DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

DEVELOPMENT OF BLOOD FLOW SENSOR USING OPTICAL FIBRES

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ABSTRACT

The development of an optical fibre-based blood flow sensor represents a significant advancement in medical diagnostics and patient care. This thesis describes a proof of concept for the design, fabrication, and testing of a novel blood flow sensor based on Fibre Bragg Gratings (FBGs) embedded in single-mode and multi-mode optical fibres. The ability of the sensor to measure blood flow rates is dependent on heating the FBG with an external light source, and the resulting temperature variations are recorded as shifts in Bragg wavelength. The study involves constructing a phantom flow system to imitate physiological conditions, calibrating a peristaltic pump for precise flow rate control, and comparing the performance of three different light sources—WLS100, HL2000, and SLS201L/M—in heating the FBG. The results demonstrate that the WLS100 light source delivered the most significant wavelength shifts, demonstrating higher heating efficiency, but the SLS201L/M had minimal effectiveness. Furthermore, silver and PDMS coatings were applied to the optical fibres to improve their durability and optical performance. The study concludes that the proposed sensor is highly sensitive and could potentially be integrated into medical devices for real-time blood flow monitoring in both arterial and venous systems. Future study will focus on improving the sensor's performance for bidirectional flow measurement and translating it into clinical settings.

Keywords: Optical Fibre, Blood Flow Sensor, Fibre Bragg Grating, Heating Light Source, Phantom Flow System, Peristaltic Pump Calibration, Silver Coating, PDMS Coating, Bi-Directional Flow Measurement.

CHAPTER 1: INTRODUCTION

Blood flow measurement is a vital parameter of various medical applications, such as monitoring patients in critical care units and diagnosing cardiovascular diseases.
Conventional techniques for monitoring blood flow, like magnetic resonance imaging (MRI) and Doppler ultrasound, can have significant limitations. These procedures can be bulky, invasive, and require specialized personnel to operate, making them less ideal for continuous monitoring and real-time data acquisition [1].To overcome these constraints, this project aims to develop an optical fibre-based blood flow sensor. Optical fibres present several advantages for blood flow sensing due to their thin, flexible, and minimally invasive nature, making them suitable for use in delicate environments like blood vessels [1] Additionally, optical fibres can efficiently transmit light, which enables remote sensing and data acquisition, increasing their potential for widespread medical applications.

The justification of this project is its potential to revolutionise healthcare diagnostics and patient care. A reliable optical fibre-based blood flow sensor could aid in the early diagnosis of cardiovascular issues, improving patient outcomes. This sensor could significantly enhance surgical procedures by delivering precise, real-time blood flow data, as well as help control chronic illnesses like hypertension and diabetes. The minimally invasive design of optical fibre sensors decreases the possibility of difficulties associated with standard blood flow measuring techniques. Furthermore, continuous monitoring capabilities could provide useful information for real-time patient care, thereby lowering morbidity and mortality rates associated with cardiovascular disease.

However, developing an optical fibre-based blood flow sensor presents a number of challenges. One of the primary challenges is optimising the sensor's accuracy to enable consistent results under a variety of physiological conditions [2]. Another important aspect is biocompatibility, which requires the sensor to be safe for long-term usage within the human body without generating unwanted effects [3]. Furthermore, enhancing signal processing techniques is essential for effectively interpreting data transmitted by the optical fibres, particularly in the dynamic and complex environment of the human circulatory system. Addressing these problems is critical to the effective implementation and clinical use of optical fibre-based blood flow sensors.

1.1 BACKGROUND

Invasive blood flow measuring techniques are essential in many medical contexts, especially cardiovascular diagnosis and surgery. These approaches involve inserting medical instruments into the body to directly assess blood flow within arteries or heart chambers. Such devices, while needing implantation into the body, provide unparalleled precision and are critical in high-risk cardiovascular procedures.

- **Thermodilution Catheters**

Thermodilution is a common method for determining cardiac output, which is an indirect measure of blood flow. It requires the use of a pulmonary artery catheter, also known as a Swan-Ganz catheter. A cold saline solution is injected into the right atrium, and the change in blood temperature as it goes through the heart is monitored, allowing cardiac output to be calculated. This technique is commonly used in critical care and during cardiac surgery to evaluate the heart's function and guide therapeutic measures [4], [5].

- **Electromagnetic Flowmeters**

Electromagnetic flowmeters monitor blood flow by detecting the voltage generated when blood (a conductor) flows across a magnetic field induced by the device. This voltage varies in proportion to the velocity of blood flow. The device is usually inserted around a blood artery to provide real-time flow measurements. These devices are frequently employed in vascular surgery and research settings to provide exact measurements of blood flow in specific arteries or veins [6].

- **Transit-Time Ultrasound Flowmeters**

Transit-Time Flow Measurement (TTFM) provides real-time data on mean graft flow, pulsatility index, diastolic filling, and backward flow, allowing surgeons to evaluate graft functionality and make intraoperative decisions such as graft revisions. High-Frequency Ultrasound (HFUS) is often used in conjunction with TTFM to offer thorough imaging of grafts, revealing abnormalities such as intimal flaps that would otherwise go undetected. Additionally, while Fractional Flow Reserve (FFR) is commonly connected with percutaneous coronary intervention (PCI), it is also used in coronary artery bypass grafting (CABG) to determine the physiological significance of coronary artery stenosis and guide graft placement decisions. These devices improve the precision and success of CABG by providing vital, real-time information during surgery. [7]

- **Intravascular Ultrasound (IVUS)**

IVUS is an imaging technique that attaches an ultrasonic probe to the distal end of a specifically designed catheter. By inserting this device into a blood vessel, one can evaluate flow and vascular anatomy by obtaining cross-sectional images of the lumen and vessel wall. IVUS is mainly used to guide stent insertion and evaluate the shape of the plaque during coronary artery operations. Additionally, it is used in research settings to examine how different treatments affect arterial flow [8].

- **Doppler Flow Probes**

Doppler ultrasonography sends ultrasonic waves from the probe into blood vessels, where they reflect off moving red blood cells, resulting in a Doppler shift, or the difference between the transmitted and received frequencies. This shift aligns with blood velocity, allowing for precise monitoring of blood flow. Invasive measurement with Doppler flow probes, which are put directly into blood vessels, yields precise and localised flow values that are critical for diagnosing vascular issues and performing research. Proper calibration and alignment are critical, especially for small or tortuous vessels, making Doppler flow probes essential for precise monitoring of vascular health [9].

1.2 MOTIVATION

The motivation for developing an optical fibre-based blood flow sensor stems from the critical need for improved means of monitoring and diagnosing cardiovascular health. Current techniques, such as Doppler ultrasound and MRI, are widely utilised but have significant limitations in terms of bulk, invasiveness, and the need for specialised operators. These limitations limit their application in continuous and real-time monitoring, which is critical for optimal patient management in a variety of medical scenarios.

- **Enhanced diagnostic capabilities**

Cardiovascular diseases (CVDs) are the major cause of death worldwide, needing advanced diagnostic tools for early identification and treatment. Because of their high sensitivity and specificity, optical fibre sensors can give more precise blood flow measurements, which are crucial in the diagnosis of illnesses such as atherosclerosis and peripheral artery disease. Studies have shown that optical fibre sensors have the ability to provide detailed hemodynamic data, resulting in better clinical outcomes.

- **Minimally invasive and flexible**

The fact that optical fibre sensors are minimally invasive gives them a significant advantage over traditional approaches. These sensors can be inserted into blood vessels with little discomfort for the patient, lowering the risk of problems including infections and vascular damage. Their flexibility allows them to easily navigate the intricate circulatory network, making them useful for a variety of clinical applications. Research has shown that minimally invasive procedures not only improve patient comfort but also shorten healing durations and hospital stays.

- **Real-time Monitoring**

Real-time blood flow monitoring is essential for managing critical care patients and performing surgical procedures. Optical fibre sensors can give continuous data, allowing physicians to make fast decisions based on current information. This continuous monitoring capacity is especially useful in critical care settings, when fast changes in the condition of a patient must be treated immediately. Advances in optical fibre technology have proved their usefulness in providing real-time, high-resolution data, which can have an important impact on patient management.

- **Technological advancements**

Recent advances in optical fibre technology, such as improvements in sensor design, biocompatibility, and signal processing, have made it possible to construct more sophisticated and reliable blood flow sensors. These technological advances have made optical fibre sensors a viable alternative to traditional blood flow measuring techniques.

1.3 AIMS AND OBJECTIVES

The aim of this project is to develop a versatile blood flow sensor that uses optical fibres to accurately measure blood flow rates by heating the sensor and measuring temperature changes.

The following objectives will be accomplished in order to achieve the above goal:

1) Design and Fabrication of Blood Flow Sensor
    - Develop a prototype blood flow sensor using optical fibre technology that is compact, flexible, and suitable for insertion into biological environments.
2) Implement Blood Flow Measurement Techniques

- Heated Sensor Method: To measure blood flow rates, heat the sensor and observe temperature changes caused by blood flow.

3) Optimize Sensor Performance Using Fibre Bragg Gratings (FBGs)
    - Integrate Fibre Bragg Gratings into the sensor design to enhance sensitivity and accuracy in measuring blood flow rates.
4) Design and Fabrication of a Blood Flow Phantom System
    - Develop a model of the blood flow system (phantom) to validate and calibrate the blood flow sensor under controlled conditions that mimic physiological flow dynamics.
5) Performance Optimization and Calibration of the Sensor
    - Conduct thorough testing and calibration methods to optimise the sensor's performance, delivering accurate and dependable blood flow readings across a wide range of physiological conditions.

CHAPTER 2: LITERATURE REVIEW

The fibre-optic sensors use the principles of light propagation through optical fibres to precisely and effectively analyse fluid flow characteristics. To support this project, a comprehensive evaluation of relevant research provides important insights into existing approaches, challenges, and opportunities in the field of flow sensing technology.

2.1 Fibre optic intravascular measurements of blood flow [1]

This literature review is based on the paper "Fibre optic intravascular measurements of blood flow: A review" by E.C. Mackle, J.M. Coote, E. Carr, and others, which has been cited 122 times. The National Institute for Health Research UCL Biomedical Research Centre and the Wellcome/EPSRC Centre for Interventional and Surgical Sciences (WEISS), both recognised biomedical research institutes, supervised the research and review. Clinical trials and testing are frequently undertaken in hospital settings or other healthcare facilities that specialise in the performance of interventional cardiology treatments. The research was published in the journal "Sensors and Actuators: A. Physical" in 2021, therefore it is a relatively new source of knowledge on intravascular flow measurements.

The purpose of this review is to assess intravascular blood flow measurements that are critical for understanding a variety of physiological and pathological conditions in the human vascular system. Traditional technologies, such as Positron Emission Tomography (PET), Magnetic Resonance Imaging (MRI), and external Doppler ultrasound, have drawbacks such as invasiveness, resolution, and long procedure times that restrict their use in real-time clinical settings. Fibre optic sensors offer a possible alternative by providing direct, real-time, and less intrusive blood flow measurements, potentially integrating smoothly into other medical devices.

The study methodically investigates many ways of measuring intravascular flow, starting with methods such as Thermodilution, Thermal Anemometry, Laser Doppler Velocimetry (LDV), Optical Coherence Tomography (OCT), Speckle Imaging and Photoacoustic Flowmetry.

Fibre Optic Intravascular Blood Flow Measurement Techniques	
TECHNIQUE	**DESCRIPTION**
Thermodilution	Measures blood flow by injecting thermal energy and recording temperature changes downstream using fibre optic sensors.
Thermal Anemometry	Measures blood flow through heat dissipation from a heated element, with fibre optics providing high sensitivity and real-time data.

Laser Doppler Velocimetry (LDV)	Detects blood cell velocity using the Doppler shift of laser light. Fibre optics allow for minimally invasive, precise blood flow monitoring in microscopic vessels.
Optical Coherence Tomography (OCT)	Enables high-resolution vascular imaging. Doppler OCT detects blood flow by detecting phase shifts in backscattered light, with fibre optics allowing for real-time intravascular applications.
Speckle Imaging	Measures flow velocities using the speckle pattern produced by coherent light scattering. It can be integrated into fibre optic systems for real-time measurements in small vessels.
Photoacoustic Flowmetry	Measures blood flow using both optical and ultrasonic techniques. Flow parameters are determined by laser-induced ultrasonic waves, while fibre optics provide signal transport and detection within the vasculature.

Fibre optic intravascular flow measurements are important in cardiology for determining coronary physiology and microvascular function. They provide critical measures such as coronary flow reserve (CFR) and index of microcirculatory resistance (IMR), which help diagnose and treat coronary artery disease and other vascular disorders. However, challenges such as motion artefacts from the beating heart, as well as the biocompatibility and durability of fibre optic sensors, need to be addressed.

2.2 Chemical modified fiber Fabry–Pérot Interferometer by Silver Mirror Reaction for Hot-Wire Anemometry [10]

The paper on Chemical Modified Fiber Fabry–Pérot Interferometer by Silver Mirror Reaction for Hot-Wire Anemometry by Cheng-Ling Lee et al. (2022) introduces a novel approach to hot-wire anemometry (HWA) that uses a chemically modified polymer air-gap fibre Fabry-Pérot interferometer (PAGFFPI) improved by a silver mirror reaction (SMR). The primary goal is to increase the absorption efficiency of laser heating energy in order to obtain high sensitivity and reliable airflow measurements.

The proposed PAGFFPI sensor uses a high thermal expansion polymer (NOA65) and is supplemented with a silver-coated layer using SMR. This improvement enables the sensor to absorb laser heating energy more effectively. The sensor construction is made up of a single-mode fibre spliced with a hollow-core fibre that has been sliced at an angle and filled with NOA65 polymer before being UV-cured. The silver coating is applied using SMR to improve the sensor's thermal response.

The experiment used a 980 nm pump laser diode (LD) to heat the SMR-coated PAGFFPI. The sensor's reaction was tested at airflow speeds ranging from 0 to 20 m/s, and different silver film thicknesses (150 nm and 270 nm) were evaluated for effectiveness. The sensor showed significant improvements in sensitivity and response times due to the silver coating. The PAGFFPI with a 270 nm silver coating achieved a sensitivity of 3.302 nm/(m/s), while the one with a 150 nm coating achieved 0.702 nm/(m/s). The sensor responded quickly, with rise and fall times of 0.14 s and 0.98 s, indicating that it may be used for real-time airflow monitoring.

Thus, the study introduces a highly sensitive and efficient fibre-optic sensor for HWA using chemical modification and advanced fabrication techniques. This sensor shows potential for applications that require precise airflow measurements, such as renewable energy systems and industrial operations.

2.3 Fiber Bragg Grating Based Hot-Wire Anemometer with Enhanced Sensitivity by Fiber Surface Frosting [11]

The paper titled "Fiber Bragg Grating Based Hot-Wire Anemometer with Enhanced Sensitivity by Fiber Surface Frosting" by Yuhan Tang et al., explores advancements in optical fibre anemometers. These sensors are critical for applications in aviation, meteorological monitoring, and industrial process control because optical fibre sensors, particularly Fibre Bragg Grating (FBG)-based hot-wire anemometers, gained significant attention for their advantages like electrically passive operation, high precision, and immunity to electromagnetic interference.

FBG-based hot-wire anemometers use the temperature sensitivity of FBGs to determine air flow velocity. The FBG is usually coated with a photothermal conversion material and heated with a laser source. The Bragg wavelength of the FBG shifts with temperature variations caused by airflow cooling the heated FBG. A variety of materials and techniques have been used to improve the sensitivity and efficiency of these sensors. Several photothermal conversion materials have been used to cover the FBGs, improving laser absorption and heat generation. Common materials include silver film, graphene, and single-walled carbon nanotubes. Silver film is especially popular for its excellent absorption efficiency and simplicity of application.

Previous research has focused on improving the sensitivity of Fibre Bragg Grating (FBG)-based anemometers by including various photothermal conversion materials such as silver film, graphene, and carbon nanotubes. Silver-coated FBGs have been widely studied because to their high absorption efficiency of the heating laser. Graphene and carbon nanotubes have also been studied because of their excellent thermal and electrical properties. These materials help to transform laser light into heat, which is required for the operation of hot-wire anemometers.

The authors note that while procedures such as cladding etching increase heating efficiency, they reduce the mechanical strength of the FBG. This study suggests a method for reducing the cladding diameter of the FBG through chemical etching, which increases heating efficiency but reduces mechanical strength. Another way is surface frosting, which involves creating grooves into the FBG surface to increase the silver film's absorption efficiency.

The results demonstrated significant sensitivity increases, with surface-frosted FBG showing up to a 313% increase in sensitivity over non-frosted counterparts. This makes it extremely competitive with other modern fibre optic anemometers, such as those that use Fabry-Perot interferometers and graphene coatings. This study contributes to the field by offering a low-cost and mechanically robust way for increasing the sensitivity of FBG-based anemometers, which promises improved performance in practical applications.

2.4 A Review of Coating Materials Used to Improve the Performance of Optical Fiber Sensors [12]

This paper is a comprehensive literature review titled "A Review of Coating Materials Used to Improve the Performance of Optical Fiber Sensors" by Changxu Li et al. that examines how different coating materials could improve the performance of optical fibre sensors. The authors, affiliated with Harbin University of Science and Technology in China, provide an in-depth investigation of several coating materials and their effect on sensor characteristics.

The study opens by discussing the growing application of optical fibre sensors in industrial production and environmental detection. It observes that, while different fibre structures have developed to fulfil varied application needs, structural changes alone cannot completely realise the potential of fibre sensors. The study is framed in the context of emerging optical materials and advancing fibre sensing theory, explaining how coating materials are being applied to basic fibre sensor structures like Mach-Zehnder Interference (MZI), Photonic Crystal Fibre (PCF), Fibre Bragg Grating (FBG), and Fabry-Pérot (F-P) to enhance their capabilities.

The review focuses mainly on improving the temperature sensitivity of fibre sensors. The authors explain that, while temperature fluctuations affect the effective length and refractive index of optical fibre sensors, the low thermal expansion and thermo-optic coefficients of SiO_2 result in comparatively low overall thermal sensitivity. To solve this, fibres are coated with compounds that have higher thermo-optical coefficients. Polydimethylsiloxane (PDMS) is known for its high negative thermal optical coefficient ($-4.66 \times 10^{-4}/°C$) and high thermal expansion coefficient ($300 \times 10^{-6}/°C$). Polyimide is discussed for its use in humidity sensing. UV-sensitive compounds are briefly described for various sensing applications. Graphene and metal ions are described for their sensing properties.

The paper provides an extensive overview of PDMS-coated sensors, including:

Fabrication Methods: The authors describe a simple gravity-assisted coating technique in which PDMS is applied to a vertically hanging fibre.

Structural variations: Tapered, core-offset, and bent fibres are among the PDMS-coated structures examined.

Performance improvements: For example, one study found temperature sensitivity rose from 47.14 pm/°C to 75.04 pm/°C after PDMS coating, which was a 1.6-fold improvement.

The paper discusses manufacturing methods for various sensor structures, such as tapering ordinary single-mode fibres or creating bowknot-type tapers by melting fibres into balls.

Beyond enhancing sensitivity, the paper underlines how coatings like PDMS might act as a protective role, especially for fragile structures like tapered fibre.

Thus, this study is a comprehensive resource for researchers and engineers working on optical fibre sensors, providing insights into how coating materials could be used to improve sensor performance across a variety of applications. The paper's strength is in its extensive explanations of sensing principles and its discussion of various sensor types and applications.

2.5 Optical Fiber Thermal Anemometer With Light Source-Heated Fabry Perot Interferometer [13]

This paper on the optical fiber thermal anemometer is an extensive history of research in fiber optic sensors and anemometers. It includes notable researchers such as Xinyong Dong, who has over 360 scientific papers and numerous citations, showing that he publishes frequently and influentially in the field of optical fibre sensors.

The research was conducted at China's Guangdong University of Technology, a leading university in optical fibre technology, in partnership with the State Key Laboratory of Optical Fibre and Cable Manufacture. The study was published in the prestigious Journal of Lightwave Technology, which covers advancements in photonics and fibre optics. It was published in May 2022 and combines the most recent technology and approaches in optical fibre sensing.

The motivation of the project is to increase the accuracy and efficiency of airflow measurement with optical fibre anemometers. The study addresses the constraints of current anemometer designs, specifically their size, complexity, and sensitivity at high airflow velocities. The research proposes a light source-heated Fabry-Perot interferometer to simplify the design while improving performance, making it useful in a variety of industries that require precise airflow measurements.

The study proposes a unique optical fibre thermal anemometer that avoids the need for external heating equipment by heating the Fabry-Perot interferometer directly with the light source. The study describes the construction method, experimental setup, and performance evaluation. It shows a high sensitivity of -3.13 nm/(m·s^-1) at low velocities and strong performance across various airflow conditions. Other researchers have acknowledged the study's novel approach and being applicable in academic and industrial settings.

Citations often highlight the uniqueness of reducing the sensor design while keeping high sensitivity, however other discussions focus on future improvements in stability and measuring range under different environmental circumstances. The number of citations highlights the significance of this study in improving the technology of optical fiber-based sensors.

2.6 Optical flow sensor for continuous invasive measurement of blood flow velocity [14]

The paper, "Optical flow sensor for continuous invasive measurement of blood flow velocity," written by Albert Ruiz-Vargas, Scott A. Morris, Richard H. Hartley, and John W. Arkwright, was published in the Journal of Biophotonics in 2019. The goal of this research is to create an optical flow sensor that can detect blood flow continuously and invasively. This is a significant development in the field of medical monitoring, especially in situations where dynamic blood flow assessment is required.

The authors are affiliated to Flinders University's Medical Device Research Institute in Adelaide, Australia. John W. Arkwright, a prominent researcher in this field, is well-known for his regular publications on optical fibre sensors and medical devices. Their research's importance is demonstrated by how frequently it is cited in the field. Although this paper adds to their current body of work, it is not a first publication but rather a component of a larger, established research program. Citations for their work are largely positive, recognising their innovative approaches and useful applications in the field of medical technology.

The study addresses the constraints of existing blood flow monitoring techniques, such as ultrasound and thermodilution, which are frequently intermittent and subject to precision mistakes due to operator variability. The need for continuous, real-time monitoring of blood flow in clinical settings, particularly during surgeries or intensive care, motivated this study. The citations are mainly positive, with an emphasis on the distinct use of FBG in medical applications and the technology's potential to improve patient monitoring in critical care settings.

2.7 Fiber Bragg Gratings in Healthcare Applications: A Review [15]

This review focusses on the usage of Fibre Bragg Gratings (FBGs) in medical applications, which is discussed in the paper, "Fibre Bragg Gratings for Medical Applications and Future Challenges: A Review." The paper published on August 24, 2020, was written by a diverse team of researchers from several institutions in Europe, Asia, and the United States, showing a significant collaborative effort in the field of FBG technology applied to medicine. The primary contributors include Daniela Lo Presti, Carlo Massaroni, Cátia Sofia Jorge Leitão, Maria de Fátima Domingues, Marzhan Sypabekova, David Barrera, Ignazio Floris, Luca Massari, Calogero Maria Oddo, Salvador Sales, Iulian Ioan Iordachita, Daniele Tosi, and Emiliano Schena.

The research paper was published in IEEE Access, a journal noted for its wide scope and open-access policy, making it easily accessible to researchers and practitioners. Since its publication, the paper has been cited 213 times by other researchers studying the development and application of sensor technology in healthcare.

The study covers the growing need for reliable and precise sensing technology in medicine, which is being driven by advances in minimally invasive surgery, physiological monitoring, and personalised healthcare. FBGs are distinguished by their unique qualities, such as biocompatibility, compact size, and resistance to electromagnetic interference, making them ideal for medical applications.

The study provides a comprehensive review of the state-of-the-art in FBG applications in medicine, including operating principles, sensor configurations, and specific medical applications such as biomechanics, minimally invasive surgery, and biosensing. It examines both the advantages and disadvantages of FBG technology, providing insights into future research areas and potential improvements in practical use. The authors explain various FBG configurations, including uniform FBGs, chirped FBGs, and tilted FBGs, each with specific applications in different medical fields. The paper also discusses the practical barriers of incorporating FBGs into medical devices, such as the necessity for robust sensor encapsulation and reducing cross-sensitivity to surrounding factors like temperature.

2.8 Optical-Fiber Measurement Systems for Medical Applications [16]

This literature review analyses the paper "Optical-Fiber Measurement Systems for Medical Applications," written by Sergio Silvestri and Emiliano Schena, both of whom are affiliated with the Università Campus Bio-Medico di Roma. Sergio Silvestri has 172 publications and 3,428 citations, and Emiliano Schena has 410 publications and 8,807 citations, indicating a significant presence in the fields of biomedical engineering and optical sensor technologies. The paper is part of a chapter of the journal Optoelectronics - Devices and Applications, which is posted on InTechOpen. It was published in October 2011, when the integration of optical fibre technologies in medical applications was gaining traction.

The paper discusses the necessity for precise and reliable measuring methods in medicine, especially in circumstances where typical electronic sensors may be insufficient due to concerns such as electromagnetic interference. FBGs are distinguished by their unique qualities, such as small size, biocompatibility, and immunity to electromagnetic fields, making them appropriate for a variety of medical applications.

The paper provides an extensive review of the design principles and measurement techniques used in FBG-based systems, with a focus on medical applications. It discusses various sensor configurations and their specific applications, such as real-time monitoring of physiological factors including pressure, temperature, and strain. The study emphasises the benefits of employing FBGs over conventional sensors, such as their high sensitivity, accuracy, and ability to operate in areas with strong electromagnetic fields, such as during MRI treatments. The research also looks at the medical uses of FBGs, such as intracranial pressure monitoring, arterial pressure measuring, and minimally invasive procedures. These applications highlight FBGs' adaptability and efficacy in improving patient outcomes through better monitoring and diagnosis.

CHAPTER 3: THEORETICAL BACKGROUND

3.1 PRINCIPLES OF BLOOD FLOW MEASUREMENT

3.1.1 Hemodynamics and the principle of blood flow

Hemodynamics is the study of the physical principles that govern blood flow throughout the circulatory system. This field is critical for understanding the distribution of blood flow and pressure throughout the circulatory system. The fundamental principles of hemodynamics focus around the relationship between blood pressure, flow, and resistance, all of which are impacted by the heart's pumping motion, blood properties, and blood vessels characteristics.

- **Basic Concepts of Hemodynamics**

Hemodynamics studies the relationship between pressures and flows in the circulatory system. Blood pressure, or the force exerted by circulating blood on the walls of blood vessels, is a vital component. The heart produces pulsatile pressure, which drives blood through a complex network of vessels. The geometric structure and mechanical properties of the vessels themselves, as well as the viscous and inertial forces acting on the blood, all influence the flow of blood through them [17].

The fundamental relationship between pressure, flow, and resistance in the vascular system is often compared to Ohm's law in electrical circuits. This analogy helps to explain how the pressure difference between two points in the circulation (analogous to voltage) pushes the flow of blood (analogous to current) against the resistance of the vessels. Vascular resistance is determined by variables such as vessel diameter and blood viscosity. The resistance can be stated numerically as follows:

$$R = \frac{\Delta P}{Q}$$

Where R is the resistance, ΔP is the pressure difference, and Q is the flow rate. This equation assumes a steady flow and highlights the crucial importance of vessel diameter in determining resistance. Small changes in diameter can lead to significant changes in resistance and flow [17].

- **Blood Pressure**

Blood pressure is the force exerted by circulating blood against the walls of blood vessels. It is produced mostly by the contraction of the heart and is one of the primary driving forces behind blood flow. Blood pressure is commonly measured in two ways: systolic pressure (peak pressure during heart contraction) and diastolic pressure (pressure during heart relaxation). Maintaining an appropriate blood pressure is vital for providing sufficient perfusion of tissues throughout the body [18]

- **Blood Flow and Vessel Characteristics**

Blood flow is the circulation of blood through the circulatory system, which is necessary for the transportation of oxygen, nutrients, and other substances. Blood flow can be either laminar (flowing smoothly in parallel layers) or turbulent (flowing chaotically). Smaller vessels are more likely to have laminar flow, whereas larger vessels or vascular disease sites can encounter turbulent flow. The type of flow considerably impacts the efficiency of blood transport, and the shear stress exerted on the vessel walls [17].

Hemodynamics is significantly affected by blood vessel properties such as elasticity and compliance. For example, large arteries such as the aorta act as pressure reservoirs, dampening the heart's pulsatile output and converting it into a constant flow in the smaller arteries and capillaries. The elasticity of the vessel walls allows them to stretch in response to the pressure pulse generated by the heart. This contributes to the propagation of the pressure wave through the arterial system [17].

- **Vascular Resistance and Microcirculation**

Vascular resistance has a significant role in influencing blood pressure and flow. It is affected by the diameter of the blood vessels, the viscosity of the blood, and the overall length of the circulatory system. In the microcirculation, where blood vessels are very small, the flow of blood is also influenced by the non-Newtonian properties of blood, such as viscosity, which vary with shear rate and haematocrit levels [18].

The distribution of blood flow in the microcirculation is strictly regulated in order to meet the metabolic demands of various tissues. The ability of arterioles and capillaries to constrict and dilate is crucial in controlling blood flow and resistance. The non-uniform distribution of haematocrit in micro vessels also effects blood viscosity and flow, resulting in complex haemodynamic behaviours that are crucial for tissue perfusion [17].

3.2 OPTICAL FIBRE THEORY

3.2.1 Basic principles of light propagation in optical fibres

Optical fibres, which are thin strands of glass or plastic, allow light to be transmitted over long distances with minimal loss, making them important in a variety of applications including telecommunications and medical imaging. Several fundamental laws of optics govern the propagation of light within optical fibres.

- **Total Internal Reflection**

Total internal reflection is the basic mechanism that allows light to propagate through optical fibres. This phenomenon occurs when light travelling through the fiber's core, which has a higher refractive index, meets the cladding, which has a lower refractive index. If light contacts this boundary at an angle larger than the critical angle, it is completely reflected back into the core, allowing the light to remain trapped within the fibre as it travels along its length [19].

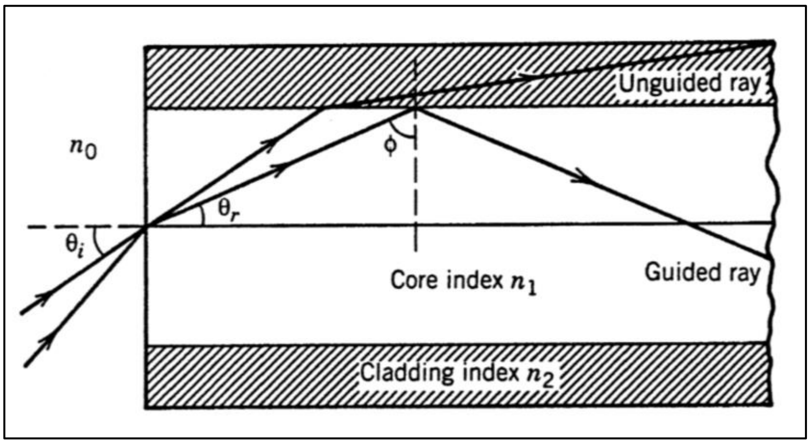

Figure 1: Light confinement by total internal reflection in optical fibre [19]

- **Waveguiding and Modes**

Optical fibres guide light by limiting it within their core. This guiding occurs because the core has a higher refractive index than the cladding, which ensures that light is constantly reflected within it. The way light passes through a fibre varies based on the fibre's design and the wavelength of the light. The different patterns of propagation are known as modes [20].

- **Single-mode fibres** can only carry one mode of light, which travels straight down the core with minimum dispersion, making them ideal for long-distance communication [19].
- **Multi-mode fibres** support numerous modes, allowing light to travel in different directions through the core. This can result in modal dispersion, in which different pathways have varying travel times, potentially causing signal distortion over long distances [19].

- **Attenuation and Dispersion**

Light attenuates or loses signal power as it travels through an optical fibre, due to a variety of factors such as absorption, scattering, and bending losses. Absorption happens when impurities in the fibre material convert light into heat, whereas scattering occurs when imperfections cause light to divert from its path. Bending losses occur when the fibre curves too sharply, causing some light to leave the core [21]

Dispersion, or the gradual spread of a light pulse over time, can also have an impact on signal quality. Chromatic dispersion occurs as different wavelengths of light travel at different speeds, resulting in pulse broadening. Modal dispersion, specific to multi-mode fibres, comes from different light routes with varied travel times, contributing to signal degradation [21].

- **Numerical Aperture**

The difference in refractive indices between the core and cladding determines an optical fibre's numerical aperture (NA), which evaluates its ability to gather light. A higher NA allows the fibre to take light from a wider range of angles, increasing the effectiveness of light coupling into the fibre [19].

- **Polarization**

Polarisation is a property of light waves that causes their electric field to oscillate in different directions. Maintaining the polarisation state of light is critical in some optical fibres, particularly those employed in specialised applications like sensors or polarization-sensitive communication systems. Polarization-maintaining fibres are designed to maintain the light's polarisation as it propagates through the fibre [21].

3.2.2 Types of optical fibres used in sensing

Optical fibres are commonly used in sensing applications because of their sensitivity, flexibility, and immunity to electromagnetic interference. Different types of optical fibres can be used for sensing, based on the application's specific needs, such as distance, precision, and measurement type. The main types of optical fibres used in sensing are single-mode fibres, graded-index fibres, and step-index fibres.

- **Single-Mode Fibres (SMF)**

Single-mode fibres have a small core diameter, typically around 8-10 micrometers, and allow only one mode of light to propagate, making them ideal for high-precision sensing applications such as interferometric sensors and distributed sensing systems like Fibre Bragg Gratings (FBG). These fibres are preferred because they have low modal dispersion, resulting in good accuracy and stability [19]. Single-mode fibres are widely used in interferometric sensors, fibre Bragg grating (FBG) sensors, and distributed sensing systems. These sensors can detect extremely minute changes in surrounding parameters, such as temperature, pressure, and strain, making them ideal for structural health monitoring, environmental sensing, and applications in the oil and gas sector.

- **Graded-Index Fibers**

Graded-index fibres have a core with a refractive index that gradually lowers from centre to cladding. This design reduces modal dispersion by allowing light rays from different paths to converge more uniformly at the output. Graded-index fibres have a larger core diameter (usually 50-62.5 micrometers) and can support various modes of light.

Graded-index fibres are commonly used in multimode sensing applications that need medium-range measurements. They are very helpful in industrial sensing situations for measuring temperature, pressure, and chemical composition. The graded-index structure improves signal quality in systems that use multiple light paths [20].

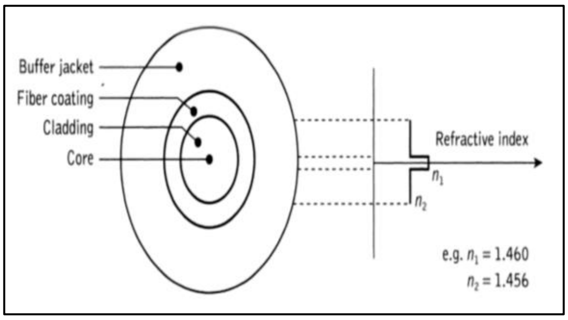

Figure 2: Typical structure for single-mode step index fibre [19]

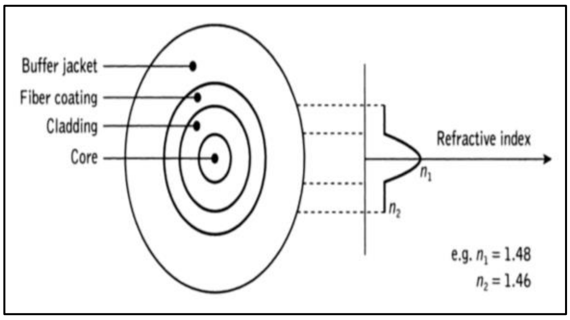

Figure 3: Typical structure for multi-mode graded index fibre [19]

- **Step-Index Fibers**

Step-index fibres feature a sharp separation in refractive index between the cladding and core, creating a sharp edge. These fibres can be classified into single-mode and multi-mode types:

- **Single-Mode Step-Index Fibres:** These fibres have a small core and only support one mode of light, resulting in high precision and low dispersion.
- **Multi-Mode Step-Index Fibres:** With a larger core, these fibres can support multiple light paths or modes, however they have higher modal dispersion than graded-index fibres. As a result, they are not ideal for long-distance or high-precision sensing.

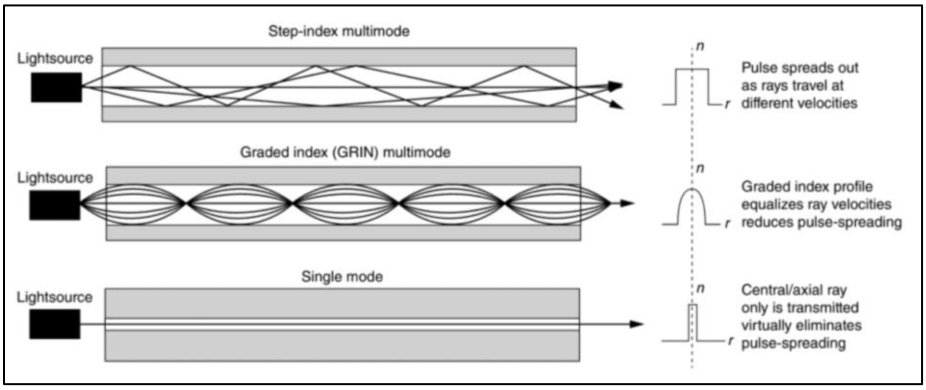

Figure 4: Transmission in step-index multimode, graded-index multimode, and single-mode optical fibres [22]

Step-index fibres are used in simple multimode sensors for short-range sensing applications that require simplicity and cost-effectiveness. These fibres are widely used for proximity sensing, liquid level monitoring, and basic temperature sensing. Multi-mode step-index fibres are especially useful in cost-sensitive environments where modest measurement precision is required [22].

3.3 FIBRE BRAGG GRATINGS (FBG)

Fibre Bragg Gratings (FBG) are an optical sensor that works by reflecting specific wavelengths of light while allowing others to pass through. This selective reflection is at the core of how FBGs work as sensors for a variety of physical characteristics, including temperature and strain. It is created by inscribing a periodic variation in the refractive index along the core of an optical fibre. This grating functions as a wavelength-selective mirror, reflecting light at a specified wavelength called the Bragg wavelength [23].

The periodic structure within the fibre core selectively reflects light at a specific wavelength while allowing other wavelengths to pass through. This property is critical to FBG's function as a sensor, because any changes in strain or temperature will affect the grating period or the refractive index, shifting the Bragg wavelength [24] [23].

- **Structure and Creation of FBG**

An FBG is formed within the core of an optical fibre, which is a thin strand of glass or plastic that transmits light. The core is the central component of the fibre through which light flows. An FBG is created by inscribing a pattern of alternating high and low refractive index patches along the fibre core. This pattern is often formed using ultraviolet (UV) laser light that modifies the refractive index of the fiber's core in a controlled manner [23].

An FBG's main feature is a periodic pattern, or "grating," that allows certain wavelengths of light travelling through the fibre to be reflected back while others continue to propagate through the fibre. The refractive index of the core and the grating's spacing determine the precise wavelength of light that is reflected [24].

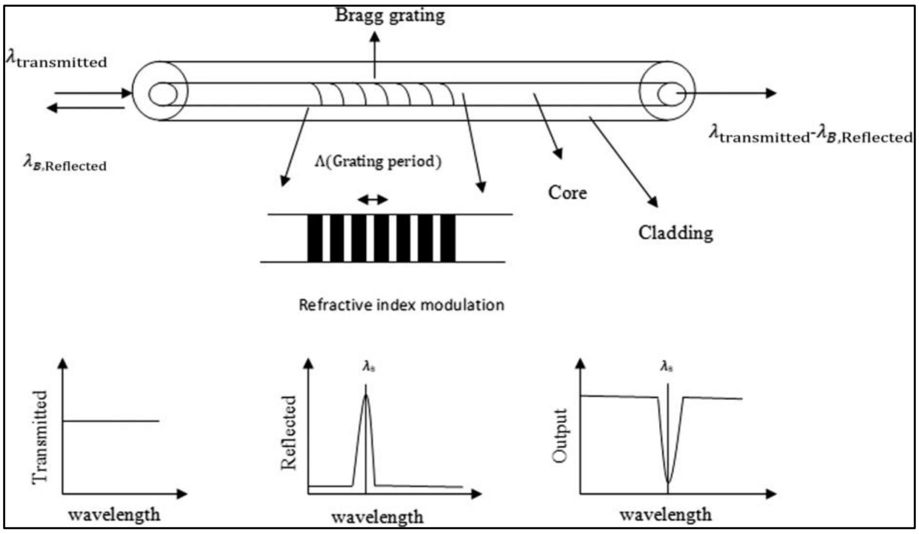

Figure 5: Structure of Fibre Bragg Grating [25]

- **Reflection and Sensing Mechanism**

When light passes through the optical fibre, it encounters the FBG. The grating reflects a specific wavelength of light, known as the Bragg wavelength, back to the light source. This reflection happens because the grating creates a condition where the light waves at that specific wavelength constructively interact with each other, amplifying the reflection [26]. The FBG functions as a sensor because the Bragg wavelength is sensitive to changes in the environment surrounding the fibre, particularly temperature and strain:

- **Temperature Sensitivity:** Temperature variations alter the refractive index of the fibre core and can cause it to expand or contract. These changes affect the conditions under which light is reflected, resulting in a shift in the wavelength reflected [24].
- **Strain Sensitivity:** As the fibre is stretched or compressed, the spacing of the grating varies. This also causes the reflected wavelength to change [23].

These fluctuations in reflected wavelength can be carefully measured and related to the temperature or strain changes that caused them.

- **Application in Flow Sensors for Temperature Measurement**

FBGs are commonly employed in flow sensors to monitor the temperature of fluids flowing through pipes or other conduits. The FBG sensor is either integrated in or attached to the fluid-containing structure. As the fluid's temperature fluctuates, it influences the FBG sensor, causing a shift in the reflected wavelength [26].

Temperature Measurement Mechanism:

- **Thermo-optic Effect:** Temperature changes affect the refractive index of the fibre core due to the thermo-optic effect. The refractive index increases with temperature, resulting in a shift to a longer Bragg wavelength [24]
- **Thermal Expansion:** Changes in temperature cause the fibre to physically expand or contract, altering the grating period and further shifting the Bragg wavelength [24]

By continuously monitoring this wavelength shift, the fluid's temperature may be accurately calculated. This is especially beneficial in industrial procedures where accurate temperature control is required. FBGs are ideal for sensing and monitoring in a wide range of applications, including temperature measurement in fluid flow systems, because they give real-time, distributed measurements along the length of the fibre and are immune to electromagnetic interference, which can affect electronic sensors. [24].

CHAPTER 4: METHODOLOGY

4.1 DESIGN OF BLOOD FLOW SENSOR

4.1.1 Detailed Design of the Optical Fibre Sensor

The optical fibre sensor measures blood flow by measuring variations in light transmission and reflection within the fibre. In this sensor, light transmitted through the fibre not only serves as a signal carrier but also heats the Fibre Bragg Grating (FBG). The FBG responds to this heating by modifying its reflecting characteristics, which are proportional to the flow rate of the surrounding fluid. The sensor must be highly sensitive to flow rate variations and capable of operating efficiently in a variety of physiological conditions, including varying temperatures and fluid viscosities. The design process involves selecting suitable materials, setting the sensor's geometry, and optimising its optical properties to achieve optimal sensitivity and accuracy.

- **Sensor Design Requirements**
  - **Sensitivity:** The sensor must be capable of detecting small changes in blood flow, which requires a high sensitivity in the optical system.
  - **Stability:** The sensor should work consistently over time, even under varying environmental circumstances.
  - **Biocompatibility:** If the sensor is to be used in vivo, the materials must be biocompatible.
  - **Ease of Fabrication:** The design should enable simple fabrication and integration into existing systems.
- **Selection of Optical Fibre**
  - **Single-mode Optical Fibre (SMF):** Single-mode fibres are ideal for maintaining a single light path, resulting in minimal dispersion and high signal integrity, which is critical for applications such as precision heating and signal processing in FBGs. Single-mode fibres operating in the 1310 nm and 1550 nm wavelength range typically have a core diameter of 8-10 micrometres, providing single-mode propagation with little signal loss. The standard cladding diameter is 125 micrometres, which provides structural stability while also protecting the core. The cladding's refractive index is lower than the core's, which helps in reflecting light back into the core and maintaining signal integrity.
  - **400-micron Multi-mode Fibre (MMF):** Multi-mode fibres with a larger core (used 400-micron fibre in this study) are beneficial for higher light intensities, possibly in

applications requiring power delivery or wider bandwidth, but at the cost of increased modal dispersion.

- **1550 nm Acrylate-coated FBG:** FBGs at 1550 nm are often used in telecommunications and sensing applications because they have minimal loss in this wavelength range. Silica is the most often used material for optical fibres because of its good optical transmission, low attenuation, and high mechanical strength. It is also compatible with the UV inscription process used to create FBGs, and the acrylate coating protects the fibre from environmental conditions while retaining its flexibility and ease of handling.

4.1.2 Choice of Materials and Components

- **Silver Coating:**
  - **Light Absorption and Heat Generation:** Adding a thin layer of silver improves the fiber's reflectivity, making it ideal for maximising light-induced heating in FBG (Fibre Bragg Grating) applications. The silver coating increases the sensor's sensitivity to temperature changes caused by the absorbed light by more effectively reflecting it. Silver's ability to absorb light and convert it to heat is used to raise the temperature of the FBG.
  - **Inert and Non-reactive Nature:** Silver is relatively inert and biocompatible, making it ideal for applications involving biological tissues or requiring minimum adverse effects. As a result, the coated fibre may be useful in medical or environmental sensing applications.
  - **Electrical and Thermal Conductivity:** Silver's high electrical and thermal conductivity contributes to its functionality.
- **PDMS Coating:**

- **Protection and Flexibility:** Polydimethylsiloxane (PDMS) is used to create a protective layer to the silver coating. PDMS helps in the maintenance of the coating's integrity, hence increasing the durability and flexibility of the fibre.
- **2x and 5x Dilution Levels:** PDMS is diluted to different concentrations (2 times and 5 times) to examine its effect on the optical properties of the fibre and sensor performance, especially how well the sensor can withstand environmental factors while remaining sensitive.

• **Light Sources for Heating:** The wavelength of the light source is selected to match the FBG's reflection peak, and the power is carefully managed to ensure that the FBG heats up in response to flow without producing damage or excessive noise in the data. The FBG heats up when light goes through the fibre. The temperature change in the FBG shifts its Bragg wavelength in a way that corresponds to the flow rate of the surrounding fluid.

- **WLS100 - White Light Source:** The WLS100 is a broadband white light source that operates across a wide spectral range, typically 350 nm to 2400 nm. Its broad spectral coverage makes it suitable for a variety of applications, including spectroscopy, optical sensing, and broadband illumination. It usually uses a halogen lamp and specialised optics to generate a stable and uniform output across the whole spectrum.
- **SLS201L/M - Superluminescent Diode Light Source:** The SLS201L/M is a superluminescent diode (SLD) light source that produces a broad but less intense output than lasers, with a spectral range that varies depending on the model, usually between 600 nm and 1700 nm. SLDs combine the properties of LEDs and lasers, resulting in a broader spectrum like LEDs but with higher intensity and coherence like lasers.
- **HL2000 - Halogen Light Source:** The HL2000 is a halogen light source that, like the WLS100, produces a continuous stable broadband spectrum ranging from 360 nm to

2400 nm. It produces a smooth spectrum output with a tungsten halogen lamp and is commonly used in applications such as spectroscopy and fibre optic sensing.

- **Pump for Flow System:**
  - **LKB BROMMA 2120 VARIOPERPEX II PUMP:** This Peristaltic Pump is commonly used in laboratories for accurate fluid handling in applications such as chromatography, biochemical tests, and other fluidic systems that require controlled flow.
  - **Flow rate:** The flow rate of the pump can be modified based on the tubing size and speed settings. Peristaltic pumps like this one typically have flow rates ranging from very low (microlitres per minute) to moderate (several millilitres per minute).
  - **Precise control:** The ability to precisely control the flow rate is most likely the main reason for selecting the LKB BROMMA 2120. In fibre optic sensor testing, particularly for systems such as FBGs, small variations in flow rate can have a substantial impact on heating or cooling rates, which in turn alter the wavelength shift detected in the sensors.
  - **Minimal pulsation:** The peristaltic design of the pump reduces pulsation, resulting in a smooth flow. This smoothness is required in optical sensor testing to avoid introducing noise or distortions into wavelength measurements, ensuring that observed shifts are caused by the sensor's response to external stimuli rather than fluctuations in fluid flow.
  - Higher flow rate pumps might have created turbulence or excessive fluid velocity, disrupting the precise temperature or pressure conditions needed to induce a noticeable wavelength change in fibre optic sensors. In some situations, the flow may be too fast for the sensor to adequately respond to temperature or pressure changes, resulting in minor or no detectable shifts.

- **Additional Components: Tubings**, in conjunction with the peristaltic pump, ensure consistent fluid flow, which is critical for accurate sensor testing, whereas **Normaplast Equal T push on connectors** enable fluid routing and distribution, allowing for complex fluidic configurations and precise delivery to the sensors. The **LC-APC duplex patch cables** and **BFT1 universal bare fiber terminator with connector** are critical components that collectively ensure precise and reliable operation of the fiber optic and fluid flow system. **SmartScope Interrogators** are advanced fibre optic interrogation systems used for high-precision monitoring and analysis of Fibre Bragg Gratings (FBGs).

4.2 BUILDING THE PHANTOM FLOW SYSTEM

4.2.1 Introduction to Phantom Flow Systems

A phantom flow system is a controlled experimental setup that simulates physiological conditions, specifically the flow of fluids such as blood through arteries or veins, in order to test and calibrate optical fibre sensors such as Fibre Bragg Gratings (FBGs). These systems are essential in biomedical research and development, as precise replication of body fluid dynamics is required to evaluate sensor performance and reliability in a setting that mimics real-world conditions. The major goal of building a phantom flow system in the study is to establish a controlled environment that simulates blood flow properties, allowing for accurate testing of the FBG sensors' responses to changes in pressure, temperature, and flow rate.

4.2.2 Design and Components of the Phantom Flow System

- **Flow Loop Design**

The flow loop of the phantom flow system is precisely designed to mimic the circulatory system's characteristics. It is made of carefully chosen materials, such as flexible, biocompatible tubing and durable connectors like Normaplast Equal T push-on connectors, to provide a smooth and uniform flow of the fluid medium. The arrangement is designed to imitate blood vessel paths, so the optical fibre sensors are exposed to flow conditions similar to those found in human arteries and veins.

- **Reservoir and Pump System**

The system has a reservoir that holds the fluid medium, which in this case resembles blood. The LKB BROMMA 2120 VARIOPERPEX II peristaltic pump circulates fluid through the system, ensuring a stable and controlled flow that can be precisely adjusted to simulate various physiological conditions. The pump's ability to deliver consistent flow rates is important to the experiment's accuracy.

- **Flow Sensors and Measurement Devices**

Additional sensors are included to the phantom flow system to monitor critical factors such as flow rate and temperature. These sensors ensure that the system performs within the parameters desired and offer real-time data that can be used to evaluate the performance of the FBG sensors being tested.

4.2.3 Assembly of the Phantom Flow System

To assemble the phantom flow system, attach the peristaltic pump to the blood vessel-like tubing system first. The tubing is channelled through the FBG structure, which is positioned in such a way that it can interact with the fluid as it moves through the system. Sensors are strategically placed using blu-tack to monitor flow parameters, and a heating light source is connected to the FBG structure to simulate temperature changes. Inspection and recalibration manage possible issues like leaks or flow irregularities such as air bubbles, ensuring system accuracy.

4.3 QUALITY OF SILVER COATING

4.3.1 Introduction to Silver Coating in Optical Fibres

Silver mirroring on the tip of an optical fibre improves performance by enhancing reflectivity, improving signal sensitivity, and retaining signal quality, all of which are critical in precise applications such as Fibre Bragg Gratings (FBG). As mentioned earlier, it allows for more accurate light interaction, which is useful in optical probes and sensors. In addition, silver's biocompatibility and stability make it appropriate for medical applications, while its thermal and electrical conductivity improves durability and performance under various conditions.

- To create a silver mirror on the end of a fiber, follow this procedure along with the chemical reactions involved:
- **Materials:**
    - Silver Nitrate ($AgNO_3$): 640 µL (0.1 M, 16.987 mg/mL)
    - Sodium Hydroxide (NaOH): 440 µL (0.8 M, 32 mg/mL)
    - Ammonia Solution (NH_4OH): 40 µL (35%)
    - Dextrose ($C_6H_{12}O_6$): 64 µL (0.25 M, 45.4 mg/mL)
    - 5 mL glass vial
    - Clamps and pipettes
- **Method:**
    1) **Preparation of Silver Nitrate Solution:**

       Add 640 µL of 0.1 M silver nitrate solution ($AgNO_3$) to a 5 mL glass vial.
    2) **Addition of Sodium Hydroxide:**

       Add 440 µL of 0.8 M sodium hydroxide (NaOH) to the vial. A brown solid precipitate (silver oxide, Ag_2O) should form, indicating the formation of silver oxide:

$$2AgNO_3 + 2NaOH \rightarrow Ag_2O + 2NaNO_3 + H_2O$$

3) **Addition of Ammonia Solution:**

   Gradually add 40 µL of ammonia solution (NH_4OH) to the mixture. If the solution does not return to a clear state, add a bit more ammonia. The ammonia will dissolve the silver oxide, forming a silver-ammonia complex:

$$Ag_2O + 2NH_3 + H_2O \rightarrow 2[Ag(NH_3)_2]OH$$

4) **Addition of Dextrose:**

   Add 64 µL of dextrose ($C_6H_{12}O_6$) to the solution. The dextrose acts as a reducing agent, reducing the silver-ammonia complex to metallic silver, which will form a mirror on the inside surface of the vial and on the tip of the fiber:

$$2[Ag(NH_3)_2]OH + RCHO \rightarrow 2Ag + 3NH_3 + H_2O + RCOONH_4$$

5) **Coating the Fiber:**

   Immerse the tip of the fiber into the solution for approximately 20 minutes. Multiple immersions may be necessary to achieve the desired thickness of the silver coating.

4.3.2 Analysis of SMF with silver and PDMS coating

- **Method 1: Silver-Coated Fibre**

- Immerse the single-mode fibre (SMF) into the prepared silver solution, ensuring that it is completely coated for approximately 20mins.
- Allow the silver coating on the fiber to cure at room temperature for 10-15 minutes.
- **Water Immersion Test:** After curing, immerse the silver-coated fiber in water for 5 days. Assess the durability of the silver coating by observing any variations in the intensity of reflected or transmitted light through the fibre. A decrease in intensity might indicate that the silver coating has degraded or detached.

- **Method 2: Silver-Coated Fibre with 2 Times Diluted PDMS**

- Immerse the SMF in the silver solution to apply a silver coating, as shown in Method 1. After the silver coating has cured for 10-15 minutes, add a protective layer of PDMS (Polydimethylsiloxane) diluted twice by dipping in the PDMS solution.
- Cure the PDMS-coated fiber in an oven for 24-48 hours at a suitable temperature
- **Water Immersion Test:** Immerse the cured PDMS-coated fibre in water for 5 days. Determine the efficiency of the 2 times diluted PDMS layer in protecting the silver coating by monitoring changes in fibre intensity. A stable intensity indicates good protection, whereas a decrease could indicate insufficient protection or PDMS layer degradation.

- **Method 3: Silver-Coated Fibre with 5 Times Diluted PDMS**

- Repeat the coating process on the SMF with 5 times diluted PDMS solution as in Method 2 and immerse the fiber in water for 5 days after the PDMS has fully cured.
- **Water Immersion Test:** Evaluate the effectiveness of the 5 times diluted PDMS coating in protecting the silver layer. The change in light intensity will indicate if the more diluted PDMS provides sufficient protection or permits the silver coating to degrade over time.

4.4 FABRICATION OF 45-DEGREE ANGLED FIBRE

- **Preparation of fibre:**
  - **Jacket removal:** Using a fibre stripper, carefully remove the protective jacket from the 400-micron multimode fibre (MMF), exposing the bare core.
  - **Cleave the fibre:** Cleave the end of the 400-micron MMF to create a clean, flat surface. To remove any dust or contaminants from the fibre, thoroughly clean it with isopropyl alcohol (IPA).

- **Setup for Polishing**: Insert the cleaned fibre into a connector. Mount the connector on the fibre polishing machine at a 45-degree angle. Secure it with screws, making sure the fibre tip isn't too long to bend or break during the polishing process.

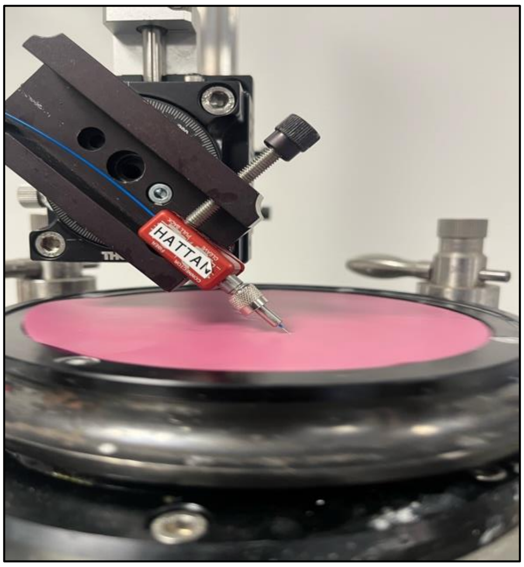

Figure 7: 400-micron fiber placed on the polishing film

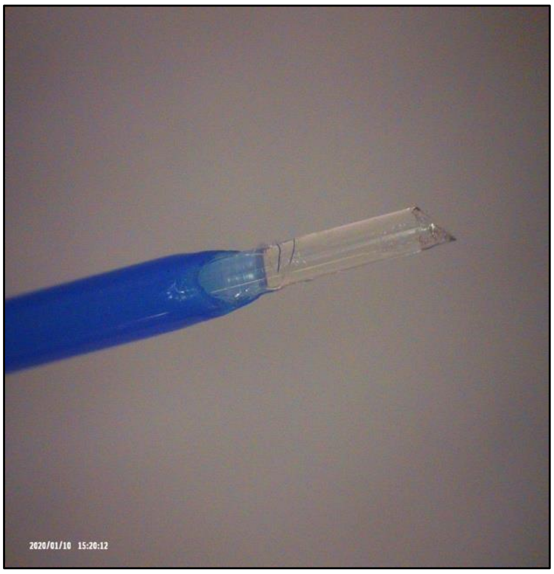

Figure 6: 45-degree angled fiber after polishing

- **Method 1: Blu-Tack-Assisted Polishing**
  - **Polishing:** Polish the fibre at a 45-degree angle on the polishing film directly. Add a few drops of water to the polishing film to achieve a smooth, even surface. This helps in getting the ideal polish while reducing the possibility of scratching or damaging the fibre. Ensure that the fibre is polished to the desired smoothness and angle.
  - **Prepare for silver coating:** After polishing, position the fibre so that the tip points upward. This can be done by using a photometer to direct light and confirm orientation. Blu-Tack the sides of the fibre, leaving only the tip exposed. This configuration ensures that the silver mirror spray only coats the tip.
  - **Silver coating:** Apply 4-5 layers of silver mirror spray, focusing on the exposed tip of the fibre. Allow each layer to dry before adding the next.

- **Blu-Tack Removal:** Once the coating has dried, carefully remove the Blu-Tack from the fibre. The end result is a 45-degree angled fibre with a clean silver coating on the tip, while the sides are uncoated.

- **Method 2: Vaseline-Assisted Polishing**

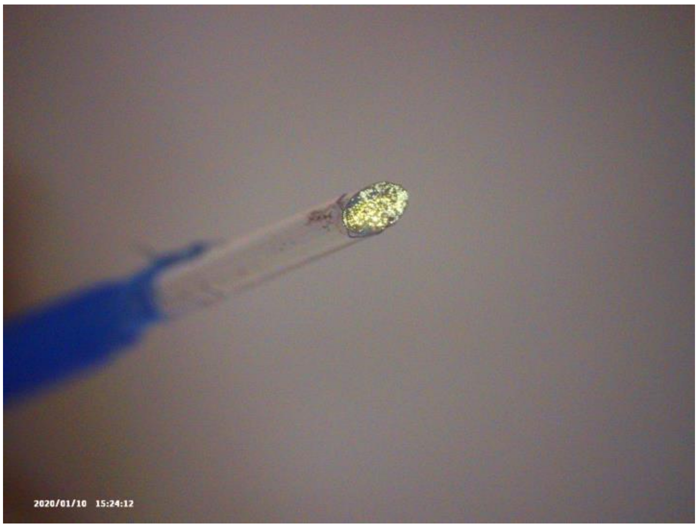

Figure 8: 45-degree angled fiber with a silver-polished tip using the Vaseline method

- **Apply Vaseline:** Before polishing, apply a thin layer of Vaseline or petroleum jelly to the fiber's sides. This layer will serve as a protective barrier, ensuring that the silver coating is only applied to the tip during the subsequent silver coating procedure.
- **Polishing:** Add a few drops of water to the polishing film to help in achieving a smooth surface during polishing. The water reduces friction and polishes the fibre to a smooth, even finish. Polish the fibre on the polishing film, keeping a 45-degree angle throughout.
- **Silver coating:** After polishing, use 4-5 layers of silver mirror spray over the fibre, concentrating on the exposed tip. Allowing the spray to dry between coats ensures consistent coverage.

- **Vaseline removal:** Once the silver coating has been applied, gently remove the Vaseline and any silver that has adhered to it with IPA. The result is a 45-degree angled fibre with a silver coating only on the tip.

4.5 HEATING FBG USING DIFFERENT METHODS

Fibre Bragg Gratings (FBGs) are widely used in a variety of sensing applications because to their sensitivity to temperature, strain, and pressure. To precisely measure these characteristics, it is often necessary to apply controlled heating to the FBGs. Several heating procedures are employed, depending on the type of fibre and the application needs. This introduction provides a variety of heating methods for FBGs, with a focus on different fibres and placement techniques.

4.5.1 Heating FBG Using SMF

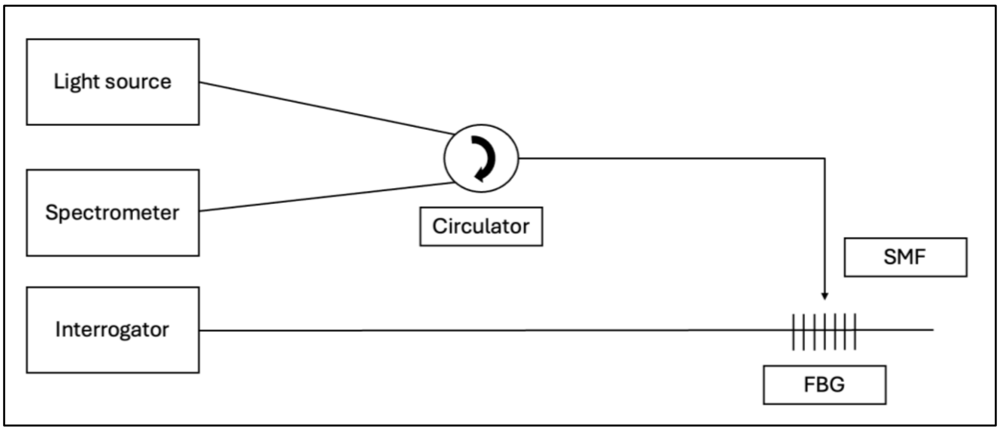

Figure 9: Block diagram of heating the FBG using external light source

- **System setup:**
  - The Light Source generates the initial optical signal that passes through the Single-Mode Fibre (SMF).
  - Circulator directs light from the source to the FBG, which then sends the reflected signal to the spectrometer.
  - A part of the SMF in which the grating reflects a specified wavelength.

- Spectrometer/Interrogator analyses the reflected signal from the FBG to detect wavelength shifts as temperature changes.

- **Heating procedure:**
  - Position the external light source so that it directs light on the part of Fibre Bragg Grating (FBG) contained in the Single-Mode Fibre (SMF). The SMF should be perpendicular to the FBG so that the light is focused directly on the grating area, maximising localised heating.
  - Activate the light source in a controlled on/off cycle, turning it on for 30 seconds to heat the FBG and then off for 30 seconds to cool the fibre. Repeat this cycle as needed to observe the heating effects.
- **Data recording:** The interrogator continuously records wavelength changes in response to variations in temperature applied to the FBG. This data can be used to assess the FBG's temperature sensitivity and response characteristics.

4.5.2 Heating FBG Using 400-micron Fibre

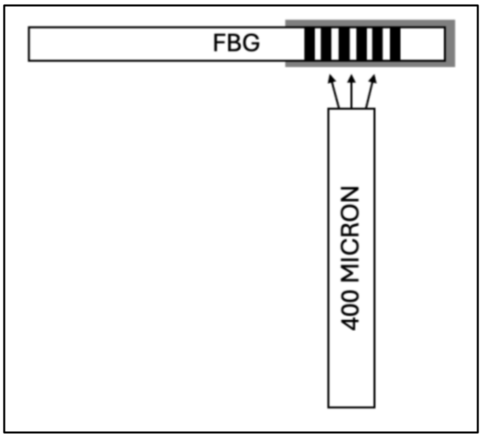

Figure 10: Silver-coated FBG placed perpendicular to 400-micron fibre using halogen light source

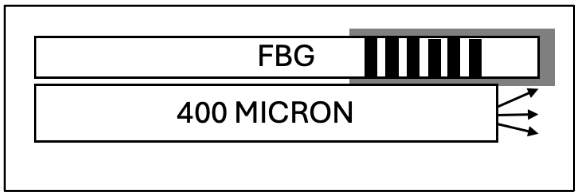

Figure 11: Heating silver-coated FBG placed adjacent to 400-micron fibre using halogen light source

- **System setup:**

- Perpendicular setup (Figure 9): Place the silver-coated Fibre Bragg Grating (FBG) perpendicular to the 400-micron fibre. This configuration directs the halogen light directly onto the FBG through the 400-micron fibre, maximizing localised heating.
- Adjacent setup (Figure 10): Alternatively, place the 400-micron fibre parallel and adjacent to the silver-coated FBG. In this configuration, the halogen light from the 400-micron fibre side-heats the FBG, making sure that the heat is concentrated along the grating.

- **Heating procedure:**
  - Connect the 400-micron fiber to a halogen light source. Ensure that the halogen light is directed on the FBG through the 400-micron fibre. The FBG's silver coating improves light absorption and reflection, resulting in localised heating.
  - Turn on the halogen light for a controlled period, typically in cycles such as 30 seconds on and 30 seconds off. This controlled heating will cause temperature fluctuations in the FBG, resulting in shifts in the Bragg wavelength.
- **Data recording:** Maintain record of the wavelength variations that occur during heating and cooling cycles. This data will enable you to assess the effectiveness of the 400-micron fibre as a heating element for the FBG. Analyse the recorded data to compare the FBG performance in both configurations.

4.5.3 Heating FBG Using 45-Degree Angled Fibre

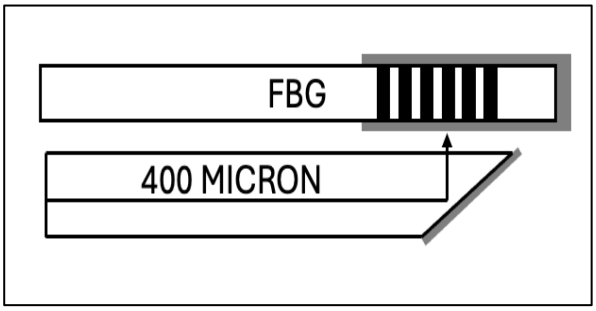

Figure 12: Heating silver-coated FBG placed adjacent to 45-degree angled 400-micron fibre

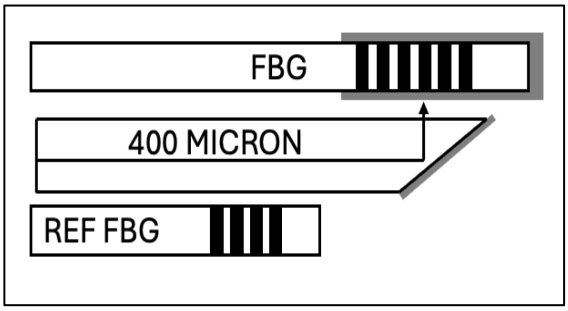

Figure 13: Heating silver-coated FBG placed adjacent to 45-degree angled 400-micron fibre and reference FBG

- **System setup:**
  - Place the 45-degree angled fibre with a silver-polished tip adjacent to the silver-coated FBG, as illustrated in Figure 11. The silver-polished tip functions as a mirror, reflecting light perpendicularly onto the FBG and concentrating heat precisely on the grating area.
  - In Figure 12, place the silver-polished 45-degree angled 400-micron fibre next to the silver-coated FBG and a reference FBG (REF FBG). The silver mirror on the fiber's tip ensures that light is efficiently reflected onto the FBG, allowing for a comparison of the heated FBG and the reference FBG, which is not directly exposed to the light source.
- **Heating procedure:**
  - In both tests, conduct the heating procedure with different light sources - WLS100 (Bentham Instruments), SLS201L/M (Thorlabs), and HL2000 (Ocean Optics) - with the 45-degree angled fibre in the same position relative to the FBG(s). Connect the 400-micron fibre to the chosen light source.
  - Use a spectrometer or interrogator to measure and record wavelength shifts for each light source in real time. This allows you to compare the temperature response and heating efficiency of each light source.
- **Data recording:** Activate the light source in controlled cycles to study the FBG's response to changes in temperature. To assess the heating impact in the dual FBG setup, monitor both the heated and reference FBGs.

4.6 TESTING FBG USING 45-DEGREE ANGLED FIBRE IN FLOW SYSTEM

- **Setup of the Flow System:**

- **Flow loop:** The system is built around a closed-loop flow configuration that includes a reservoir, a peristaltic pump, tubing, and flow sensors. The fluid circulates continuously throughout the system, replicating real-world conditions.
- **Reservoir:** Contains the fluid medium, which in this case is water. The reservoir is connected to the pump, which circulates the fluid throughout the system.
- **Peristaltic pump:** A LKB BROMMA 2120 VARIOPERPEX II pump is used to regulate the flow rate in the system. The flow rate can be changed to simulate different conditions, including slow laminar flows and faster turbulent flows.
- **Tubing:** Flexible, biocompatible tubing connects the components and guides the fluid past the FBG. The tube is intended to have minimal impact on the flow profile.
- **T push-on connectors:** A secure and leak-proof connection ensures that the fibre remains properly positioned within the flow system, with no fluid leaks or disruption.
- **Sensor structure:** This fibre is connected to the light source through the tube. Its silver-polished tip reflects the light onto the FBG, which is embedded into the fibre or put adjacent to it together with the reference FBG, providing a baseline or control measurement.

• **Experimental Procedure:**

- **System Initialization:** Fill the reservoir with the chosen fluid medium, water. Prime the peristaltic pump and tubing to remove any air bubbles and ensure a consistent, uninterrupted flow.
- **Fiber Installation:** Insert the 45-degree angled fibre into the tubing in the desired location and secure using blu-tack. Ensure that the fibre is properly positioned, with the silver-polished tip orientated to reflect light onto the FBG.
- **Heating Setup:** Connect the light source to the 45-degree angle fibre. Adjust the light source so that it is focused directly on the FBG. Using the pump, adjust the flow rate

to preference. Typical flow rates can range from slow (0.8ml/min), steady (venous blood flow) to fast (10ml/min), more turbulent (arterial blood flow). Repeat with different light sources.

- **Data Collection:**
  - Begin the experiment by turning on the light source to heat the FBG as the fluid flows past it.
  - During the experiment, use the flow sensors to monitor and record the flow rate and temperature.
  - The smart scope records the FBG's response in wavelength shifts in real-time.
  - Analyse the results to determine the FBG's temperature sensitivity in the flow environment. This involves identifying the relationship between induced temperature changes (by the light source) and associated wavelength shifts.

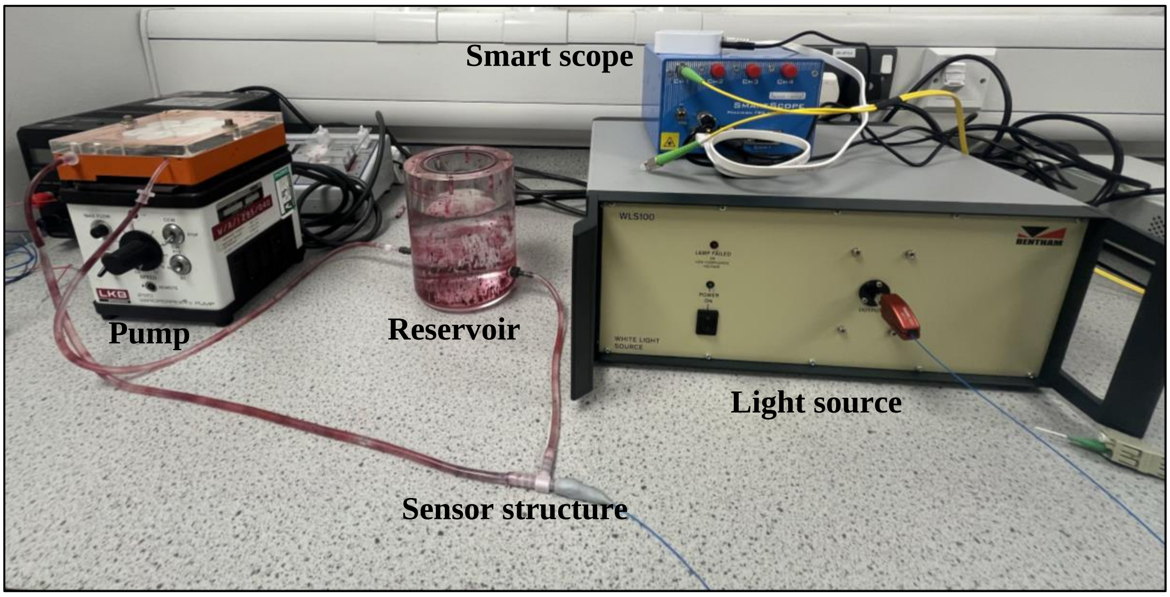

Figure 14: Setup of the experimental procedure using WLS100 heating light source

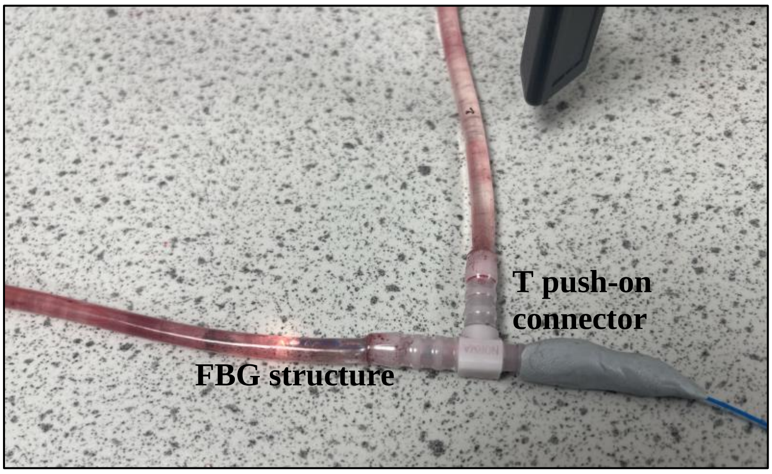

Figure 15: Heating FBG using light source in the flow system

4.7 CALIBRATION OF PUMP

4.7.1 Importance of Calibration

Pump calibration is essential for obtaining accurate and dependable flow measurements in experiments, especially when precise control over fluid delivery is required. Calibration verifies and adjusts the pump's flow rate settings, ensuring that the actual flow rate matches the desired or programmed rate. This is critical in experiments where flow rates have a direct impact on the results, such as fluid dynamics research, chemical reactions, or testing sensors like Fibre Bragg Gratings (FBGs) in a flow system. Without adequate calibration, there can be large differences between expected and actual flow rates, resulting in inaccurate data, unreliable results, and potentially incorrect conclusions.

4.7.2 Calibration Procedure

- **Materials:**
  - Measuring cylinder
  - Stopwatch or timer
  - Water (as the calibration fluid)
  - The pump to be calibrated

- **Method:**
  - **Setup:** Connect the pump to a water reservoir. Attach the pump's outlet tubing to the measuring cylinder, ensuring that the setup is secure and leak-free.
  - **Initial Calibration at Low Flow Rate:** Set the pump to the lowest flow rate you intend to test, starting with 0.8 mL/min. Start both the pump and the stopwatch. Allow the pump to continue until it has dispensed exactly 1 ml of water into the measuring cylinder. Stop the timer once the water level reaches 1 ml.
  - **Record the Time:** Take note of the time it takes to dispense 1 ml of water. Repeat this step three times to achieve consistency and an average result.
  - **Increase Flow Rate:** Adjust the pump to a higher flow rate (e.g., 1 ml/min, 2 ml/min, 5 ml/min, up to 10 ml/min). Repeat the measurement process for each flow rate, recording the time taken to dispense 1 ml of water at each setting.
  - **Calculate Flow Rate:** For each flow rate setting, calculate the actual flow rate using the formula:

    $$Flow\ rate = \frac{1\ ml}{Time\ taken\ (in\ mins)}$$

    Compare the actual flow rate with the programmed flow rate.
  - **Final verification:** Once the pump has been modified to meet the desirable flow rates across the specified range, run it through a final verification to verify consistent and accurate performance.

CHAPTER 5: RESULTS AND DISCUSSION

As outlined in the methodology, the design and testing of an optical fiber-based blood flow sensor involve a number of essential components and procedures that all contribute to the overall reliability and performance of the sensor. The results from various stages of material selection, experimental procedures, and sensor design are discussed and interpreted below.

5.1 ANALYSIS OF MATERIAL SELECTION AND COATING DURABILITY

- **Impact of Silver and PDMS Coating:**

In this section, we examine the impact of silver coating on three different Single-Mode Fibres (SMFs): S1 (Silver Coated), S2 (Silver + PDMS 2 times), and S3 (Silver + PDMS 5 times). The figures below show intensity vs. wavelength measurements for each fibre before and after the silver coating was applied.

- The graph in Figure 16 compares the intensity of SMF (S1) before and after applying the silver coating.

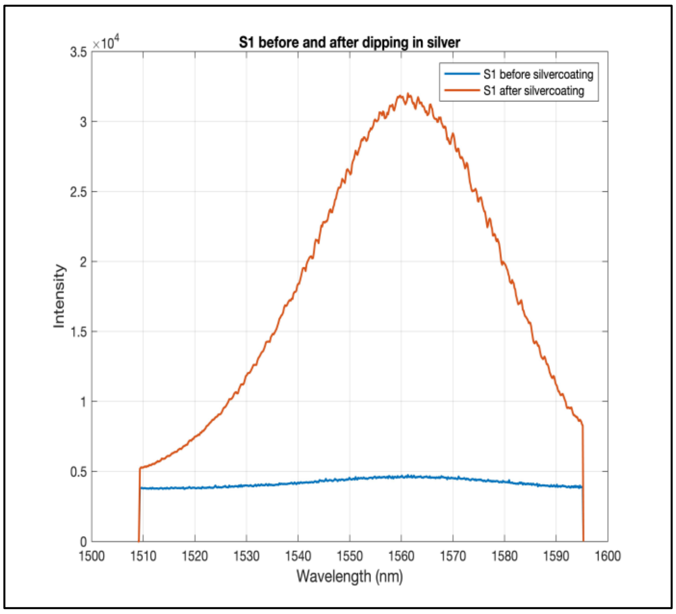

Figure 16: Plot of S1 before and after silver coating

- The intensity of the light reflected by the fibre significantly rises after the silver coating, showing that the silver improves the fiber's reflecting properties.
- The silver coating efficiently functions as a reflecting layer, increasing total light intensity. However, this increase in intensity must be balanced against potential

durability issues, since the silver coating alone may degrade in wet or mechanically stressed environments.

- The Figure 17 shows the performance of S2 before and after silver coating, followed by a 2x diluted PDMS layer. The Figure 18 presents the intensity comparison for S3, which is coated with silver and a more diluted (5x) PDMS layer.
- Similar to S1, the intensity increases significantly following the silver coating. The PDMS layer does not appear to lower the intensity, implying that it successfully protects the silver while maintaining optical performance.
- The 2x PDMS coating provides a good balance between protection and high optical performance. The PDMS layer protects the silver from environmental degradation while still keeping its reflective qualities, as indicated by the maintained intensity levels.

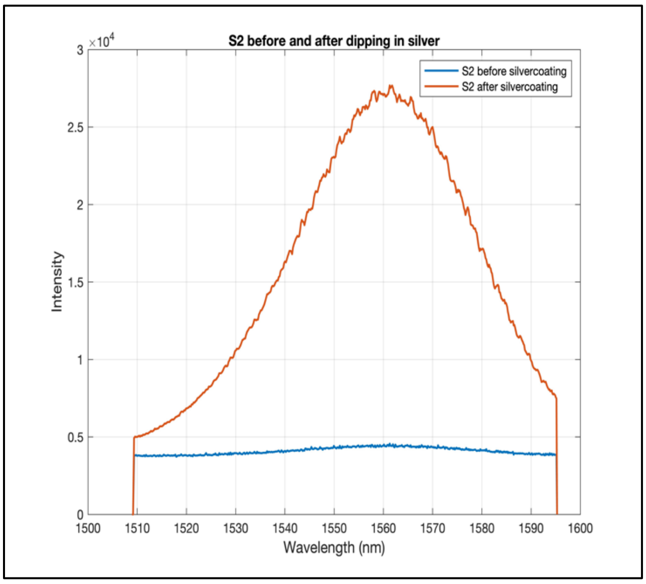

Figure 18: Plot of S2 before and after silver coating

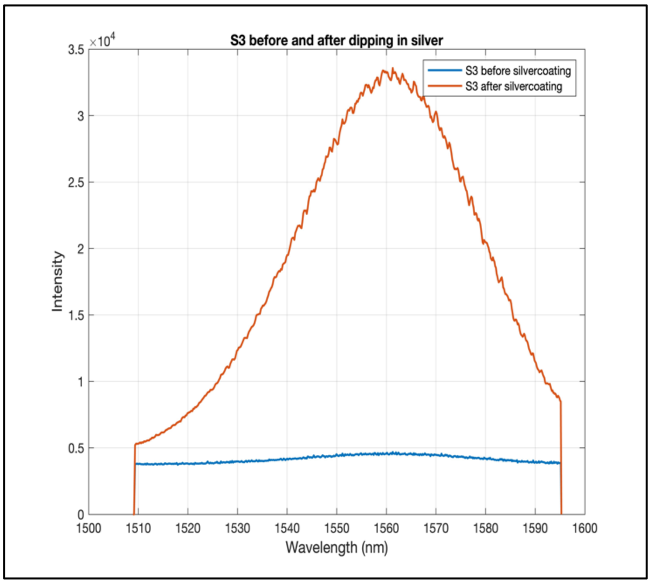

Figure 17: Plot of S3 before and after silver coating

- S3, like S1 and S2, shows an increase in intensity following the silver coating. Although the 5x PDMS layer is thinner and may provide less mechanical protection than the 2x layer, it retains the fiber's reflecting qualities. This implies that S3 is acceptable for applications that require a lighter, less invasive protective layer, as long as the fibre is not subjected to extreme conditions.

- **Durability of Coating by Water Immersion:**

In this section, we investigate the durability of three different SMFs (S1, S2, and S3) after immersing them in water for five days. The purpose is to determine whether the intensity of reflected light from the fibres decreases with time, indicating coating degradation or potential water absorption.

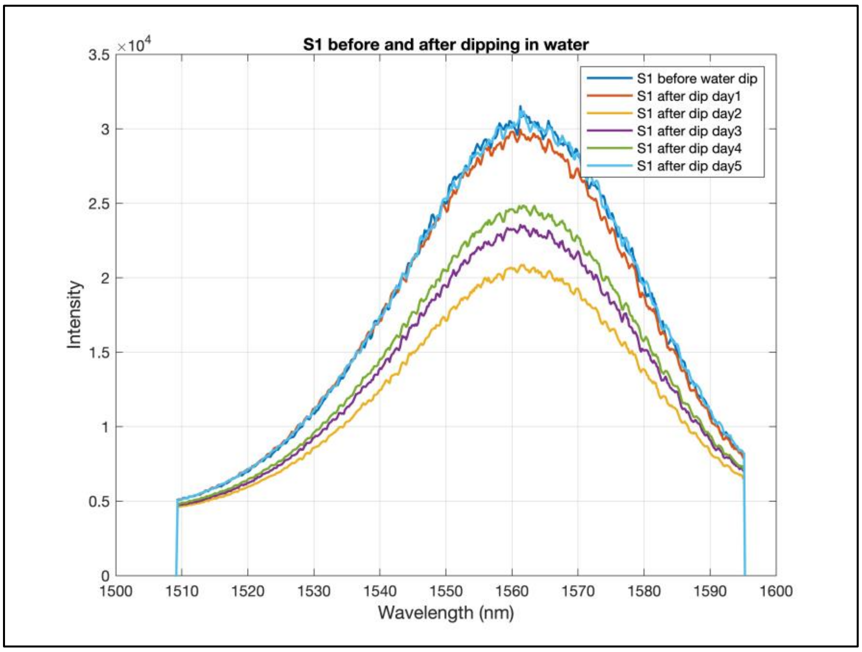

Figure 19: Plot of S1 before dipping in water and after dipping for 5 days

- **S1 (Silver Coated):** Without a protective PDMS coating, the silver-coated fibre degraded significantly in water, with a noticeable decrease in intensity over a five-day period. This indicates that silver alone is not suited for applications that require prolonged exposure to moisture.
- **S2 (Silver + PDMS 2 times):** Adding a 2x PDMS coating provides significant water resistance while only slightly reducing intensity. This shows that the coating level is sufficient for the majority of practical moisture-related applications. It provides the best balance of durability and optical performance, making it the preferred option.

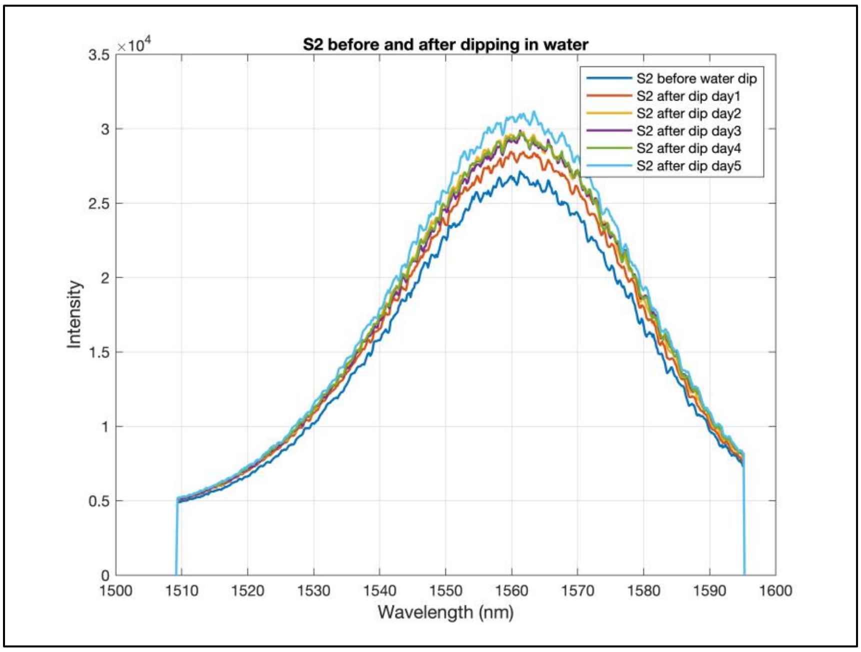

Figure 20: Plot of S2 before dipping in water and after dipping for 5 days

- **S3 (Silver + PDMS 5 times):** The more diluted 5x PDMS coating, while still efficient in preventing considerable intensity loss, provides a thinner layer of protection. The intensity remains almost unchanged during the five-day period, with only a small decrease seen. This makes S3 ideal for conditions where optical clarity is essential, but it may be less effective than S2 in cases where mechanical durability is also important.

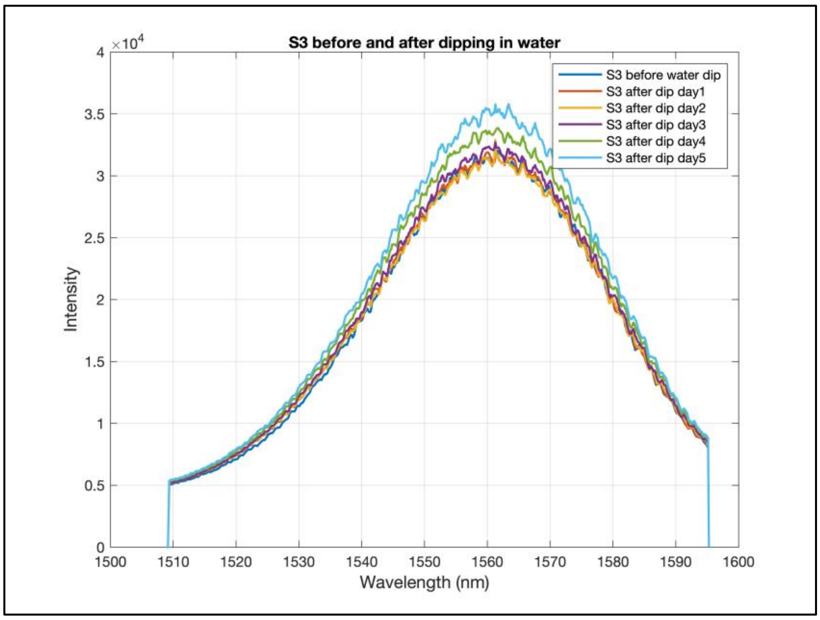

Figure 21: Plot of S3 before dipping in water and after dipping for 5 days

5.2 EFFECTIVENESS OF THE HEATING METHODS

The comparison of various heating methods—using SMF, 400-micron fibre, and 45-degree angled fibre—provides the most efficient approach to induce changes in temperature in the FBG for reliable flow measurement.

5.2.1 Heating using SMF

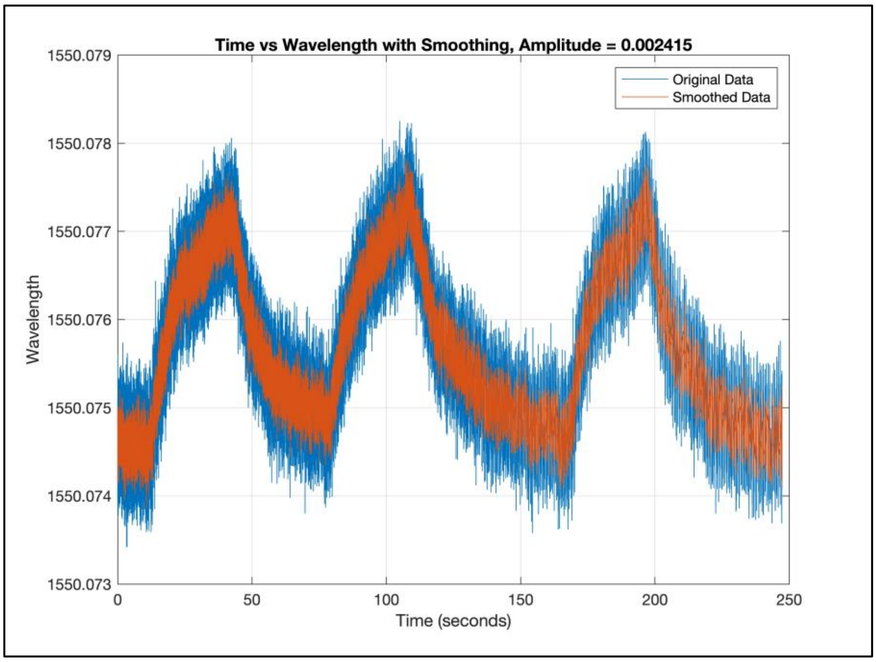

Figure 22: Wavelength variation over time due to heating of a Fiber Bragg Grating (FBG) using a Single-Mode Fiber (SMF)

- The graph in Figure 22 provided shows the relationship between time and wavelength shift, with the original data in blue and smoothed data using filter in orange. The amplitude of the wavelength shift is recorded as 0.002415 nm (or 2.415 pm).
- **Wavelength Shift Interpretation:** Given that an FBG sensor's typical sensitivity is around 10 pm/°C, a wavelength shift of 10 pm corresponds to a 1°C temperature change [27] [28]. The observed amplitude of 2.415 pm represents a temperature shift of approximately 0.2415°C.
- **Temperature Sensitivity:** The small amplitude of the wavelength shift indicates that temperature changes caused by the SMF heating method are subtle. This shows a high

level of control over the heating process, which allows for precise temperature adjustments in the FBG.

The continuous oscillation in the wavelength shift shows the controlled on/off heating cycle's ability to produce repeatable and observable temperature changes.

- **Discussion: Effectiveness of SMF Heating Method**
  - The system's high sensitivity, as indicated by the 0.2415°C temperature change corresponding to a 2.415 pm shift, suggests that the SMF heating method is ideal for experiments and applications requiring precision and control over small temperature changes, such as high-resolution temperature sensing or environments with only minor thermal variations to be detected.

    Alternative approaches, such as employing a larger diameter fibre or an angled fibre, may be more appropriate for applications that require significant heating or faster response times.

5.2.2 Heating Using 400-Micron Fiber

The graphs show the wavelength shift over time for both configurations:

- **Perpendicular Configuration:**
  - **Wavelength Shift Interpretation:** The amplitude of the wavelength shift is 0.0174 nm (or 17.4 pm). Using the sensitivity of 10 pm/°C, this corresponds to a temperature change of approximately 1.74°C.
  - The perpendicular configuration shows a larger wavelength shift (17.4 pm), indicating a greater temperature change in the FBG. This shows that the perpendicular setup is more efficient at focussing heat on the FBG, resulting in a larger temperature increase. The higher temperature change indicates the configuration's effectiveness in applications that require stronger or faster heating.

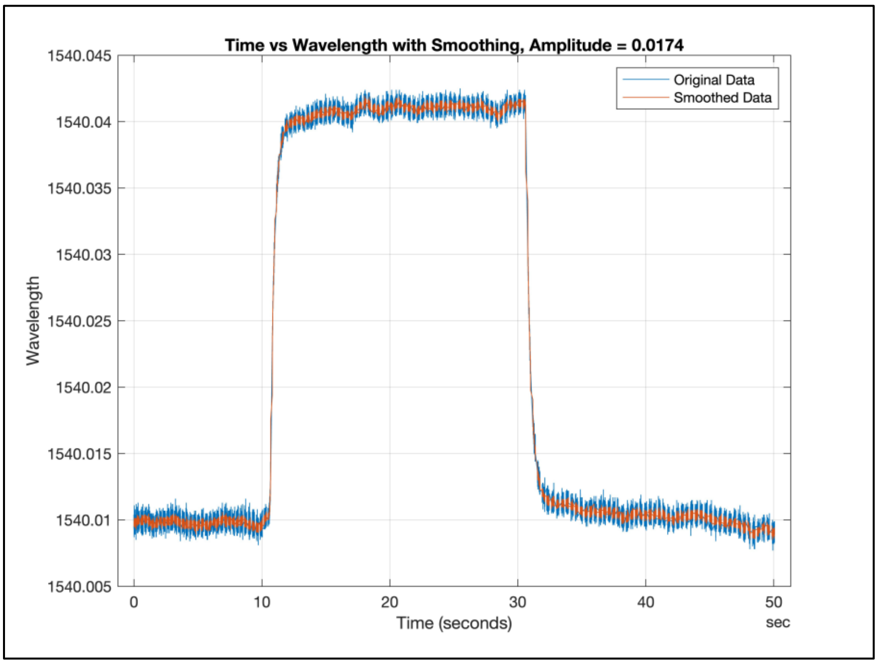

Figure 23: Wavelength variation over time due to heating of a Fiber Bragg Grating (FBG) using a 400-micron fiber in perpendicular configuration.

- **Parallel Configuration:**
  - **Wavelength Shift Interpretation:** The amplitude of the wavelength shift is 0.0066 nm (or 6.6 pm). This corresponds to a temperature change of approximately 0.66°C.
  - The parallel configuration produces a smaller wavelength shift (6.6 pm), implying a less intense temperature change. However, the graph for this configuration shows significant irregularities and noise. This could be due to the spectrometer's performance or possible alignment errors in the configuration.
  - The noise and irregularities indicate that the parallel setup may have had inconsistencies in the way light was transmitted to the FBG, maybe due to variances in light coupling or interference effects. These factors may affect the method's capacity to produce consistent and accurate temperature measurements.

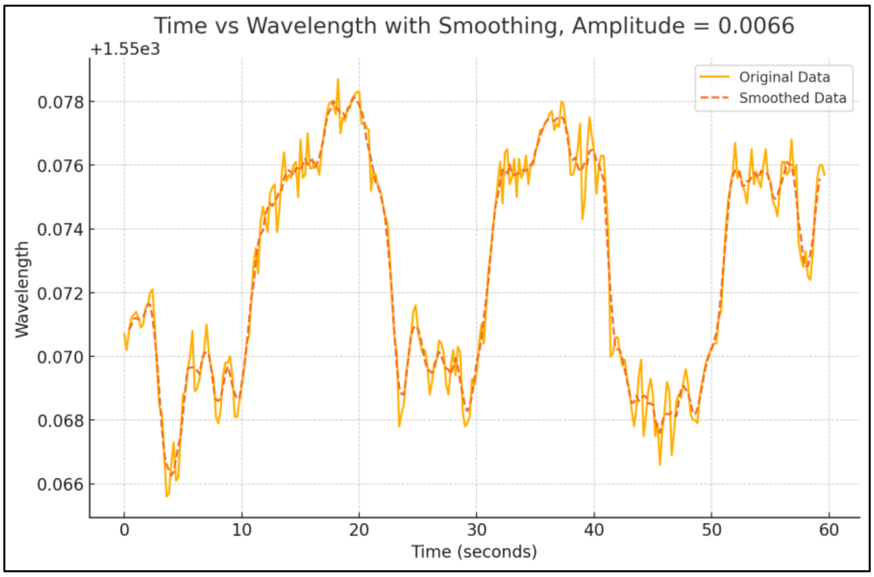

Figure 24: Wavelength variation over time due to heating of a Fiber Bragg Grating (FBG) using a 400-micron fiber in parallel configuration.

- **Discussion: Effectiveness of 400-micron Heating Method**
  - A comparison of perpendicular and parallel configurations with a 400-micron fibre demonstrates that the perpendicular setup provides the most effective heating, resulting in higher temperature change in the FBG. This makes it suitable for applications requiring rapid and substantial heating.
  - However, the parallel setup, while perhaps more feasible in certain situations, showed considerable irregularities and noise, most likely due to spectrometer issues or alignment inconsistencies.
  - Overall, the 400-micron fibre heating approach outperforms the SMF method, particularly when higher changes in temperature are necessary.

5.2.3 Heating Using 45-Angled Fiber

- **Choosing FP400URT fiber over FP400ERT for polishing:**
  - For the 45-degree angled fabrication, the FP400URT fibre was preferred over the FB400ERT because of the ease of handling and the suitability for accurate polishing.

- The 400 µm core of the FP400URT has minimal or no coating, allowing for more precise and seamless polishing at the necessary 45-degree angle. When making a reflecting surface, this is very important, especially when the fiber tip is silver coated to enhance reflectivity [29].

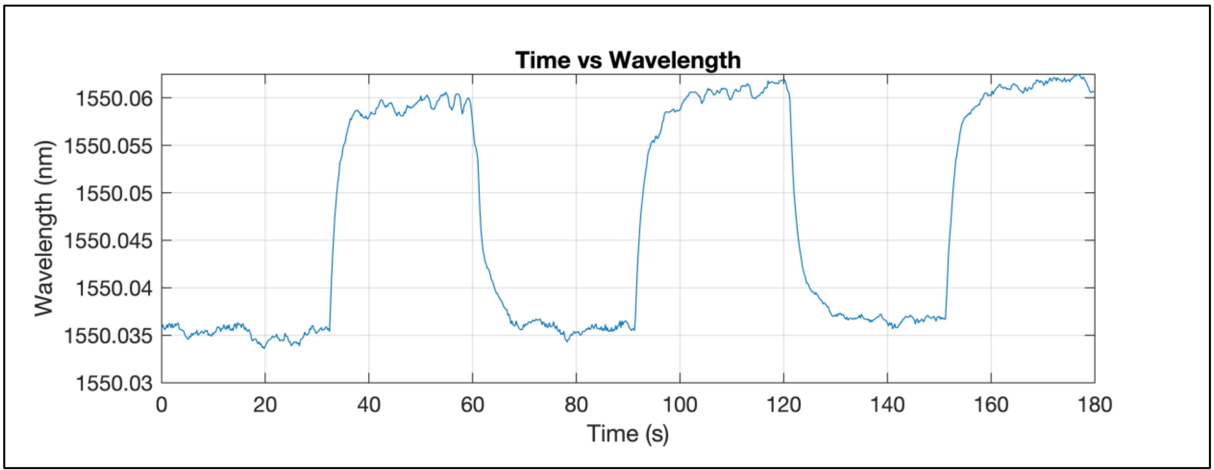

Figure 25: Wavelength variation over time due to heating of a Fiber Bragg Grating (FBG) using 45-Degree Angled Fiber without coating

- The thicker coating on the FB400ERT would need to be carefully stripped away, increasing complexity and the possibility of errors during fabrication [30].
- Additionally, the FP400URT's higher numerical aperture (NA) enables improved light capture and transmission, which is critical for the desired optical application.
- Overall, the FP400URT's absence of a thick coating, combined with its ease of handling and excellent polishing results, made it the best option for achieving the precise 45-degree angle required for optimal optical performance.

- **Uncoated structure:**
  - **Wavelength Shift Interpretation:** The first measurement showed a wavelength shift or amplitude of 0.0286 nm (or 28.6 pm) when using the uncoated 45-degree angled fiber with the silver-polished tip.
  - Given that a 10 pm wavelength shift corresponds to a 1°C temperature change, this implies a temperature change of approximately 2.86°C. This significant shift

demonstrates the effectiveness of the 45-degree angled fiber in generating substantial heating of the FBG.

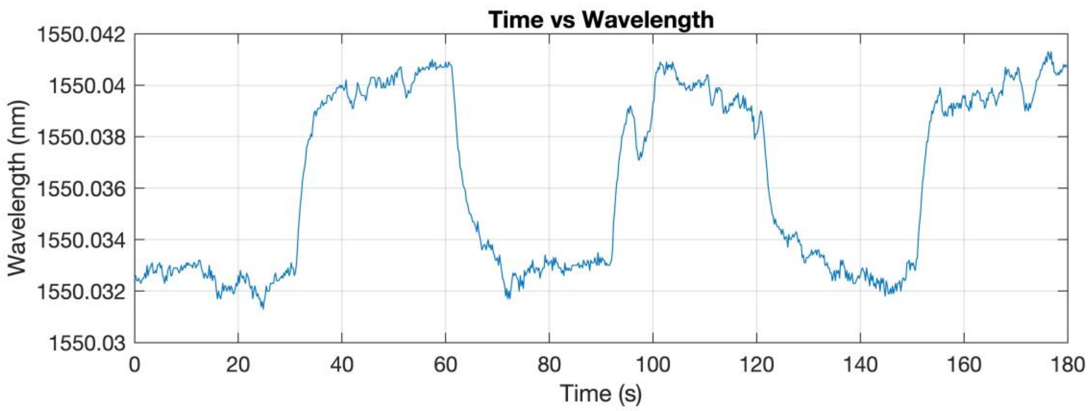

Figure 26: Wavelength variation over time due to heating of a Fiber Bragg Grating (FBG) using 45-Degree Angled Fiber after PDMS coated

- **PDMS coated structure:**
  - **Wavelength Shift Interpretation:** After coating the structure in a 2x diluted PDMS solution, the wavelength shift decreased to 0.0096 nm (or 9.6 pm).
  - This corresponds to a temperature change of approximately 0.96°C. The reduction in wavelength shift indicates that the PDMS coating, while providing protection, also dampens the heating effect, reducing the overall temperature change in the FBG.
- **Discussion: Effectiveness of the 45-Degree Angled Fiber**
  - When kept uncoated, the FP400URT 45-degree angled fibre with the silver-polished tip is extremely effective in focussing light and causing a considerable temperature to rise in the FBG, as evidenced by the 28.6 pm wavelength shift. This demonstrates that the setup is best suited for applications that demand high, localised heating.
  - **Impact of PDMS Coating:**

    A 2x diluted PDMS coating reduces the wavelength shift to 9.6 pm, indicating a decrease in the temperature change caused in the FBG. The PDMS most likely functions as a thermal buffer, dissipating some of the heat away from the FBG and reducing the total heating effect.

- Therefore, The 45-degree angled fibre with a silver-polished tip is the most effective heating solution for FBGs, especially in its uncoated form, with highest temperature variations. However, its implementation requires precise alignment, and the choice to coat it with PDMS creates a balance between protection and moderate heating.
- This method outperforms both SMF and traditional 400-micron fibre heating methods, making it the best option for applications that require large temperature changes. This configuration in a flow system can be examined further using other heating light sources.

5.2.4 Testing 45-Angled Fiber Heating in Flow System

In the dual FBG setup, both the heated FBG and a reference FBG are monitored to determine the effect of heating. After confirming the effectiveness of the 45-degree angled fiber in generating a significant temperature change, the structure is tested in a flow system with different light sources:

- **Wavelength Shift with WLS100 light source: Broadband White Light Source**

The graph in Figure 27 illustrates the wavelength shift observed when using the WLS100 light source to heat the Fiber Bragg Grating (FBG) within the flow system. The results demonstrate a significant and consistent wavelength shift, indicating that the WLS100 is highly effective in generating heat and inducing temperature changes in the FBG.

- **Magnitude and Consistency:** The WLS100 light source shows a significant and constant wavelength shift as the flow rate increases from 0.8 ml/min to 10 ml/min. The wavelength shift varies from about 0.0015 nm to 0.0007 nm depending on the flow rate. Given that a temperature resolution of 0.1°C corresponds to an FBG sensor's typical sensitivity of 10 pm/°C (0.01 nm/°C) [28][27], these shifts indicate temperature changes ranging from 0.15°C to 0.07°C. This steady decrease in wavelength shift as flow rate increases shows that the heat generated by the WLS100 is effectively absorbed by the FBG; however, larger flow rates help dissipate the heat more quickly, resulting in a smaller temperature increase and hence a reduced wavelength shift.

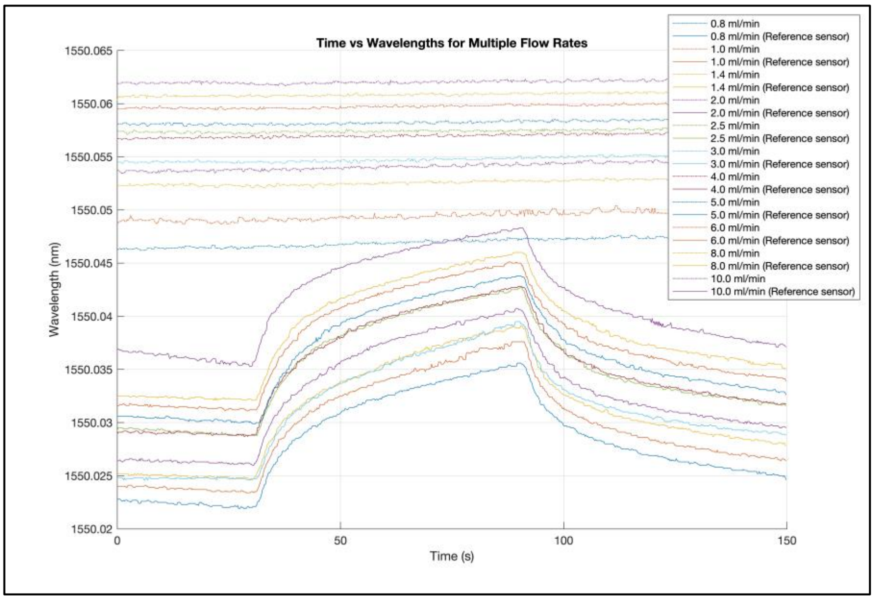

Figure 27: Wavelength shift for the WLS100 light source

- **Stability:** At lower flow rates, the wavelengths stay steady, indicating that the system encounters less interaction or disturbances. The system exhibits a noticeable wavelength shift at higher flow rates, indicating that the system's sensitivity to flow increases above a certain threshold (about 3.0 ml/min).
- **Efficiency:** The reason for the WLS100's efficiency in this configuration is probably that its spectrum output corresponds to the FBG's absorption properties. Because of this alignment, the FBG is able to effectively provide localised heating by absorbing the maximum amount of energy from the light source.

- **Wavelength Shift with SLS201L/M light source: Broadband Tungsten-Halogen Light Source**

The graph in Figure 28 represents the wavelength shift observed when using the SLS201L/M light source. The results show a minimal wavelength shift, indicating that the SLS201L/M is less effective at heating the FBG compared to the WLS100 and HL2000 light sources.

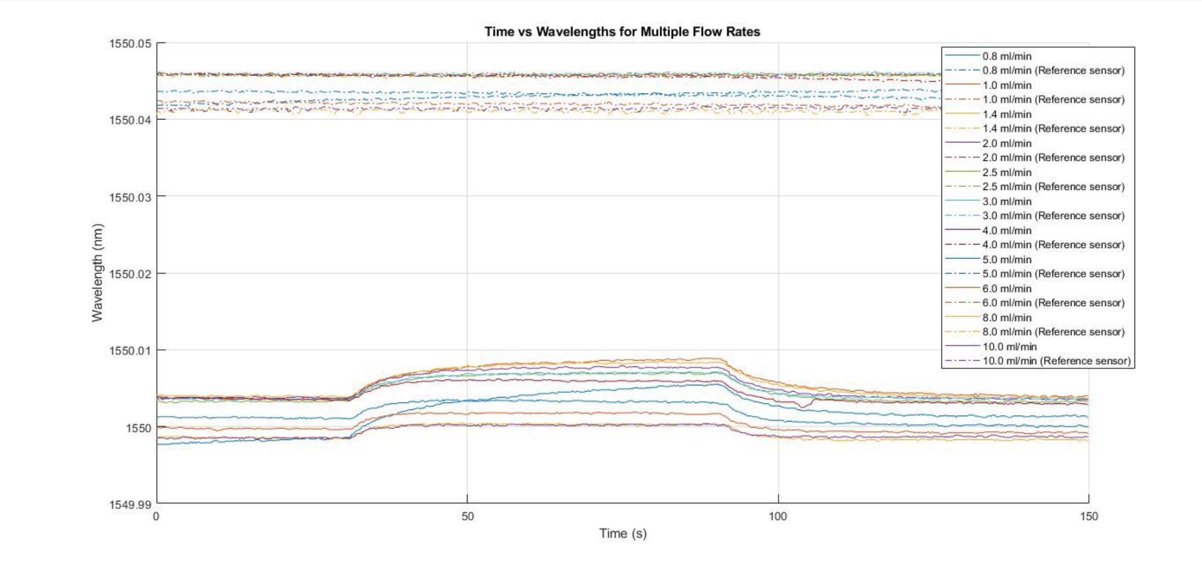

Figure 28: Wavelength shift for the SLS201L/M light source

- **Minimal Shift:** At the lowest flow rate of 0.8 ml/min, the SLS201L/M light source produces a wavelength shift of about 0.0078 nm, and at the highest flow rate of 10 ml/min, 0.002 nm. This corresponds with variations in temperature of roughly 0.78°C to 0.2°C. The graph shows a distinct clustering of wavelengths based on flow rates, with lower flow rates clustering higher (around 1550.04 nm) and higher flow rates clustering lower (around 1549.99 nm).The fact that these variations are smaller in magnitude indicates that the SLS201L/M does not produce enough heat to noticeably alter the FBG's temperature.
- **Stability:** For lower flow rates (up to 2.0 ml/min), the system appears very stable with minimal wavelength variation over time.
- **Lower Power Output:** Additionally, the SLS201L/M may have a lower overall power output compared to the other light sources, further reducing its ability to heat the FBG effectively.

- **Wavelength Shift with HL2000 light source: Halogen Light Source**

The graph in Figure 29 shows the wavelength shift observed with the HL2000 light source, which performs better than the SLS201L/M but not as effectively as the WLS100.

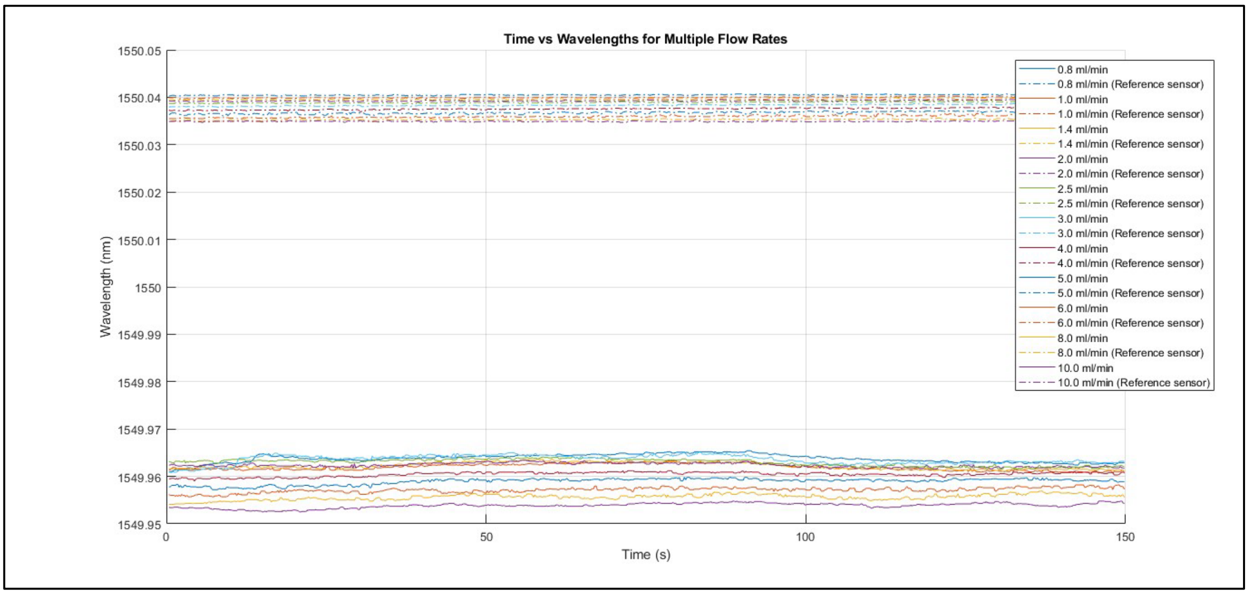

Figure 29: Wavelength shift for the HL-2000 light source

- **Moderate Shift:** At 0.8 ml/min, the HL2000 produces a moderate wavelength shift that varies to 0.0023 nm at 10 ml/min. This corresponds to variations in temperature of roughly 0.44°C to 0.23°C. Even though this shift is more noticeable than it was with the SLS201L/M, it is still not as efficient as the WLS100. Since there is a minimal wavelength shift in the FBG, the temperature changes caused by the HL2000 light source are presumably not that significant, which would limit its sensitivity and effectiveness as a flow sensor. Reiterating the system's consistency is the reference FBG, which continues to remain stable as expected.
- **Stability:** In the upper cluster, the wavelengths remain quite stable over time for lower flow rates (up to 4.0 ml/min). about between 1550.05 and 1550.04 nm.
- Higher flow rates (5.0 ml/min and above) have steady wavelengths as well, but they appear slightly more variable than at lower flow rates. However, this graph shows the

stability of the system across all flow rates, with very minimal changes in wavelength over time.

- **Potential Limitations:** The HL2000 may not be as well-suited for scenarios that require quick and significant temperature changes. However, it could be beneficial in situations where controlled, moderate heating is preferable, and where the WLS100 might generate too much heat.

- **Discussion: Effectiveness of the Heating Light Sources**

- The WLS100 is the most practical and efficient choice for heating the FBG inside the flow system, according to the study of the wavelength changes under various light sources. The WLS100 is perfect for applications requiring accurate and reliable heating because of its high wavelength shift, which indicates that it is well-matched to the FBG's absorption characteristics. Despite its limited effectiveness, the HL2000 provides a balanced performance that could be helpful in applications where controlled heating is necessary.
- The WLS100's broad visible spectrum and higher colour temperature make it the ideal candidate for FBG applications requiring precise and significant temperature shifts.
- Given these observations, the SLS201L/M might not be the best choice for applications that require substantial heating of FBGs. However, it might be helpful in cases where minimal heating is needed or where reducing the chance of overheating is important.

5.2.5 Results for Flow Rate vs Amplitude Using Different Light Sources

- The graph in Figure 30 illustrates the performance of the WLS100 light source. The amplitude starts significantly higher than in the two cases, showing the WLS100's improved ability to cause changes in temperature in the FBG. As the flow rate increases, the amplitude lowers, but it remains higher than the other light sources. This shows that the WLS100 is more effective at maintaining higher temperature-induced changes in the FBG across a wide range of flow rates.

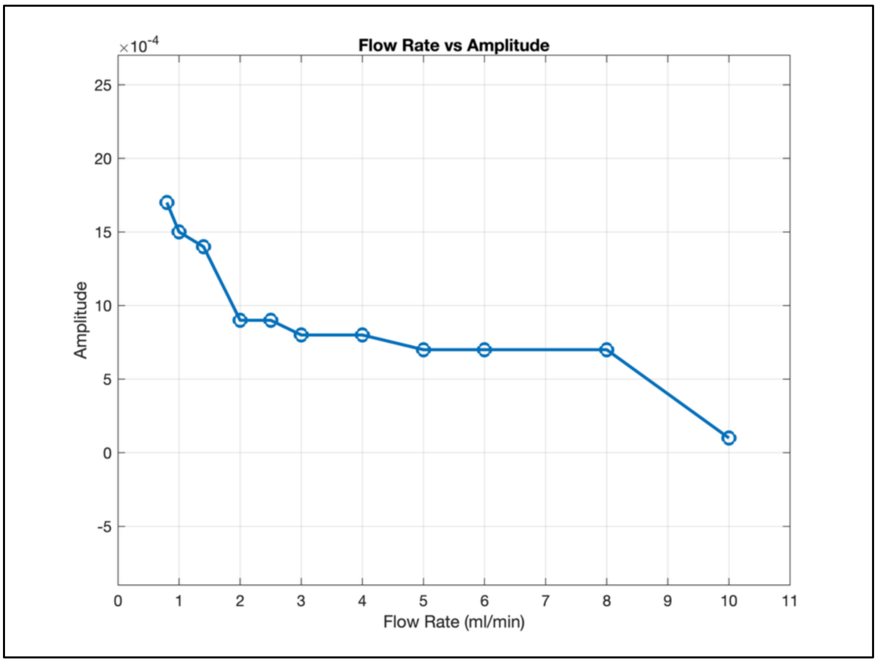

Figure 30: Relationship between flow rate and amplitude when heating an FBG using WLS100

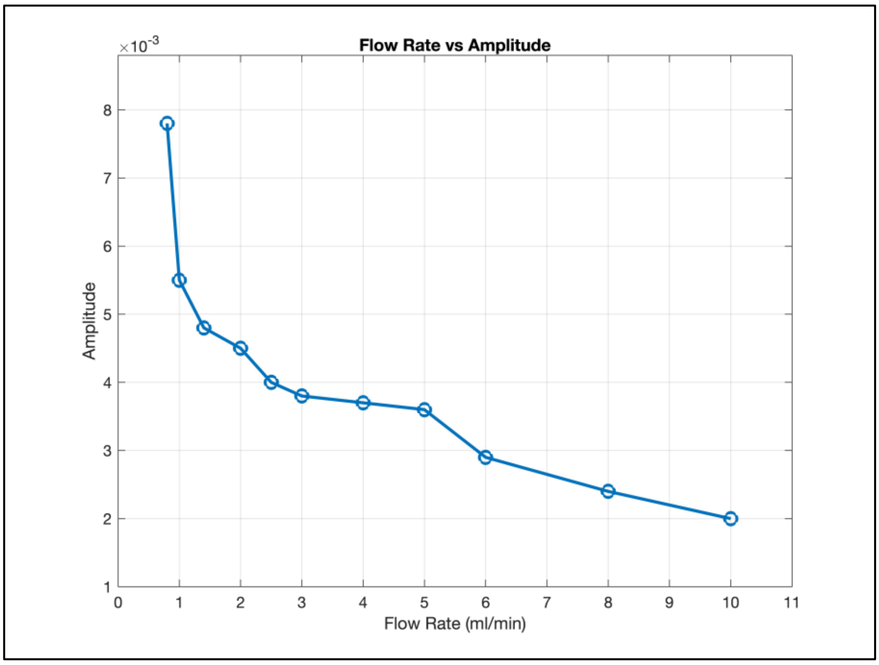

Figure 31: Relationship between flow rate and amplitude when heating an FBG using SLS201L/M

- The graph in Figure 31 depicts the amplitude-flow rate relationship for the SLS201L/M light source. The pattern is comparable to the HL2000, with a sharp beginning decrease in amplitude as the flow rate increases. The SLS201L/M has a steeper drop in amplitude at low flow rates, implying that it is less effective at sustaining temperature changes in the FBG than the HL2000. The amplitude stabilises at a lower value, showing that the SLS201L/M performs less efficiently in this application.

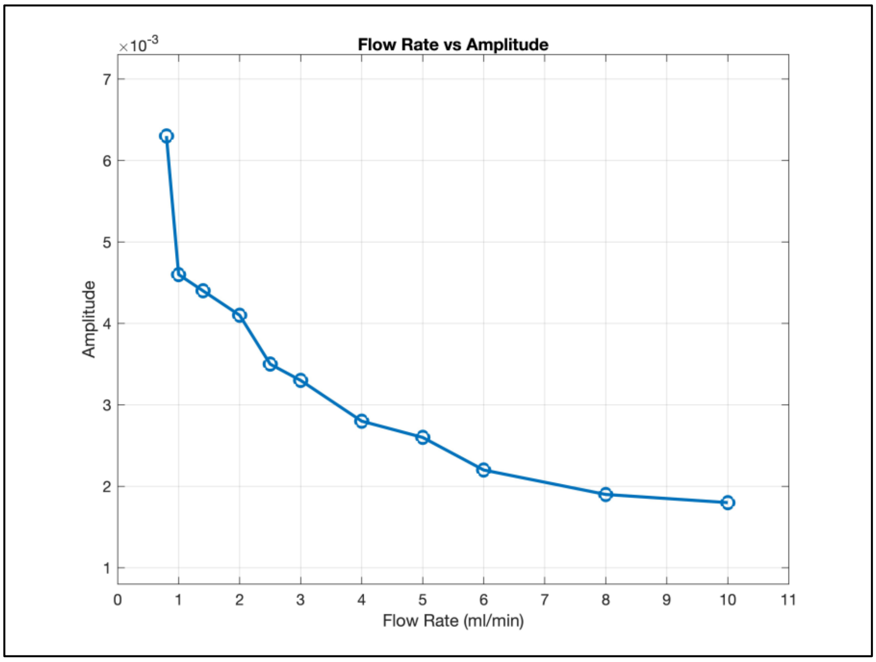

Figure 32: Relationship between flow rate and amplitude when heating an FBG using HL2000

- The graph in Figure 32 depicts amplitude variation as a function of flow rate with the HL2000 light source. The amplitude is relatively high at low flow rates but decreases gradually as flow rate increases. This pattern suggests that the HL2000 may efficiently produce temperature changes in the FBG at lower flow rates, resulting in greater amplitude. However, as the flow rate increases, the heating efficiency drops, resulting in a reduction in amplitude.

- **Summary of the results:**

LIGHT SOURCE	EFFECTIVENESS	ROLE OF REFERENCE FBG	SUITABILITY FOR FLOW SENSOR
WLS100 Wavelength Range: 300nm - 2500nm [31]	**Highly effective:** Significant heating, well-matched to FBG absorption characteristics.	Reference FBG shows stable baseline, confirming the experimental setup's accuracy across all light sources. Stability is crucial to ensuring accurate temperature measurements by comparison to the heated FBG.	**High:** Strong, consistent shifts ideal for flow sensing applications requiring precise temperature control.
SLS201L/M Wavelength Range: 360nm - 2600nm [32]	**Less effective:** Minimal heating, possible spectral mismatch with FBG.	Reference FBG shows minimal noise, confirming low interaction with this light source.	**Low:** Minimal shifts suggest insufficient heating for effective flow sensing.
HL-2000 Wavelength Range: 360nm - 2400nm [33]	**Moderately effective:** Some heating, but less than WLS100.	Reference FBG shows slight drift but maintains overall stability.	**Moderate:** Adequate for moderate heating applications but limited for sensitive flow measurements.

5.2.6 Discussion of Calibration Results

- The calibration graph in Figure 33 shows the relationship between the flow rate selected on the peristaltic pump and the time required to dispense 1 ml of water. As expected, flow rate and time have an inverse relationship: as flow rate increases, the time required to dispense 1 ml of water decreases.

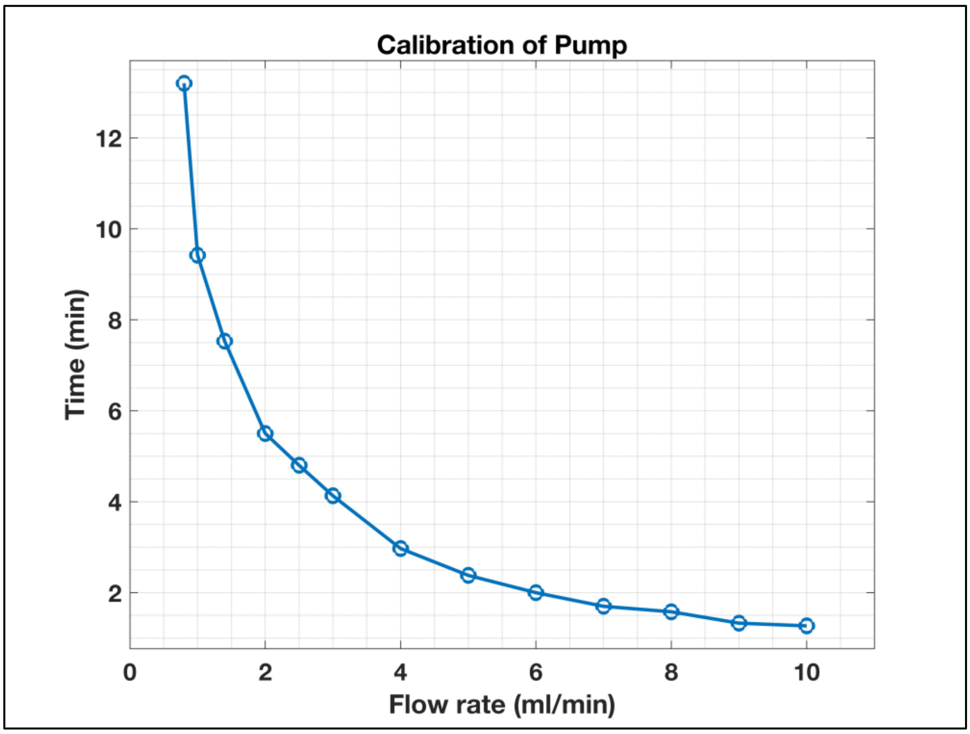

Figure 33: Relationship between flow rate (ml/min) and the time taken (min) to dispense 1 ml of water

Flow Rate (ml/min)	Time Taken (min)
0.8	13.20
1.0	9.42
1.4	7.53
2.0	5.50
2.5	4.80
3.0	4.13
4.0	2.97
5.0	2.38
6.0	2.00
7.0	1.70
8.0	1.58
9.0	1.33
10.0	1.27

Table 1: Flow rate and time taken to dispense 1 ml of water during pump calibration

- **Non-Linear Behaviour at Low Flow Rates:** The graph shows a nonlinear connection, especially at lower flow rates. For example, dispensing 1 ml at 0.8 ml/min and 1 ml/min takes significantly longer and does not reduce linearly with higher flow rates. Peristaltic pumps exhibit non-linear behaviour at lower flow rates, making them less accurate and stable at the lower end of their operating range.
- **Improved Linearity at Higher Flow Rates:** As the flow rate exceeds 2 ml/min, the time required to dispense water becomes more consistent, showing improved linearity and predictability of the pump's performance. This improves the pump's reliability at higher flow rates, where flow control is crucial for experiments requiring fluid dynamics or sensor testing, such as Fibre Bragg Gratings (FBGs) in a flow system.

• **Pump Calibration Implications:** The calibration process reveals that the peristaltic pump may need to be adjusted or compensated at lower flow rates in order to attain the required accuracy. The divergence from linearity at lower rates indicates that careful monitoring and calibration are required while operating in this range. However, at higher flow rates, the pump functions more predictably, which is useful for experiments that require consistent and precise fluid delivery.

5.3 CHALLENGES AND SOLUTIONS

CHALLENGE / LIMITATION	DESCRIPTION	PROPOSED SOLUTION
Difficulty in Achieving Uniform Silver Coating	Variations in coating thickness and uniformity may cause inconsistencies in the FBG's reflective properties and, as a result, temperature sensitivity.	Refine the coating process for better control over thickness and uniformity or explore alternative coating methods.
Ineffectiveness of SLS201L/M Light Source	Minimal wavelength shift, indicating lower effectiveness in heating FBG.	Use SLS201L/M only in low-temperature change applications, or switch to more powerful sources like WLS100.

Spectrometer Noise	Interference in data collection due to noise, particularly in parallel heating configurations.	Apply signal processing techniques such as filtering or smoothing to reduce noise.
Instability in Temperature Control	Significant noise and irregularities observed in SMF parallel heating method.	Improve light source stability, use noise filters, or consider alternative heating methods.
Difficulty in Practical Implementation	Perpendicular heating method is challenging for in-body applications due to alignment and placement issues.	Explore alternative heating methods like angled fibres that can be more easily integrated into practical setups.
Challenges in Maintaining Consistency Across Flow Rates	Variability in flow rates, particularly at the lower end, affecting experimental results.	Regular recalibration and use of more advanced pumps that ensure consistent flow rates across the range.
Limited Wavelength Shift with Higher Flow Rates	Decreased effectiveness of heating mechanisms at higher flow rates.	Increase the intensity or duration of the light source exposure or optimize the flow system design.

5.4 FUTURE SCOPE OF WORK

The proof-of-concept presented in this project paves the way for a number of developments in the future, particularly in biological applications and fluid dynamics. Here are some potential areas for future research and application:

- **Bidirectional Flow Sensing:**
  - **Application in Arteries and Veins:** The current setup can be modified to measure bidirectional flow, which is essential for monitoring blood flow in both arteries and veins. By improving the sensor's sensitivity and positioning, it might be used to detect both the magnitude and direction of flow, providing a more complete picture of circulatory dynamics [34].
  - **Development of Dual-Sensor Systems:** By integrating several Fibre Bragg Grating (FBG) sensors or using arrays of sensors, flow in both directions within a single

vessel can be measured simultaneously. This would be especially useful in medical diagnostics when understanding the bidirectional nature of blood flow is critical, such as in cases of venous reflux or arterial stenosis.[35]

- **Prototype Actualization for Real-Life Application**:
  - **Integration with Medical Devices:** The sensor could be placed in minimally invasive medical devices like catheters or stents to provide real-time monitoring of blood flow in patients. This could be especially valuable during surgeries or for long-term monitoring of patients with cardiovascular problems.
  - **Wearable Health Monitors:** Developing a wearable version of this sensor could allow patients with chronic diseases to monitor their blood flow continuously and non-invasively. This could lead to improved management of disorders such as hypertension and diabetes, where blood flow is an important sign of health.
  - **Commercial Medical Devices:** Scaling the prototype for commercial usage involves not only improving the sensor's accuracy and reliability, but also ensuring that it passes strict regulatory criteria for medical devices. Collaboration with medical device manufacturers could help bring this technology into the market, potentially enhancing patient outcomes in a number of clinical situations.
- **Improvements in Sensor Design and Materials:**
  - **Advanced Coatings and Materials:** Developing new materials or coatings to improve the sensor's durability and sensitivity may broaden its application area. For example, biocompatible coatings that inhibit clot formation or biofouling could improve the sensor's performance in long-term medical implantation [36].
  - **Miniaturisation:** Further miniaturisation of the sensor may lead to its use in even smaller vessels, such as capillaries, or in other fluid systems with restricted space.

APPENDIX

APPENDIX A – RISK ASSESSMENT FORM

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Activity / Task Risk Assessment Form

RISK ASSESSMENT FORM

Business Unit: Faculty of Engineering, Optics and Photonics Research Group	**Location(s) of Activity:** Optics and Photonics Research Group (OPG) L4 Lab	**Risk Assessment Ref:**
Activity Title: Development of Blood Flow Sensor using Optical Fibres		
Activity Outline: To develop a versatile blood flow sensor that uses optical fibres to accurately measure blood flow rates Optimize sensor performance using Fibre Bragg Gratings Design and fabrication of a blood flow phantom system		
Those at risk / affected parties: Lab users (student and staff)		
Risk Assessor Name: Asmitha Alagarsamy	Signature: A · Asmitha	Date: 06/05/2024
Responsible person / Line Manager Name: Dr. Ricardo Goncalves Correia	Signature:	Date:
Master Risk Assessment Reference where applicable:	**Related procedure references or links:**	
Review Period: Every 6 months		

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
Silica fibre & glass substrate	Skin injury, cuts	Low	Nitrile gloves should be used all through process and disposed correctly before exiting the Lab. Glass slides to be disposed properly after use. Be careful about the glass within the blue tack	Low
Electrical equipment	Electric shock, electrical fire, and burns	High	Ensure that all equipment has been checked for electrical safety, with a visible and in date PAT sticker. A visible inspection should be undertaken before the equipment is used. Cables should be placed safely (out of the way and the water container).	Medium
Exposure to chemicals (UV glue, Isopropyl Alcohol, Acrylic colours)	Skin irritation, Respiratory issue, and dizziness	Medium	Nitrile gloves should be used and disposed immediately when done. UV glue should be placed chemical lab. Tag the container for the fake blood. Always place them in safe place.	Low
Exposure to Optical Radiation (UV light source)	Eye damage, skin burns	High	Always place away from eyes when using light source. Avoid looking directly at the light source. Using fibre to control the light transmission direction. Placing the light source lower than eye level.	Low
Mechanical Hazards (Fiber tools like scribe, cutter, stripper)	Skin injury, cuts	Medium	Nitrile gloves should be used	

Activity/Task Risk Assessment Form: SAF-FOR-RA-HML — Page 1 of 5, Version 1 — May 2019, Refer to Health and Safety Office for latest version

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Activity / Task Risk Assessment Form

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

Activity/Task Risk Assessment Form: SAF-FOR-RA-HML — Page 2 of 5, Version 1 — May 2019, Refer to Health and Safety Office for latest version

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Activity / Task Risk Assessment Form

Waste handling	
Emergency	Emergency phone number: 8888
Training, supervision and competency	The procedure should only be performed during operating hours (9 a.m. to 5 p.m., Monday through Friday). If the procedure needs to be extended after hours, notify the facility technician and the second trained coworker ahead of time.
Other	All the activities only

Competency Record

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

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).

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Activity / Task Risk Assessment Form

- **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 authorize 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.

Activity / Task Risk Assessment Form

- **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 favor 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) Substitution (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.

APPENDIX B - MATLAB CODE FOR CALIBRATION OF PUMP

```
% Flow rate (ml/min)
flow_rate = [0.8, 1, 1.4, 2, 2.5, 3, 4, 5, 6, 7, 8, 9, 10];

% Time (min)
time = [13.20, 9.42, 7.53, 5.50, 4.80, 4.13, 2.97, 2.38, 2.00, 1.70, 1.58, 1.33, 1.27];

% Create the plot
figure;
plot(flow_rate, time, '-o', 'LineWidth', 2, 'MarkerSize', 8);

% Title and labels
title('Calibration of Pump', 'FontSize', 18, 'FontWeight', 'Bold');
xlabel('Flow rate (ml/min)', 'FontSize', 16, 'FontWeight', 'Bold');
ylabel('Time (min)', 'FontSize', 16, 'FontWeight', 'Bold');

% Increase the font size of the axes
set(gca, 'FontSize', 14, 'FontWeight', 'Bold');

% Add grid
grid on;

% Display the plot with adjusted axis limits
xlim([0, max(flow_rate) + 1]);
ylim([min(time) - 0.5, max(time) + 0.5]);

% Add minor grid lines for better readability
grid minor;
```

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