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DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

FABRICATION OF D-SHAPED OPTICAL FIBER FOR SENSING APPLICATIONS

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Abstract

The research emphasises the use of acrylic mould encapsulation and wheel polishing processes in the manufacturing of D-shaped optical fibres particularly intended for biochemical sensing applications. The study discusses the difficulties and constraints that arise in the manufacturing process, such as the need to stabilise fibres in moulds and optimise polishing parameters in order to obtain the necessary intensity drops. The improved performance of acrylic moulds due to minimal fabrication challenges such air bubbles and material hardness was highlighted in a comparative investigation of fibres manufactured using acrylic and epoxy resin encapsulations.

The study demonstrated these techniques are feasible for producing very sensitive fibres by successfully fabricating D-shaped fibres with different intensity drops (20% and 50%). subsequently in order to improve these fibres' sensitivity for ammonia sensing applications, layer-by-layer (LBL) deposition was applied employing DAR/TSPP methods. A successful demonstration of ammonia sensing employing a fibre with a 20% intensity reduction marks the research's conclusion and demonstrates the strong relationship between intensity fluctuations and changes in refractive index. By further refining the 50% intensity drop fibres for comparable uses, the work opens the door for future research that might increase their effectiveness in biochemical sensing settings operating in real time.

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1 INTRODUCTION

1.1 Background

Optical fibres are waveguides used to transmit light and comprised of four parts: the core, cladding, buffer, and jacket. The core is a cylindrical portion constructed of dielectric material with a predetermined refractive index. The core is surrounded by cladding consisting of glass or plastic with a low refractive index, which reduces light loss from the core to the surrounding air. An elastic covering termed the buffer, constructed of plastic, encases the cladding and shields the fibre from physical damage and scattering losses caused by micro-bending. The outermost layer is the jacket, which indicates the specific type of fibre.

Due to its exceptional purity, quartz glass is used to make the majority of optical fibres. With a data transfer speed of more than 10 GB per second, they are widely utilised for photonics, data transmission, and invoicing transmission. Optoelectronics, sensors, micromachines, fine metals, ceramic powders, and protective coatings are just a few of the industries in which they find use. Compared to wired and wireless communications that make use of materials other than optical fibres, optical fibre communication allows for communication over larger distances and at faster rates [1].

Beyond conventional communication applications, optical fibres have tremendous promise for the development of chemical and biological sensors. This innovation is being driven by an increased demand for cost-effective, home-based, and in-situ measuring solutions in healthcare and other significant sectors. Optical fibres may be constructed to detect a wide range of chemical and biological characteristics by taking advantage of their environmental sensitivity. These fibres can be functionalised with certain coatings or nanomaterials to improve their capacity to detect and respond to a variety of chemical and biological signals. Their accuracy, miniaturization, and versatility make them beneficial for applications demanding real-time monitoring [2].

Their unique benefits are driving the development of optical fibre-based technologies for chemical and biological sensing. Optical fibres are suited for remote or at-home diagnostics because they are intrinsically resistant to electromagnetic interference, offer real-time and in-situ monitoring capabilities, and are simple to integrate into portable equipment [3]. They can be deployed in challenging circumstances owing to their compact size and adaptable design, which increases their use in industrial operations, environmental monitoring, and healthcare. Optical fibre-based sensors, offering high sensitivity and specificity for an array of applications, are expected to play an integral role in the future of sensing technologies with advancements. Considering optical fibres can handle high data rates and long-distance transmission, they are widely used in communication technology and are essential to the current communication infrastructure. Their distinct qualities and adaptability keep pushing developments and uses in a variety of engineering fields [1]

1.2 Significance of optical fibre sensing

During the last twenty years, the scientific and industrial communities have paid particular attention to optical fibre sensors, or OFS. Various advantages of these sensors include their resistance to electromagnetic interference, their durability over time, their tolerance to chemicals, and their capacity for multiparameter, distributed, and distant sensing. Large infrastructures like buildings, tunnels, and bridges can be monitored with OFS thanks to these advantages. They can also be used in medical settings where their low cost and disposable nature make them ideal for patient monitoring during procedures or as chemical or biosensors in biochemical laboratories.

Both the optical fibre types and modification affect the efficiency of OFS in a given measurement. In general, the composition and structure of the fibre determine its characteristics. OFS have been produced with a range of fibres, from highly structured fibres derived from unique materials to conventional silica glass single-mode fibres (SMF). Standard SMF fibres are frequently used in large-scale production because to the preference for straightforward, recognised solutions, particularly when it comes to disposable biosensors [3]

Numerous OFS, especially those used for chemical or biosensing, need the light to interact with an external medium through an evanescent field, in contrast to telecommunications applications where the aim is to keep the light isolated within the fibre. The guiding conditions inside the fibre are impacted by modifications that alter the external medium's optical characteristics. For there to be any meaningful interaction between the directed light and the outside medium, the electromagnetic field inside the fibre must make contact with it. This interaction has been achieved by a variety of techniques that have been documented, such as the employment of fibre tapers, photonic crystal fibres (PCF), long-period gratings produced in a fibre core, and interferometric structures made by splicing dissimilar fibres.

In order to improve the interaction between the light and the external medium, several techniques have also been used to remove portions of the fibre cladding. These procedures, which include mechanical, chemical, and ablation approaches, result in the production of D-shaped fibre sections that function as the sensor's active component. Because of their flexibility and versatility, OFS are important for a variety of applications, including biochemical sensing, medical diagnostics, and infrastructure monitoring [4].

1.3 D-shaped optical fibres: Overview and benefits

D-shaped optical fibres, especially for biochemical applications, mark a substantial advancement in sensing technology. These fibres have extraordinary optical properties and distinct mode field characteristics. They are also quite sensitive to changes in the refractive index of the surrounding material. D-shaped fibres are more desired than standard optical fibres because of these properties, and they have the potential for novel sensing applications [3], [4], [5]

These fibres undergo a rigorous multi-step side-polishing treatment with the goal of minimising loss and obtaining accurate dimensions. To polish the surface perfectly, it starts with coarse abrasive particles for rough polishing and moves on to fine polishing. Because the fibres are fragile and tiny in size, tight dimension controls and safety precautions are necessary throughout the process [6].

The goal of this research is to produce D-shaped fibres by polishing their surfaces to change the length, depth, and curve of the cut after they have been encased in acrylic moulds. We want to improve the performance and versatility of optical fibres by using state-of-the-art production technology, opening up new opportunities for sophisticated sensing applications in many sectors.

1.4 Problem statement

Fabricating D-shaped optical fibres can be challenging due to the intricate approaches required to achieve exact control over the fibre’s geometry and optical characteristics. Traditional manufacturing procedures can lack accuracy and homogeneity, resulting in discrepancies in the performance of the fibres.

These discrepancies have an influence not only on the optical characteristics of the fibres, but also on their integration into sensing systems, especially in biochemical applications. Conventional methods of manufacture constrain the potential of D-shaped optical fibres, which offer distinctive characteristics such as improved evanescent field interaction, making them ideal for very sensitive biological sensing.

The development of dependable and affordable manufacturing processes that can yield high-quality D-shaped optical fibres with constant and repeatable performance characteristics is one of the primary challenges in this industry. The requirement to optimise the fibres' design in order to improve their sensitivity, stability, and endurance in a variety of sensing conditions exacerbates this issue. The accuracy required by current technologies is frequently insufficient, resulting in fibres that fail to accomplish the precise specifications needed for high-performance sensing applications.

The goal of this project is to create and enhance manufacturing methods especially designed for D-shaped optical fibres used in biochemical sensing in order to address these constraints. Precision polishing and encapsulation in acrylic moulds/epoxy resin are two of the innovative ways used to improve the strength, sensitivity, and usefulness of these fibres. The project seeks to achieve greater performance characteristics that will increase the use of optical fibre-based sensing technologies in more contexts by methodically improving the fabrication process.

1.5 Aims & Objective

This project aims to develop and improve techniques for fabricating D-shaped optical fibres for biochemical sensing applications. The objective is to increase the strength and utility of these fibres by using cutting-edge techniques such precision polishing and encapsulation in acrylic mould. By systematically improving sensitivity, stability, and durability, the manufacturing process is being refined with the goal of achieving higher performance characteristics, which will increase the usability of optical fibre-based sensing technologies in a wider range of application areas.

To achieve this objective, the following goals are essential:

Objective	Achievement
Conduct an in-depth literature analysis	Profound examination carried out, resulting in an extensive understanding of materials, methods, and uses, which determined the design and manufacturing procedure.
Design an exact production process for D-shaped optical fibres	Precisely formed D-shaped optical fibres as a consequence of the geometry, material composition, and polishing methods being successfully optimised.
Establish and implement a reliable encapsulating or embedding method	Developed and evaluated a strong encapsulation technique that successfully shielded fibres from environmental influences and mechanical stress.
Evaluate the viability of creating side-polished fibre sensors with an acrylic mould and epoxy resin	Side-polished fibre sensors were successfully manufactured and tested using an acrylic mould. While attempts to employ epoxy resin proved to be significantly more difficult than expected and did not produce the required results, the acrylic mould proved to be effective and enabled for parameter optimisation and better sensor performance.
Develop a side polishing fibre production process with advanced methods	Improved the process's overall quality and efficiency by smoothly switching from antiquated to cutting-edge production procedures.
Produce and evaluate side-polished optical fibres	Enhanced side-polished optical fibres were created and extensively examined. Their performance was put through a thorough evaluation process, with a focus on ammonia sensing, and they fulfilled the predetermined performance levels.

Optimize side polishing sensors' sensitivity	The development and implementation of a layer-by-layer deposition protocol made it feasible to precisely optimise the fibre. Through this technique, the fibres' sensitivity was greatly improved, thus turning them into extremely sensitive sensors for target analyte detection.
Analyse sensitivity parameters for biochemical sensing applications	Accurately detected changes in refractive index by successfully analysing the sensitivity of the D-shaped optical fibres. The main emphasis was on sensitivity, which turned out to be essential for the sensor's capacity to detect these variations.
Analyse potential uses of enhanced D-shaped optical fibres in biochemical sensing	Demonstrated the adaptability of the fibres by identifying certain target analytes and performance standards for biochemical sensing applications.
Collaborate with stakeholders to ensure economic and practical viability	Although preliminary measures have been implemented, comprehensive cooperation with academic and industry partners need to be created. To completely investigate the sensors' practical and financial feasibility, more investigation is required. In order to get these sensors closer to commercial readiness and practical use, our research paves the door for further investigations.

1.6 Scope of the research

Innovations in manufacturing processes, material science, and sensing technologies have fuelled a broad and promising field of study in D-shaped optical fibres for sensing applications. These fibres have the potential to change an array of sectors, including chemical sensing, biological diagnostics, and environmental monitoring, as they keep evolving. The goal of the research is to investigate and test the limits of the capabilities of D-shaped optical fibres in these domains.

The refinement and enhancement of manufacturing methods is one of the main objectives of upcoming research. The production of D-shaped fibres has been made possible by the application of contemporary technologies, such as femtosecond laser inscription, while traditional techniques like chemical etching and laser machining still offer great potential. By precisely and carefully altering the fibre's shape and refractive index, this system makes it possible to create highly specialized and sensitive fibres. Furthermore, it is anticipated that the creation of hybrid structures which mix D-shaped fibres with cutting-edge substances like graphene, metal nanostructures, or polymer coatings will pave the way for new developments in the improvement of the fibres' optical qualities and sensing capacities[7].

Additional research should focus on establishing sensing methods that take use of the special qualities of D-shaped fibres. While methods like Mach-Zehnder interferometry, surface plasmon resonance (SPR), and evanescent wave sensing have demonstrated considerable promise, there is yet need for further optimisation[7]. Researchers can enhance the sensitivity, selectivity, and general performance of the sensing devices by fine-tuning these processes.

The higher sensitivity and specificity of D-shaped optical fibres offer considerable potential in a variety of growing disciplines, including environmental monitoring, which necessitates precise detection of contaminants and changes in environmental conditions. D-shaped fibres might be utilised in biomedical diagnostics to create minimally invasive sensors that can track biomarkers in real time and help diagnose illnesses early. Furthermore, the capacity to functionalise these fibres' surfaces with particular biomolecules may enable focused sensing uses, such the identification of certain poisons or infections[7].

Ultimately, it will be necessary to address the practical and financial concerns of creating and using these cutting-edge sensors. The subsequent research should concentrate on creating affordable fabrication techniques that may be expanded for commercial manufacturing while guaranteeing the sensors' durability and reproducibility under various operating circumstances. The next generation of optical fiber-based sensors that are very sensitive, selective, and adaptable will be made possible by the findings of this research.

2 LITERATURE REVIEW

2.1 Journal Article 1: From D-shaped to D-shape optical fibre – A universal solution for sensing and biosensing applications: Drawn D-shape fibre and its sensing applications[8]

The article presents a unique method for creating D-shaped optical fibres with the goal of improving biosensing and sensing efficiency. This study offers a thorough examination of a novel fabrication method and was carried out by distinguished researchers from many Polish universities, including Warsaw University of Technology, Łukasiewicz Research Network - Institute of Microelectronics and Photonics, and the University of Warsaw. The majority of the study was carried out in Warsaw at the Łukasiewicz study Network and the Faculty of Physics at the University of Warsaw. The team was directed by Grzegorz Stepniewski and included Adam Filipkowski, Dariusz Pysz, Jakub Warszewski, Ryszard Buczynski, Mateusz Smietana, and Rafal Kasztelanic. In 2023, the results were published in the Measurement journal published by Elsevier.

The study tackles the drawbacks of traditional D-shaped fibres, which frequently need chemical or mechanical post-processing that might reduce their efficacy. This is motivated by the need to improve optical fibre sensing features. In order to create homogenous sensing fibres with a thermodynamically flattened sensing surface, researchers devised a novel production method that does not require further processing. For a wide range of sensing applications, this invention offers increased sensitivity and dependability.

Through creative preform modification and advanced fibre drawing methods, they were able to produce fibres with unique core-guided modes that are perfect for sensor applications. One of their primary strategies was to keep the surface quality good without doing any additional processing, which was essential for improving sensing abilities. To test their findings, they created lossy-mode resonant sensors with D-shaped fibres coated in tiny layers of indium tin oxide (ITO), which greatly boosted sensitivity.

The creation of reliable sensing fibres with exact dimensions and surface properties was made possible by the research's novel fabrication technique, which reverses the traditional procedure. The resultant fibres had a 7 by 8 µm core size, a sensing surface spacing of 2 µm, and a surface roughness of RMS = 40 nm. The integration of numerical models and experimental trials enabled a comprehensive exploration of the structure, optical characteristics, and sensor performance of these D-shaped fibres, indicating their potential as a flexible lossy-mode resonance-based sensing platform.

Overall, the research describes a novel approach for producing D-shaped optical fibres for sensing purposes. The results have the potential to pave the way for novel sensing and biosensing applications while also pushing the boundaries of optical fibre sensing technology. This study paves the way for future breakthroughs in the developing field of optical fibre technology by emphasising its revolutionary potential via rigorous testing and new production procedures.

2.2 Journal Article 2: Side-polished fibres[9]

The article provides a thorough examination of the creation, description, and theoretical analysis of side-polished optical fibres. It was published by Shiao-Min Tseng and Chin-Lin Chen of Purdue University's School of Electrical Engineering. With an emphasis on the creation and enhancement of fiber-optic components including couplers, modulators, and amplifiers. This study which was published in Applied Optics in June 1992 takes place during a time of tremendous progress in optical fibre technology. The difficulties in producing side-polished fibres, which are essential for a variety of optical systems, are particularly addressed in Tseng and Chen's work.

The necessity to develop a repeatable method for producing side-polished fibres with limited loss spurred the researchers' attention because of the vital role that these fibres play in fibre-optic communication and sensing applications. Prior to their efforts, quartz or fused silica blocks were frequently utilised in side-polished fibre fabrication processes, which made it difficult to produce outcomes that were reliable and low-loss. In an inventive move, Tseng and Chen supported the optical fibres throughout the polishing process with silicon V-grooves, which provided a number of benefits. Anisotropic etching's ability to produce precise V-grooves and silicon wafers' accessibility in optically polished forms made polishing them more dependable and regulated.

The actual polishing was done using polyurethane pads and colloidal silica slurries, both mechanically and chemically. This technique was created to guarantee that the polishing was consistent and wouldn't result in appreciable losses, which had been a serious flaw in earlier methods. Tseng and Chen used a liquid-drop method to analyse the attenuation properties of the polished fibres in order to assess the efficacy of their methodology. This method validated their production methodology by enabling a direct comparison with theoretical predictions, in addition to providing exact measurements.

This work makes a substantial addition to theory analysis, since the authors compare their experimental findings to models that have already been established by scholars like Leminger and Zengerle, Vassallo, Sharma, Kompella, and Mishra. In particular, they offer generalised parameters, V, b, and Vex, that allow a more thorough analysis of how external media affect side-polished fibres' attenuation constant. Understanding how guided waves inside the fibre interact with surrounding surroundings when sections of the fibre cladding are removed has been greatly advanced by this contrast of theory and experiment.

Tseng and Chen are renowned experts in the field of optical fibres and photonics, and this is not their first work, pursuant to their publishing history. Both have authored several publications on subjects pertaining to optical fibres, with an emphasis on the creation of optical fibre components and the way guided waves interact with their surroundings. The scientific world has taken notice of their findings, and this specific work has been mentioned 243 times, indicating its considerable influence. The fact that most of the citations are positive highlights how significant their contribution to side-polished fibre technology is. This paper's practical applicability in manufacturing procedures and the comprehensiveness of its theoretical analysis have garnered attention from researchers, with a legitimate reason. It has had a lasting impact on the advancement of fiber-optic technologies by acting as a benchmark for later research endeavours focused on enhancing and comprehending side-polished optical fibres.

2.3 Journal Article 3: D-Shaped Plastic Optical Fiber Sensor for Testing Refractive Index[10]

The increasingly pressing need for extremely sensitive and reasonably priced refractive index (RI) sensors is the focus of the research by Feng De-Jun and colleagues that was published in the IEEE Sensors Journal, Vol. 14, No. 5, May 2014. In particular, RI sensors are essential in food safety, environmental monitoring, and biochemical analysis. Conventional radiofrequency (RI) sensors, such as surface plasmon resonance (SPR), long-period fibre grating, and interferometry, encounter difficulties with regard to complexity, high prices, sensitivity, and external influences. A D-shaped plastic optical fibre (POF) sensor was designed in this study as a consequence of researchers' exploration of alternative possibilities in response to this. In order to show why POF technology is a good option for RI sensing, the authors emphasise its benefits, which include flexibility, tensile strength, and affordability. As of the most recent count, this article has been mentioned 115 times. The influence and relevance of the research within the scientific world, notably in the field of refractive index (RI) sensing, are highlighted by this citation record.

The main goal of this work is to create a D-shaped POF sensor with improved linearity and sensitivity by applying side-polishing procedures to increase the measuring range of RI. The sensor operates on the basis of attenuated total internal reflection, which implies that optical transmission is attenuated as a result of the interaction between the external environment and the evanescent wave on the fiber's surface. The researchers want to improve the sensor's function and make it useful for a range of uses by altering the probe's curvature radius and the depth of the D-shaped groove.

In this case, theoretical analysis is significant particularly whilst comprehending the working principle of the sensor. The intensity of the evanescent wave, which is produced by numerous internal reflections and interacts with the outside world, is impacted by variations in the refractive index. The authors present the idea of the V-number, a mathematical framework for determining the effective V-number in the D-shaped area and a description of the number of modes in the fibre. The foundation for recognising how variations in the ambient refractive index affect the optical power distribution inside the fibre and allow precise RI detection is provided by this analysis.

In terms of experimental design, the researchers provide a thorough process for creating the wheel side-polished D-shaped POF sensor. Praise for the method's affordability, ease of usage, and simplicity makes it a good choice for RI sensing on a large scale. The light source in the experiment is an LED light source, and there is also a power meter, spectrometer, and solution of sucrose with different refractive indices. Researchers demonstrate the sensor's capacity to detect fluctuations in RI by measuring the transmission power of light through the fibre while the RI of the surrounding medium varies.

The experiment's findings demonstrate that the D-shaped POF sensor has a high correlation coefficient ($R^2 = 0.996$) and a strong linear correlation between transmission loss and refractive index in the 1.333 to 1.455 range. By modifying the groove depth and curvature radius, the scientists are able to maximise the sensitivity of the sensor, demonstrating its efficacy and promise for useful applications in RI sensing. Notwithstanding, a comparative analysis with alternative RI sensing technologies would have furnished a more all-encompassing assessment of the sensor's respective benefits and constraints.

Overall, this analysis offers insightful information on the advancement of POF-based RI sensors, emphasising the D-shaped POF sensor's promise as an easy-to-use, reasonably priced RI sensing option. The study establishes the foundation for further research endeavours that attempt to enhance sensor efficacy and broaden its scope of use.

2.4 Journal Article 4: Highly Sensitive and Wide Dynamic Range Side-Polished Fiber optic Taste Sensor[11]

In this article, which is published in Sensors and Actuators B: Chemical, Khalilian, Khan, and Kang propose a unique side-polished optical fibre sensor that is intended to identify flavor compounds at low concentrations. A sensing membrane is integrated into a single-mode side-polished optical fibre, and the sensor makes use of the intensity modulation concept. N,N-dimethylacetamide (DMAC), polyvinyl chloride (PVC), and six solvatochromic dyes are combined to create the membrane.

The evanescent field absorption technique is the basis of this notion. The intensity of the light received is modulated when the sensor's membrane comes into touch with a taste material, causing variations in the dye's transfer band that affect the waveguide's refractive index. Due to this modification, the sensor can now identify flavour compounds in a broad range of concentrations. Six taste compounds that correspond to the five major tastes were used in the research to test the sensor: glucose and sucrose (sweetness), NaCl (saltiness), HCl (sourness), quinine (bitterness), and L-glutamic acid (umami).

The absorption of an evanescent field is dependent on the field's penetration depth into the surrounding medium, according to theoretical research. A number of variables, including the wavelength, angle of incidence, and refractive indices of the surrounding medium and fibre cladding, affect this depth. The absorption characteristics of the medium that comes in contact with the polished fibre segment have an impact on the transmitted power of the sensor.

The sensor responded linearly to the tasting compounds in the concentration range of 1 M to 1 mM, according to the results of the experiment. R-dye and auramine O were found to have the best sensitivity and linearity, respectively. In addition, the sensor demonstrated a 90-second quick reaction time and a 100-second recovery time at ambient temperature.

In addition to being more resistant to electromagnetic and electrical interference, the study demonstrated the advantages of optical fibre sensors over electrochemical ones, including the capacity to collect large amounts of phase, polarisation, and wavelength data. Its high sensitivity, stability, and broad dynamic range set the proposed side-polished fiber-optic (SPFO) taste sensor apart and make it ideal for a range of uses in the food, pharmaceutical, and biosafety sectors.

The findings of this research showed that an SPFO sensor covered in a solvatochromic dye membrane could efficiently and broadly detect a variety of flavour compounds. The relevance and influence of this study in the subject of optical fibre sensors is demonstrated by the 26 citations it has received. In addition to offering a viable substitute for current flavour assessment techniques, the sensor's sturdy architecture and quick reaction times have great promise for real-world applications.

2.5 Journal Article 7: A High-Precision D-Shaped Fiber Polishing Method and its Sensing Characteristics of Different Polishing Depths[14]

An inventive technique for accurately fabricating D-shaped optical fibres for surface plasmon resonance (SPR) sensing applications is presented in this research by Huiqing Niu, Yunchao Li, Yanjun Zhang, Zhengqiang Yan, Jiangping Kuang, and Guowen An. The Weapon Industry Test and Measuring Academy, North University of China, and the State Key Laboratory of Dynamic Measurement in China are the sites of this study, which aims to fulfil the pressing demand for precise and economical D-shaped fibre manufacturing techniques. These techniques are essential for improving the performance of SPR sensors.

The article, which was published in a prestigious Springer journal in 2024, carefully outlines the study schedule from receipt on January 16, 2024, to clearance on February 19, 2024. The goal of the project was to create a simple, low-cost side-wheel polishing tool that could consistently and precisely produce D-shaped optical fibres. The ability of the fibres to sense more accurately is crucial, especially when it comes to detecting refractive index (RI), which has important applications in environmental monitoring and biosensing.

The authors list and discuss the drawbacks of the methods currently used to produce D-shaped optical fibres, including chemical etching, direct writing using a femtosecond laser, and traditional polishing. They point out the disadvantages of these techniques, such as inadequate depth control, surface roughness, and expensive prices, while also noting their benefits, such as simplicity or precision.

In order to get around these restrictions, the researchers created a unique side-wheel polishing device that can create D-shaped optical fibres with unmatched precision. To confirm the accuracy of their polishing apparatus, they carefully described the artificial fibres using scanning electron microscopy (SEM). In order to produce D-shaped SPR sensors, the best parameters were found by modelling, which served as the foundation for further research.

To create the SPR effect for RI detection, gold sheets were placed to the D-shaped optical fibres' surface at different polishing depths. Thorough assessments of sensor sensitivity produced remarkable outcomes: a peak sensitivity of 3317.14 nm/RIU falling within the crucial range of 1.341–1.400. This shows how well the suggested technique works to produce D-shaped fibres with improved sensing capabilities, opening the door for ground-breaking developments in SPR sensing technology.

In essence, this work represents a paradigm change in optical fiber-based sensing by providing a detailed and well-implemented method for fabricating high-precision D-shaped fibres for SPR sensing. This study not only improves our understanding of SPR sensing but also encourages creativity and establishes the foundation for ground-breaking developments in sensing technology by fusing theoretical insights with practical data.

2.6 Journal Article 8: Precision Fabrication of D-Shaped Single Mode Optical Fibers by In Situ Monitoring[15]

M. H. Cordaro, D. L. Rode, T. S. Barry, and R. R. Krchnavek offer an innovative and extremely accurate method for creating D-shaped single-mode optical fibres in this research, published in the Journal of Lightwave Technology, Vol. 12, No. 9, September 1994. With remarkable precision, the cladding layer of the fibre is removed using this process, which combines mechanical lapping with in situ optical transmission monitoring, down to a depth of 1 µm. The in-situ monitoring method was based on the attenuation of higher-order propagating modes, and the researchers used a cylinder lap dressed with diamond to accomplish high-pressure mechanical lapping. Numerous benefits arise from this novel approach: unparalleled precision, high lapping rate, fast processing, and superior optical surface quality.

Using an approximate geometrical-optics model, the experimental data were analysed, offering a theoretical foundation for interpreting the real-world uses of this method, especially in optical communications. The project is important for progressing the production of D-shaped optical fibres, which are needed for fiber-to-waveguide coupling and evanescent field sensing. The development of single-mode evanescent-field devices, which need extremely precise and repeatable measurements of the depth of the removed layer, depends heavily on the accuracy of this approach. The study also advances the field of passive coupling techniques, in which the planar polymer optical waveguides and standard circular cross-section optical fibres may be efficiently coupled thanks to the flat side of the D-shaped fiber's assistance with alignment.

M. H. Cordaro and his group at Washington University's Department of Electrical Engineering in St. Louis, Missouri, spearheaded the research study. The project, which showcases cooperation between academic and military research institutes, was partially financed by the Rome Laboratory Photonics Centre. The research's influence might be further expanded by the possibility of applications in defense-related optical communication systems, as suggested by the partnership with the Rome Laboratory Photonics Centre. On March 8, 1994, the manuscript was received, and on June 15, 1994, it was updated. This chronology denotes a pivotal moment in the early phases of D-shaped optical fibre research, which has since attracted substantial interest due to its use in a variety of optical devices. In particular, for applications requiring evanescent fields and passive coupling between optical fibres and waveguides, the work addresses a vital requirement for precision production processes for single-mode optical fibres. Removing the cladding layer with such accuracy is crucial to reducing losses and facilitating effective light coupling.

This research effectively closes this gap by offering a dependable and repeatable technique to get the necessary accuracy. The scientists created a method that combines in situ optical transmission monitoring with mechanical lapping with a cylinder lap clad with diamonds. The monitoring method provides accurate control over the lapping process since it is based on the attenuation of higher-order modes. The study's robustness is further increased by the use of geometrical optics to analyse the experimental data, which offers theoretical support for validating the experimental findings. The methodology demonstrates how experimental methods and theoretical analysis were carefully balanced to provide a precise and dependable production process. This paper's citation count of 51 is a noteworthy indicator of its significance. Its significance and impact in the field of optical fibre since publication.

Furthermore, the above research significantly advances the area of optical fibre production, especially for high precision applications. It is methodologically solid and well-structured, and the critical evaluation underlines these aspects. It also makes obvious the significance of the study for academic research and real-world applications in optical communications.

2.7 Book - chapter 9: Fibre-Optic Chemical Sensor Approaches Based on Nano assembled Thin Films: A Challenge to Future Sensor Technology[16]

This chapter provides an extensive overview of three different kinds of fiber-optic chemical sensor designs: evanescent wave fiber-optic sensors (EWFOS), tapered fiber-optic sensors, and optical fibre long period gratings (LPGs). It was undertaken at the Gwangju Institute of Science and Technology (GIST) in South Korea and Cranfield University in the UK. Sergiy Korposh, Stephen James, Ralph Tatam, and Seung-Woo Lee authored the book, which was published by IntechOpen in 2013.

The relevance of optical fiber-based sensing is emphasised in this chapter in a number of areas, such as security, medical diagnostics, and environmental monitoring. Starting with a brief history of optical phenomena and the evolution of modern optical fibres, it emphasises that the exploration of optical fibre sensors is driven by the demand for sensitive, dependable, and reasonably priced sensors.

Based on their approaches of sensing, the authors divide fiber-optic sensors into intrinsic and extrinsic categories. Additionally, they investigate how interferometric sensors could respond to outside inputs in a sensitive and targeted manner. Optical fibre sensors' practical uses, measurement methods, and design concerns are explored, with a focus on how versatile and useful they are for a variety of sectors.

To improve repeatability, the chapter carefully describes experimental techniques such coating deposition and sensor manufacturing processes. Additionally, it emphasises the useful uses of fiber-optic chemical sensors in environmental monitoring and industrial process management, including gas sensing and refractive index measurements.

With a focus on the necessity of novel materials and creative techniques to optimise sensor performance, the chapter closes with views into the potential development of fibre optic sensors. It provides an overview of the field's opportunities and difficulties, laying the groundwork for future study and advancement.

To summarise, this chapter offers an extensive comprehension of the importance of fibre optic sensors in many applications and showcases current research endeavours aimed at improving sensor performance by means of sophisticated materials and techniques. A robust basis for future research and innovation in the field is laid by this study, which has been mentioned 24 times. It also highlights the potential and difficulties that lie ahead in the advancement of fiber-optic sensor technology.

2.8 Journal Article 9: Refractive Index Sensing with D-Shaped Plastic Optical Fibers for Chemical and Biochemical Applications[17]

Refractive index (RI) sensing is the focus of the paper by Filipa Sequeira et al. that was published in Sensors 2016, Vol. 26, Pg No. 211. It has been referenced 79 times and examines the creation and optimisation of low-cost, intensity-based plastic optical fibre (POF) sensors. In partnership with other European institutions, the Instituto de Telecomunicações and CESAM, University of Aveiro, Portugal, undertook research that highlights the significance of precise and reasonably priced detection technologies for chemical and biochemical applications. The primary goal of the project is to advance the field of optical fibre sensors (OFS) by optimising the length of D-shaped POF sensors to improve sensitivity and resolution.

The authors analyse how varying lengths of the sensing zone impact the sensor's performance using both experimental and numerical simulations. According to their results, a 6 cm length produces the maximum sensitivity for RI ranges between 1.33 and 1.39, highlighting the need of exact optimisation in sensor design. This work expands on earlier research that showed POFs to be a versatile and affordable substitute for conventional glass optical fibres (GOFs). Previous study has emphasised the broad applications of POFs; however, this work presents a fresh component of the research by concentrating on the optimisation of the sensing region.

The main goal of the study is to maximise the sensitivity and resolution of the sensor by adjusting the length of the D-shaped sensing zone, particularly in the RI ranges of 1.33 to 1.39 and 1.41 to 1.47. This optimisation is important since the impact of sensor length on performance was not thoroughly investigated in earlier research. Using commercially available POFs composed of polymethyl methacrylate (PMMA), the researchers used both experimental and computational simulations to methodically evaluate various lengths of the sensing area. According to their research, the optimum sensitivity ($6.48 \times 10{-}3$ RIU) was found in the 6 cm sensing zone in the 1.33 to 1.39 RI range, while the higher RI range showed more consistent performance at fluctuated lengths.

This research contributes to the area of optical fibre sensors by providing a reliable and affordable method for high-resolution RI sensing. Collaboration between many institutions—including contributions from Italy's Second University of Naples and the University of Pavia—underlines the study's interdisciplinary characteristics by combining telecommunications, chemical, and engineering capabilities. Conducted in the midst of a major optical fibre technology innovation phase, the research fills a vital gap in the literature

The study's solid approach, which combines experimental validation and numerical modelling, guarantees both the reliability and applicability of the results. Furthermore, these sensors are more accessible for a wider range of applications due to the use of inexpensive materials and simple construction methods. Although the research significantly advances the optimisation of sensor design, additional research might look into scaling the technique for more complicated situations. All things considered, this study makes a significant addition to the continuing research and development of low-cost, high-performing sensors for chemical and biological applications.

3 THEORY & PRINCIPLE

3.1 Types of Optical Fibers

According to how light propagates, optical fibres may be roughly divided into two types: single-mode fibres (SMF) and multi-mode fibres (MMF), as seen in figure 1. Each variety is appropriate for a particular set of applications because to its distinct characteristics.

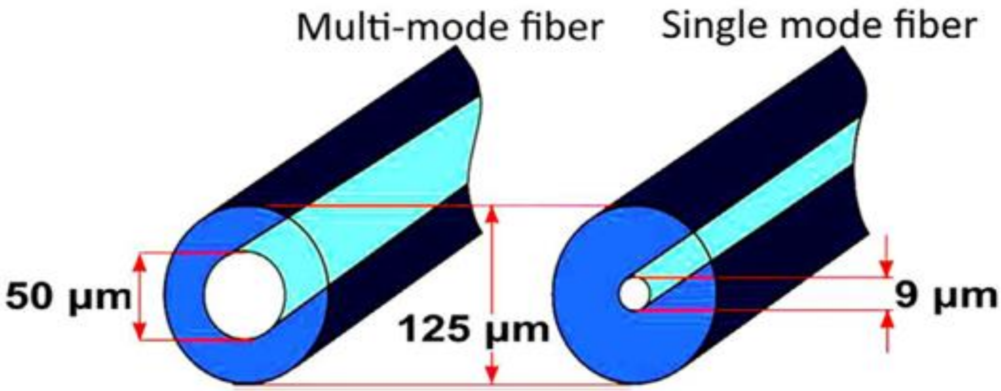


Figure 1: Dimensions of single-mode and multi-mode fibres[1]

3.1.1 Single-Mode Fiber (SMF)

The purpose of Single-Mode Fibres (SMF) is to enable light to go through the fibre in a single, unique mode or path. This is made possible by an extremely tiny core diameter, usually between 8 and 10 micrometres, which limits light propagation to just one mode [18]. The distinctive quality of SMFs has several benefits, especially for applications requiring for long-distance transmission and great accuracy. The following are important attributes of single mode fibres:

- **Minimal Dispersion:** Modal dispersion, or the phenomenon where various modes move at different rates, is almost averted since only one mode of light propagates through the fibre [19]. Maintaining the quality of the signal is essential for precise measurements in high-precision sensing applications, where this feature is equally helpful [20].

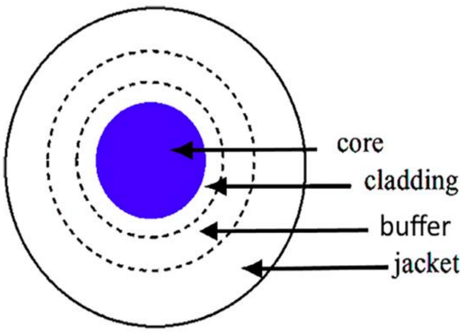
- **High Data Rate:** SMFs have large bandwidth capacities, which allow them to carry data at very fast rates. SMFs' capacity to process massive amounts of data rapidly and effectively also makes them perfect for use in high-resolution sensing technologies, where speedy data transmission and capture are crucial[21].
- **Application:** SMFs play a key role in biochemical sensing because of their long-range signal coherence and sensitivity maintenance capabilities. They are therefore very useful for identifying subtle variations in the surrounding environment or metabolic processes. The accuracy and stability provided by SMFs, for example, guarantee that even the tiniest fluctuations can be precisely recorded when detecting changes in refractive index or monitoring particular biomolecular interactions, making them a popular option in advanced sensing applications [22].

3.1.2 Multi-Mode Fiber

Optical fibres with a greater core diameter, usually between 50 and 62.5 micrometres, are known as multi-mode fibres (MMF). Multiple modes or channels of light can propagate simultaneously in this bigger core, leading to unique features and uses that set it distinct from Single-Mode Fibres (SMF) [1].

- **High Dispersion:** The increased modal dispersion of MMFs is one of their fundamental properties. Light propagates via several routes or modes inside the fibre, leading to a phenomenon known as modal dispersion, which is the spreading out of light pulses over time.
- **Short Range Applications:** MMFs are usually used in short-range applications where shorter distances yet demand high data rates.
- **Cost-Effectiveness:** In general, MMFs are less expensive to produce and install than SMFs.
- **Applications:** MMFs are utilised for certain sensing applications where range and sensitivity requirements are less precise. They can be used, for instance, to industrial sensing or environmental monitoring, where cost and resilience may be more important considerations than high sensitivity or long-distance transmission. Their capacity to concurrently transport many light modes may also be utilised to diverse sensing applications, where different modes can be employed to detect distinct factors [23].

3.2 Principle of Operation of Optical Fiber



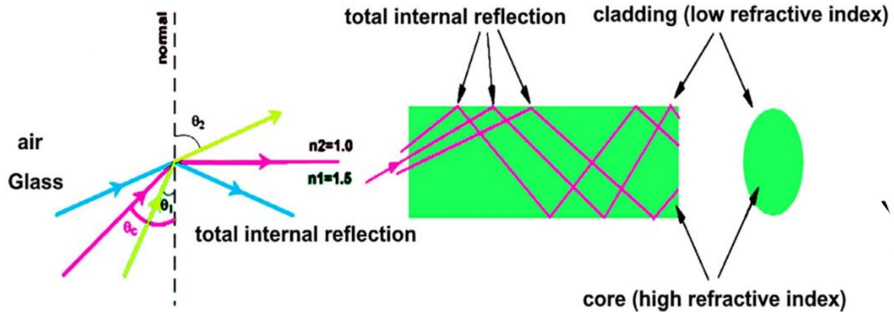


Figure 2: Four section structure of optical fiber[1]

Figure 3: Total internal reflection in glass and air medium & fibre structure[1]

The operation of optical fibres is founded on the idea of total internal reflection, which takes place at the interface where the fiber's cladding and core intersect. This effect guarantees that light entering the core stays contained inside it, as long as the internal angle of incidence is larger than the critical angle. In contrast to passing into the cladding, light that satisfies this requirement reflects back into the core and continues down the fibre.

As shown in figure 3, depending on the angle of incidence (θi), light behaves differently when it comes into contact with an interface between two substances that have different refractive indices, such glass and air. The light will flow into the opposite medium if θi is less than the critical angle (θc). On the contrary, light will be reflected back into the original medium if θi is bigger than θc. This idea is essential to the operation of optical fibres.

The core of the fibre structure has a greater refractive index than the cladding. This distinction guarantees that complete internal reflection is used in directing light through the core. The cladding stops light from escaping into the surrounding air and minimises light loss from the core. It is usually composed of glass or plastic with a reduced refractive index [1].

3.3 Evanescent Field and Sensing Principle

The evanescent field, a vital component of light wave behaviour inside the fibre, is a foundation for the core sensing concept of D-shaped optical fibres. The portion of the optical signal that reaches into the cladding or surrounding media just beyond the core is known as the evanescent field. This extension happens when light travels through the fibre and some of the optical energy seeps into the cladding rather than being entirely enclosed inside the core.

The evanescent field in a regular optical fibre is usually restricted at the core and interacts with the outside world very little. On the other hand, D-shaped optical fibres have their geometry changed by purposefully removing a piece of the cladding. This alteration increases the evanescent field's interaction with external elements like temperature fluctuations, changes in refractive index, or the presence of certain chemical or biological agents. It also enables the evanescent field to spread farther into the surrounding environment.

The evanescent field of a conventional optical fibre is typically confined to its core and experiences minimal external interaction. Conversely, the geometry of D-shaped optical fibres is altered by deliberately removing some of the cladding. This alteration strengthens the evanescent field's interaction with outside factors such as variations in temperature, shifts in refractive index, or the existence of certain chemical or biological agents. Furthermore, it permits the evanescent field to extend farther into the surroundings[24].

D-shaped fibres have an enhanced the interaction, which makes them more sensitive and useful for sensing applications. The evanescent field detects changes in the surrounding environment, such as the addition of a target analyte or a change in temperature, and this causes the light signal passing through the fibre to alter in a detectable way. These alterations are observable and may be examined to reveal important details about the surroundings of the fibre[3].

This sensing strategy is made more versatile by the ability to fine-tune the interaction between the evanescent field and the external medium by varying the degree of cladding removal or the specific design of the D-shaped fibre. D-shaped optical fibres are therefore very useful in applications such as environmental monitoring, biochemical sensing, and other areas where it's crucial to detect even the smallest changes in the surrounding environment. The creation of sophisticated sensors that take advantage of the special characteristics of the evanescent field for high-sensitivity detection is supported by this idea.

4 METHODOLOGY

4.1 Preliminary Experiment: Analysis of Bending Loss

An analysis of the bending loss in optical fibres was done in a pilot experiment during the primary stage of the research. The goal was to comprehend the effects of fibre bending on light propagation, with a focus on Single-Mode Fibres (MMF). Since severe bending may significantly attenuate the optical signal, bending loss is a crucial issue in evaluating the effectiveness of fibre optic systems.

The power loss usually reduces with increasing bend radius (R). However, the reduction ceases after a while, and instead an oscillating behaviour in the power loss (L) with respect to the bend radius is evident. This indicates that extending the bend radius beyond a particular point may result in increased power loss as opposed to reduced power loss. Understanding this oscillation behaviour is crucial for designing and refining fibre optic systems, especially in situations where bending is inherent.

In-depth investigation of this connection was the goal of this initial effort, which contributed to the design of further experiments in the study and offered significant insights about the behaviour of light inside bent fibres.

4.1.1 Experimental Setup

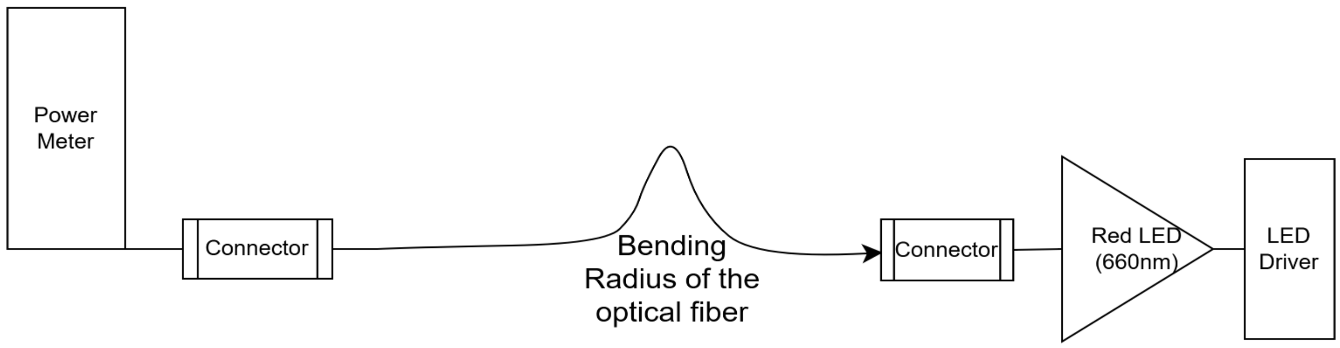


Figure 4: Schematic representation of the bending radius losses of optical fibre experiment.

A setup that provided accurate measurement of the bend radius was used to submit optical fibres of different diameters to controlled bending. In order to measure bending radius losses in single mode optical fibres particularly, a red LED (660 nm) was employed as the light source for the experiment, which entailed passing light through the fibres at a specified wavelength. Power loss as a function of bend radius was measured by utilising a power meter to capture the output power after bending.

The F-PS750 Extremely Highly Photosensitive Single-Mode Fibre was utilised for the purpose of the study. The fibre has an inherent photosensitivity due to its co-doping of germanium and boron. A 1 nm wide, 47 dB deep, and 15 mm long transmission is possible with this 780 nm single-mode fibre. The implementation of this particular single-mode fibre enabled precise measurements along with evaluation of the bending loss characteristics, especially in light of its high photosensitivity and optical attributes.

4.1.2 Data Acquistion and Evaluation

The correlation between bend radius and signal intensity loss was investigated solely for single-mode fibres (SMF). A set of procedures was followed throughout the experiment to guarantee precise and reliable data collecting.

4.1.3 Implementation Steps

1. **Fibre Sample Preparation:** The F-PS750 Very Highly Photosensitive Single-Mode Fibre was utilised in the experiment. To reveal the bare glass fibre, the fibre was initially stripped of its covering. It was then cleaved to provide a smooth, clean end face. Following cleaving, the fibre was inserted into the bullet connection to guarantee correct alignment and maximum light transmission.
2. **Light Transmission Configuration:** The light source was a red LED with an emission wavelength of 660 nm. The light was coupled into the single-mode fibre, and different bend radii were applied to the transmitted light as it passed through the fibre.
3. **Controlled Bending**: The fibre was progressively bent to various radii. In order to calculate the power loss resulting from bending, the power meter recorded the output power for each bend radius.

4. **Data collection:** For each designated bend radius for the Single-Mode Fibre, power meter values were obtained. To guarantee accuracy and dependability, the measurements were made several times. In particular, because of its extreme photosensitivity, special consideration was given to the F-PS750 fibre’s behaviour when bent.

5. **Evaluation of Bending Loss:** The correlation between the bend radius and the signal intensity loss was ascertained by analysing the data that was gathered. Finding the critical bend radius the point at which noticeable power loss starts to happen was the main goal. Furthermore, power loss's oscillatory behaviour at specific bend radii was observed, offering further insight on how bending influences light propagation.

6. **Interpretation of the outcomes:** The findings were applied to provide a baseline knowledge of bending losses in single-mode fibres. Power loss was found to drastically rise when the bending radius reduced. Understanding the restrictions of fibre bending in real-world applications depends on this relationship between smaller bend radii and higher power loss. This knowledge was essential for guiding decisions made later on in the fabrication and polishing of the fibre.

4.2 Fabrication of D-Shaped Fibers with Acrylic Mould Encapsulation

The second stage of the project entailed encapsulating acrylic moulds for fabricating D-shaped optical fibres. The purpose of this approach was to assess the viability and efficiency of forming and keeping optical fibres firmly in acrylic throughout the polishing process, especially in the case of forming D-shaped profiles that improve evanescent field interaction.

The fibre is vitally supported and stabilised during the polishing process by the acrylic mould, which also greatly reduces the mechanical stress on the fibre. The acrylic material provides an ideal blend of flexibility and stiffness, with a Young's modulus of around 2.4 to 3.2 GPa. By providing adequate support, this characteristic helps to maintain the optical integrity of the fibre by averting any physical deformations such as micro bending that could happen during the polishing process.

In order to maximise the evanescent field's interaction with the surrounding environment, the setup assists in maintaining exact alignment and form of the D-profile by encasing the fibre in the acrylic mould. In order to prevent faults or stress spots from being introduced during the polishing process that might impair the fibre's performance in sensing applications, it is very crucial to employ acrylic mould encapsulation.

4.2.1 Acrylic Mould Fabrication

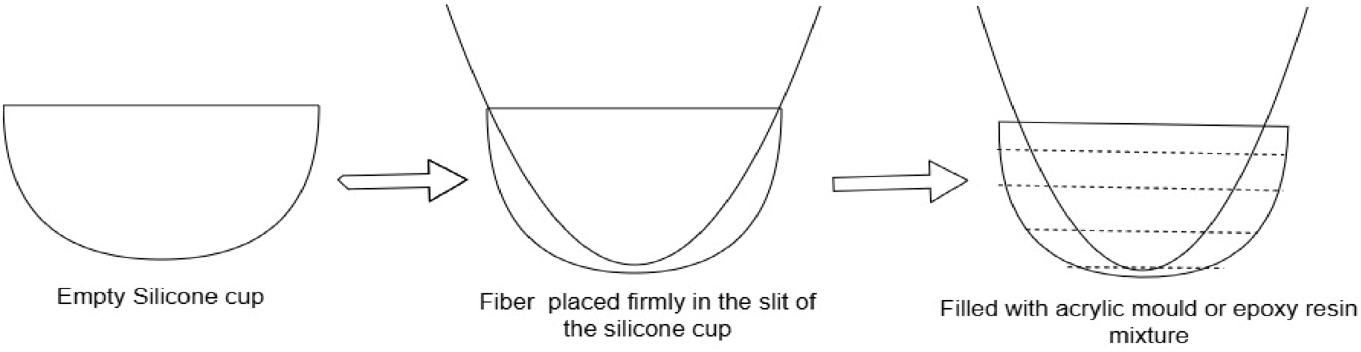


Figure 5: Encapsulation steps of the fibre

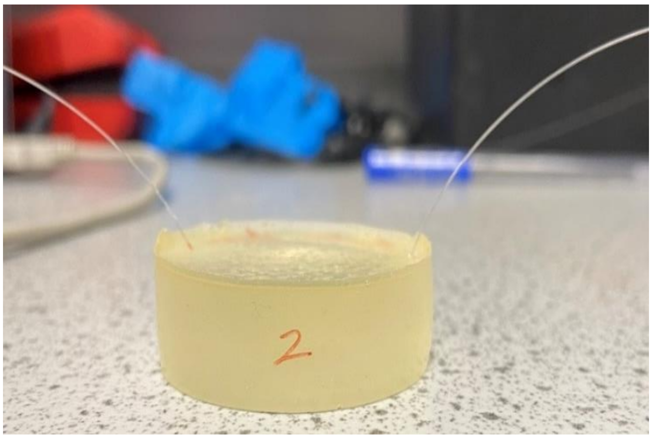


Figure 6: Sample of fibre encapsulation in acrylic mould

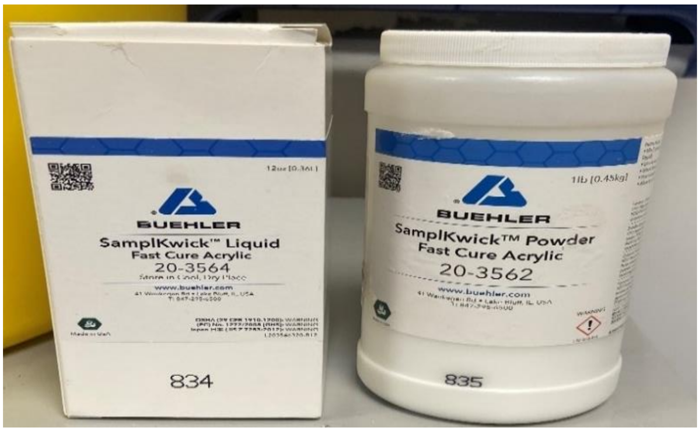


Figure 7: Acrylic mould mixture components

To safely enclose the optical fibres throughout the moulding and polishing procedure, acrylic moulds had been developed. As shown in figure 5, SamplKwik Liquid Fast Cure Acrylic (20-3564) and SamplKwik Powder Fast Cure Acrylic (20-3562) from Buehler were utilised for the purpose of this study. These substances were chosen because of their high adhesion and quick curing qualities, which make them perfect for building a sturdy and long-lasting mould. Acrylic was used for experimental setups because of its practicality as a cheap and easily generates material.

The components of the SamplKwik acrylic were combined as follows:

- **Mixing Instructions:** Combine 1-part SamplKwik Liquid (20-3564) with 2 parts by volume of SamplKwik Powder (20-3562). Alternately, use two parts liquid to three parts powder for a larger quantity. To guarantee adequate curing, it is crucial to avoid combining more than three volume ounces (about 90 ml) of powder at the same time.
- **Blending:** To get a homogeneous consistency, blend the ingredients well for 15 to 20 seconds.
- **Pouring:** To guarantee uniform distribution and avoid premature curing, pour the mixture into the mould promptly as possible.

After pouring, the mixture was given ten minutes to cure, solidifying and encasing the mould. By assuring that the mould offered the required stability and support during the ensuing shaping and polishing procedures, this technique lowered the possibility of mechanical stress and allowed for exact control over the fiber's profile.

4.2.2 Fiber Fixation and Polishing Procedures

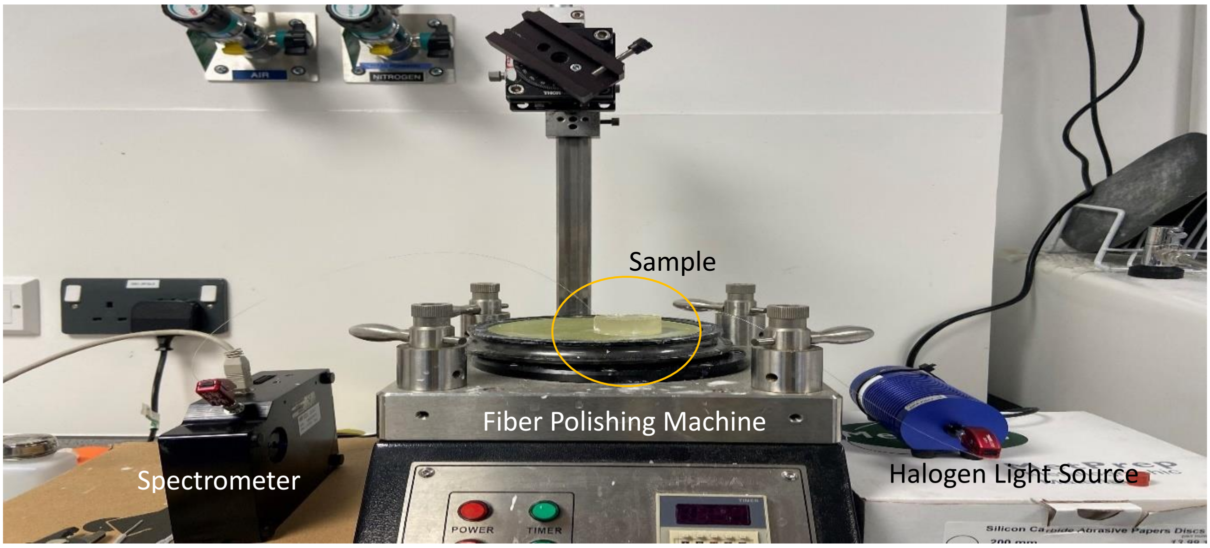


Figure 8: Fiber polishing setup

The D-shaped fibres were prepared and moulded precisely for the biochemical sensing applications for which they were intended, by means of a series of meticulous processes in the fibre fixation and polishing process.

The measures that were taken for fixing the fiber are outlined below:

1. **Fiber Selection**: Due to their applicability in biochemical sensing, two varieties of single-mode optical fibres were chosen for the D-shaped fibre fabrication:

- **780HP - Single Mode Optical Fiber**: Designed with a 125 µm cladding diameter and optimized for 780-970 nm, employing resources from Thorlabs.
- **SMF 28E+**: A conventional single-mode fibre from Fibre Instrument Sales, Inc. (FIS) with a cladding diameter of Ø125 µm.

2. **Fiber Placement**: To ensure that the fibre is held firmly in place throughout the curing process, a silicone cup was manufactured and tiny slits were made on the upper rim edges.

3. **Acrylic Encapsulation**: SamplKwik powder and liquid were incorporated in the prescribed proportions to create SamplKwik acrylic mix. After transferring the liquid into the silicone cup to completely enclose the fibre, it was left to cure.

4. **Fiber Setup**:

- The protective covering, or Jacket, was removed from the ends of the fibre once it had cured, exposing the exposed glass fibre.
- To generate a smooth, clean surface, the stripped end was then cut using a fibre cleaver.
- To get rid of any dirt or impurities, isopropyl alcohol (IPA) was applied to the split end of the fibre.

5. **Polishing Setup**:

- The prepared fibre was placed into an FS-20A type fibre polishing machine as shown in figure 7.
- An Ocean Optics Halogen Light Source (HL-2000, OFS-Fiber-38) was connected to one end of the fibre via a bullet connection
- An Ocean Optics spectrometer (HR4000) was attached to the other end.

6. **Polishing Process**: Using fine abrasive materials, the cladding was gently removed until the fibre was polished with 30 µm polishing film to a D-profile. The polishing was carried out methodically to ensure exact control over the process of removal.

7. **Monitoring and Intensity Measurement**:

- Throughout the polishing procedure, the fibre was constantly observed with Ocean Optics spectrometer (HR4000) using the OceanView software. To gauge how far along the cladding removal process was, readings were recorded at varied intervals and intensities.
- The intensity measurements were essential in figuring out how much polishing was done. Significant intensity dips suggested further cladding removal, which impacted the core and the evanescent field.
- The objective was to get an exact D-shaped profile that would improve the fiber's sensitivity for biological sensing applications by enhancing the evanescent field's interaction with the outside world.
- The procedure was closely watched to prevent damage to the fibre and guarantee that it would function to the extent it could to identify biochemical interactions.

The D-shaped fibres were manufactured with the requisite accuracy and precision according to these procedures, which also made them extremely efficient for use in biochemical sensing a field where sensitivity to slight environmental changes is crucial.

4.3 Fabrication of D-Shaped Fibers with Epoxy Resin Encapsulation

The creation of D-shaped optical fibres using epoxy resin encapsulation was the next stage of the study. The purpose of this procedure was to assess the degree to which epoxy resin holds optical fibres throughout the polishing process, especially when forming D-shaped profiles that improve evanescent field interaction.

With a Young's modulus of around 2.5 to 3.5 GPa, the epoxy resin utilised in this procedure. This modulus permits the exact shape required to obtain the required D-profile, while also being well-suited for preserving the fibre. The fibre is kept safely encased during the polishing process due to the epoxy resin selection

The procedure used with the acrylic mould was the same as the procedure used to create D-shaped fibres using epoxy resin. The efficiency of epoxy resin was compared to acrylic by using the identical method, with a focus on how well it preserved fibre integrity and reduced mechanical stress throughout the polishing process.

4.3.1 Epoxy Resin Fabrication

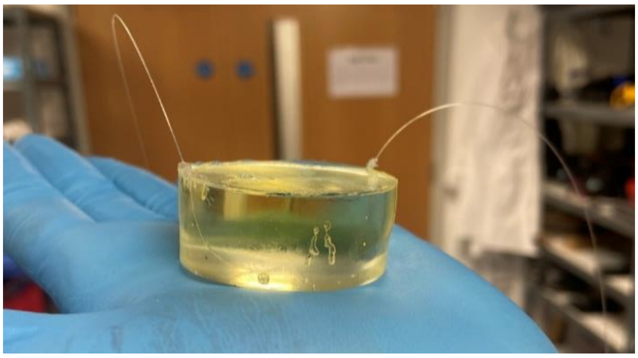


Figure 10: Sample of fiber encapsulation in epoxy resin

Figure 9: Epoxy resin mixture components: a) Epokwick FC-Epoxy Resin (20-3453-128) b) Epokwick FC-Epoxy Hardener (20-3453-032)

The optical fibres were securely encapsulated in epoxy resin moulds during the polishing procedure. As shown in figure 8, Using Buehler's Epokwick FC-Epoxy Resin (20-3453-128) and Epokwick FC-Epoxy Hardener (20-3453-032), this was accomplished. Because of their superior quality and quick curing times, these materials were chosen to ensure that the fibres were firmly buried as the resin hardened.

The detailed instructions for combining and applying the epoxy resin for fibre encapsulation are given below:

1. **Preparation**: Before encasing the sample in the epoxy resin, make sure it is completely clean and dry to ensure optimal adhesion and curing.
2. **Mixing by Volume**: Combine one component Epokwick FC Hardener (20-3453-032) with four parts Epokwick FC Resin (20-3453-128).
3. **Mixing by Weight**: By weight, combine 4.4 parts resin and 1 part hardener.
4. **Mixing Procedure**:
   - For optimal effects, mix the hardener and resin for no longer than two minutes.
   - Use the mixture right away after preparing it, since stirring it for more than two minutes potentially discolour it.
   - Use a lift-and-stir motion while gently tilting the cup holding the resin and hardener to ensure the mixture has been thoroughly incorporated.

5. **Pouring and Curing**:

- Fill the fiber-containing mould with the epoxy resin that has been well blended.
- To ensure that the mixture fully solidifies and secures the fibre in place, let it cure for two hours.

This systematic technique assures that the epoxy resin is prepared, mixed, and cured correctly, giving the optical fibre a sturdy and stable encapsulation while it is being moulded and polished.

4.3.2 Fiber Fixation and Polishing procedure

A comprehensive set of procedures was followed during the fibre fixing and polishing process utilising epoxy resin encapsulation to assure the ideal setup and fabrication of D-shaped fibres intended for biochemical sensing applications.

The steps involved are described as follows:

1. **Selection of Fibers**: Two distinct single-mode optical fibres were chosen for biochemical sensing because they were considered acceptable:

- **780HP - Single Mode Optical Fiber**: Specifically designed for the wavelength range of 780-970 nm, with a cladding diameter of 125 µm, purchased from Thorlabs.
- **SMF 28E+**: A typical single-mode fibre from Fibre Instrument Sales, Inc. (FIS) with a cladding diameter of Ø125 µm.

2. **Fiber Placement**: To keep the fibre in place during the encapsulating and curing processes, it was carefully inserted into the slits on the silicone cup's rim.

3. **Encapsulation with Epoxy Resin**:

- Epokwick FC-Epoxy Resin and Hardener were utilised, combined in accordance with the guidelines.
- To prevent fading and provide a homogeneous mixture, the hardener and resin were fully combined for a maximum of two minutes.
- After firmly embedding the fibre in the silicone mould using the mixture, the mould was let to cure for two hours.

4. **Preparation of Fiber Ends**:

- The fiber's jacket (protective layer) was removed at the end after curing, revealing the glass.
- A fibre cleaver was then used to cut the exposed end, ensuring a smooth, clean surface.
- To get rid of any impurities or debris, the split end was cleaned with isopropyl alcohol (IPA).

5. **Polishing Setup**: After preparation, the fibre was put into a fibre polishing machine (FS-20A model). The fiber's ends were attached to a spectrometer (HR4000) from Ocean Optics for monitoring, and the other end was connected to a bullet connection that was coupled to a Halogen Light Source (HL-2000, OFS-FIBER-38) from Ocean Optics.
6. **Fiber Polishing**: The cladding was meticulously removed using fine abrasive tools, and the fibre was methodically polished with 30 µm polishing film to produce a D-profile. For accurate shape, the polishing procedure was constantly monitored.
7. **Spectrometer Monitoring**:

- During the polishing process, the performance of the fibre was consistently examined. At several points in time, measurements of intensity were taken, and the degree of cladding removal was correlated with the intensity reductions.
- To gauge the progress of the cladding removal, readings were obtained at various intensity drop percentages (e.g., 10%, 25%, 50%, and 75%). Determining the exposure of the core and its interaction with the evanescent field relies significantly on these data.
- More substantial intensity drops suggested cladding removal, which had an immediate impact on the fiber's sensitivity during the final implementation.

4.4 Fabrication of D-Shaped Fiber by Wheel Polishing

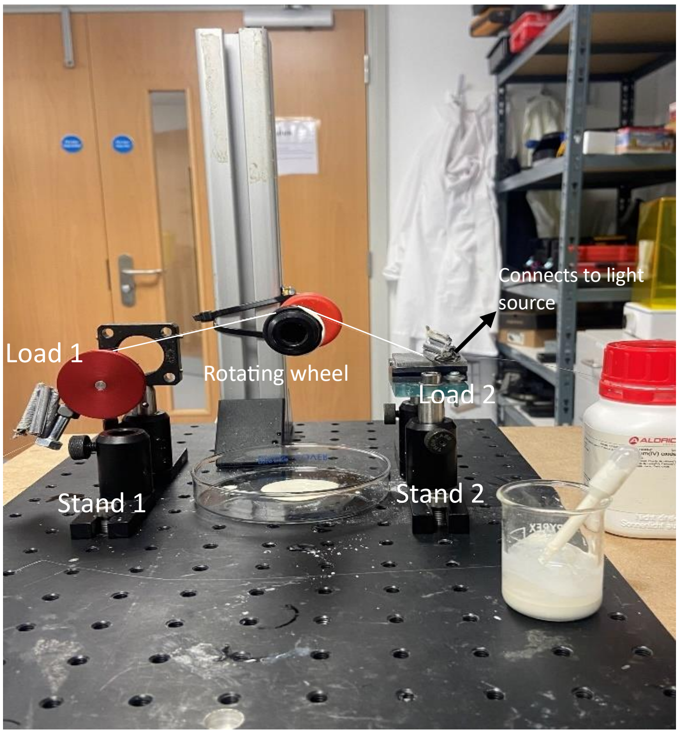


Figure 11: Front view of wheel polishing setup

Figure 12: Side view of wheel polishing setup

Wheel polishing, a precise and regulated process, is used to fabricate D-shaped fibres that are intended to improve the fibre's contact with the external environment, especially for sensing applications. With this technique, the fibre cladding may be uniformly removed, resulting in a D-shaped profile that optimises the contact between the evanescent field and the substrate.

1. **Fiber Preparation**: This approach made use of the same two types of single-mode optical fibres as the prior fabrication technique:

- **780HP - Single Mode Optical Fiber**: Specifically designed for the wavelength range of 780-970 nm, with a cladding diameter of 125 µm, purchased from Thorlabs.
- **SMF 28E+**: A typical single-mode fibre from Fibre Instrument Sales, Inc. (FIS) with a cladding diameter of Ø125 µm.
- Fibres were prepared both with and without jacket (protective coats).

2. **Wheel Polishing Setup**:

- Polishing is done using a machine with a revolving wheel and motor. The wheel's smooth, rubber-like material construction ensures that it creates the right amount of friction without causing damage to the fibre and is at a height of about 12 cm.
- To secure the fibre during polishing, two rings are fastened to the wheel cork. These rings serve to keep the fibre in place and aligned while the wheel revolves.
- To regulate the pace at which cladding is removed, the revolving wheel's speed is adjusted correspondingly. With the help of an ISO-TECH power supply, this speed may be precisely controlled according to the demands of the polishing procedure.
- There are two stands in the setup:
  - Stand 1 (Height: 10.8 cm): Uses different weights fastened with magnets to hold the fibre firmly in place; this is known as Load 1 (L1). Its purpose is to keep the fibre under regulated tension and pressure while polishing.
  - Stand 2 (Varied Height): Known as Load 2 (L2), it is utilised to secure the fibre using a magnet. This support makes sure that during the polishing procedure, the fibre is steady and orientated correctly.

3. **Load Configuration and Fiber Connections:**

- One end of the fibre is stripped of its jacket and cleaved to provide a clean, flat surface when the setup is finished and the loads are correctly configured.
- The Halogen Light Source (HL-2000, OFS-Fiber-38) from Ocean Optics then connects to this stripped and cleaved end of the fibre, and the spectrometer (HR4000) from Ocean Optics is connected to the other end of the fibre. As the polishing process moves forward, this guarantees that the fibre is appropriately aligned and stabilised, enabling precise real-time monitoring of the light transmission. The configuration makes it easier to make accurate modifications and measurements, assuring that the fibre's integrity is maintained while yet achieving the required D-shaped profile.

4. **Polishing Process**:

Figure 13: Cerium oxide used as a fine abrasive for wheel polishing

- A solution mix of deionised water and cerium (IV) oxide(1 mg/mL) from Aldrich (>=99.0%) is used to polish the fibre. Different milligrams of cerium oxide are carefully combined with deionised water to formulate the solution's concentration.
- Drops of this polishing solution are applied to the fibre as the wheel spins. To form the D-shaped profile, a portion of the cladding is gradually removed while the fibre is polished by the cerium oxide solution, which functions as a fine abrasive.
- The power supply meticulously regulates the wheel's speed and the pressure it exerts to reach the required degree of accuracy, assuring consistent cladding removal without causing damages to the fibre core.

5. **Intensity Monitoring**:

- The optical characteristics of the fibre are continually observed during polishing using the OceanView software. The fibre is illuminated by the Halogen Light Source, and a spectrometer is used at the other end to measure the light intensity.
- At various percentages of intensity decrease, such as 10%,25%,50%, and 75%, intensity measurements are obtained. These measures aid in tracking the removal of cladding and serve as a reference for polishing to guarantee the precise creation of the D-shaped profile.

6. **Post-Polishing Inspection**

- **Microscopic Inspection**: To verify consistency and accuracy in the removal of the cladding, the completed D-shaped fibre is examined under a microscope. Making sure the fibre has been formed according to plan requires this step.
- **Layer-by-Layer (LBL) Deposition Protocol**: An LBL deposition procedure is used to the fibre after it reaches the desired intensity decrease. The fibre is delicately covered in several layers throughout this procedure, which turns it into a useful sensor with increased sensitivity.

4.4.1 Layer by Layer (LBL) of DAR/TSPP Deposition Protocol

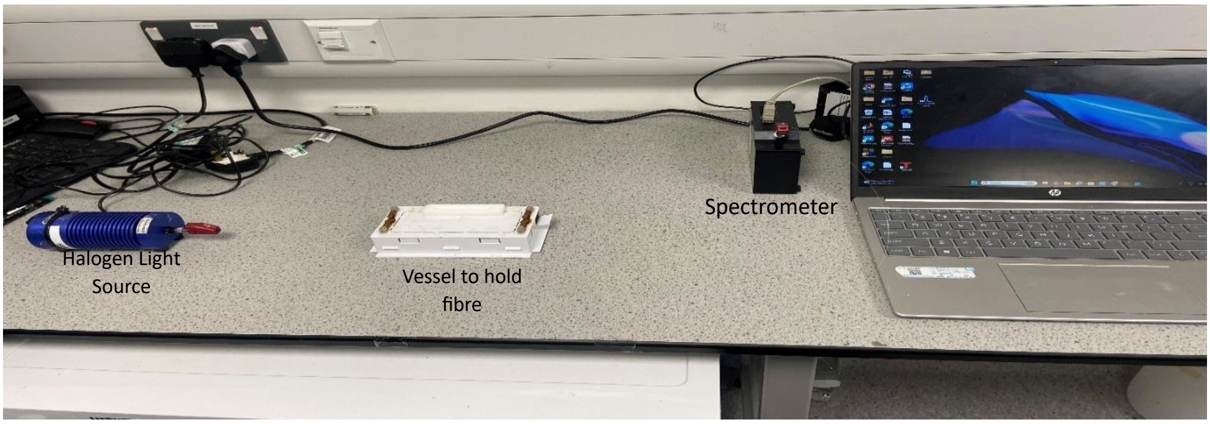


Figure 14: Layer by Layer (LBL) deposition setup

The D-shaped optical fibre is polished to the appropriate intensity drop, and then a DAR/TSPP deposition process is carried out to improve its sensitivity for sensing applications. In order to enhance the fibre's sensitivity and specificity in detecting target analytes, the Layer-by-Layer (LBL) deposition process was chosen in particular because it enables exact control over the thickness and homogeneity of the deposited layers. Applying DAR and TSPP layers with the goal on the fibre surface results in a well-defined nanostructure that increases the interaction between the evanescent field and the surrounding medium, decreasing the detection limits and improving detection accuracy. The technique that follows has been optimised to incorporate the needs of polished fibre and ensure the efficient and uniform application of deposition layers.

1. **Preparation and Fiber Fixation**

- Hold the polished fibre securely so that the polished, uncoated portion is completely submerged in the deposition vessel.
- The vessel has to be dry and clean before commencing the deposition process. • Make sure the fibre is stable and does not move during the deposition process.

2. **KOH Treatment**

- **Solution Preparation**: Dissolve 1 weight percent KOH into a 2:3 water-ethanol solvent. For the deposition procedure, this combination aids in surface preparation of the fibre.
- **Application**: Ensure that the liquid entirely covers the exposed portion of the fibre when you pour the KOH solution into the vessel. Give the fibre at least twenty minutes to soak. By adding hydroxyl group and cleaning the fibre surface, this step increases the adhesion of layers that follow
- **Washing**: After the procedure, remove the KOH solution from the vessel using a pump. Use deionised (DI) water to rinse the container three times. To ensure a complete cleaning, fill the vessel with DI water and remove it a few seconds during each rinse cycle.

3. **Drying:** Nitrogen (N_2) flow should be used to completely dry the fibre. Making sure the fibre is totally dry before applying the DAR solution is dependent upon this procedure. In order to prevent any leftover moisture from affecting the quality of the deposition, a steady and regulated nitrogen flow must be employed.

4. **DAR Deposition**

- **Solution Preparation**: Disodium 4,4'-diazoaminobenzene-2,2'-disulfonate) should be diluted with water to a weight percentage of 0.1–0.2 wt%. Cover the vessel with aluminium foil or an opaque container to keep the solution shielded from outside light.
- **Application**: Fill the vessel with the DAR solution, making sure the polished portion of the fibre is completely immersed. After 12 minutes, remove the fibre from the solution. This procedure creates the first layer of the deposition, which is necessary for the TSPP layer that occurs.

- **Protection**: To assure uniform deposition and avoid photodegradation of the DAR solution, shield the vessel from outside light throughout the soaking time.
- **Refractive Index Monitoring**: Using a spectrometer and a halogen light source, the refractive index change is continuously tracked during the DAR deposition process.

5. **Washing and Drying**

- **Washing:** Employing a pump, remove the solution following the DAR deposition and rinse the vessel three times with DI water, using the same protocol as after the KOH treatment.
- **Drying**: Before adding the next layer, dry the fibre completely with a nitrogen flow once again to eliminate any remaining moisture.

6. **TSPP Deposition**

- **Solution Preparation**: Tetrasodium 4,4',4'',4'''-porphyrin-5,10,15,20-tetrasulfonate hydrate, Mw = 934.99) should be prepared as a 1 mM solution in water.
- **Application**: After adding the TSPP solution to the vessel, let the fibre sit in it for 12 minutes. This creates the second deposition layer, which increases the sensitivity of the fibre to detect specific analytes when paired with the DAR layer.
- **Refractive Index Monitoring**: The spectrometer and halogen light source are used to continually measure the refractive index change throughout the TSPP deposition, much like they do for the DAR deposition.

7. Final Washing and Drying

- **Washing**: After removing the TSPP solution, give the vessel three more washes with DI water.
- **Drying**: Use nitrogen flow to completely dry the fibre, making sure the fiber's surface is totally free of moisture.

8. Layer Repetition: When the required number of DAR/TSPP layers is reached, repeat steps 2 through 7 of the deposition procedure. For the desired sensing application, additional layers usually improve the fiber's sensitivity and specificity.

9. **Post-Deposition Inspection and Testing:** Once layer-by-layer deposition is finished, the fibre is put through a demanding testing procedure to ensure that it functions as a sensor. To ensure that the fibre satisfies the requirements for its intended application, its transmission qualities and reaction to target analytes are assessed.

Through constant refractive index monitoring, our optimised approach ensure that the polished D-shaped fibre is effectively coated with DAR and TSPP layers. The fiber's readiness for high-sensitivity detection in sophisticated sensing applications is ensured by the testing process.

4.5 Fiber Validation Process

4.5.1 Analysis of Different Concentrations of IPA and Deionized Water

Figure 15: Setup for Analysis of varied IPA Concentrations

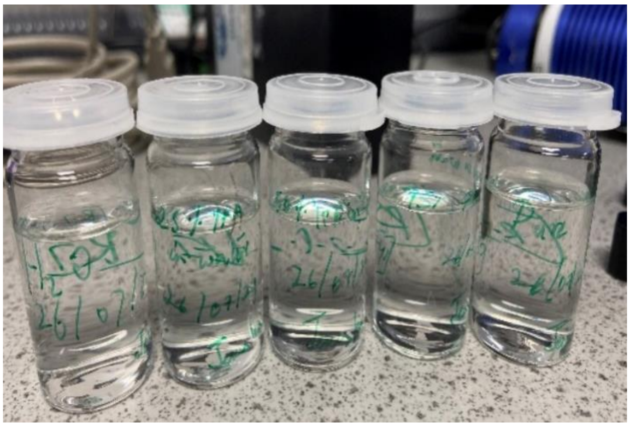


Figure 16: Solutions of different IPA concentrations

This protocol describes the ideal procedures for assessing how the refractive index and intensity of the polished fibre alter in response to different ratios of IPA to deionised water (DI water). The objective is to assess the fibre's reaction in a regulated and consistent way to varying IPA concentrations.

1. **Preparation of IPA Solutions**

- **Solution Preparation**: Prepare four distinct IPA concentrations by combining it with deionised water:
    - **100% IPA**: Pure Isopropyl Alcohol.
    - **75% IPA**: 75 parts IPA with 25 parts deionized water.

- **50% IPA**: 50 parts IPA with 50 parts deionised water
    - **25% IPA**:25 parts IPA with 75 parts deionized water.
    - **100% DI Water**: Pure deionized water.
- **Labelling**: It is crucial to mark each solution precisely to prevent confusion while evaluating.

2. **Initial Baseline Monitoring**

- Use a spectrometer and halogen light source to record the fiber's initial refractive index and intensity before subjecting it to any solutions.
- Note these baseline values are for comparison in the subsequent experiments.

3. **Testing Sequence**

- **Increasing Concentration Sequence**:
    - Immerse the fibre in three minutes of 100% deionised water.
    - Monitor on how the refractive index and intensity change.
    - After the fibre is exposed, wash it well with DI water to get rid of any remaining solution, and then use nitrogen flow to dry it.
    - The same procedure should be followed for IPA levels of 25%, 50%, 75%, and 100%.
- **Decreasing Concentration Sequence**:
    - Repeat the testing procedure in reverse order, using 100% IPA first, followed by 75% IPA, 25% IPA, then 100% DI water. The fibre should be immersed in the solution for three minutes for every concentration. Monitoring the variations in the refractive index and intensity.
    - Cleaning and Desiccation: Use DI water to give the fibre a thorough cleaning after each exposure, and then use nitrogen flow to dry it.

4.5.2 Ammonia Sensing

To ensure that the sensor operates reliably and precisely, the fibre validation procedure is essential for ammonia sensing. An elaborate and optimised approach for verifying the D-shaped fiber's effectiveness as an ammonia sensor is discussed below.

1. Pre-Sensing Preparation

- **Post-Deposition Photoreaction**: The fibre needs to be exposed to light for the whole night following the completion of the DAR/TSPP deposition. Keep the fibre exposed to light; this will cause a required photoreaction that will stabilize the deposited layers and get the fibre ready for sensing applications.

2. Ammonia Sensing Procedure

- **Initial Monitoring**: Use a spectrometer and halogen light source to start by tracking the untreated fiber's baseline response. In this process, the fiber's initial refractive index and intensity levels are determined prior to its exposure to ammonia.
- **Ammonia Exposure - Level 1 (Low Concentration)**:
  - **Preparation**: Prepare an ammonia solution with 1000 parts per million.
  - **Application:** After applying the ammonia solution to the fibre, allow it interact with it for three minutes.
  - **Washing and Drying**: To get rid of any remaining ammonia, give the fibre a good wash with DI water after the three-minute exposure. To be sure the fibre is entirely dry before moving on, use a nitrogen flow to dry it for one minute.
- **Ammonia Exposure - Level 2 (High Concentration)**:
  - **Preparation**: Prepare an ammonia solution with 1000 parts per million.
  - **Application:** After applying the Level 2 ammonia solution to the fibre, allow it three minutes to interact with the fibre.

- Washing and Drying: Following the three-minute exposure, thoroughly wash the fibre with DI water and let it dry for three minutes with a nitrogen flow.

3. **Repetition for Consistency**:

- **Cycle Repetition**: Proceed through the complete procedure three times, including the washing, drying, and ammonia exposure (Level 1 and Level 2). The performance and constancy of the fibre in detecting ammonia must be tested, and this demands repetition.
- **Data Collection:** To evaluate the sensitivity and reproducibility of the fibre in detecting ammonia, meticulously record the changes in the refractive index and the intensity dips after each cycle. To record the fibre's reaction to the ammonia, continuously track the intensity decrease and change in refractive index during the phases of exposure, washing, and drying.

5 RESULTS AND DISCUSSION

5.1 Bending Loss Analysis in SMF

An analysis of the bending loss in optical fibres, particularly Single-Mode Fibres (SMF), was the main goal of the preliminary research. The resulting power loss was carefully monitored when the fibres were bent in controlled ways with different radii. The bending radius and power loss have a direct correlation, as table 1 shows. The power loss dramatically increased with decreasing bending radius, indicating that SMF is bending sensitive.

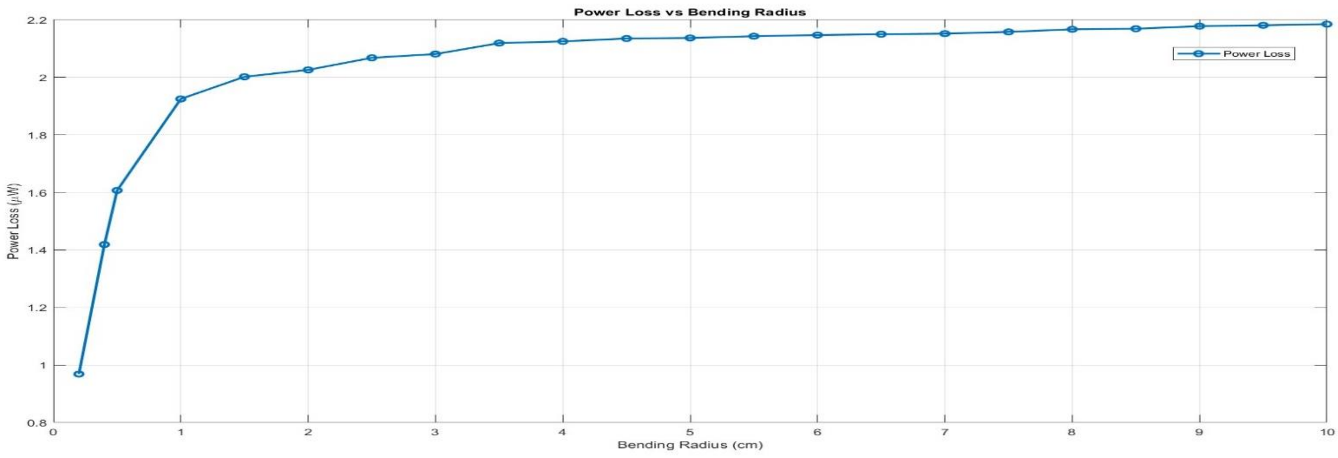


Figure 17:Graph of the power loss at different bending radii

Table 1: Analysis of power loss acquired at different bending radii

Bending Radius (cm)	Power Loss (μw)
0.2	0.9686
0.4	1.419
0.5	1.607
1	1.925
1.5	2.002
2	2.026
2.5	2.068
3	2.081
3.5	2.119
4	2.125
4.5	2.135
5	2.137
5.5	2.143
6	2.147
6.5	2.150
7	2.152
7.5	2.158
8	2.167
8.5	2.169
9	2.178
9.5	2.181
10	2.185

The following are the conclusions drawn from Table 1 and Figure 2:

1. **Reduction in Power in Tight Bends:** There is a significant 968.6 nW power loss in the fibre at a bending radius of only 0.2 cm. This huge loss suggests that excessive bending leads to a big loss in transmitted power because a sharp bend dissipates a significant amount of the light signal.
2. **Reduction in Power Loss:** Power loss decreases substantially when the bending radius rises from 0.2 cm to 10 cm. For example, the power loss drops to 1.925 μW at a 1 cm bending radius, suggesting that the fibre keeps more of its signal as the bend gets weaker. Larger radii show that this trend continues, indicating the fiber's enhanced capacity to transmit light with less attenuation caused by bending.

3. **Stabilization of Power Loss**: The power loss stabilises at bending radii greater than 5 cm, increasing very slightly with further radius rise. For instance, the power loss is 2.137 µW at a 5 cm radius and marginally increases to 2.185 µW at a 10 cm radius. This indicates a threshold where the fibre may be bent with low additional signal degradation, suggesting that beyond a certain point, increasing the bending radius further has minimal influence on power loss.

4. **Implications for Fiber Handling**: The data emphasises how susceptible Single-Mode Fibres (SMFs) are to bending, especially at lower radii. SMFs should be handled cautiously and severe bends should be avoided as a way to maintain signal integrity, as indicated by the noticeable power loss at tight bends. It is possible to bend the fibre within a safety range without suffering a major loss of signal strength. Optimising fibre performance requires an understanding of these bending dynamics, especially in situations where maintaining good signal quality is crucial.

5.2 Effectiveness D-Shaped Fiber Fabrication Using Acrylic Mould

A D-shaped fibre was effectively fabricated by polishing the fibre with the FS-20A polishing machine, which was outfitted with a 30-micron polishing film. During this method, an SMF28E fibre without a jacket was encapsulated. A notable decrease in intensity was seen during the polishing procedure, signifying the gradual removal of the cladding and the growing exposure of the fibre core. The enhancement of the evanescent field interaction with the surrounding environment, which increases the fiber's sensitivity to changes outside, is directly linked to this intensity reduction.

By examining how the D-shaped fibre responded to varying amounts of isopropyl alcohol (IPA) combined with deionised water, the sensitivity of the material was further confirmed. The refractive index and intensity fluctuations of the fibre were attentively observed as the IPA concentration changed, as indicated in. This investigation verified that the sensitivity of the fibre improved when the core was exposed to more light, enabling more accurate detection of changes in the surrounding medium.

The D-shaped fiber's sensitivity was maximised by carefully monitoring the intensity decrease and refining the polishing procedure, making it an excellent choice for precise sensing applications.

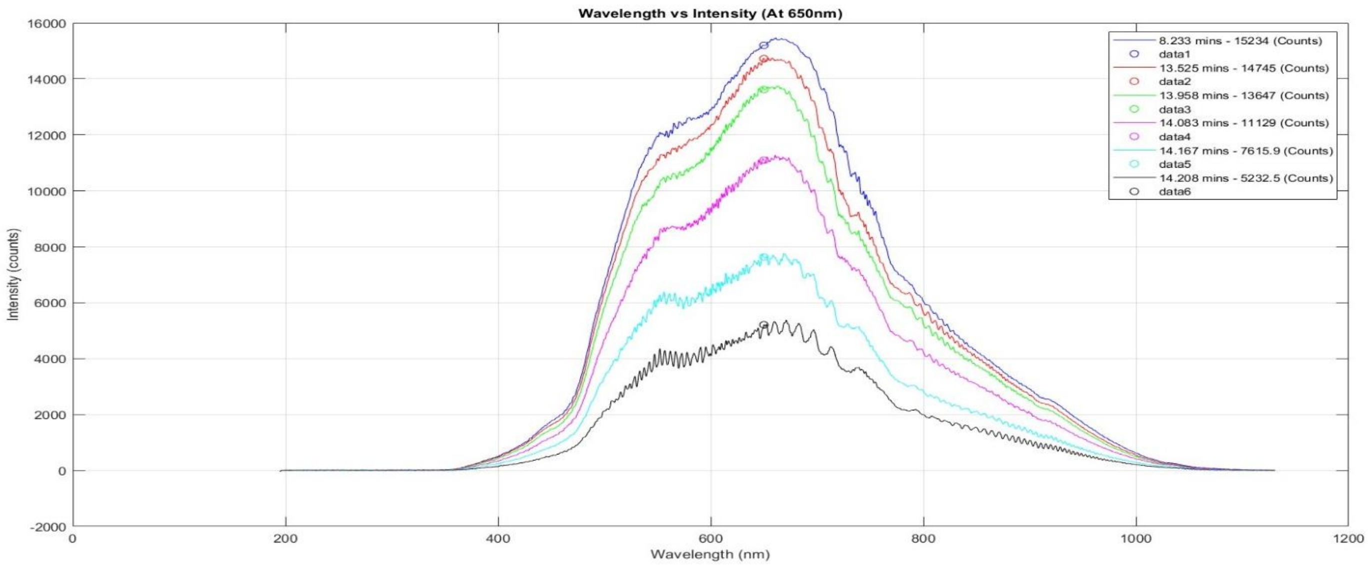


Figure 18: Intensity Drop Graph for Fabricating D-Shaped Fibres Using Acrylic Mould

The intensity drops across different time intervals throughout the polishing process is shown in figure 18. Interestingly, no discernible decrease in intensity was seen prior to 8.233 minutes, which is why the monitoring procedure was initiated at that time. Specifically, the intensity drop was seen at 650 nm with a halogen light source. A wide range of light, including the 650nm wavelength, is produced by the halogen light source, which is essential for determining how the evanescent field interaction changed as the polishing process developed. We were able to see minute variations in the fibre's sensitivity to its surroundings at this particular wavelength, which aided in ensure that the required D-shaped profile was achieved.

As shown in Table 2 and Figure 19, the intensity and percentage decrease throughout the various polishing periods have been recorded and assessed and beyond this intensity drop the fibre would snap.

Table 2: D-Shaped Fibre Fabrication: Polishing Time vs. Intensity and Percentage Drop

Polishing Time (Minutes)	Intensity (Counts)	Intensity drop percentage
8.233	15234	0%
13.525	14745	3.2%
13.958	13647	10.4%
14.083	11129	27%
14.167	7615.9	50%
14.208	5232.5	65.7%

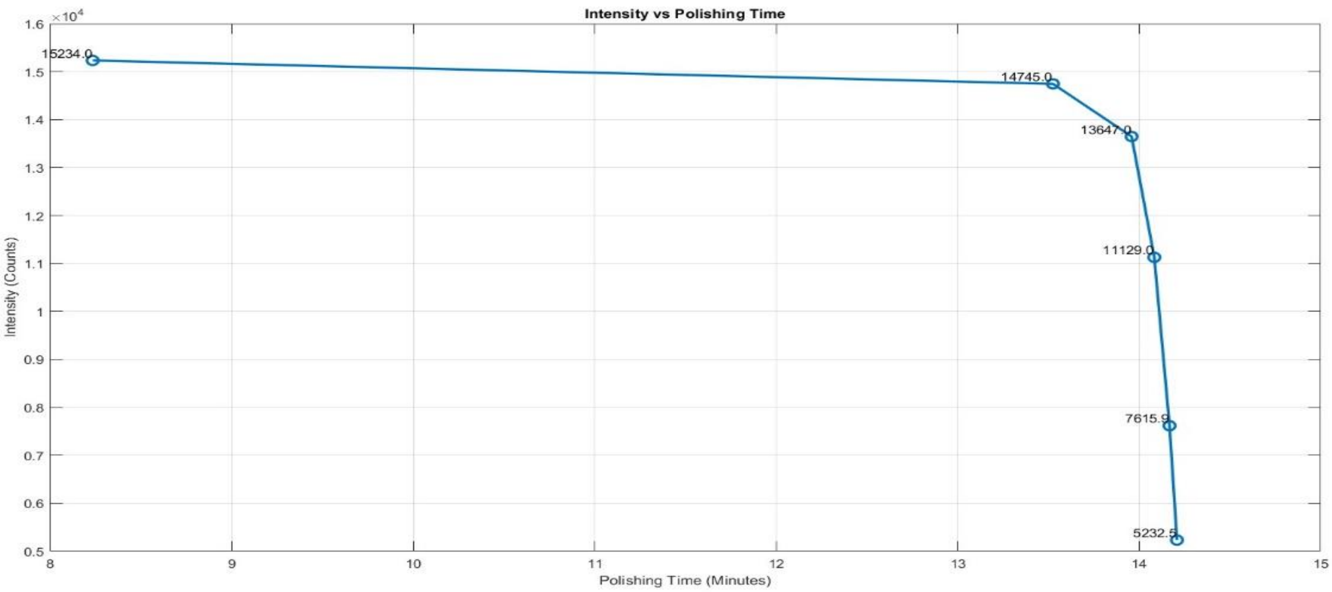


Figure 19: Intensity vs Polishing time for Fabricating D-Shaped Fibres Using Acrylic Mould

The D-shaped fibre is subjected to evaluation of various IPA and deionised water concentrations after attaining a 65.7% intensity decrease. Its intensity is assessed at 650 nm, as shown in figure 20. In increasing concentrations, the IPA is added.

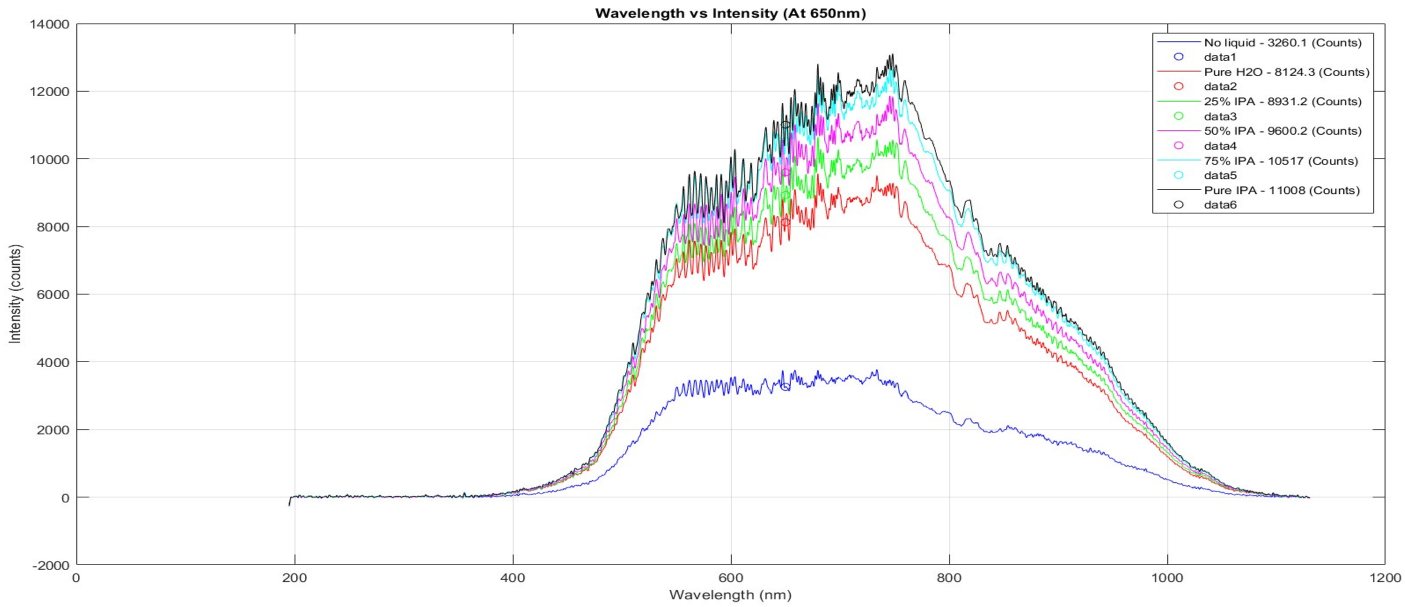


Figure 20: Graph of increasing IPA concentration on D-Shaped fibre in acrylic mould

There is a significant correlation between IPA content, refractive index, and intensity at 650 nm, according to the data in Figures 21 and table 3. The refractive index of the mixture rises in tandem with the concentration of IPA, resulting in a proportional increase in intensity. The greatest intensity shifts are shown between "No liquid" (3260.1 counts) and "Pure H2O" (8124.3), and subsequently between "75% IPA" (10517 counts) and "Pure IPA" (11008 counts). This suggests that the addition of a liquid (water, for example) and the IPA concentration that follows have a substantial impact on the optical properties of the fibre, especially at higher concentrations. This shows that the evanescent field interaction of the D-shaped fibre depends considerably on the refractive index of the surrounding medium, which makes it a viable instrument for accurate refractive index-based sensing.

Table 3: Increasing IPA Concentrations in Deionised Water: Refractive Index and Intensity at 650 nm

IPA Concentration with Deionised water	Refractive Index	Intensity at 650nm (Counts)
No liquid	1	3260.1
Pure H2O	1.333	8124.3
25% IPA	1.355	8931.2
50% IPA	1.3654	9600.2
75% IPA	1.3741	10517
Pure IPA	1.3780	11008

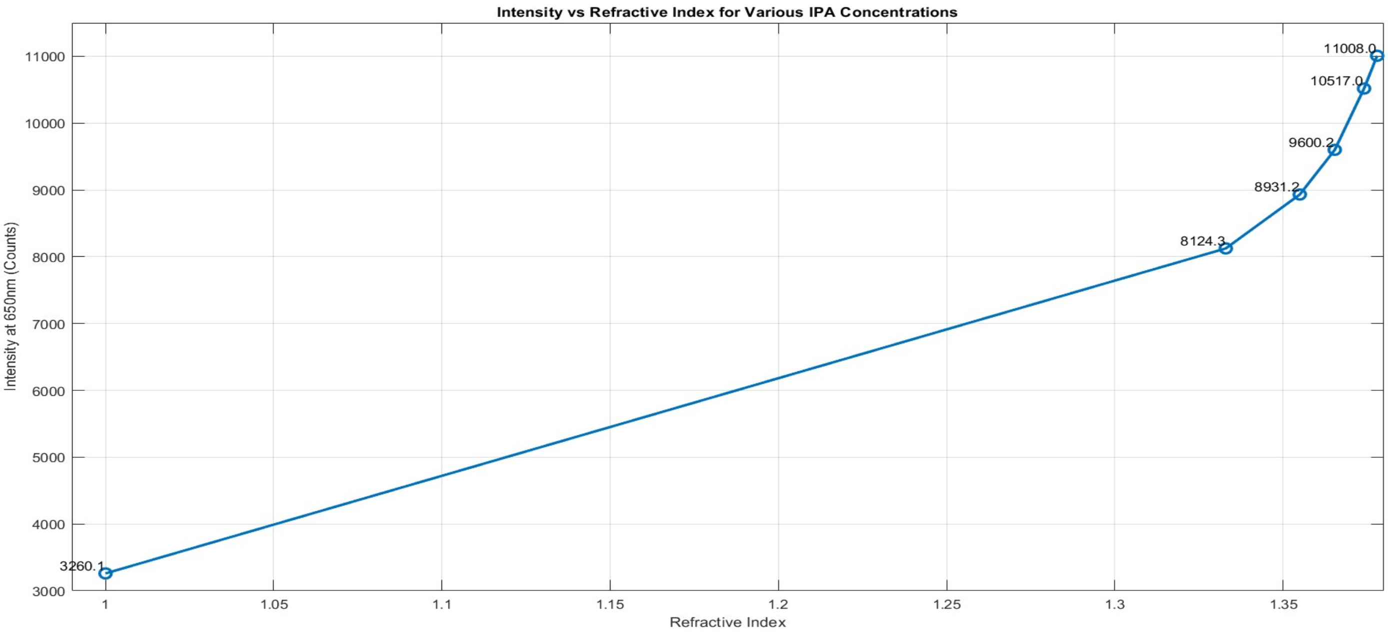


Figure 21: Refractive Index vs intensity for increasing IPA concentration on D-Shaped fibre in acrylic mould

Next, as Figure 22 shows, the identical procedure is carried out using decreasing concentration of IPA.

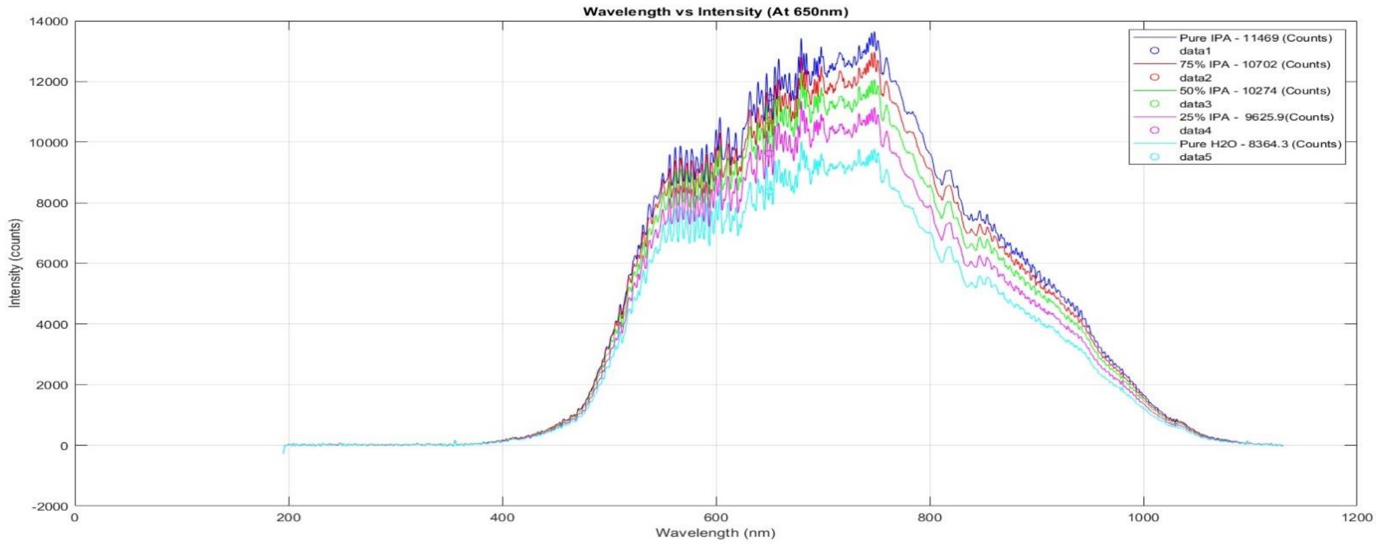


Figure 22: Graph of decreasing IPA concentration on D-Shaped fibre in acrylic mould

As observed in table 4 and figure 23, the intensity measured at 650 nm constantly diminishes as the concentration of IPA drops from pure IPA (100%) to pure H2O (0%). This is the anticipated behaviour, which is consistent with the trend seen in the data on rising concentrations, where intensities increased with IPA concentrations. Pure IPA has a refractive index of 1.3780, whereas pure H2O has a refractive index of 1.333. There is a definite beneficial correlation between the refractive index and intensity, as demonstrated by the data on rising concentration: greater refractive indices are correlated with higher intensity values.

The slight variations in intensity between the sequences of increasing and decreasing concentrations could be related to a minimal hysteresis effect, in which the fiber's reaction to changes in refractive index is somewhat influenced by its prior exposure to various concentrations. The minor variations, however, suggest that the fiber's reaction is largely consistent and reliable.

Table 4: Decreasing IPA Concentrations in Deionised Water: Refractive Index and Intensity at 650 nm

IPA Concentration with Deionised water	Refractive Index	Intensity at 650nm (Counts)
Pure H2O	1.333	8364.3
25% IPA	1.355	9625.9
50% IPA	1.3654	10274
75% IPA	1.3741	10702
Pure IPA	1.3780	11469

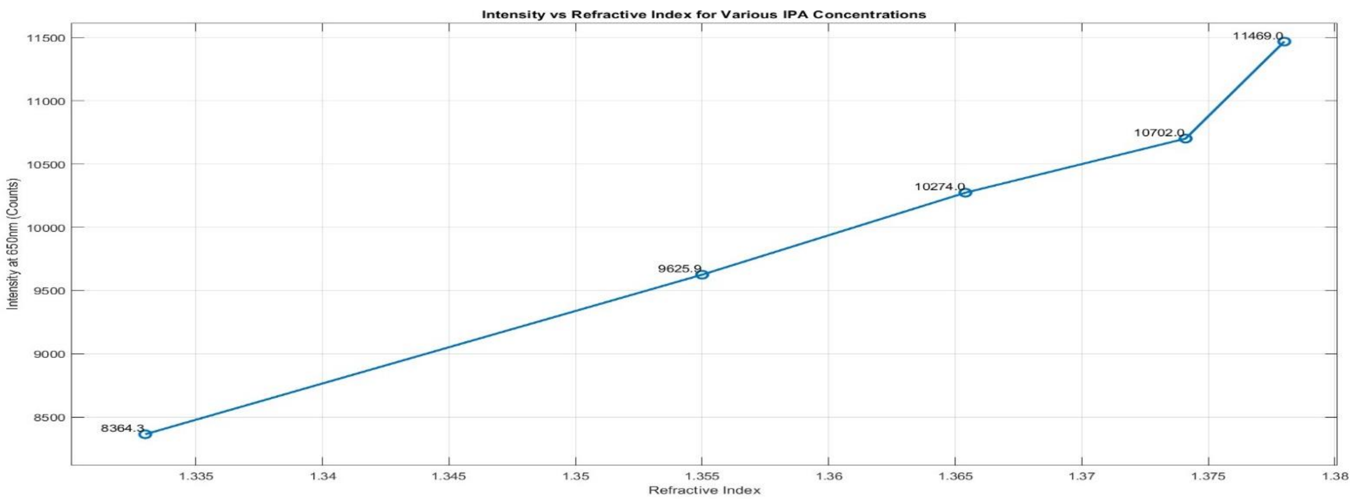


Figure 23: Refractive Index vs intensity for decreasing IPA concentration on D-Shaped fibre in acrylic mould

According to the research, the D-shaped fibre responds to variations in IPA concentration in a steady and predictable manner, with intensity rising in both increasing and decreasing sequences as the refractive index rises. The fibre is especially well-suited for biochemical sensing applications, where accurate and repeatable detection of refractive index changes is essential for measuring biochemical interactions and detecting target analytes with high sensitivity.

5.3 Effectiveness of D-Shaped Fiber Fabrication by Wheel Polishing Mechanism

This fabrication approach effectively created two D-shaped fibres with intensity decreases of 20% and 50% utilising fibre without jacket, employing the setup depicted in Figures 11 & 12. Through Layer-by-Layer (LbL) deposition, the fibre with a 20% intensity reduction was further developed into a sensor, and its ammonia detection capabilities were validated. This illustrates how the wheel polishing mechanism may produce accurate D-shaped fibres that are appropriate for contemporary sensing applications.

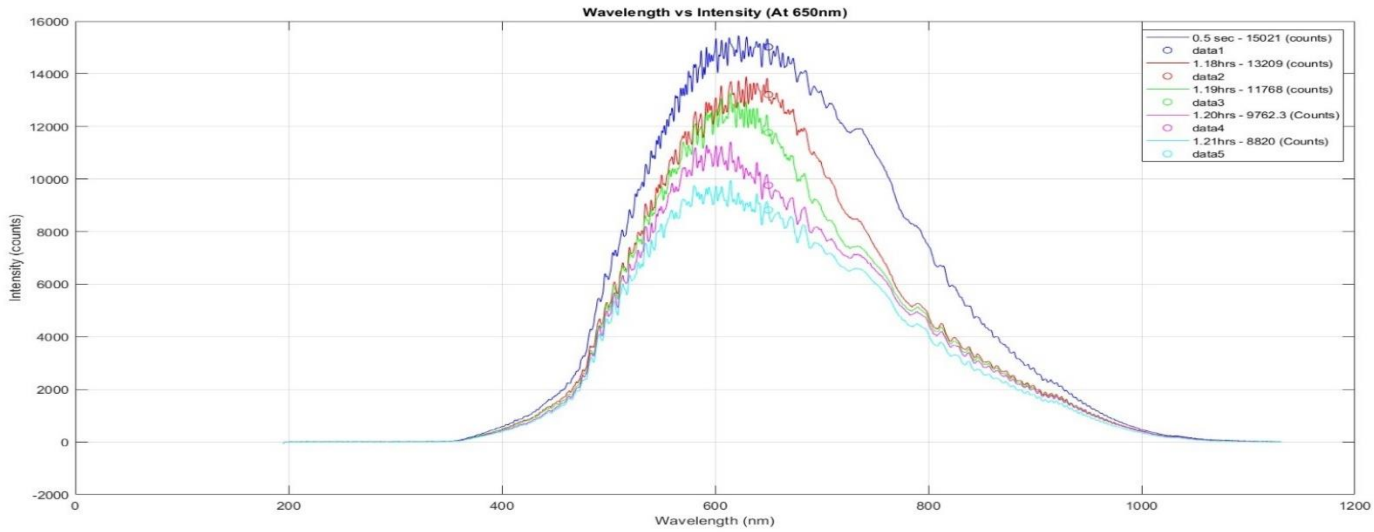


Figure 24: Fabrication of 41.27% (40% approx.) intensity drop D-shaped Fiber

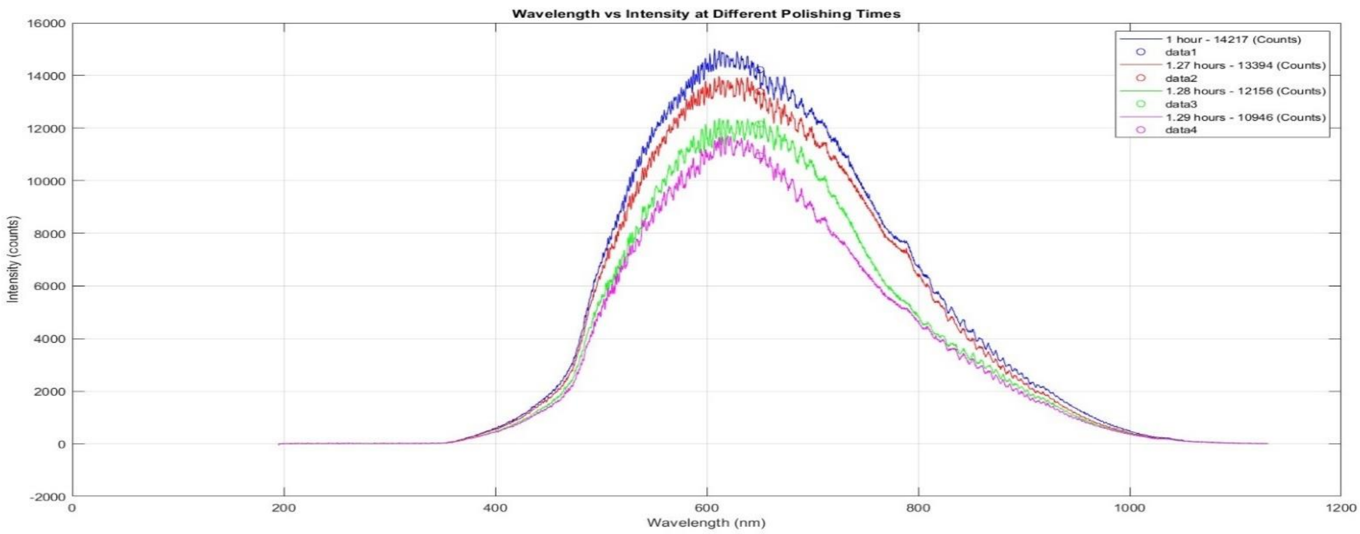


Figure 25: Fabrication of 23.01% (20% approx.) intensity drop D-shaped Fiber

As seen in figures 24 and 25, the graphs reveal that it takes around 1.21 hours to get a 50% intensity decrease and 1.29 hours to reach a 20% intensity drop. The main cause of this variance in time is the modifications made to stand 2's height throughout the polishing procedure. The stand's height was adjusted to 10 cm for a 20% intensity drop and 10.5 cm for a 50% intensity drop.

Furthermore, the spinning wheel's speed was adjusted to 11.28 for a 20% intensity decrease and to 10.007 for a 50% intensity drop. Because the fibre become more brittle as more of the fibre cladding was removed, the slower speed for the 50% drop was required. Reducing the pace of operation reduced the possibility of injuring the fibre, allowing for a more accurate and controlled cladding removal process. The reason the intensity reduction happened quicker at the higher stand height and slower speed is because this modification allowed for a larger area of cladding removal, which led to a deeper angle and depth in the D-shaped fibre than the 20% intensity decrease.

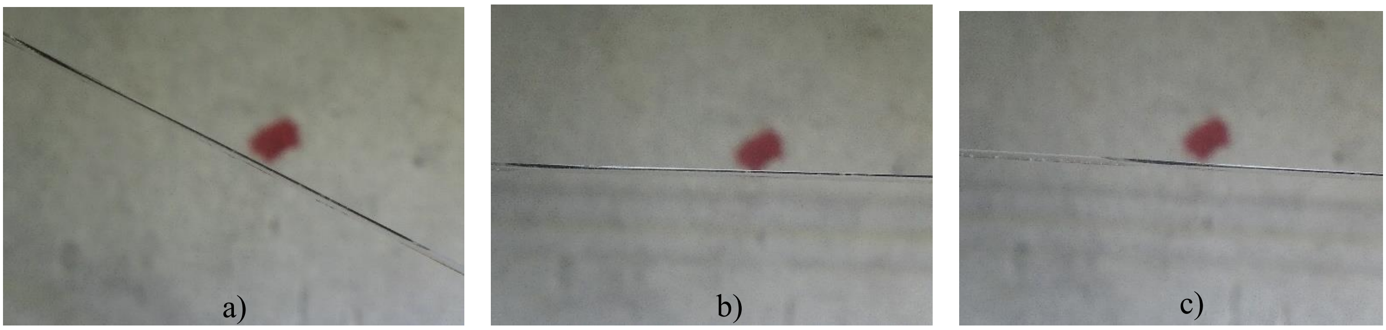


Figure 26: a), b) & c) Different view of the 40 % intensity drop (approx.) d-shaped fibre under digital microscope.

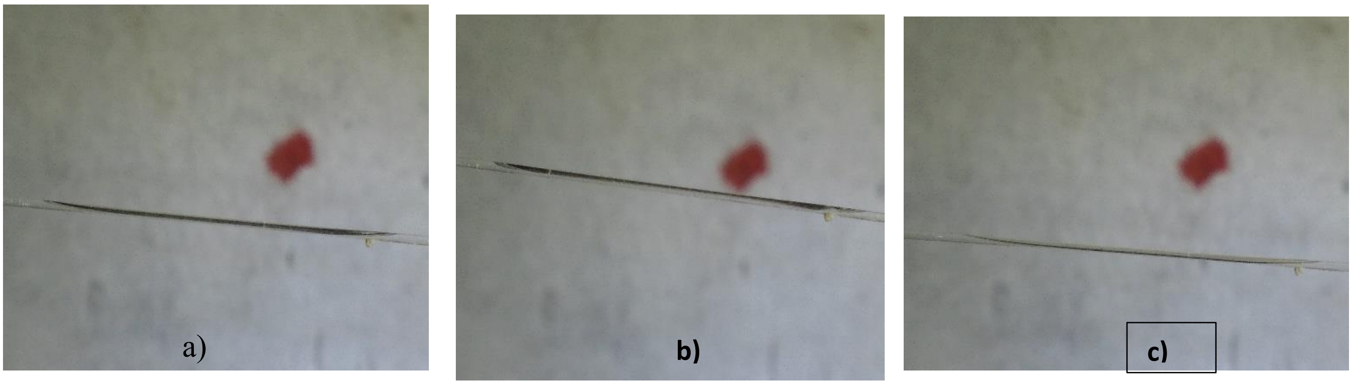


Figure 27: a), b) & c) Different view of the 20 % (approx.) intensity drop d-shaped fibre under digital microscope.

The 50% intensity drop fibre had a more progressive polishing process, with a longer polishing area and more significant cladding removal, as Figures 26 and 27 clearly show. On the other hand, the 20% intensity drop fibre exhibits a larger depth of material removed but a less quantity of cladding removed, with a shorter polishing area.

Table 5: Polishing Parameters and Drop in Intensity for D-Shaped Fibres at Varying Polishing speed and Stand Elevations

D-shaped fibre with 23.7 % Intensity drop (Speed of Polishing Wheel – 11.28RPM, Stand 2 - 10cm)		D-shaped fibre with 41.27 % Intensity drop (Speed of Polishing Wheel – 10.007RPM, Stand 2 – 10.5cm)	
Polishing Time (Hours)	Intensity (Counts)	Polishing Time (Hours)	Intensity (Counts)
1	14217	0.000139	15021
1.27	13394	1.18	13209
1.28	12156	1,19	11768
1.29	10946	1.20	9762.3
		1.21	8820

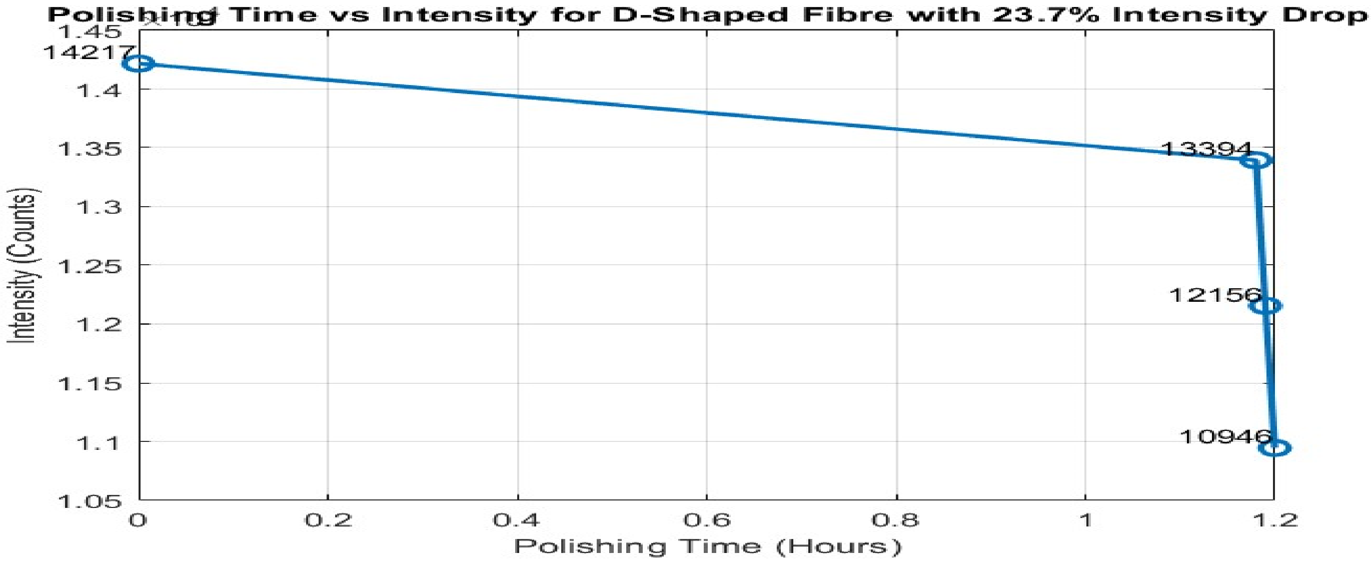


Figure 28: Polishing time vs Intensity for D-shaped fibre with 23.7 % Intensity drop

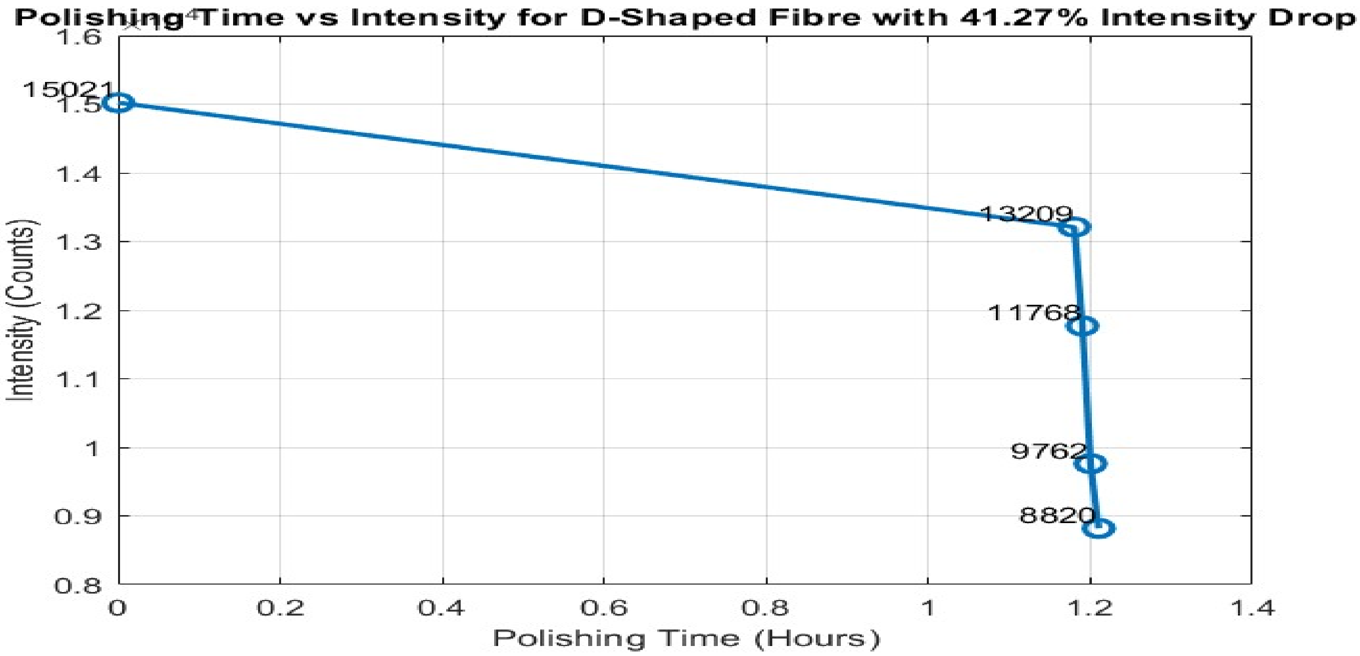


Figure 29: Polishing time vs Intensity D-shaped fibre with 41.27 % Intensity drop

The graph presented in Figure 29 clearly illustrates the 50% intensity drop fibre showed enhanced sensitivity despite the shorter polishing time, suggesting that it might be more effective and efficient for biochemical sensing applications. Because of its enhanced sensitivity, this fibre may be more adept at picking up on minute environmental changes, which is important in biochemical sensing, where accuracy and responsiveness are critical.

5.3.1 Analysis of LBL Deposition Protocol

The DAR/TSPP deposition process was used to further develop the D-shaped fibre into a sensor when it achieved the 20% intensity decrease, as seen in the figure 30. The fiber's sensitivity and specificity were improved by this deposition procedure, which made it appropriate for identifying certain biochemical responses.

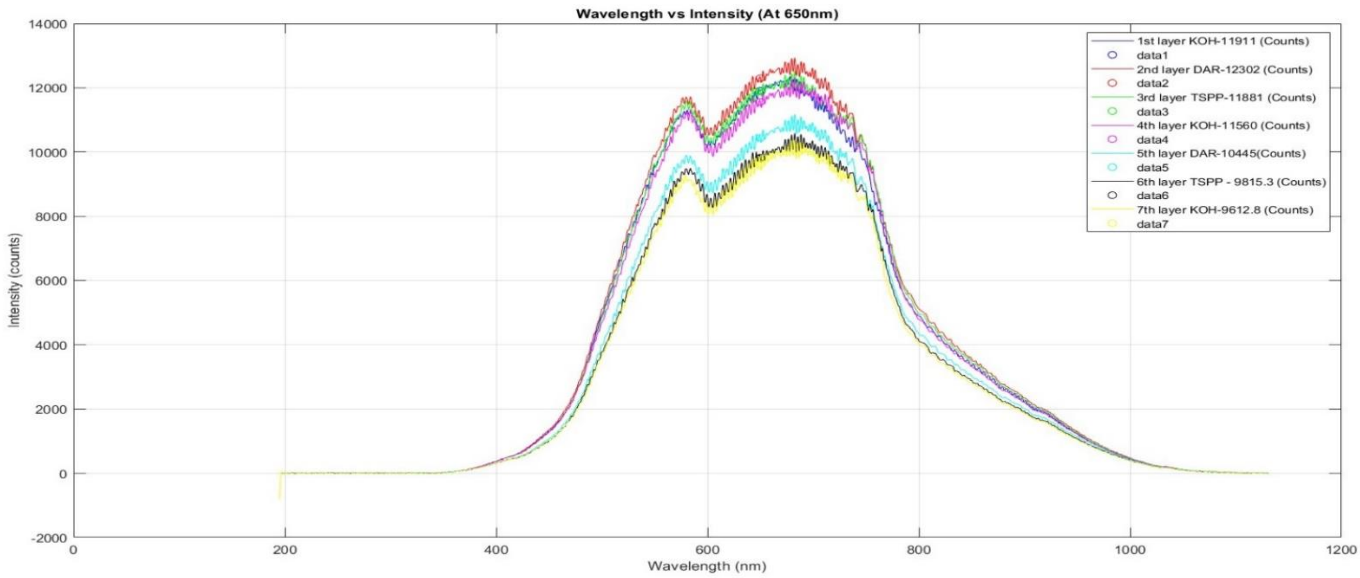


Figure 30: 7 Layers of LBL Deposition (DAR/TSPP Protocol)

The graph shows that the intensity decreases more as the number of DAR/TSPP layers grows, improving the fibre's sensitivity in the process. This enhanced sensitivity makes the fibre more useful for biochemical sensing since it makes it possible to detect even minute changes in the surroundings with greater accuracy. However, for a number of reasons, only 7 layers were placed throughout the deposition process:

- **Optimal Sensitivity:** The fibre's sensitivity reaches its peak after a predetermined number of layers. Subsequent layers could result in diminishing returns, where the complexity and possible hazards posed by adding more levels outweigh the improvement in sensitivity.

- **Structural Integrity:** The mass and total thickness of the coating on the fibre increase with each successive layer. The fibre's mechanical stability and susceptibility to damage might be decreased by excessive stacking, particularly when handling or handling the fibre further.
- **Consistency and Reproducibility:** Keeping the number of layers at 7 guarantees a balance between increased sensitivity and reproducibility of the sensor's performance. Additional layers may cause the deposition process to become more variable, producing conflicting findings for various sensors.

5.3.2 D-shaped Fiber Validation: Ammonia Sensing

Following DAR and TSPP coating, the fibre with a 20% intensity reduction was examined for ammonia sensing.

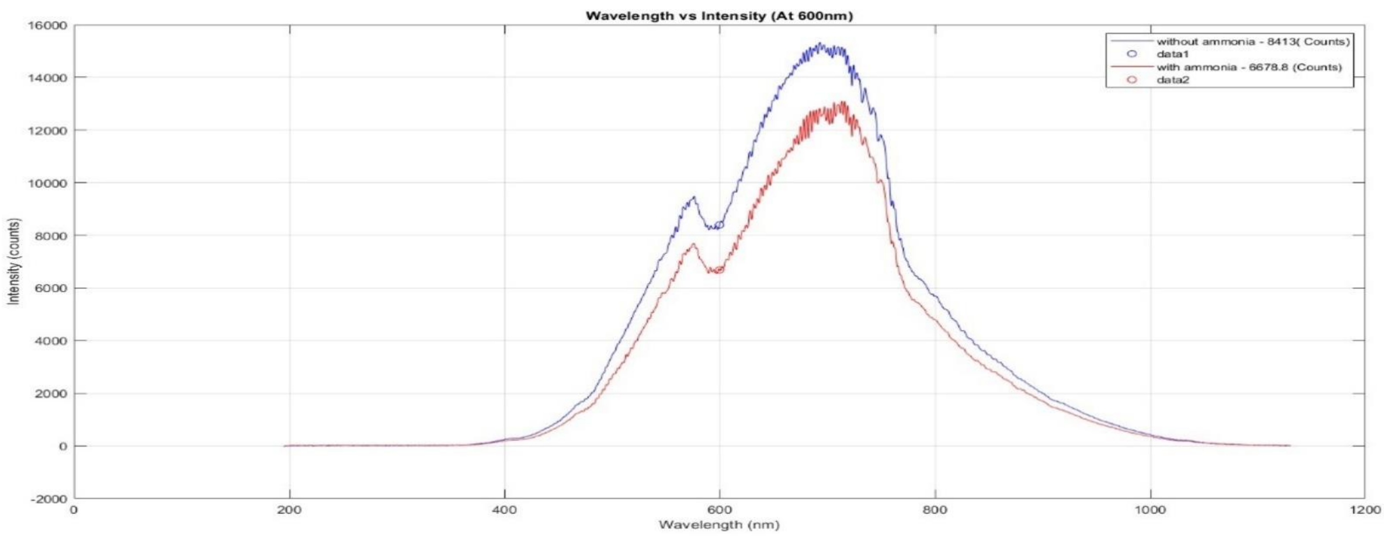


Figure 31: Graph of ammonia sensing with 20% intensity drop

The observations derived from Figure 31 are outlined below:

- **Impact of Ammonia on Intensity:** The intensity decreases to around 6678.8 counts when exposed to ammonia, but the intensity without ammonia is greater, peaking at about 8413 counts. Ammonia significantly reduces intensity throughout the spectrum. The decrease in intensity suggests that the ammonia interacts with the fibre coated with DAR/TSPP, influencing the fibre's ability to transmit light.

- **Intensity dip at 600nm**
    - **Absorption Properties of the Coating:** A drop in intensity at this specific wavelength may be caused by unique absorption properties of the DAR/TSPP coating on the fibre. Due to their molecular structure, some materials, particularly those utilised in thin-film coatings or sensor functionalisation, might show selective absorption peaks or troughs at particular wavelengths.
    - **Interaction with Ammonia:** Another possibility for the drop might be a local absorption peak brought on by an interaction between the DAR/TSPP coating and ammonia. The observed drop at 600 nm could originate from ammonia's interaction with the coated fibre, which may change the refractive index or cause absorption at specific wavelengths.

5.4 Effectiveness of D-Shaped Fiber Fabrication Using Epoxy Resin

The attempt to fabricate a D-shaped fibre with epoxy resin failed as a result of a number of major problems. Below is a detailed description of each of these problems:

- **Air Bubbles in the Mixture**:

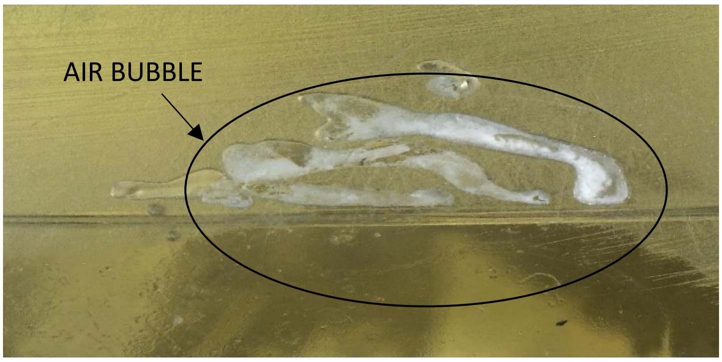


Figure 32: Epoxy resin sample with air bubble

Air bubbles were added to the mixture while the epoxy resin and hardener were being mixed. The final cured material suffered flaws as a result of these trapped air bubbles in the resin. Air bubbles may be especially problematic in fibre optic applications because they cause surface irregularities on the fibre, which can interfere with the evanescent field's homogeneity and perhaps produce false sensing findings or even damage the fibre.

- **Excessive Hardening of the Epoxy Resin**:

The epoxy resin overhardened, hardening far more than was expected. The fibre was so fragile as a result of this over-hardening that it snapped with very little polishing. The resin's brittleness made it extremely difficult to mould the fibre into the required D-profile since it broke with slight polishing pressure.

- **Adhesion to the Silicone Cup**:

Figure 33: Ripped silicone cup during fabrication process with epoxy resin

The high adherence of the epoxy resin to the silicone cup that was utilised as the mould was one of the primary issues. The silicone was firmly bound to the epoxy resin, making it challenging to extract the without causing damage, in contrast to the acrylic mould, which was readily detached after curing. The desired D-shaped profile was broken and the fibre deformed as a result of the strong adhesion.

- **Residue from the Silicone Cup**:

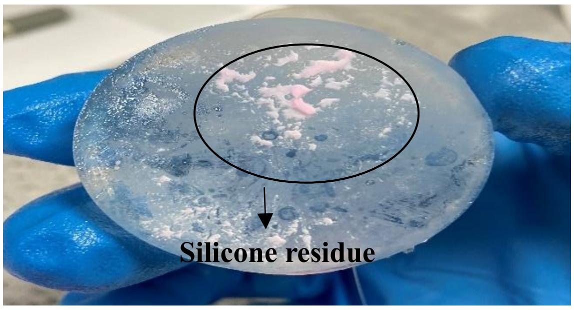


Figure 34: Epoxy resin sample with silicone residue

After the fibre had been removed out of the silicone cup, it was discovered that silicone residue was adhering to the epoxy's surface. The residue from the silicone cup added contaminants that might interfere with the polishing process and degraded the fibre. Due to the possibility of residue pulling off and adding to the already brittle fiber's stress, these contaminants not only reduced the quality of the surface but also raised the possibility of fibre breaking during polishing.

- **Extended Curing Time**:

The epoxy resin needed a lot longer time to cure than expected. The epoxy took 2 hours or longer to set than other materials that cure more quickly, which greatly slowed down the production process. The fabrication was made more difficult by the longer curing period, which also raised the possibility of air bubble production and other complications during the curing process.

- **Surface Stickiness After Curing**:

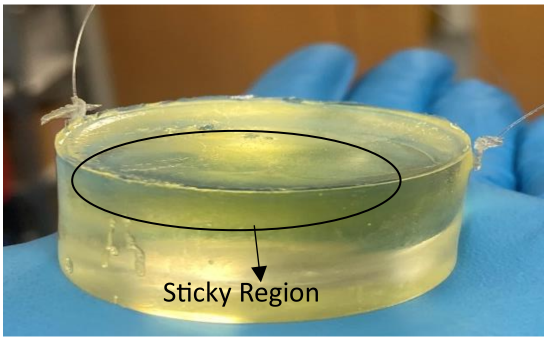


Figure 35: Epoxy resin sample with upper sticky region

The surface of the material stayed sticky even after the epoxy resin had dried. This prolonged stickiness suggested that the resin mix was off or that the curing was not complete. Handling the fibre was challenging due to its sticky surface, which additionally raised the risk of contamination or damage during later processing stages like polishing.

There were several difficulties in creating the D-shaped fibre using epoxy resin, ranging from air bubbles in the mixture to adhesion and curing problems. These issues led to the creation of a fibre that was not only polluted and structurally damaged, but also challenging to shape and polish. These reasons led to the decision that the epoxy resin was inappropriate for this specific application, emphasising the necessity for various materials or altered methods for fabricating D-shaped fibres for optical sensing applications that need sensitivity.

5.5 CHALLENGES AND LIMITATIONS

5.5.1 Initial Fabrication: Partial curing

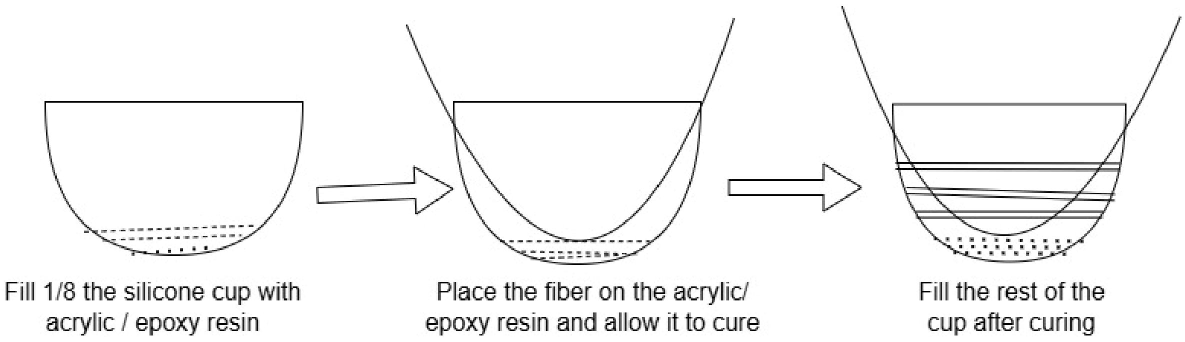


Figure 36: Steps for encapsulation through partial curing

The first method was to use the SamplKwik acrylic mix and epoxy resin to partially fill a silicone cup, about 1/8 of the way. Originally, the fibre was supposed to be placed into the mould after the acrylic/epoxy resin mixture had half set, which took around five minutes to two hours to cure. The fixing effort was unsuccessful because the fibre drifted as the mould started to dry, preventing it from obtaining the proper orientation.

5.5.2 Limitations Faced During the Fibre Encapsulation Process

There were various kinds of difficulties with the fibre fixation procedure throughout the production of the D-shaped fibre, especially when employing acrylic and epoxy resin.

Process Step	Challenge	Solution	Outcome
Preliminary attempt at fixing fibre in acrylic	Difficulties in Partial Curing: While partial curing, the fibre floated, making it difficult to place.	The silicone cup's upper rim was slitted slightly to create a secure retaining area for the fibre.	Throughout the curing process, the fibre was kept firmly in place, guaranteeing proper alignment for the following stages.

Using Blu-Tack to Secure	Adhesion Issue: Blue tack was unable to adhere securely on the smooth silicone surface, which resulted in the fibre shifting.	A dependable way to hold the fibre in place while it cured was through slits in the silicone cup's rim.	prevented fibre movement, enabling secure and accurate curing placement.
Meniscus Formation	Meniscus Development The formation of meniscus produced by heat emission during the mixing of SamplKwik Liquid Fast Cure Acrylic (20-3564) and SamplKwik Powder Fast Cure Acrylic (20-3562) disrupted the mixture's uniform distribution and enabled uneven polishing.	To stop meniscus development, a piece of glass was glued to the bottom of the cup using optical adhesive.	Facilitated the acrylic mixture's drying process by ensuring a smooth and equal surface.

5.5.2.1 Fluctuation Based on the Fibers Load Application

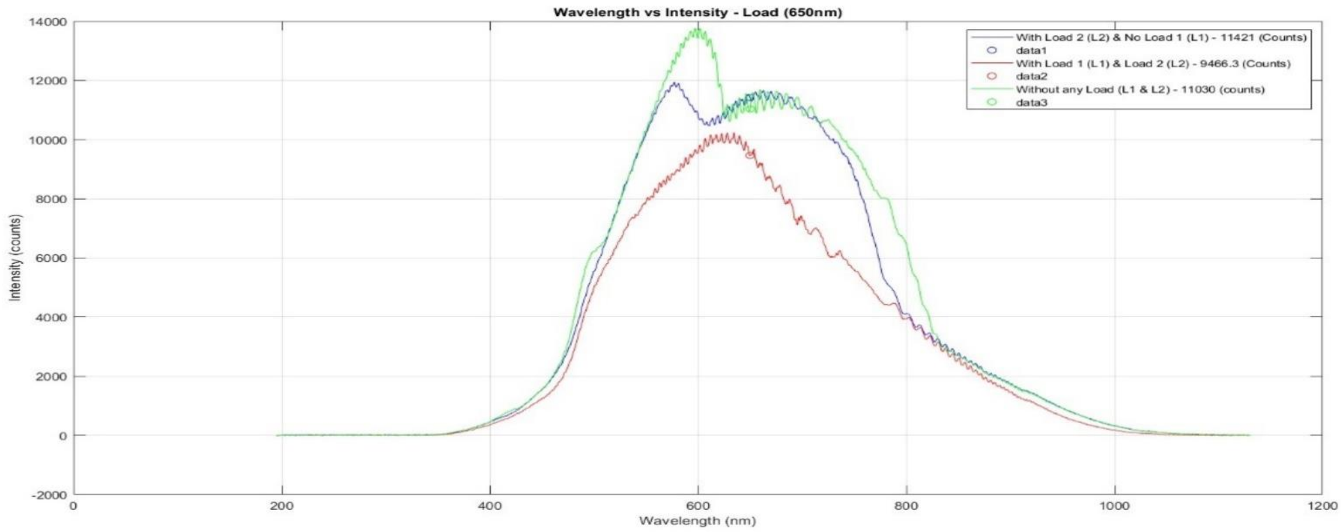


Figure 37: Variation due to Load L1 & L2

The intensity profile of the D-shaped fibre is clearly affected by the load application, as can be seen in the figure 37. A compression effect is specifically shown by a sharp reduction in intensity when the fibre is exposed to the stress.

- **Effect of Load on Fibre Structure:** Mechanical stress caused by a load applied to a fibre may alter the fibre's physical structure. The fibre may microband as a result of this tension, which will weaken the light that passes through it more. The cladding or core of the fibre may compress as a result of the applied stress, altering the distribution of refractive indices inside the fibre. This redistribution may cause more light to be scattered or absorbed, which would result in a noticeable decrease in intensity.
- **Load-Induced Optical Losses:**
    - **Bending Losses:** Regardless of how little the bending is, the load may cause the fibre to bend. When light passing through a fibre encounters bends that diverge from its intended route, bending losses take place. A further decrease in transmitted intensity results from this deviation because some light escapes the core, particularly in a D-shaped fibre where the cladding has already been partially removed.

- **Stress-Optical Effects:** Stress-optical effects are a result of load-induced stress that alter the refractive index of the fibre material. Additional light scattering or reflection inside the fibre as a result of this alteration may result in additional intensity loss.

6 CONCLUSION

Using acrylic mould encapsulation and wheel polishing procedures, D-shaped optical fibres were successfully fabricated. The required D-shaped profile was obtained via thorough process optimisation, which included fine tuning the polishing settings and fibre fixation. Consistent outcomes were assured throughout the fabrication process since the acrylic mould encapsulation offered the required solidity and support. Furthermore, it was found that the wheel polishing process was a useful technique for eliminating the cladding and improving the evanescent field's interaction with the surrounding environment. This increased sensitivity of the fibre is important for biochemical sensing applications.

Layer-by-layer deposition of DAR/TSPP was employed to further develop the fibres generated with a 20% intensity reduction into sensors. These sensors showed great potential for applications involving biochemical sensing, such ammonia detection. The produced D-shaped fibres' increased sensitivity was validated by the notable intensity decreases seen in a variety of settings, which means that they can accurately detect the most minor biochemical interactions.

Future research will concentrate on designing a sensor with a 50% intensity decrease made of D-shaped fibre. With additional cladding removed and polishing conditions optimised, this fibre showed considerably higher sensitivity, suggesting considerable potential for demanding biochemical sensing applications. The 50% intensity drop fibre may be further improved to provide a highly sensitive and dependable sensor for sophisticated biochemical and environmental monitoring by using comparable deposition procedures and carrying out thorough testing. This research establishes a solid framework for future advancements in optical fibre sensor technology, especially in the area of biochemical sensing.

APPENDIX

Activity / Task Risk Assessment Form

Business Unit:	**Location(s) of Activity: Optics and Photonics Research Group**	**Risk Assessment Ref:**
Activity Title: Fabrication of D Shaped Optical Fibers for Sensing Applications		
Activity Outline: The aim of this project is to design and refine D-shaped optical fibre fabrication systems for sensing applications, specifically biochemical sensing. By using cutting-edge methods including precise polishing, encapsulation inside unique moulds, and embedding inside 3D-printed structures, the goal is to improve the strength and functioning of these fibres.		
Those at risk / affected parties: Student, laser workers, non – laser worker, others e.g. cleaners, maintenance, contractors, visitors)		
Risk As Name: Jerusha Beulah Jawahar Wilson David	Signature:	Date: 06/05/2024
Responsible person / Line Manager Name: Dr. Ricardo Corriea	Signature:	Date:06/05/2024
Master Risk Assessment Reference where applicable:	**Related procedure references or links:**	

What are the hazards?	List the harm associated with the hazard	Risk Evaluation without controls in place High/Med/Low	What control measures are, or will be put, in place to control the risk? List all elimination, substitution, engineering and/or administrative controls	Risk Evaluation with controls in place High/Med/Low
Laboratory Hazard	Vulnerability to chemicals, electrical equipment, and sharp items while working in a laboratory.	Med	• Obtain the required safety training for laboratories before commencing any work. • Consistently put on personal protection equipment (PPE) suitable for the job, such as lab coats, gloves, and safety glasses. • Keep your workstation tidy and orderly to minimise the risk of slips and falls. • Know where safety equipment, such as fire extinguishers and eyewash stations, is located and how to use it appropriately. • Adhere to the safety data sheets' (SDS) recommended practices for the handling and disposal of chemicals.	Low

Eye Damage	When using lasers for alignment or characterisation, attention needs to be taken to prevent eye injury.	High	• Wear laser safety goggles that are appropriate for the laser wavelength and have the right optical density. • In the vicinity of laser operation places, post warning signs. • To avoid inadvertent beam exposure, secure the laser configuration.	Med
Mechanical Hazard	Sharp edges and dust particles can be generated during machining or polishing operations.	Med	• To protect yourself from airborne particles, employ the proper respirators or dust masks. • When interacting with sharp items or using machinery, wear gloves and safety eyewear. • To keep materials from transforming into projectiles, securely clamp them during milling operations. • Put sharp waste items in the proper containers for dumping.	Low
Electrical Hazard	Electrical shock risks might arise from electrical equipment used for testing or manufacture.	Med	• Before using, check equipment and electrical cables for breakage. • Never use wet hands to handle machinery or use it near water sources. • When dealing conductive materials or water, use Ground Fault Circuit Interrupter (GFCI) outlets.	Low
Machine Breakage	Broken machine parts or components. exposed live wires, short circuits, Friction or sparking, certain machines containing volatile substances,	Low	• Carry out routine preventive maintenance on all equipment in compliance with the instructions provided by the manufacturer. • Before each usage, check the equipment for signs of wear and tear. • To prevent abuse, familiarise yourself with proper operation techniques. • Establish a procedure for securely isolating and shutting down equipment in the event of a problem.	Low
Limited Supply of Crystal Bond	production lines may be forced to halt,	Low	• Find other materials that may be easily accessible and have comparable qualities.	Low

	Increased Cost, Quality Issues		• Taking lead times and any delays into account, order enough crystal bond to finish the job. • To reduce waste during mould manufacture, put a conservation plan into place. • Take into account substitute mold-making methods that might not call for the crystal bond.	
Problems with the Fabrication of the Mould	Heat and burns, Fire and Explosion Risks, Ergonomic Hazard	Med	• Create a precise mould creation process to guarantee reproducibility and uniformity. • Before employing the real crystal bond or final mould material, practise and test the mould construction method using waste materials. • Keep a careful eye on the mould creation procedure and spot any possible problems early. • Have a fallback strategy in place in the event that the Mould fails or isn't up to par. This might entail building the Mould anew, employing other manufacturing techniques, or getting the crystal bond from another source.	Low

Activity / Task Risk Assessment Form

University of Nottingham
UK | CHINA | MALAYSIA

Justification for selection of controls

Summarise justification for selecting control measures that are not to the highest, reasonably practicable standard or compliant with industry standard e.g. use of personal protective equipment rather than engineering means of control: State N/A if not applicable

Additional Requirements (if not recorded elsewhere)

First Aid	**Amy Pearson: (L4-A08/09)** amy.pearson@nottingham.ac.uk **Chris Sprange: (L4- APM Hub B02)** christopher.sprange@nottingham.ac.uk
Waste handling	
Emergency	**Emergency Number: 8888**
Training, supervision and competency	**The Procedure should be carried out during operational hours (9am to 5pm, Monday through Friday)**
Other	**All the activity only**

Competency Record

Name of worker	Measure of competency	Assessor comments	Competent to perform activity Y/N?	Signature (Worker)	Signature (Assessor)	Date

Activity / Task Risk Assessment Form

Guidance on completing the form

This form may be used to record the risk assessment for any University activity whether that be lab or workshop-based, an event, on or off-site working, etc. Separate templates exist for Biological work, Laser work and Fieldwork.
Only complete a risk assessment if you have a good understanding of the activity being assessed and you have been instructed in the principles of carrying out a risk assessment (refer to your Business Unit arrangements on risk assessments).

- **Responsible Person**
  The manager who is responsible for the activity should approve the risk assessment, this indicates they agree the risk assessment is sufficiently detailed, they agree the control measures are appropriate and will be implemented and they authorise the work to commence. The Responsible Person may be a PI in the academic setting or a local line manager or head of section in non-academic sections of Schools/Faculties and Professional Services.

- **Those at risk / affected parties**
  Identify individuals or groups of people who might be affected by the Hazard. Besides staff and students consider visitors, members of the publics, volunteers and others who could be affected.

- **What are the hazards?**
  The definition of a Hazard is the potential for something to cause harm, e.g. chemicals, radiation, lasers, fire. In the Hazards column, list the hazards which could reasonably be expected to result in significant harm.

- **List the harm associated with the hazard**
  For each hazard, there may be one or more types of harm that could occur. For example, working with cryogenic substances - harm may be asphyxiation, cold burns or fire/explosion and each is likely to require different control measures to be implemented. It is recommended each is given a separate line on the form.

- **Risk Evaluation – High (H), Medium (M) or Low (L)**
  Decide whether the hazard presents a high, medium or low risk, based upon your knowledge of the severity of harm, frequency of activity and number and nature of the people involved. This is subjective which is why you must have good knowledge of the activity in order to undertake the risk assessment. Hazards that remain high risk once evaluated after control measures are put in place, must not proceed without further consideration.

- **What control measures are, or will be put, in place:**

List what is, or will be put in place to reduce the likelihood of harm or make any harm less serious. These precautions should meet legal standards, represent good practice and reduce risk as far as reasonably practicable. They should also take into account the hierarchy of control and favour elimination, substitution, engineering methods over administrative controls. Fundamentally, ensure the risks are reduced so far as is reasonably practicable.

- **Review Period:**

  The University advises that all risk assessments are revised every two years to ensure validity. For activities undergoing change, consider a shorter timeframe for review. For lower risk activities, you may consider a longer timeframe. Comply with your Business Unit arrangements.

- **Justification for selection of controls**

  In brief, the hierarchy of control in terms of robustness is: (1) Elimination (2) Substituion (3) Engineering Control (4) Administrative Control. If not implementing a higher level of control, justify the reasons why a low level is appropriate in the situation.

- **Areas for additional consideration in your risk assessment or associated procedures**

  Consider training and supervision, manual handling, waste disposal, first aid, emergency situations such as spillage, access to medical assistance. It may be more appropriate for these to be covered as part of a safe working procedure or standard operating procedure.

Code for graphical representation of data collected

```
% Extract time from the file labels
time = [3.258,6.1,6.1083,6.166];

% Extract the intensity values from the table
intensity_at_650nm = intensityTable.Intensity_at_650nm;

% Plot the graph time vs Intensity
figure;
plot(time, intensity_at_650nm, '-o', 'LineWidth', 2, 'MarkerSize', 8);
xlabel('Time (minutes)');
ylabel('Intensity at 650 nm (Counts)');
title('Intensity at 650 nm vs Time');
grid on;

% add text labels to each data point
for i = 1:length(time)
    text(time(i), intensity_at_650nm(i), sprintf('%.2f', intensity_at_650nm(i)), ...
        'VerticalAlignment', 'bottom', 'HorizontalAlignment', 'right');
end
```

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