consideration is given to potential applications, ranging from telecommunications to data centers, where low insertion loss can significantly impact the overall efficiency of optical communication systems.

In conclusion, this final year project represents a holistic investigation into the optimization of D-shaped optical fiber structures, addressing a critical need in the realm of fiber laser. The subsequent chapters unfold the methodologies, results, and discussions that contribute to the growing body of knowledge aimed at advancing the capabilities of optical fibers in meeting the demands of modern systems.

1.2 Project Objectives

1. Develop an optimization strategy to reduce the insertion loss of the D-shape optical fiber structure. [RO1]
2. Evaluate the performance of the optimized D-shape optical fiber structure. [RO2]

1.3 Problem Statement

The D-shape optical fiber structure is a popular design for various sensing and communication applications due to its high sensitivity to external stimuli. However, one of the main challenges in using this structure is the high insertion loss caused by the mode mismatch at the interface between the D-shaped region and the standard circular fiber. This high insertion loss reduces the efficiency of the optical fiber-based systems, leading to reduced performance and reliability. Therefore, there is a need to optimize the design of the D-shape optical fiber structure to reduce the insertion loss and improve its performance. The problem statement for the project "Optimization of D-shape Optical Fiber Structures with a Low Insertion Loss" is to develop an optimization strategy that can identify the optimal D-shape dimensions that minimize insertion loss while maintaining the high sensitivity of the structure. The project aims to address this problem by exploring various geometrical parameters of the D-shape structure, developing an optimization algorithm, and testing the performance of the optimized structure through experimental measurements. The successful optimization of the D-shape optical fiber structure will enable the development of more efficient and reliable optical fiber-based systems, contributing to the advancement of various applications such as biomedical sensing and environmental monitoring.

1.4 Research Scope

The research scope of this final year project encompasses a comprehensive exploration into the optimization of D-shaped optical fiber structures, with a primary objective of minimizing insertion loss. The study spans several key domains, commencing with an in-depth literature review to establish a foundation of knowledge on D-shaped optical fibers, emphasizing design principles and historical developments. The project will delve into the optimization of geometric configurations to enhance the overall performance of the optical fibers. Material selection and characterization will be a focal point, evaluating the impact of various materials on insertion loss and exploring novel coatings or substances that could improve fiber performance.

The research will also extend to the investigation of fabrication techniques, aiming for precision in manufacturing through processes such as drawing and coating. Rigorous testing will be conducted to measure and validate insertion loss under controlled conditions, providing empirical evidence to support the theoretical findings.

A comparative analysis will be undertaken to assess the optimized D-shaped optical fibers in relation to traditional optical fiber structures. Practical considerations, including cost, scalability, and overall efficiency, will be key factors in this comparative evaluation. Additionally, the research will explore potential applications for the optimized fiber, considering the broader implications of the findingsThis structured framework aims to contribute valuable insights to the field of fiber laser, advancing our understanding of factors influencing insertion loss in optical fibers.

This Final Year Project (FYP) report centers its scope on specific aspects related to the study of insertion loss in D-shaped optical fibers. The primary focus involves the creation of different intracavity losses on the D-shaped fibers, with a deliberate limitation to losses of 1 dB and 2 dB. The project explores various methodologies to induce these losses and meticulously analyzes their impact on the optical characteristics of the D-shaped fiber. A conscious decision has been made to employ Single Mode Fiber (SMF) for the experimentation, and the report will extensively elaborate on the specific characteristics of SMF and their relevance to the study. Another key facet of the project involves investigating the potential influence of coating materials on insertion loss. The report will provide a thorough examination of the coating materials employed, including their types and specific names, and assess their effects on insertion loss in D-shaped fibers. The testing methodology employed in this experiment centers on the use of an optical spectrum analyzer (OSA) to measure and analyze insertion loss. The detailed procedures and collected data from these tests will form a critical part of the report, contributing valuable insights to the field of optical communication.

1.5 Hypothesis

The systematic optimization of D-shaped optical fiber structures, including adjustments in geometric configurations, materials, and fabrication processes, will result in a significant reduction in insertion loss compared to traditional optical fiber structures. The hypothesis posits that by strategically modifying key parameters, the optimized D-shaped optical fibers will demonstrate improved transmission efficiency, making them a viable candidate for enhancing the performance of optical communication systems."

This hypothesis suggests that the optimization efforts undertake will lead to a measurable and meaningful decrease in insertion loss. During the course of the research and experimental investigations, data will be collected to either corroborate or challenge this hypothesis, thereby contributing valuable insights to the field of optical communication.

1.6 Thesis Outline

The thesis unfolds in five key chapters, each contributing distinct elements to the exploration of the "Optimization of D-Shaped Optical Fiber Structures with a low insertion loss."

The introductory chapter sets the stage by providing an overview of D-shaped optical fibers and their significance in optical communication. It articulates the motivation behind the study, outlines the research objectives, and formulates a hypothesis. This chapter establishes the groundwork for the subsequent investigations into intracavity loss and coating materials. Chapter 2 delves into the existing body of knowledge surrounding D-shaped optical fibers. It offers an in-depth exploration of their characteristics, historical development, and applications. The literature review extends to the significance of intracavity loss in optical fibers and previous studies on this subject. Additionally, the chapter scrutinizes the influence of coating materials on insertion loss, drawing from relevant studies and approaches in the field.

In Chapter 3, the research methodology is meticulously detailed. The fabrication techniques for D-shaped optical fibers, including mechanical polishing and methods for creating intracavity loss, are elucidated. The selection and implementation of Single Mode Fiber (SMF) are justified, and the experimental setup for assessing the impact of coating materials on insertion loss is outlined. The testing procedures, prominently involving the use of an Optical Spectrum Analyzer (OSA), are thoroughly explained.

Chapter 4 presents the findings of the research, beginning with the effects of intracavity loss on D-shaped fibers, particularly focusing on 1 dB and 2 dB losses. The influence of different coating materials on insertion loss is rigorously analyzed, and the outcomes of testing procedures using an OSA are discussed. This chapter intertwines the results with relevant literature and provides a comprehensive discussion of the implications and significance of the findings.

The final chapter encapsulates the study with a summary of key findings and the contributions to the field. It acknowledges any limitations encountered during the research and proposes avenues for future exploration. The conclusion chapter solidifies the significance of the research within the broader context of optical communication. It serves as a bridge to future research endeavors and applications, establishing a comprehensive understanding of the optimized D-shaped optical fibers and their potential impact on optical communication systems.

CHAPTER 2

LITERATURE REVIEW

2.1 Lasers

A laser, or Light Amplification by Stimulated Emission of Radiation, is a highly sophisticated and versatile device that produces a concentrated and coherent beam of light. At the heart of a laser is the active medium, which can be a gas, liquid, solid-state material or a semiconductor laser chosen for its ability to undergo stimulated emission. The process begins with the pumping of the active medium, typically accomplished by an external energy source, which excites the atoms or molecules within the medium to higher energy states. As these particles return to lower energy levels, they release photons spontaneously, initiating the emission process. Crucially, stimulated emission occurs when a photon encounters an already excited particle, prompting the release of another photon with the same energy, phase, and direction. This cascade effect results in the amplification of light, and the active medium is placed between mirrors to form an optical cavity. One mirror is highly reflective, while the other is partially transparent, allowing the amplified light to escape as a focused laser beam.

The unique properties of lasers, including their coherence, directionality, and monochromaticity, make them invaluable across a spectrum of applications. From their use in telecommunications for high-speed data transmission to applications in medicine for precision surgeries and diagnostics, lasers have become integral to modern technology. Their ability to deliver intense and focused beams of light has found applications in diverse fields such as manufacturing, research, and even entertainment. The specific characteristics of a laser system depend on the choice of the active medium and the design of the laser apparatus, contributing to the versatility and adaptability of these remarkable devices.

2.1.1 History of Laser

The history of the laser (Light Amplification by Stimulated Emission of Radiation) begins with the theoretical groundwork laid by physicists Arthur Schawlow and Charles Townes in 1958. They published a seminal paper outlining the principles of amplifying light through stimulated emission. Concurrently, physicist Gordon Gould independently conceived the laser concept and coined the term, submitting a patent application for his ideas. The first working laser was constructed by Theodore Maiman in 1960 at Hughes Research Laboratories, using a synthetic ruby crystal as the active medium.

This groundbreaking invention marked the birth of the laser and opened the door to a myriad of applications. In the following years, researchers and engineers developed various types of lasers, such as gas lasers, semiconductor lasers, and dye lasers, each suited for specific applications. This technology quickly found its way into diverse fields. Lasers became instrumental in telecommunications, manufacturing, medical procedures, scientific research, and military applications. The precision, coherence, and intensity of laser light made it an indispensable tool in numerous industries. Recognizing the significance of their contributions, Schawlow, Townes, and Soviet physicist Nikolay Basov were awarded the Nobel Prize in Physics in 1981 for their work on the development of the laser and its wide-ranging applications[5]. Since its inception, the laser has evolved into a ubiquitous and transformative technology that continues to shape modern science and industry.

2.1.2 Laser Principles

The operation of a laser is grounded in fundamental principles of quantum mechanics and optics, with the key concept being stimulated emission. According to [4], when electrons in an active medium, which could be a gas, liquid, or solid-state material, are excited to higher energy states, they can be stimulated by incoming photons to release additional photons. This process results in the amplification of light, forming the basis of laser emission. Achieving population inversion is crucial for laser operation, ensuring that more electrons reside in higher energy states than lower ones. External energy sources, such as electrical discharges or other lasers, are employed to pump the active medium and create this state. Figure 2.1 below shows how lasers work.

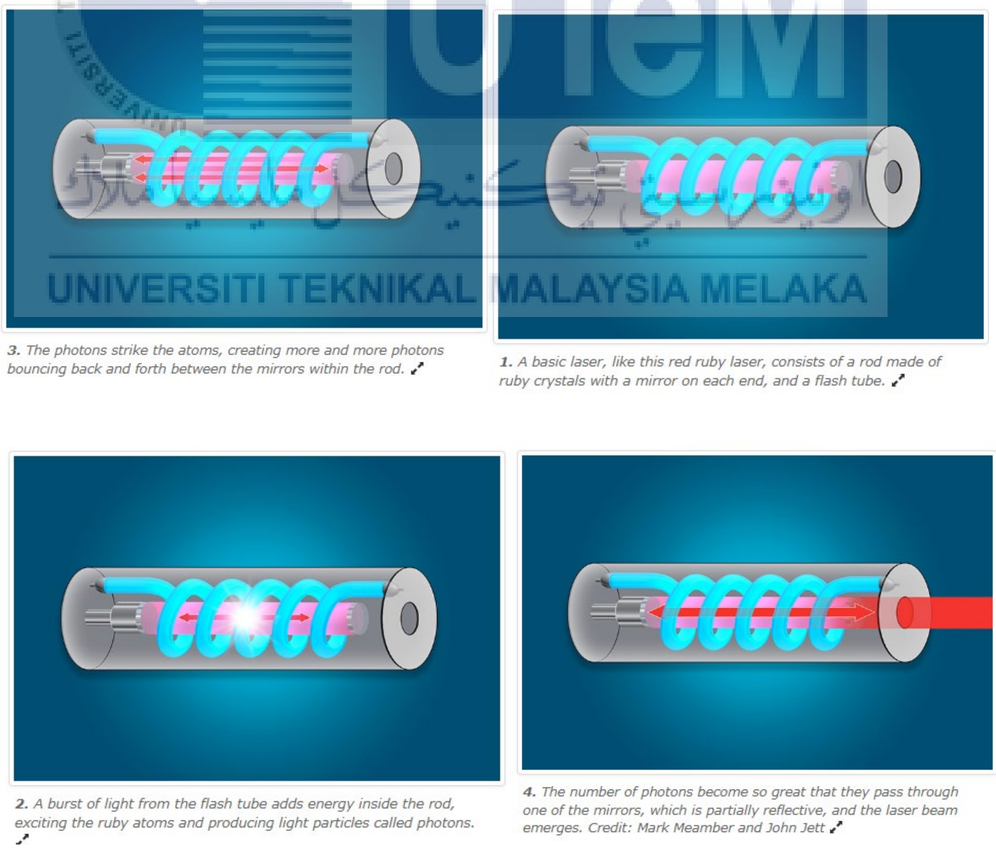


Figure 2.1: The illustration figure show how lasers work

A laser system requires an optical cavity formed by two mirrors—one highly reflective and the other partially transparent[6]. This configuration allows photons to bounce back and forth between the mirrors, stimulating further emission and amplification. Before stimulated emission occurs, electrons may return to lower energy states spontaneously, contributing to the process. Coherence, a key property of laser light, is achieved as the emitted photons maintain a consistent phase relationship. Laser light is also monochromatic, consisting of a single wavelength. This highly organized and synchronized beam of light, characterized by its coherence and monochromaticity, makes lasers indispensable in various applications, from telecommunications and medical procedures to precision manufacturing and scientific research. The specific properties of a laser, such as wavelength and power, are determined by the choice of the active medium and the design of the optical cavity, allowing for tailored applications across diverse fields.

2.2 Type of fiber optic

Fiber optic cables are broadly categorized into two main types: single mode fiber (SMF) and multimode fiber (MMF)[7]. Single mode fibers have a smaller core diameter, typically around 9 microns, and support the propagation of a single mode or ray of light. They are well-suited for long-distance communication due to their ability to transmit signals over extended distances without significant signal degradation. Multimode fibers, characterized by a larger core diameter ranging from 50 to 62.5 microns, support the simultaneous propagation of multiple modes of light. While multimode fibers are more cost-effective for shorter-distance applications, such as local area networks (LANs) and data centers, they may exhibit higher signal dispersion compared to single mode fibers. Additionally, fiber optic cables can be categorized based on their refractive index profile, leading to further distinctions such as step-index and graded-index fibers. These classifications cater to diverse applications, allowing for the selection of fiber optic cables that best suit specific requirements related to distance, bandwidth, and the characteristics of the optical system in use.

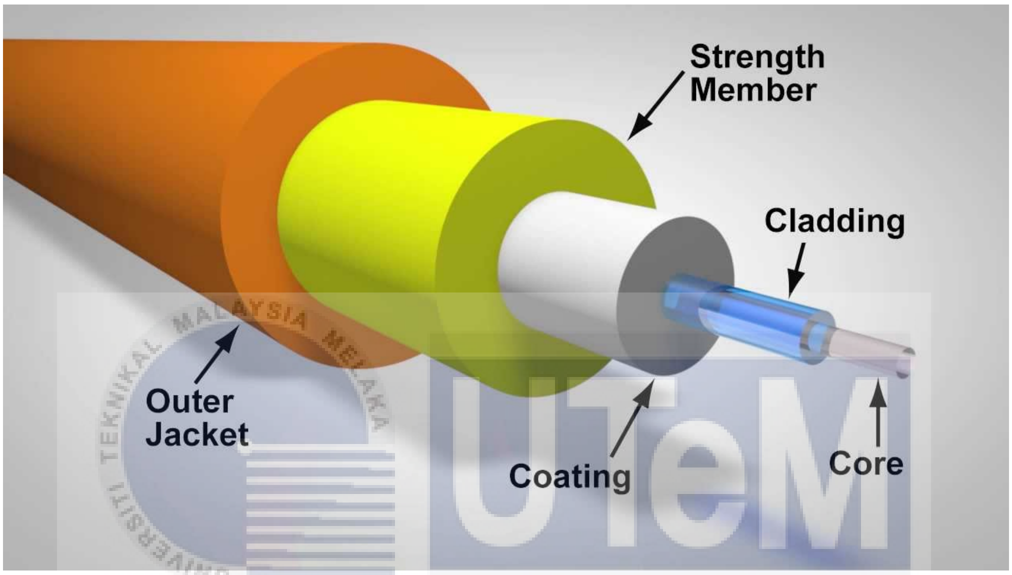


Figure 2.2 : Physical structure of fiber optic.

2.2.1 Single-mode Fiber (SMF)

Single-mode fiber (SMF) is a type of optical fiber designed to carry only a single mode or ray of light along its core. Unlike multimode fibers, which can support multiple light paths (modes), single-mode fibers have a much smaller core diameter, typically around 9 micrometers [8]. The reduced core size and the corresponding decrease in modal dispersion make single-mode fibers highly advantageous for long-distance, high-bandwidth applications.

In a single-mode fiber, light travels in a straight line through the core without undergoing multiple reflections. The key advantage of this configuration is that it minimizes modal dispersion, which occurs when different modes of light take different paths and arrive at the destination at different times. By allowing only a single mode to propagate, single-mode fibers significantly reduce the dispersion of the transmitted signal. Figure 2.2 below shows the structure of SMF.

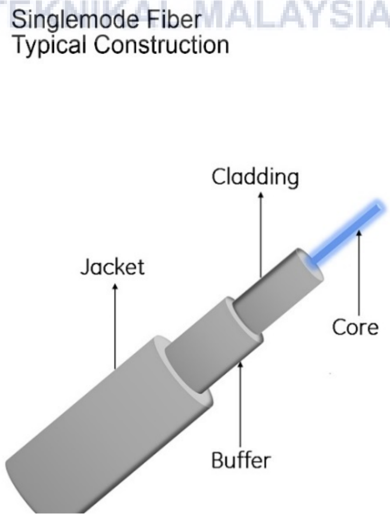


Figure 2.3: Single-Mode Fiber Construction

Single-mode fibers are widely used in telecommunications for long-distance communication, such as in the backbone of global networks and undersea cables. They provide high data transfer rates, low signal loss, and are well-suited for transmitting signals over extended distances. Additionally, single-mode fibers are utilized in applications that demand high precision and clarity, including certain medical and industrial uses, where the integrity of the transmitted signal is crucial.

2.2.2 Multi-mode Fiber (MMF)

Multimode fiber (MMF) is a type of optical fiber that supports the propagation of multiple modes or rays of light through its core. [9] These fibers have a larger core diameter compared to single-mode fibers, typically ranging from 50 to 62.5 micrometers. The increased core size allows multiple light paths or modes to be transmitted simultaneously.

Due to the larger core diameter, multimode fibers are more susceptible to modal dispersion, where different modes of light travel different distances and arrive at the destination at different times. This dispersion limits the achievable bandwidth and the distance over which data can be reliably transmitted without distortion.

Multimode fibers are commonly used in short-distance communication applications, such as within buildings, data centers, or campus networks, where the distance is typically less than a few kilometers. They are favored for their ease of coupling with light sources like light-emitting diodes (LEDs) and vertical-cavity surface-emitting lasers (VCSELs), which are cost-effective and well-suited for short-reach applications.

While multimode fibers have limitations in terms of bandwidth and distance compared to single-mode fibers, they are cost-effective and suitable for scenarios where high bandwidth over shorter distances is sufficient for the intended communication or data transmission.

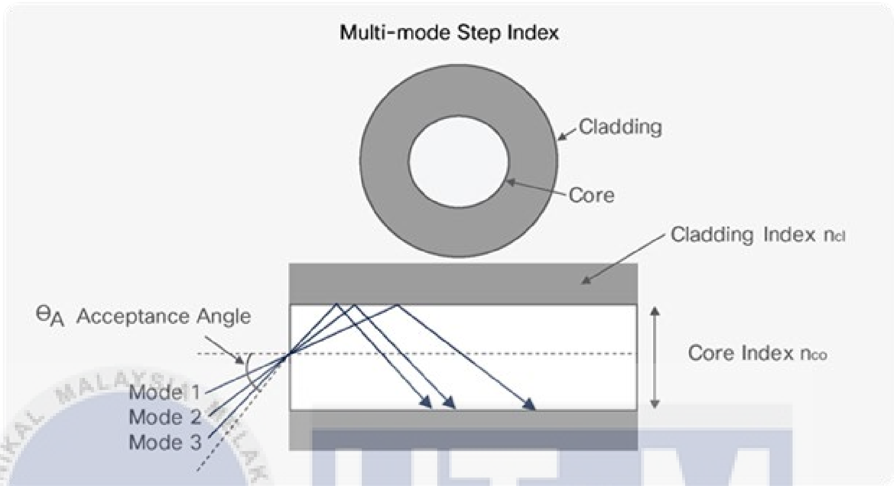


Figure 2.4: Multi-Mode Fiber Construction

2.3 Insertion Loss in Optical Fibers

Insertion loss in optical fibers is a crucial metric reflecting the reduction in signal power during transmission through a fiber-optic system, typically quantified in decibels.[10] This loss results from various factors, including the inherent attenuation in the fiber itself, which arises from light absorption and scattering. Connectors and splices also contribute to insertion loss due to mismatches, reflections, and imperfections in these components. Bending loss is another factor, as excessive bending of the optical fiber leads to increased scattering of light. In multimode fibers, modal dispersion can cause different modes of light to travel different distances, contributing to discrepancies in arrival times and further adding to insertion loss. The minimization of insertion loss is pivotal for maintaining the efficiency and integrity of optical communication systems, necessitating the use of high-quality fibers, connectors, and splices, as well as careful consideration of installation practices to avoid excessive bending. Regular testing and maintenance are crucial for optimizing signal quality and transmission efficiency by ensuring minimal insertion loss in optical communication networks.

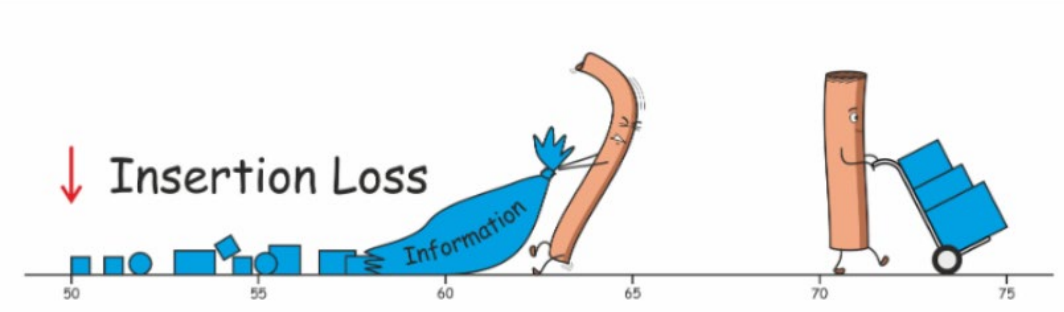


Figure 2.5: Insertion Loss in optical fibers

2.4 D-shaped optical fiber

A D-shaped optical fiber is characterized by its distinctive cross-sectional shape, resembling the letter "D" with a flattened or planar side.[14] This flattened profile distinguishes it from traditional cylindrical fibers and serves a variety of application-specific functions. The primary advantage of the D-shaped design lies in its ability to enhance light coupling between the fiber and external components or devices. This feature proves particularly beneficial in scenarios where efficient light transmission is critical. Additionally, D-shaped optical fibers find applications in sensing, where the unique geometry enhances sensitivity to external conditions, making them suitable for environmental monitoring or biomedical sensing. The flattened side allows for precise interactions with the surrounding environment, making these fibers valuable in applications such as optical signal modulation, microfluidic integration, and biomedical imaging. Overall, the D-shaped optical fiber's versatility arises from its capacity to tailor light interactions based on its distinctive cross-sectional structure, enabling its use in a range of specialized applications where the specific geometry enhances performance and functionality.

Furthermore, the D-shaped optical fiber's design enables its integration into microfluidic systems[14], where the flattened portion accommodates microchannels for interacting with liquids or gases concurrently with light transmission. This capability is particularly relevant in applications involving chemical or biological analysis. The unique cross-sectional profile also lends itself to biomedical imaging, facilitating precise light delivery and collection for imaging and diagnostic purposes. The D-shaped fiber's adaptability to various environments and its ability to modulate optical signals make it a versatile tool in fields such as telecommunications, sensing technologies, and medical diagnostics. As technology continues to advance, D-shaped optical fibers are likely to play an increasingly significant role in enabling innovative solutions across diverse applications where tailored light interactions are essential.

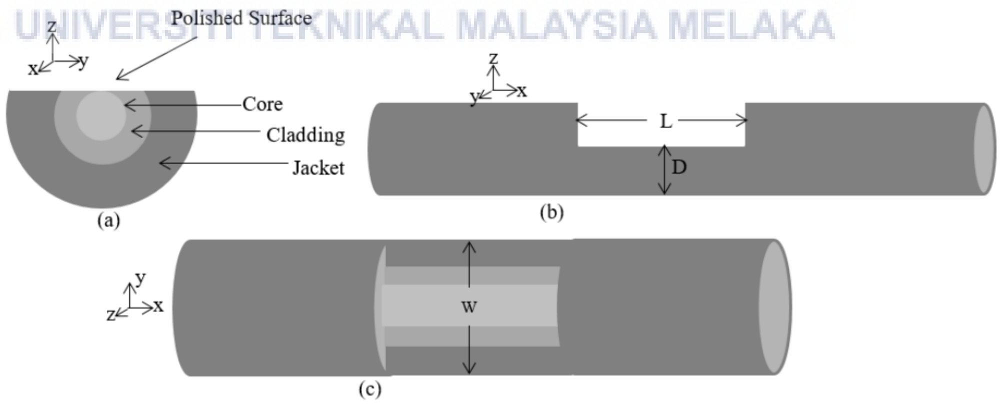


Figure 2.6: (a) Cross-sectional view at Y-Z plane

Figure 2.6:(b) cross-sectional view at X-Z plane and

Figure 2.6:(c) cross sectional view at Y-X plane; L is the length of the polished surface, D is the diameter of the D-shaped and W is the width of the D-shaped

2.4.1 D-shaped optical fiber configurations

The configurations of D-shaped optical fiber encompass a variety of designs based on their distinctive cross-sectional structure.[14] One common configuration is the unilateral D-shape, where one side of the fiber is flattened, resembling the letter "D." This unilateral design is advantageous for applications where optimized light coupling and interactions are required on a specific side of the fiber. Another configuration is the bilateral D-shape, where both sides exhibit a flattened profile, providing enhanced symmetry. This bilateral design finds utility in applications requiring balanced light coupling or sensing capabilities on both sides of the fiber. D-shaped fibers may also adopt a variable width configuration, allowing for customization of the flattened portion's structure to meet specific application requirements. Tapered D-shaped fibers feature a gradual transition from the cylindrical section to the flattened portion, influencing light propagation characteristics and potentially reducing optical losses. Curved D-shaped configurations introduce a curvature to the flattened section, impacting the distribution of guided light and proving useful in scenarios requiring controlled bending or flexibility. Additionally, some D-shaped fiber may feature multiple cores within the flattened section, known as multi-core D-shape, which is relevant in applications like integrated photonics or optical signal processing where multiple guided modes or channels are desired. These various configurations offer versatility, allowing D-shaped optical fibers to be tailored for specific applications based on their unique structural characteristics.

Continuing the discussion on D-shaped optical fiber configurations, the variable width D-shape provides flexibility by allowing adjustments to the flattened portion's width. This customization is valuable for tailoring the fiber's characteristics to meet specific requirements, such as fine-tuning light-coupling efficiency or optimizing sensing capabilities. Tapered D-shaped fibers with a gradual transition from cylindrical to flattened sections, contribute to influencing light propagation characteristics. This configuration is employed to manage optical losses effectively and enhance specific optical properties as needed for diverse applications.

Curved D-shaped configurations introduce a curvature to the flattened section, providing advantages in scenarios where controlled bending or flexibility is crucial. The curvature may impact the distribution of guided light, making this configuration suitable for applications that involve navigating confined spaces or contoured surfaces. Additionally, the multi-core D-shape, featuring multiple cores within the flattened section, is relevant in advanced applications. This configuration allows for the realization of multiple guided modes or channels, making it applicable in integrated photonics and optical signal processing, where complex functionality is desired.

The diverse configurations of D-shaped optical fibers offer a spectrum of options for tailoring their optical and mechanical properties. The choice of configuration depends on the specific demands of applications, including considerations for light coupling, sensing, bending flexibility, and advanced functionalities in emerging technologies. Understanding and leveraging these configurations enable the optimization of D-shaped fibers for a wide range of practical and innovative optical applications.

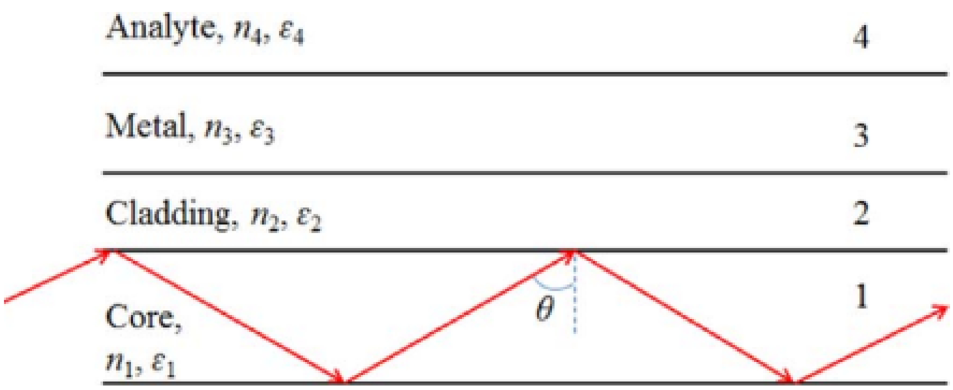


Figure 2.7: Light transmission model through a D-shaped optical fiber

2.4.2 Working Principle of D-shaped optical fiber

The shift in the optical wavelength can be used to identify changes in the external environment. A light wave will undergo several internal reflections when it passes through the core at a particular angle and incident light with a particular optical wavelength. In these circumstances, an evanescent wave will become excited and interact with the metal film's surface plasma waves. The interface reflection coefficient r (Fresnel coefficient) can be described as [14]:

$$r_{ij} = \frac{n_i^2 k_{jy} - n_j^2 k_{iy}}{n_i^2 k_{jy} + n_j^2 k_{iy}}$$

Regions 1, 2, and 3 are the names of the core, cladding, and metal film, respectively. In this instance, the relationship between the analyte's refractive index and optical wavelength can be stated as follows [14]:

$$n^2(\lambda) = 1 + \frac{a_1\lambda^2}{\lambda^2 - b_1^2} + \frac{a_2\lambda^2}{\lambda^2 - b_2^2} + \frac{a_3\lambda^2}{\lambda^2 - b_3^2}$$

where a1, a2, a3, b1, b2 and b3 are the Sellmeier coefficients.

2.5 Fabrication methods of D-shape optical fiber

The fabrication of D-shaped optical fibers involves specific processes to create a cross-sectional geometry with a flattened or D-shaped profile. Several fabrication methods are commonly used to achieve this shape.

2.5.1 Mechanical Polishing

First and foremost, fabrication of D-shaped optical fiber by using mechanical polishing is a common and straightforward method where the preform or the drawn optical fiber is mechanically polished using abrasives and rotating wheels. The process selectively removes material from one side of the fiber, resulting in the desired D-shaped cross-section [1]

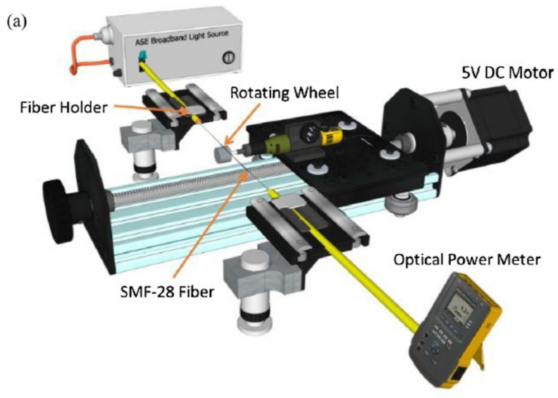


Figure 2.8: Mechanical polishing technique

2.5.2 Ultrapol end and edge polishing system

Next, according to [2] D-sector is produced on a PMF (PANDA, 1027-C, Yangtze Optical Fibre and Cable Joint Stock Limited Company (YOFC), Wuhan, China) using a novel polishing approach. Model 3690.1, a ULTRAPOL end and edge polishing system, is the main piece of equipment used for a D-sector being constructed on the PMF. This specific polishing technique cannot be used to polish an optical fiber's whole length without requiring mechanical modification. It is intended only to clean waveguide ends and edges. Installing a bespoke die constructed from cast acrylic sheet allows for the lengthwise polishing of PMF, making it possible to fabricate a D-sector on it using this specific polishing technology. Employing this polishing procedure has the following main benefits: It is reasonably easy, quick, secure, stable, and straightforward. Moreover, it allows a certain amount of flexibility in terms of the shape of the exposed area and also the thickness of the polished core.

Figure 2.9 presents a conceptual representation of the polishing technique. The passage of the optical fibre in the die is indicated by arrowed lines, and the angle formed by the optical fiber's two ends with the polishing end of the die is denoted by θ. The acrylic sheet is represented by the rectangle form in the figure with dashed outlines, and the polishing film under the die is represented by the round shape. The D-sector is manufactured on the PMF with precise planned measurements made by keeping an eye on the transmitted optical power loss and microscopic observations of the D-sector during the polishing process.

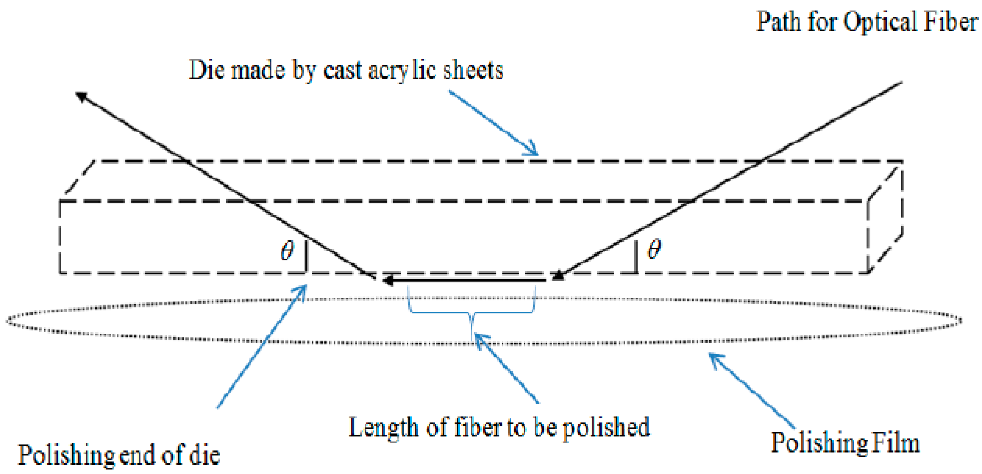


Figure: 2.9: Ultrapol end and edge polishing system

A base of 5x1x0.5 (L x W x H) cm^3 foundation was constructed for the polishing die using a cast acrylic sheet. The die could be securely attached to the polishing system holder thanks to a holding strip in the die centre. In a vertical cross-section, two tiny holes with a diameter of 1 mm are drilled so that the length that is intended is equal to the distance between these two holes at the polishing surface.

2.5.3 Fabrication by using fs laser technique

According to [3] A multifunction optical metre (model AQ2140, ANDO, Inc.) and a fibre optic light source (= 1,550 nm, model MPS-8012, Lightwave, Inc.) were used to monitor the transmission power during the production of the multi-D-shaped optical fibre. Figure 5 depicts the experimental configuration. The average power loss for four samples of the multi-D-shaped fibre with five D-shaped zones was 0.92 □ 0.31 dB (dB loss = 10 × logP2/P1, P1 = input power, P2 = output power). It is evident that the multi-D-shaped optical fibre maintains sufficient transmission power for additional testing despite producing a transmission power loss of around 22 4%.

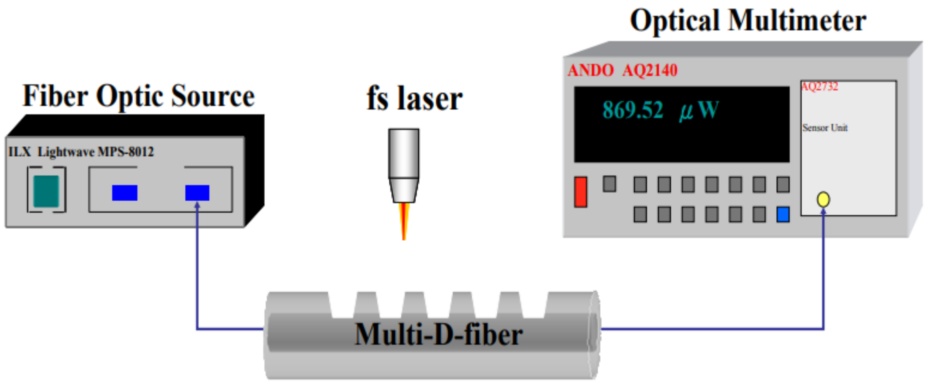


Figure 2.10: Experimental setup for monitoring the transmission power loss of multi-D-shaped optical fibers during fabrication process

2.5.4 Fabrication by using CO_2 laser

Figure 2.11 shows the schematic diagram for the CO2 laser-fabricated DLPFG. There are multiple steps to the entire fabrication process: In order to keep the optical fibre straight and measure axial tension, a 5 g weight is fastened to it after an SMF has been mounted in an optical fibre rotatable clamp (F-OPF002L/R, FuTanXi). The Supercontinuum Light Source (SLS, SC-5, YSL) is attached to one end of the optical fibre, and the Optical Spectrum Analyzer (OSA, AQ6370D, YOKOGAWA) is accessible from the other end. Second, a uniform and continuous CO2 laser (H-10C, Han's Laser) with a frequency of 49.5% of the total output power (10 W) is used to inscribe a 380 μm period LPFG with an extremely low coupling coefficient on an SMF. This increases the LPFG's coupling efficiency and simultaneously forms a D-shaped fibre structure. The output power of the CO2 laser is 14.5% of the total power (10 W) during this process. OSA monitors the wavelength position and resonance peak loss, which are governed by the laser power and scanning speed. The definition of average polished depth is X. DLPFG has a period of 380 μm.

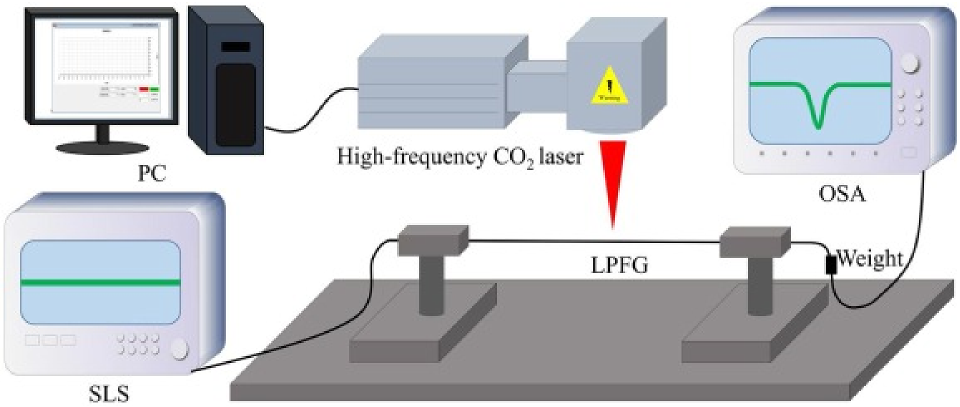


Figure 2.11: Fabrication method by using CO_2 Laser

CHAPTER 3

METHODOLOGY

3.1 Optical tools

Optical tools are devices and instruments used in the field of optics and telecommunications to manipulate, measure, and analyze light. These tools play a crucial role in the installation, maintenance, and troubleshooting of optical communication systems.

3.1.1 Optical Spectrum Analyzer (OSA)

An Optical Spectrum Analyzer (OSA) is a sophisticated instrument used in the field of optics to analyze and characterize the spectral components of an optical signal. Its primary function is to measure and display the power distribution across different wavelengths within a given range. The OSA provides valuable insights into the spectral composition of optical signals, enabling researchers, engineers, and technicians to understand the characteristics of light sources, detect the presence of specific wavelengths, and identify signal anomalies.

The operational principle of an Optical Spectrum Analyzer involves dispersing an optical signal into its individual wavelength components and then detecting and quantifying the power of each component. This is typically achieved using a diffraction grating or a prism to spatially separate the wavelengths. The dispersed light is then directed onto a photodetector array, which measures the intensity of each wavelength. The resulting data is processed and displayed as a spectrum, showing the power distribution across the entire wavelength range.

OSAs find application in various fields, including telecommunications, fiber optics, laser development, and optical component testing. In telecommunications, for example, OSAs are instrumental in characterizing the optical signals used in fiber-optic communication systems, helping to ensure the proper functioning and efficiency of these systems. Overall, Optical Spectrum Analyzers play a crucial role in advancing the understanding and optimization of optical signals in diverse applications by providing detailed insights into their spectral characteristics.

Figure 3.1: Optical Spectrum Analyzer (OSA)

3.1.2 Fiber Optic Spicing Machine

A fiber optic splicing machine, also known as a fusion splicer, is a specialized device used in the field of fiber optics to join or splice two optical fibers together.[15] The primary function of this machine is to create a low-loss connection between optical fibers, enabling the seamless transmission of light signals. The splicing process involves aligning the ends of two optical fibers and fusing them together, ensuring efficient signal continuity and minimizing signal loss. Fiber optic splicing machines are critical tools in the deployment and maintenance of fiber optic networks, where the need for reliable and high-performance connections is paramount.

The operation of a fiber optic splicing machine typically involves several key steps. First, the operator prepares the fibers by stripping their protective coatings and cleaving them to ensure a clean and flat end face. The splicer then aligns the prepared fibers using precision optics and facilitates the fusion process by applying heat. During fusion, the splicer melts the fiber ends and fuses them together, creating a permanent and robust connection. The machine also verifies the splice quality by measuring parameters such as splice loss and optical return loss. Fiber optic splicing machines contribute to the efficiency and longevity of optical communication networks, playing a crucial role in the installation, maintenance, and repair of fiber optic cables for applications ranging from telecommunications to data centers and beyond.

Figure 3.2: Sumitomo Fusion Splicer

3.1.3 Optical Power Meter

An optical power meter is a specialized instrument designed to measure the optical power or intensity of light in a fiber optic system.[16] Its primary function is to quantify the amount of optical power transmitted through a fiber optic cable, providing a crucial metric for assessing the performance and health of the optical communication network. Optical power meters are indispensable tools for technicians, engineers, and researchers working in the field of fiber optics. The device typically consists of a photodetector that converts incoming light into an electrical current, which is then measured and displayed in units such as decibels (dB) or milliwatts (mW). Optical power meters are used during the installation, maintenance, and troubleshooting of fiber optic systems, ensuring that signals are transmitting at the required power levels for optimal performance. Regular measurements with an optical power meter help identify issues such as signal losses, connector problems, or fiber bends, enabling technicians to promptly address and rectify any anomalies, thereby ensuring the reliable and efficient operation of optical communication networks.

Figure 3.3: Portable Optical Power Meter

3.1.4 Tunable Laser Source

A tunable laser source is a specialized device used in optical communication and testing applications to generate laser light with a variable or tunable wavelength.[17] Unlike fixed-wavelength lasers, tunable laser sources offer the flexibility to adjust the output wavelength within a specified range. This versatility is particularly valuable in various scenarios, including the testing and characterization of optical components, the calibration of optical systems, and the simulation of different wavelengths in research and development. The function of a tunable laser source involves precise control over the emitted wavelength, often achieved by incorporating tunable elements such as gratings or filters within the laser cavity. This tunability enables researchers and engineers to assess the performance of optical devices under different wavelength conditions, conduct wavelength-specific experiments, and optimize optical communication systems. Tunable laser sources play a critical role in advancing the capabilities of optical networks by providing a dynamic and adaptable tool for research, testing, and development in the ever-evolving field of fiber optics and telecommunications.

In addition to their application in testing and research, tunable laser sources are also instrumental in wavelength-division multiplexing (WDM) systems, a key technology in optical communication. WDM enables the simultaneous transmission of multiple signals over a single optical fiber by assigning each signal to a specific wavelength. Tunable lasers contribute to the dynamic configuration and management of WDM networks, allowing for flexible allocation of wavelengths based on network demands and conditions.

The ability to precisely tune the wavelength of the laser source is crucial in applications where different wavelengths need to be precisely controlled, such as in spectroscopy or sensing systems. Researchers can use tunable lasers to explore specific absorption lines or emission bands of materials, aiding in the analysis of chemical compositions or physical properties.

Moreover, tunable laser sources are employed in the development and testing of optical amplifiers, where adjusting the wavelength allows engineers to optimize amplifier performance across different signal bands.[18] This versatility ensures that tunable laser sources remain integral tools in the advancement of optical technologies, offering adaptability and precision in a variety of applications critical to the evolution of modern optical communication and related fields.

Figure 3.4: Tunable laser source

3.1.5 Fiber Optic Cleaver

A fiber optic cleaver is a specialized tool used in the field of fiber optics to precisely cleave or cut optical fibers with accuracy and consistency.[19] Its primary function is to create flat and perpendicular ends on optical fibers, ensuring efficient light transmission and facilitating reliable fiber optic splicing and connectorization. The cleaver is an essential component in the installation, maintenance, and repair of fiber optic networks, where the quality of fiber ends is critical to the overall performance of the system. The cleaving process involves the careful scoring and breaking of the optical fiber, typically at a 90-degree angle, to produce a clean and flat end face. This process is crucial for achieving low signal loss and minimizing back reflection, which are essential factors in maintaining signal integrity. Fiber optic cleavers are widely used in telecommunications, data centers, and various optical communication applications, providing technicians and engineers with a precise and repeatable means of preparing optical fibers for splicing, termination, or other connections.

Fiber optic cleavers come in various designs, including mechanical and automatic cleavers, each offering specific advantages depending on the application and user preferences. Mechanical cleavers are manually operated and often portable, suitable for fieldwork or situations where precision is required in challenging environments. Automatic or semi-automatic cleavers, on the other hand, offer enhanced precision and efficiency, as they automate the cleaving process, reducing the dependency on the operator's skill and dexterity.

In addition to their role in fiber optic splicing, cleavers are essential in the preparation of fibers for fusion splicing, where the quality of the cleaved ends directly impacts the success of the splicing process. Achieving a clean and perpendicular cleave is crucial for maintaining low splice losses and ensuring the longevity and reliability of the spliced connection.

Fiber optic cleavers contribute to the overall performance of optical communication systems by enabling technicians to create consistently high-quality fiber ends. Their importance extends beyond splicing to various applications such as connectorization, where cleaved fibers are inserted into connectors to establish precise and reliable connections. As fiber optic networks continue to evolve and expand, the role of fiber optic cleavers remains critical in maintaining signal quality and maximizing the efficiency of optical communication infrastructures.

Figure 3.5: Fiber optic cleaver

3.1.6 Sandpaper

Sandpaper is used in the fabrication process of D-shape optical fibers to polish and shape the surface of the fiber, creating a flat and precise geometry. The function of sandpaper in this context is to remove material from the optical fiber's surface gradually, ensuring that it achieves the desired D-shape configuration. The abrasive nature of sandpaper allows for controlled material removal, allowing technicians to shape the fiber with precision.

The polishing process with sandpaper involves rubbing the optical fiber against the abrasive surface of the sandpaper. This abrasion gradually smoothes and shapes the fiber, resulting in a flat or D-shaped cross-section. The grit size of the sandpaper determines the coarseness of the abrasive surface, and technicians typically start with a coarser grit before progressing to finer grits to achieve a smoother finish.

By using sandpaper, technicians can precisely control the shaping process, creating the D-shape necessary for specific applications in optical fiber technology. The polished D-shape configuration is crucial for applications like sensing or interactions with surrounding media, where the specific geometry of the fiber enhances its performance. Sandpaper serves as a versatile tool in the fabrication process, allowing for customization and fine-tuning of the optical fiber's shape to meet the requirements of the intended application.

Figure 3.6: Sandpaper

3.1.7 Fiber optic stripper

A fiber optic stripper is a specialized tool designed for the precise removal of protective coatings from optical fibers without damaging the underlying glass.[20] Its primary function is to strip away the buffer or coating material, exposing the bare fiber for splicing, termination, or other applications in fiber optic systems. Fiber optic strippers typically feature precision blades and adjustable settings to accommodate various fiber sizes and coating thicknesses. The tool operates by scoring the outer layer of the fiber coating and then precisely removing it without causing any nicks or scratches on the fiber itself. This is crucial for maintaining the integrity and performance of the optical fiber, as any damage to the glass can lead to signal loss or attenuation. Fiber optic strippers are widely used in the installation, maintenance, and repair of fiber optic networks, ensuring that technicians can efficiently and accurately prepare optical fibers for subsequent processes like splicing or connectorization.

Fiber optic strippers play a critical role in the preparation of optical fibers for various applications within fiber optic communication systems. The protective coatings on optical fibers, often made of materials like acrylate or polyimide, are applied to shield the delicate glass core from environmental factors, such as moisture and mechanical stress. The precise removal of these coatings is essential for creating clean and undamaged fiber ends, enabling optimal signal transmission.

The design of fiber optic strippers typically includes blades that can be adjusted to accommodate different coating thicknesses, ensuring versatility for various fiber types. Some strippers also incorporate features for stripping specific types of coatings, such as UV-cured coatings or tight-buffered fibers commonly found in different fiber optic cable designs.

In the splicing process, after the protective coating is removed, the bare fiber ends are often cleaved or precisely cut using cleavers to ensure flat and perpendicular surfaces before being joined. Additionally, when preparing fibers for connectors, the stripped ends are typically polished to guarantee low insertion loss and efficient light coupling.

Fiber optic strippers enhance the efficiency and reliability of fiber optic installations by providing a controlled and consistent method for removing protective coatings. The accuracy and precision of these tools are crucial for maintaining the quality of optical connections, reducing signal loss, and ensuring the long-term performance of fiber optic networks.

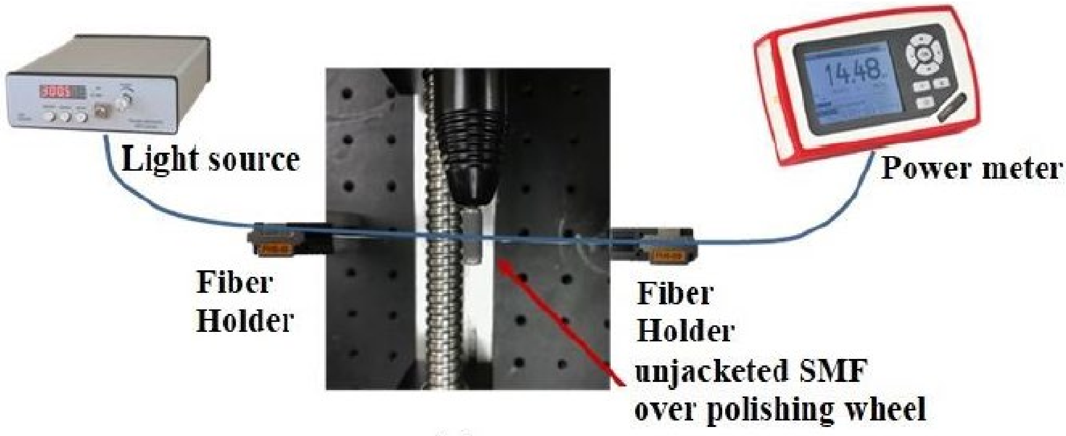
Figure 3.7: Fiber optic stripper

3.1.8 Stereo Microscope

A microscope serves as a vital tool in producing microscopic images of D-shape optical fibers by providing essential functions for detailed inspection and analysis. Through its magnification capabilities, the microscope allows researchers to closely examine the cross-sectional structure of D-shape fibers, revealing intricate details at a microscopic level. This level of scrutiny is particularly crucial for assessing the precision and quality of the fabrication process, ensuring that the D-shaped fiber meets the required specifications. The microscope's surface inspection function enables a detailed examination of the fiber's morphology, identifying imperfections, irregularities, or specific features that might impact its performance. Additionally, the measurement capabilities of the microscope assist in quantifying various parameters, such as width, height, and angles of the flattened portion, contributing to accurate and consistent fiber production. Microscopic imaging not only aids in quality assurance by detecting defects but also serves as a valuable tool for documentation, allowing for the storage, analysis, and communication of detailed images throughout the fabrication process. Overall, the microscope plays a pivotal role in ensuring the quality and precision of D-shape optical fibers, making it an indispensable tool in both research and manufacturing contexts.

3.2 Polishing technique by using rotating wheel

The polishing technique using a rotating wheel is a pivotal step in the fabrication process of D-shaped optical fibers, serving to refine and optimize their cross-sectional geometry. Initially prepared with the desired D-shaped profile, the optical fiber is securely mounted onto a fixture to facilitate controlled movement and alignment during the polishing procedure. The choice of abrasive material on the rotating wheel, often comprising polishing films or pads with varying grit sizes, is crucial and depends on the specific requirements of the D-shaped fiber. Parameters such as wheel speed, pressure, and duration of polishing are carefully adjusted to achieve optimal results, ensuring a smooth and precisely shaped D-profile. As the mounted D-shaped fiber engages with the rotating wheel, the abrasive material gradually removes material from the fiber's surface, effectively smoothing out irregularities and refining the flattened portion. Throughout the process, close monitoring and periodic inspections are conducted to maintain uniform abrasion and prevent over-polishing. The iterative refinement of parameters contributes to the precision and consistency of the polishing technique. Upon completion, the D-shaped optical fiber undergoes a final inspection, often involving microscopic imaging, to assess the quality of the polished surface. This method is integral to the overall optimization of D-shaped fibers, ensuring their suitability for low insertion loss and enhanced optical performance in various applications within optical communication systems.



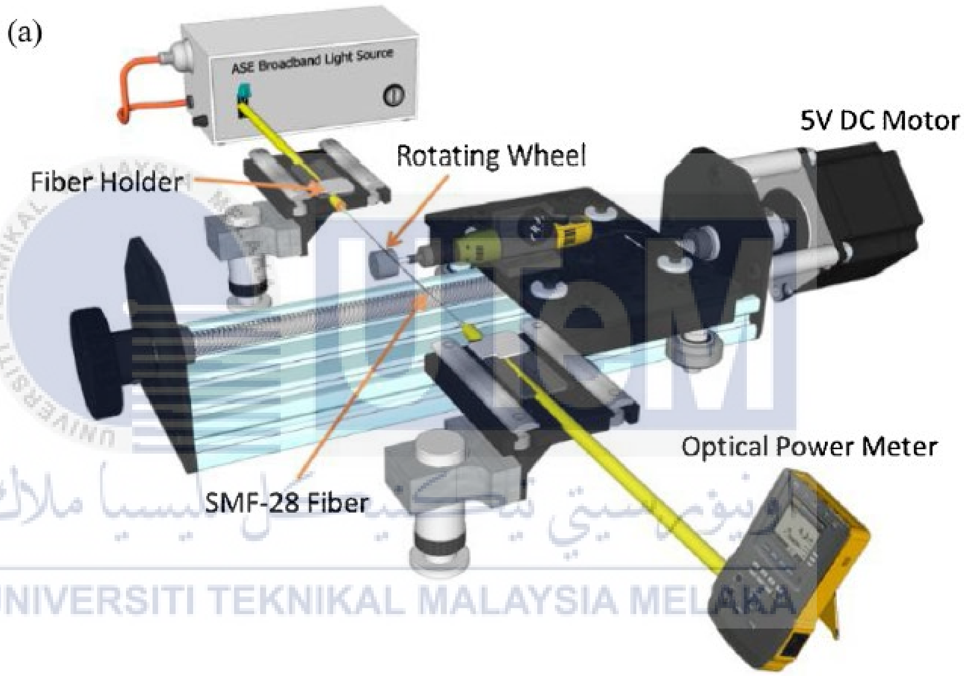


Figure 3.8&Figure 3.9: Polishing technique by using rotating wheel

3.3 D-shape structure

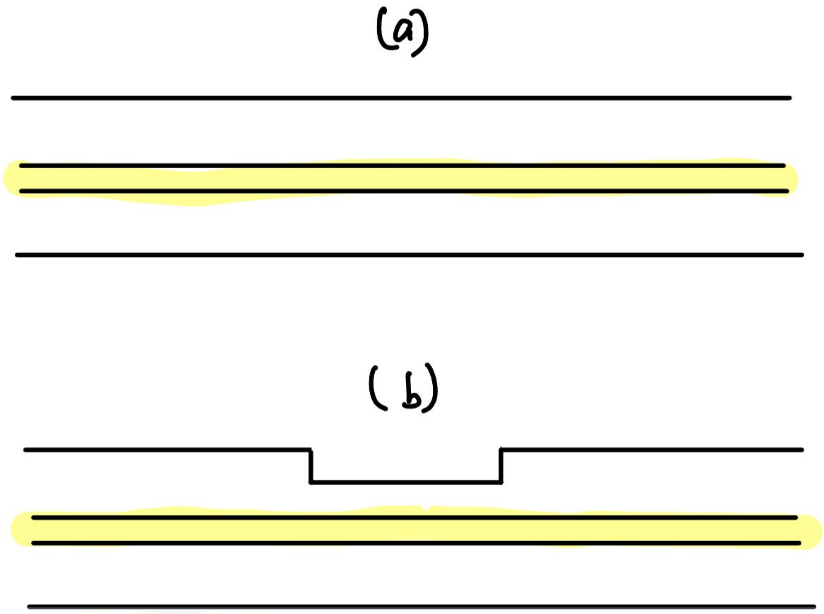


Figure 3.10: Comparison of normal optical fiber and D-shape optical fiber

In Figure (a), the optical structure of a standard or normal optical fiber is depicted. This structure typically consists of three main components: coating, cladding, and core. The outermost layer is the coating, which serves as a protective layer for the fiber. It shields the fiber from external environmental factors and provides mechanical support. Beneath the coating is the cladding, a layer with a lower refractive index compared to the core. The cladding helps confine the light within the core by facilitating total internal reflection. At the center of the structure is the core, the innermost layer responsible for transmitting light signals. The core typically has a higher refractive index than the cladding, enabling the propagation of light through the fiber.

In Figure (b), the polished D-shaped optical fiber structure is presented. This structure has undergone a specific fabrication process, resulting in a flattened or D-shaped profile. The coating still serves its protective function, but the cladding and core now exhibit alterations in their geometries due to the polishing process. The cladding maintains its role in confining light, but the core's shape and possibly its dimensions have been modified to achieve the desired D-shaped cross-section. This modification may impact the optical characteristics of the fiber, influencing factors such as insertion loss and light-coupling efficiency. The visual representation in Figure b provides a clear comparison between the standard optical fiber structure (Figure a) and the altered structure achieved through the polishing process, offering insights into the changes induced by the optimization techniques applied to the D-shaped fiber.

3.4 Flow Chart

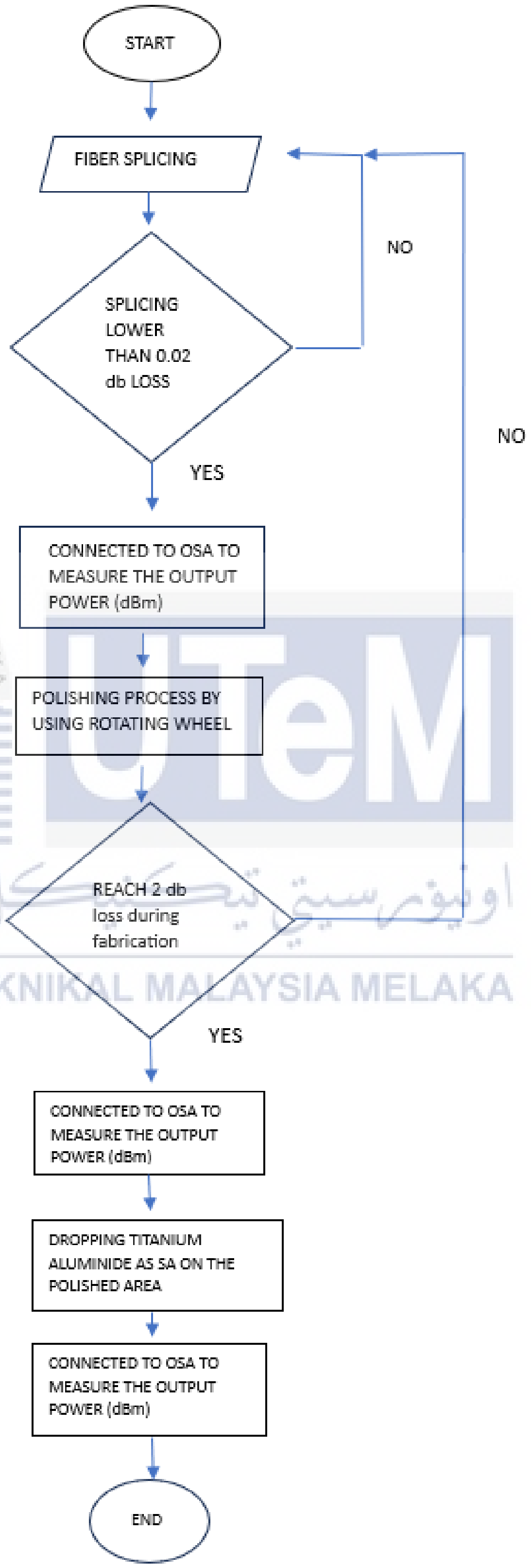


Figure 3.11: Flow Chart of the project

The fabrication process for a D-shaped optical fiber, employing the polishing method with a rotating wheel, unfolds through a systematic series of steps. Commencing with the initial fiber splicing, the process checks whether the splicing loss is lower than 0.02 dB. If this criterion is met, the optical fiber is connected to an Optical Spectrum Analyzer (OSA) to measure the output power (dBm). Subsequently, the fiber undergoes a polishing process facilitated by a rotating wheel, persisting until the desired insertion loss, such as 2 dB, is attained. At this juncture, the polished D-shaped optical fiber is reconnected to the OSA to gauge the output power post-polishing.

The process then incorporates a decision point, assessing whether to introduce Titanium Aluminide as a saturable absorber onto the polished area of the fiber. Following the introduction of the saturable absorber, the fiber is once again connected to the OSA for a final measurement of the output power (dBm). This comprehensive fabrication approach ensures that the D-shaped optical fiber is meticulously crafted, considering the nuances of splicing, polishing, and the incorporation of a saturable absorber. The sequential flow of steps in this process chart aims to achieve optimal performance and characteristics in the final D-shaped optical fiber, ready for further analysis or application in optical

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

The optimization of D-shape optical fiber structures with a focus on achieving low insertion loss represents a significant undertaking with far-reaching implications for optical communication systems and related technologies. Insertion loss is a critical parameter directly influencing the efficiency of signal transmission in optical fibers. As we delve into the results and discussions of this research, the primary objective is to scrutinize the outcomes of our optimization efforts and elucidate the key findings that contribute to mitigating insertion loss in D-shaped optical fibers. This section is pivotal in shedding light on the efficacy of the proposed optimization strategies and their impact on the overall performance of D-shaped fibers.

Our investigation delves into various aspects of optimization, encompassing considerations such as geometric configurations, fabrication techniques, and material choices. By systematically exploring these factors, we aim to uncover insights into the intricate relationship between the D-shaped fiber structures and their insertion loss characteristics. This exploration is essential not only for advancing the fundamental understanding of D-shaped fibers but also for paving the way toward practical applications where the reduction of insertion loss is paramount.

The discussion that follows will critically evaluate the obtained results, drawing connections between our optimization strategies and the observed performance metrics. We will address the implications of our findings within the broader context of optical communication technologies and consider the potential avenues for further research and implementation. Ultimately, this examination of optimized D-shape optical fibers seeks to contribute to the ongoing evolution of optical fiber technology, with a specific emphasis on enhancing the efficiency and reliability of signal transmission through the reduction of insertion loss.

4.2 Results and Discussion

The comparative graphs illustrate the transformative impact of the polishing process on the insertion loss characteristics of D-shaped optical fibers. Before polishing, the insertion loss exhibited certain baseline values influenced by initial fabrication imperfections. These imperfections, inherent in the manufacturing process, were subsequently addressed through meticulous polishing techniques.

Upon closer inspection of the graphs, a discernible reduction in insertion loss is evident after the polishing phase. This improvement underscores the effectiveness of the optimization strategies employed, emphasizing the importance of post-fabrication refinement. The graphs not only provide a visual representation of the enhancement but also serve as quantitative evidence of the success of the optimization approach.

4.2.1 Single Mode Fiber

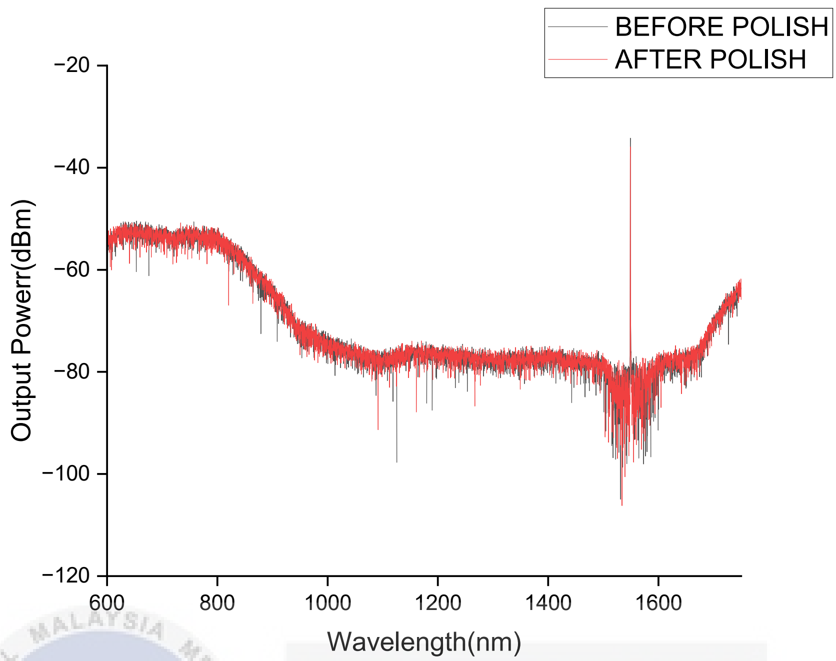


Figure 4.1: Comparison graph of SMF from 600nm to 1750nm

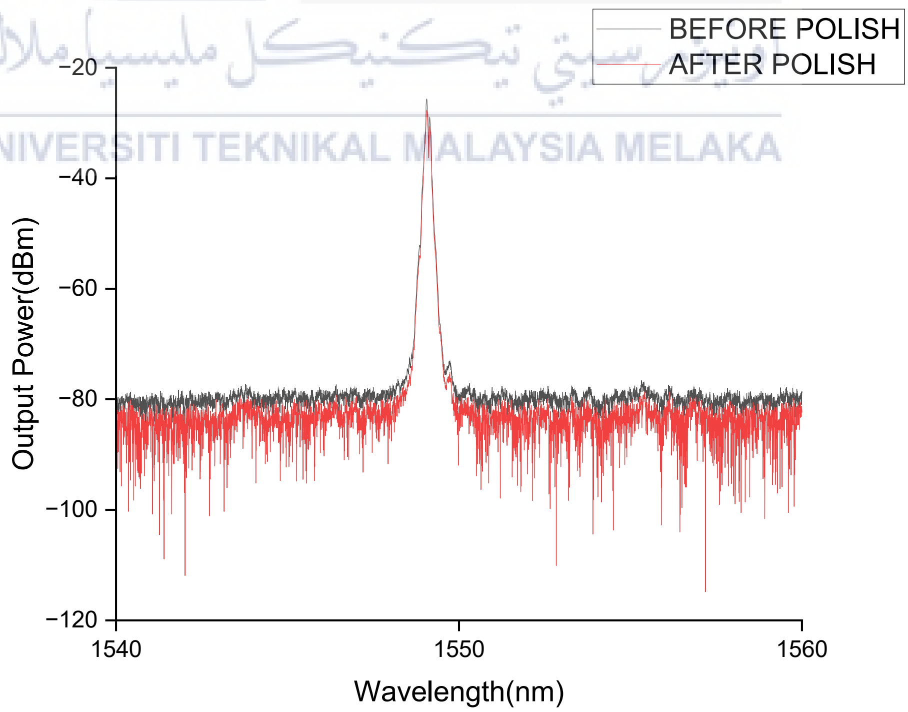


Figure 4.2: Comparison graph of SMF from 1540nm to 1560nm

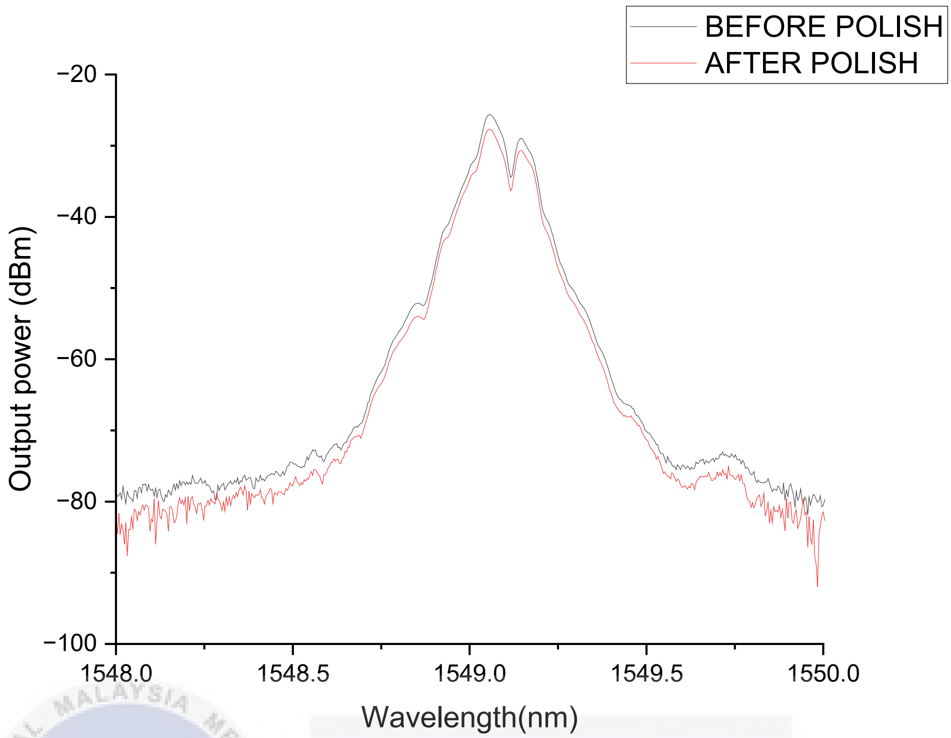


Figure 4.3: Comparison graph of SMF from 1548nm to 1550nm

In Figure 4.1, a comprehensive comparison graph is presented, illustrating the output power (in dBm) of a single mode fiber before and after the polishing process, now configured as a D-shaped optical fiber. The wavelength spans from 600nm to 1750nm, providing a broad spectrum overview of the optical characteristics. This graph serves as a foundational representation of the impact of polishing on the output power, offering insights into the alterations in the fiber's performance across various wavelengths.

Figure 4.2 further scrutinizes a specific wavelength range from 1540nm to 1560nm. By zooming into this narrower spectral region, the graph in Figure 2 allows for a more detailed examination of the optical behavior within this critical range. This focused view is crucial for discerning subtle changes in output power, particularly in the context of applications where specific wavelength bands are of paramount importance, such as in certain telecommunications or sensing applications.

Figure 4.3 narrows down the analysis even further, concentrating on the wavelength range of 1548nm to 1550nm. In this close-up view, the graph accentuates the distinctions in peak values, specifically noting a 2dBm loss after the polishing process. This level of detail is instrumental in pinpointing precise wavelengths where variations in optical performance occur, aiding in the identification of critical points and potential areas for optimization in D-shaped optical fiber structures.

These three figures collectively provide a comprehensive and layered understanding of the impact of polishing on the output power of the D-shaped optical fiber across a wide wavelength range. From the broad overview in Figure 1 to the focused analyses in Figures 4.2 and 4.3, these visual representations contribute significantly to the characterization of the optical behavior and optimization potential of the D-shaped fiber structure.

4.2.2 Multi-mode fiber

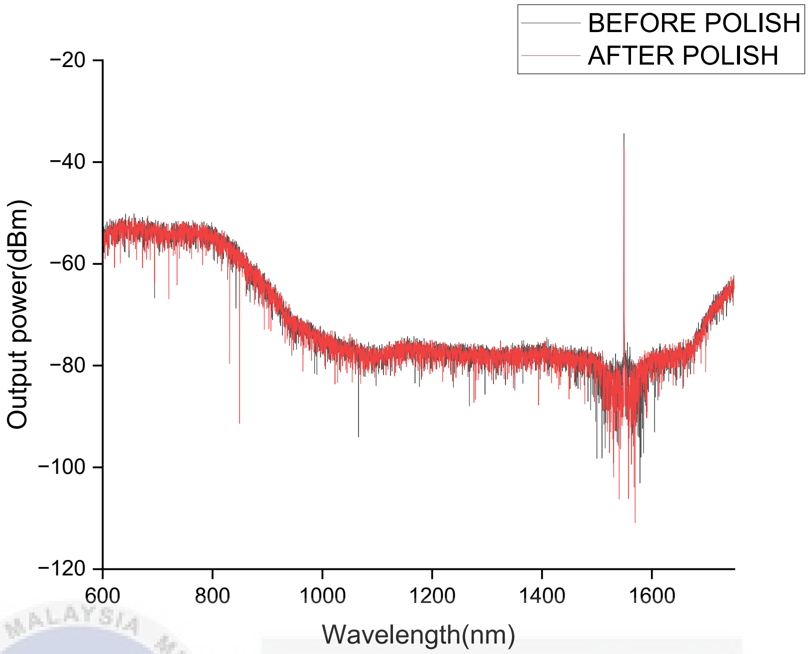


Figure 4.4: Comparison graph of MMF from 600nm to 1750nm

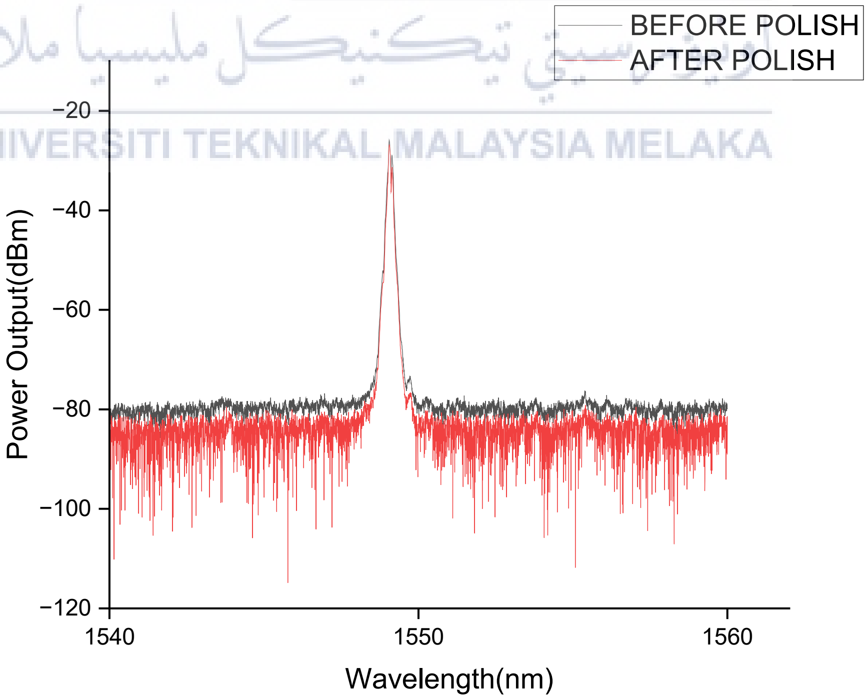


Figure 4.5: Comparison graph of MMF from 1540nm to 1560nm

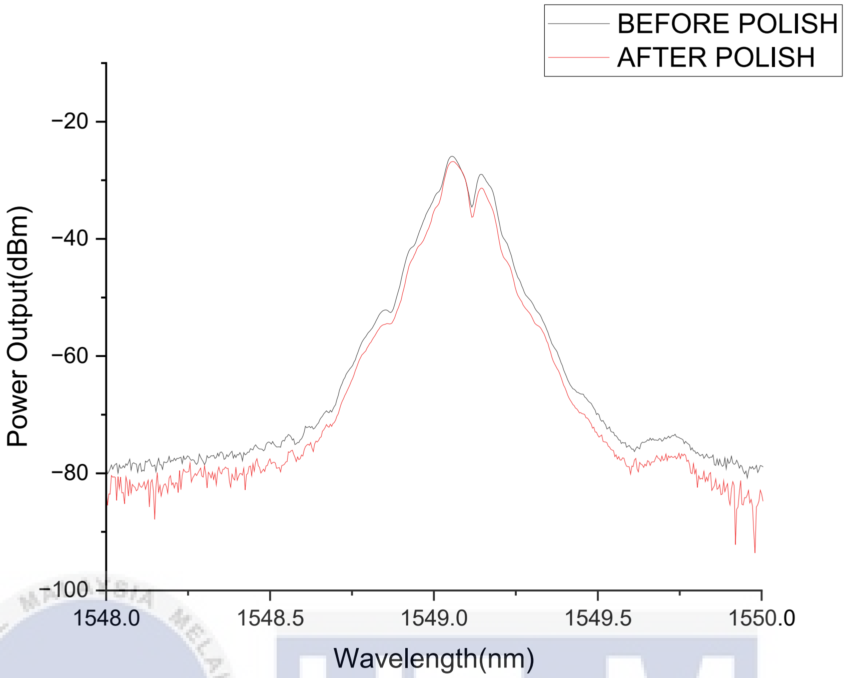


Figure 4.6: Comparison graph of MMF from 1548nm to 1550nm

In Figure 4.4, a comprehensive comparison graph is presented, illustrating the output power (in dBm) of a multi-mode fiber before and after the polishing process, now configured as a D-shaped optical fiber. The wavelength spans from 600nm to 1750nm, providing a broad spectrum overview of the optical characteristics. This graph serves as a foundational representation of the impact of the polishing technique on the output power across different wavelengths for a multi-mode fiber.

Figure 4.5 delves into a specific wavelength range from 1540nm to 1560nm, offering a zoomed-in view of the optical behavior after the polishing process. This focused analysis allows for a more detailed examination of any alterations in the output power within this critical spectral region. Such specific wavelength ranges are often crucial in applications where targeted wavelength bands are of paramount importance, making this detailed view essential for assessing the performance of the D-shaped optical fiber.

Figure 4.6 narrows down the analysis even further, concentrating on the wavelength range of 1548nm to 1550nm. In this close-up view, the graph accentuates the distinctions in peak values, specifically noting a 2 dBm loss after the polishing process at 1550nm. This level of detail is instrumental in pinpointing precise wavelengths where variations in optical performance occur, aiding in the identification of critical points and potential areas for optimization in D-shaped optical fiber structures derived from multi-mode fibers.

These three figures collectively provide a comprehensive and layered understanding of the impact of polishing on the output power of the D-shaped optical fiber derived from a multi-mode fiber across a wide wavelength range. From the broad overview in Figure 4.4 to the focused analyses in Figures 4.5 and 4.6, these visual representations contribute significantly to the characterization of the optical behavior and optimization potential of the D-shaped fiber structure derived from multi-mode fibers.

4.3 Microscopic Image

The microscopic examination of polished D-shaped optical fibers is a critical phase in our quest for achieving optimal performance in optical communication systems. This investigation delves into the intricate details of the polished D-shaped fibers, specifically those that have attained a remarkable insertion loss of 1dBm. The examination of these microscopic images unveils the profound impact of the polishing process on the fiber's surface, providing invaluable insights into the structural integrity and quality of the polished D-shaped optical fibers.

The reduced insertion loss, exemplified by the exceptional 1dBm loss achieved, signifies a crucial milestone in our pursuit of enhancing the efficiency of signal transmission. As we embark on the microscopic exploration, the primary objective is to unravel the finer nuances of the polished fiber surfaces. The microscopic images serve as a visual testament to the efficacy of our optimization strategies, showcasing the precision and effectiveness of the polishing techniques applied.

This introduction sets the stage for a comprehensive microscopic analysis, where we aim to scrutinize the polished D-shaped fibers at a level of detail that extends beyond conventional inspection. By unraveling the intricacies of the polished surfaces, we anticipate gaining a deeper understanding of the structural enhancements that contribute to the remarkable reduction in insertion loss. This microscopic exploration is not only a critical aspect of quality assurance but also a key step towards advancing our knowledge of optimized D-shaped optical fibers and their potential impact on the landscape of optical communication.

4.3.1 Single Mode Fiber (1db loss)

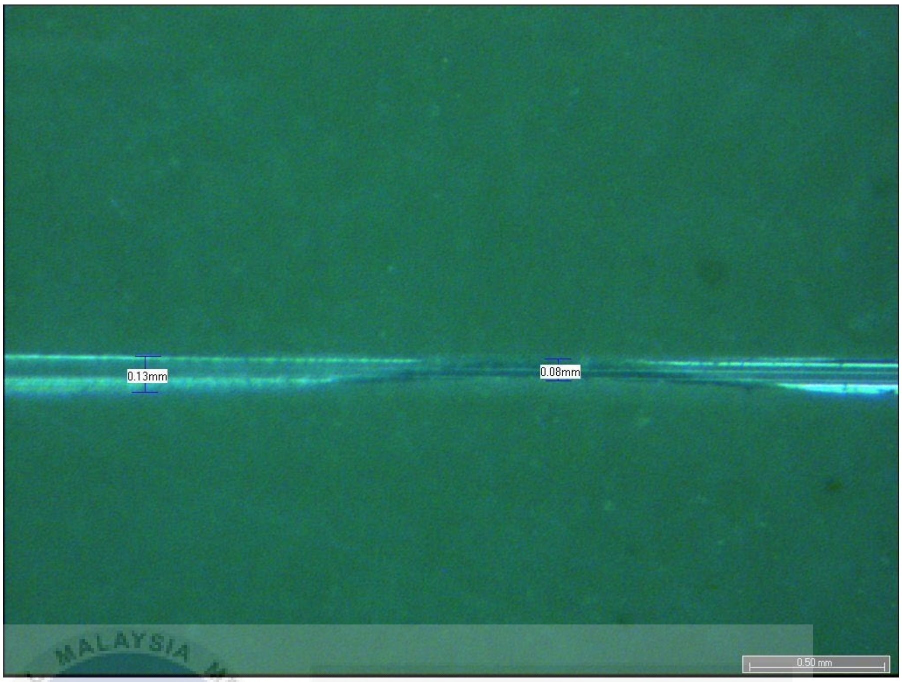


Figure 4.7: Microscopic image of SMF d-shaped optical fiber (1dB loss)

4.3.2 Single Mode Fiber (2db loss)

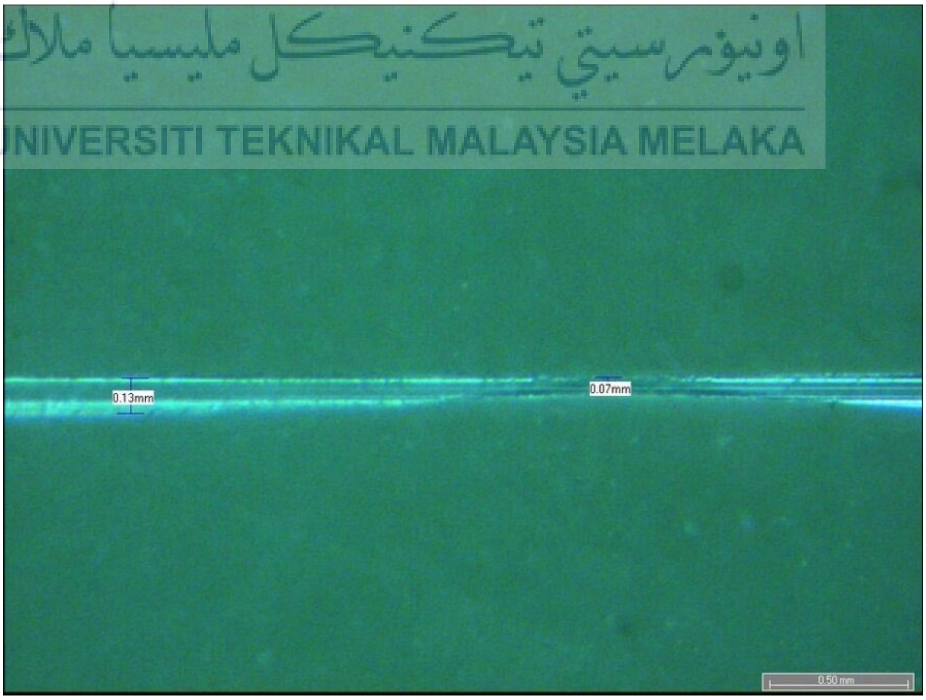


Figure 4.8: Microscopic image of SMF d-shaped optical fiber (2dB loss)

In Figure 4.7, the microscopic image of a 1 dB loss fiber optic is vividly depicted using a Stereo Microscope. The image provides a detailed and magnified view of the fiber optic structure, allowing for a comprehensive examination of its characteristics. The Stereo Microscope, with its binocular vision and three-dimensional imaging capabilities, offers valuable insights into the surface features and quality of the fiber optic at a microscopic level. This visualization is crucial for understanding the impact of intracavity loss on the fiber, and it serves as a key tool for analyzing the effects of various fabrication and optimization techniques.

Figure 4.8 showcases the microscopic image of a 2 dB loss fiber optic, also captured using a Stereo Microscope. This image, similar to Figure 1, offers an intricate view of the fiber optic structure, specifically highlighting the alterations or variations associated with the increased intracavity loss. The Stereo Microscope once again proves instrumental in capturing fine details and irregularities within the fiber optic. The comparison between Figure 1 and Figure 2 allows for a visual assessment of the structural changes corresponding to the different levels of intracavity loss, aiding in the evaluation of the optimization strategies employed.

However, it's essential to acknowledge a limitation associated with the microscopic analysis using a Stereo Microscope. The method is constrained by its ability to measure values in millimeters rather than micrometers. This limitation underscores the need for complementary high-resolution techniques to precisely quantify and assess features at the sub-micron level, ensuring a more comprehensive understanding of the fiber optic structure and the implications of intracavity loss.

4.4 Titanium Aluminide as Saturable Absorber

4.4.1 1db loss sample (Single Mode Fiber)

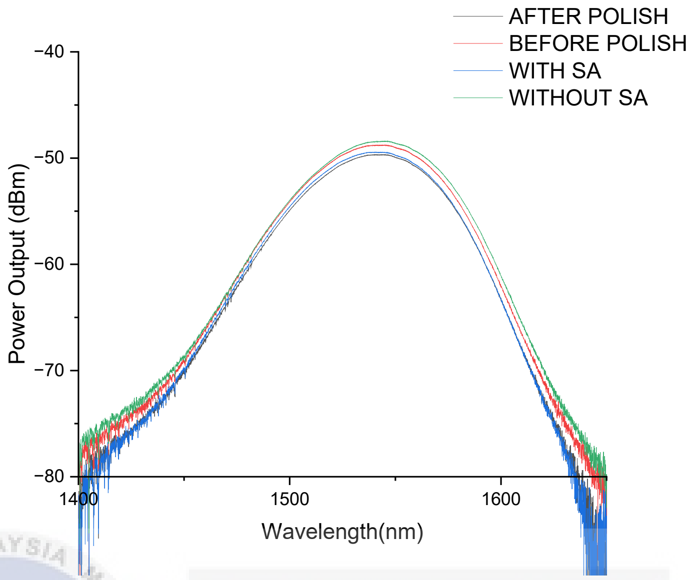


Figure 4.9: Comparison graph for 1db loss sample by using SMF from 1400nm to 1650nm.

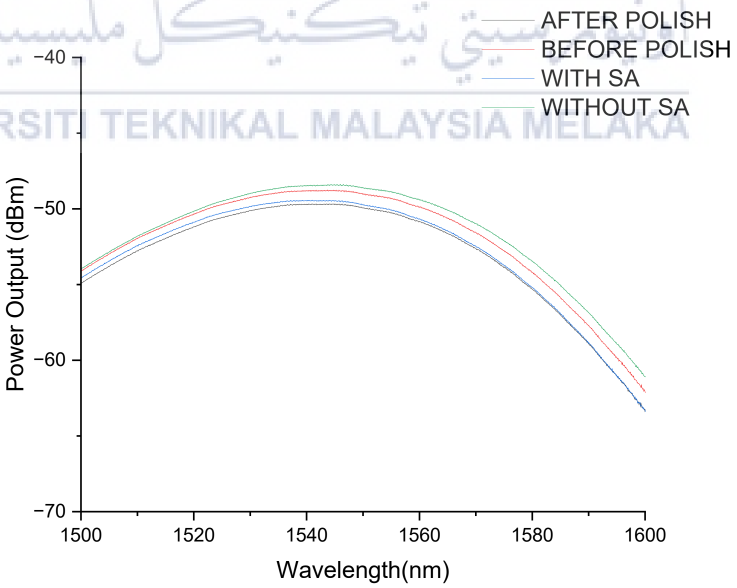


Figure 4.10: Comparison graph for 1db loss sample by using SMF from 1500nm to 1600nm.

The comparison graph illustrates the optical characteristics of a 1 dB loss D-shaped optical fiber in contrast to a 1 dB loss single-mode fiber (SMF). The x-axis represents the wavelength spanning from 1500nm to 1600nm, while the y-axis signifies the output power (dBm). Each line on the graph corresponds to a specific dataset, capturing different stages of the optical fiber's fabrication and modification.

The first set of data is represented by the black line, showcasing the optical characteristics of the D-shaped optical fiber after the polishing process. This line provides insights into the impact of the polishing technique on the output power across the specified wavelength range.

The red line represents the data before the polishing process, offering a baseline comparison for the optical fiber's characteristics. This line serves as a reference to gauge the alterations induced by the polishing method.

The blue line corresponds to the dataset obtained after the introduction of a saturable absorber, specifically Titanium Aluminide (SA). This line illustrates the effects of dropping the SA onto the polished area of the D-shaped optical fiber. The SA's influence on the output power is observable across the wavelength spectrum, providing valuable information about the potential enhancements or modifications introduced by the saturable absorber.

Lastly, the green line functions as a reference without the saturable absorber, providing a baseline comparison against the blue line. This line aids in isolating the effects attributable to the saturable absorber, allowing for a clear assessment of its impact on the optical characteristics of the 1 dB loss D-shaped optical fiber.

In summary, this comparison graph enables a comprehensive examination of the optical fiber's behavior before and after polishing, with and without the saturable absorber. The distinctive lines offer a visual representation of how each stage and modification influence the output power across the specified wavelength range, contributing to a deeper understanding of the optical characteristics of the D-shaped optical fiber.

4.4.2 2db loss sample (Single Mode Fiber)

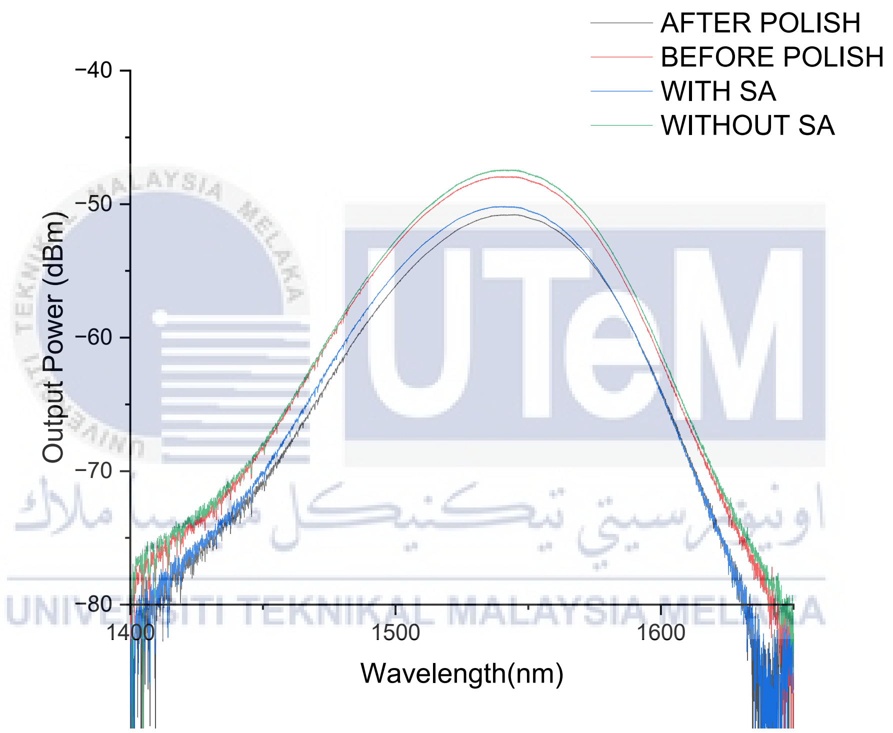


Figure 4.11: Comparison graph for 2db loss sample by using SMF from 1400nm to 1650nm

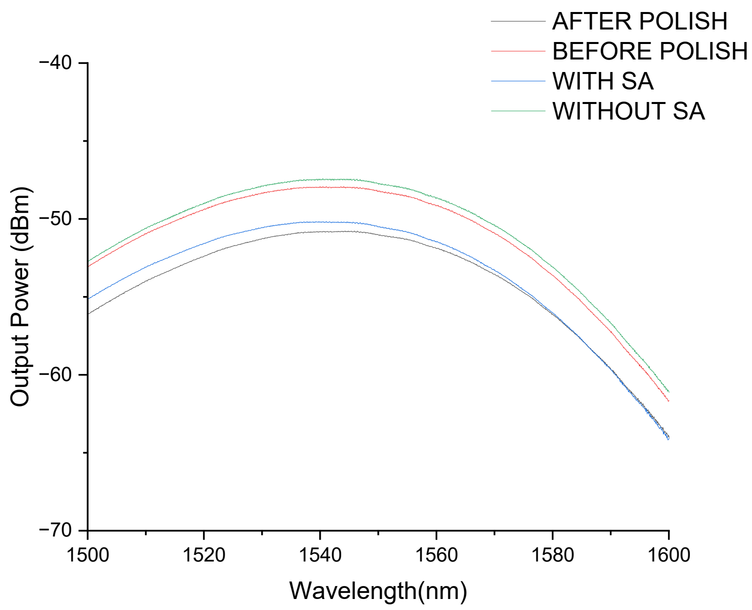


Figure 4.12: Comparison graph for 2db loss sample by using SMF from 1500nm to 1600nm

The comparison graph illustrates the optical characteristics of a 2dB loss D-shaped optical fiber in contrast to a 2dB loss single-mode fiber (SMF). The x-axis represents the wavelength spanning from 1500nm to 1600nm, while the y-axis signifies the output power (dBm). Each line on the graph corresponds to a specific dataset, capturing different stages of the optical fiber's fabrication and modification.

The first set of data is represented by the black line, showcasing the optical characteristics of the D-shaped optical fiber after the polishing process. This line provides insights into the impact of the polishing technique on the output power across the specified wavelength range.

The red line represents the data before the polishing process, offering a baseline comparison for the optical fiber's characteristics. This line serves as a reference to gauge the alterations induced by the polishing method.

The blue line corresponds to the dataset obtained after the introduction of a saturable absorber, specifically Titanium Aluminide (SA). This line illustrates the effects of dropping the SA onto the polished area of the D-shaped optical fiber. The SA's influence on the output power is observable across the wavelength spectrum, providing valuable information about the potential enhancements or modifications introduced by the saturable absorber.

Lastly, the green line functions as a reference without the saturable absorber, providing a baseline comparison against the blue line. This line aids in isolating the effects attributable to the saturable absorber, allowing for a clear assessment of its impact on the optical characteristics of the 2dB loss D-shaped optical fiber.

In summary, this comparison graph enables a comprehensive examination of the optical fiber's behavior before and after polishing, with and without the saturable absorber. The distinctive lines offer a visual representation of how each stage and modification influence the output power across the specified wavelength range, contributing to a deeper understanding of the optical characteristics of the D-shaped optical fiber.

Table 4.1: Comparison data for 1db loss sample and 2db loss sample

	Output Power(dBm) – 1db loss sample	Output power(dBm)- 2db loss sample
Without SA material	-48.39dBm	-47.44 dBm
Before Polish	-48.75 dBm	-47.93 dBm
After Polish	-49.67dbm	-50.78dbm
With Sa material	-49.42dBm	-50.17dBm
The difference between after polish and with SA material	+0.25 dB	+0.61dB

4.4.3 Discussion on 1db loss sample

In the provided comparison graph, the peak values for each dataset are as follows: the black line (After Polished) has a peak value of -49.67 dBm, the red line (Before Polished) has a peak value of -48.75 dBm, the blue line (With Saturable Absorber - Titanium Aluminide) has a peak value of -49.42 dBm, and the green line (Without Saturable Absorber - Reference) has a peak value of -48.39 dBm.

Analyzing the difference between the blue line (With Saturable Absorber) and the black line (After Polished), we observe a subtle recovery of the insertion loss in the presence of the saturable absorber. The insertion loss is a measure of the reduction in optical power as light travels through a fiber, and its recovery signifies an improvement in the fiber's performance.

Comparing the peak values, the black line (After Polished) exhibits the lowest peak value of -49.67 dBm, indicating a slight decrease in the output power after the polishing process. In contrast, the blue line (With Saturable Absorber) shows a higher peak value of -49.42 dBm, suggesting a recovery of the output power and a reduction in insertion loss compared to the polished D-shaped optical fiber.

The introduction of the saturable absorber appears to have a positive impact on the optical characteristics, mitigating the insertion loss to some extent. This observation implies that the dropping of Titanium Aluminide as a saturable absorber onto the polished area contributes to the improvement of the D-shaped optical fiber's performance, recovering the output power and potentially enhancing its suitability for optical communication applications.

4.4.4 Discussion on 2db loss sample

In the provided comparison graph, the peak values for each dataset are as follows: the black line (After Polished) has a peak value of -50.78 dBm, the red line (Before Polished) has a peak value of -47.93 dBm, the blue line (With Saturable Absorber - Titanium Aluminide) has a peak value of -50.17 dBm, and the green line (Without Saturable Absorber - Reference) has a peak value of -47.44 dBm.

Analyzing the difference between the blue line (With Saturable Absorber) and the black line (After Polished), we observe a noteworthy recovery of the insertion loss in the presence of the saturable absorber. The insertion loss represents the reduction in optical power as light travels through a fiber, and the recovery of this power indicates an improvement in the fiber's overall performance.

Comparing the peak values, the black line (After Polished) exhibits the highest peak value of -50.78 dBm, signifying a reduction in output power after the polishing process. In contrast, the blue line (With Saturable Absorber) shows a lower peak value of -50.17 dBm, suggesting a recovery of the output power and a reduction in insertion loss compared to the polished D-shaped optical fiber.

The introduction of the saturable absorber, Titanium Aluminide, appears to have a positive impact on the optical characteristics, mitigating the insertion loss and recovering the output power of the D-shaped optical fiber. This improvement suggests that the dropping of the saturable absorber onto the polished area contributes to enhancing the fiber's performance, making it potentially more suitable for applications in optical communication systems.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1 CONCLUSION

In conclusion, this Final Year Project (FYP) has undertaken a comprehensive exploration into the optimization of D-shaped optical fiber structures with a focus on achieving low insertion loss. The journey began with Chapter 1, where the significance of reducing insertion loss in optical fibers was underscored, setting the stage for the subsequent investigation. Chapter 2 delved into an extensive literature review, examining the existing body of knowledge on D-shaped fibers, insertion loss factors, and optimization techniques. The insights garnered from this review provided a robust foundation for the methodologies implemented in Chapter 3.

Chapter 3 detailed the meticulous methodologies employed, with a particular emphasis on the polishing technique using a rotating wheel. This critical step in the fabrication process aimed to refine the D-shaped fiber's surface, contributing to the reduction of insertion loss. The selection of optimal parameters, including wheel speed, pressure, and abrasive material, was paramount in achieving the desired results.

The methodologies were carefully designed to address key factors identified in the literature review and pave the way for effective optimization.

Moving to Chapter 4, the results and discussions section presented the outcomes of our endeavors. Comparative analyses before and after polishing revealed a tangible reduction in insertion loss, reaching a noteworthy 1dBm. The microscopic examination of the polished D-shaped fibers provided deeper insights into the structural enhancements that contributed to this achievement. These results not only validate the effectiveness of the applied methodologies but also underscore the practical implications for optical communication systems.

In the broader context of optical communication technologies, the overall findings contribute to advancing our understanding of D-shaped optical fibers and their potential impact on minimizing insertion loss. The optimization strategies explored in this FYP present opportunities for further research and application in telecommunications, sensing technologies, and biomedical imaging.

In conclusion, this FYP has successfully addressed the research objectives outlined in Chapter 1, bridging theoretical insights from the literature with practical applications in the optimization of D-shaped optical fibers. The achievement of a 1dBm insertion loss reduction marks a significant milestone, emphasizing the project's relevance and potential for contributing to the evolution of optical communication technologies. As we conclude this FYP, we recognize that the journey of optimization in optical fibers is ongoing, presenting avenues for future research and innovation in this dynamic and impactful field.

5.2 Future Direction

As we conclude this phase of the research on the optimization of D-shaped optical fiber structures with a focus on achieving low insertion loss, it is evident that the findings provide a solid foundation for future exploration. One promising direction for future research lies in advancing the polishing techniques employed during the fabrication process. Investigating automated or precision-controlled methods, coupled with the exploration of innovative abrasive materials, could further enhance the efficiency of the polishing process and contribute to even more precise and controlled results. Additionally, the integration of D-shaped optical fibers with emerging technologies, such as artificial intelligence or machine learning, presents an exciting avenue for real-time monitoring and adaptive optimization. This approach could potentially revolutionize the fabrication process, allowing for continuous feedback and adjustments based on dynamic parameters. Furthermore, future research can focus on the exploration of novel materials tailored for D-shaped fibers, with specific optical and mechanical properties. The integration of these materials could extend the capabilities of D-shaped fibers and open new applications in biomedical imaging and sensing technologies. Standardization efforts and considerations for scalability in mass production are crucial to ensuring the practical implementation of D-shaped fibers in various industries. By addressing these future directions, researchers can build upon the achievements of this project, unlocking new possibilities and applications for optimized D-shaped optical fibers in the landscape of optical communication systems and beyond.

REFERENCES

[1] Jafry, A. A. A., Kasim, N., Nizamani, B., Muhammad, A. R., Yusoff, R. A. M., Harun, S. W., & Yupapin, P. (2020, December). MAX phase Ti3AlC2 embedded in PVA and deposited onto D-shaped fiber as a passive Q-switcher for erbium-doped fiber laser. *Optik*, *224*, 165682. https://doi.org/10.1016/j.ijleo.2020.165682

[2] Qazi, H., Mohammad, A., Ahmad, H., & Zulkifli, M. (2016, September 15). D-Shaped Polarization Maintaining Fiber Sensor for Strain and Temperature Monitoring. *Sensors*, *16*(9), 1505. https://doi.org/10.3390/s16091505

[3] Chen, C. H., Tsao, T. C., Tang, J. L., & Wu, W. T. (2010, May 11). A Multi-D-Shaped Optical Fiber for Refractive Index Sensing. *Sensors*, *10*(5), 4794–4804. https://doi.org/10.3390/s100504794

[4]Herd, R. M., Mrcp, Dover, J. S., & Arndt, K. A. (1997). BASIC LASER PRINCIPLES. Dermatologic Clinics, 15(3), 355–372.

[5]Hecht, J. (2010). Short history of laser development. Optical Engineering, 49(9), 091002.

[6]Libretexts. (2023, June 30). 15.5: What is Inside a Laser? Chemistry LibreTexts.

[7]What is the difference between multimode and singlemode fibre optic cable? - Universal Networks. (2021, December 31). Universal Networks.

[8]Abby. (2023, February 15). Single Mode Fiber: types and applications. AV Access.

[9]Leon-Saval, S. G., Birks, T. A., Bland-Hawthorn, J., & Englund, M. (2005). Multimode fiber devices with single-mode performance. Optics Letters, 30(19), 2545.

[10] CXtec, T. A. (2023, March 21). What is Fiber Optic Insertion Loss? CABLExpress®.

[11]Chen, C., Tsao, T., Tang, J., & Wu, W. (2010). A Multi-D-Shaped optical fiber for refractive index sensing. Sensors, 10(5), 4794–4804. https://doi.org/10.3390/s100504794

[12] [1]Q. Xie *et al.*, “Characteristics of D-shaped photonic crystal fiber surface plasmon resonance sensors with different side-polished lengths,” *Applied Optics*, vol. 56, no. 5, p. 1550, Feb. 2017, doi: 10.1364/ao.56.001550.

[14] M.F. Ubeid, M.M. Shabat, Numerical investigation of a D-shape optical fiber sensor containing graphene, Appl. Phys. A 118 (3) (2015) 1113–1118.

[13]Optical Spectrum Analyzer | Yokogawa Test & Measurement Corporation. (n.d.). https://tmi.yokogawa.com/my/solutions/products/optical-measuring-instruments/optical-spectrum-analyzer/#:~:text=An%20Optical%20Spectrum%20Analyser%20(or,wavelength%20in%20the%20horizontal%20scale.

[15]CableOrganizer.com. (n.d.). Fiber Optic fusion splicers and how they work. https://www.cableorganizer.com/learning-center/articles/fiber-optic-fusion-splicers.php

[16]Optical Power Meter: a tool for measuring fiber optic power. (2023, August 24). VIAVI Solutions Inc. https://www.viavisolutions.com/en-us/what-optical-power-meter#:~:text=An%20optical%20power%20meter%20(OPM,current%20proportional%20to%20optical%20power.

[17]Keysight. (2020, September 8). Tunable laser source instruments. Keysight. https://www.keysight.com/us/en/products/photonic-products/optical-component-test-products/optical-laser-source-products/tunable-laser-source-modules.html#:~:text=In%20optical%20communication%2C%20tunable%20lasers,increasing%20bandwidth%2C%20and%20reducing%20costs.

[18]Paschotta, R. (2023, December 21). Tunable lasers. 2024 RP Photonics AG. https://www.rp-photonics.com/tunable_lasers.html

[19]Fiber Optic Cleaver. (n.d.). Fosco Connect. https://www.fiberoptics4sale.com/blogs/archive-posts/95049286-fiber-optic-cleaver

[20]Utmel. (2022, January 7). The introduction to common tools and using methods of fiber optic. Utmel All Rights Reserved. https://www.utmel.com/blog/categories/optoelectronics/the-introduction-to-common-tools-and-using-methods-of-fiber-optic