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# Converged data and sensing Over optical fiber networks

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TITLE OF PROJECT: Converged data and sensing over optical fiber networks

**DECLARATION:**

In accordance with Rule G5.11.4, I hereby declare that the above-mentioned  
treatise/ dissertation/ thesis is my own work and that it has not previously been  
submitted for assessment to another University or for another qualification.

**SIGNATURE:**



**DATE:** 25/07/2022

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## ACKNOWLEDGMENT

*“Usebenzile Makhambula”*

I am overwhelmed with gratitude and humility for everyone who has helped me translate the concepts of this work into something concrete that is well above the level of simple.

Firstly, I would like to express my sincere gratitude to my supervisor , Prof. Tim Gibbon, for providing me with the wonderful golden opportunity to pursue this magister scientiae degree. Meeting Prof Gibbon has been one of the most life transforming things to happen for both my academic career and personal growth. He offered priceless counsel and supported me during trying times. His drive and assistance made a significant difference in the successful conclusion of this research work.

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Lastly I want to point out my family’s support system and thoughtfulness, they have always been there for me and stood by my side throughout everything.

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## Abstract

Internet connectivity, data and sensors have become increasingly important across all spheres of business and industry, especially in the mining sector. Recent years have seen deeper mining explorations as a result of the depletion of natural resources in shallow strata. Due to complex and unexpected geological conditions as well as significant ground stresses, deep stratum mining operations encounter a number of difficulties. It is essential that the mining industry be more innovative with their equipment and monitoring systems given the rise in expenses caused by energy consumption, concessions to surface integrity, worldwide freshwater shortage, as well as health and safety of miners. Any attempt to eliminate these mining consequences must start with early discovery. An effective plan to anticipate, prevent, or manage geohazards events must be in place because to these complex and unpredictably occurring geological circumstances.

Due to their capacity to combine gigabits of data from remote locations within the mine to a centralized control centre, optical fiber offers a variety of distinctive advantages within the mining industry. In order to attain maximum productivity, modern and effective mining operations use enhanced control techniques and increasing mechanization. Additionally, optical fibers can be utilized in a mine to safely monitor seismic activity, methane, roof collapses, rock bursts, explosions, and dangerous underground mine settings.

Multimode or multi-core fibers represent a particularly intriguing alternative for transmissions over small distances, especially for broad band local area networks like LANs, as they enable the use of affordable components. Due to the current state of these issues, there is a drive to create fiber optic communication links that can also function as distributed optical fiber sensors, where each point along the fiber can function as a continuous array of sensors.

In this thesis, we suggested and experimentally demonstrated a converged solution for precise vibration sensing and high-speed data in mining applications. With wireless access for people and equipment inside cavities, the solution uses multimode fiber to link nearby mining cavities. To track vibrations and earth tremors causing rock falls, polarization-based vibration sensors over multimode fiber is used. With a modal dispersion penalty of just 1.6 dB, photonic data transmission across 100 m of multimode fiber is successfully accomplished. Successful 1.7 GHz wireless transmission across a distance of 1 m is demonstrated, and vibrations between 50 Hz and 1 kHz may be reliably detected to within 0.02 percent of the true value.

## List of acronyms

<b>5G</b>	<b>5<sup>th</sup> Generation</b>
<b>ADSL</b>	Asymmetric Digital Subscriber Line
<b>BER</b>	Bit Error Rate
<b>BERT</b>	Bit Error Rate Transceiver
<b>CD</b>	Chromatic Dispersion
<b>DBR</b>	Distributed Bragg Reflectors
<b>DFB</b>	Distributed Feedback Laser
<b>DOP</b>	Degree Of Polarization
<b>DTS</b>	Distributed Temperature Sensors
<b>ESA</b>	Electrical Spectrum Analyzer
<b>FBG</b>	Fiber Bragg Gratings
<b>FEC</b>	Forward Error Correction
<b>FIG</b>	Fiber Interferometers
<b>IoT</b>	Internet Of Things
<b>IP</b>	Internet Protocol
<b>LAN</b>	Local Area Network
<b>LED</b>	Light Emitting Diode
<b>LPFG</b>	Long Period Fiber Gratings
<b>MEMS</b>	Micro-Electromechanical Systems
<b>MMF</b>	Multimode Fiber
<b>MSHA</b>	Mine Safety And Health Administration's
<b>MZM</b>	Mach-Zehnder Modulator
<b>OM4</b>	Optical multimode fiber with 4700 MHz/km bandwidth
<b>PD</b>	Positive-Intrinsic-Negative
<b>PIN</b>	Positive-Intrinsic-Negative
<b>PMD</b>	Polarization Mode Dispersion
<b>PRBS</b>	Pseudo Random Bit Simulator
<b>SMF</b>	Single Mode Fiber
<b>SOP</b>	State Of Polarization
<b>TCO</b>	Total Cost Of Ownership
<b>UV</b>	Ultra Violet
<b>VCSEL</b>	Vertical Cavity Surface Emitting Laser
<b>VOA</b>	Variable Optical Attenuator
<b>WDM</b>	Wavelength Division Multiplexing
<b>Wi-Fi</b>	Wireless Fidelity



# CHAPTER 1

# **Introduction to optical fibers and its use in mining applications**

## **1.1 Introduction**

Optical fibers have revolutionized the concept of smart mines. “Smart mines” refers to several next generation features being developed all around the world. These include processes that use information, autonomy, and technology to obtain enhanced safety, minimize operational costs, and gain better productivity for a mine site. Mining corporations emphasize on enhancing productivity by providing state-of-the-art software and solutions [1]. Thanks to their timely delivery and sensors, fibre optics have a huge role within the industrial sector, particularly in mining. Optical fibers in mining are capable of successfully performing multiple functions at the same time. Optical fibre systems are able to deliver important information about operations from a mine site back to the control centre. Fiber optics deployment in mining is increasing so rapidly, to a point where it is predicted to become standard practice, for companies interested in having state-of-the-art equipment and practices.

Fiber optics are also immune to induced currents and electromagnetic interference created by the size of massive electrical equipment often seen in mining operations because they are made of glass. Fiber optics systems can be created expressly for use in mining and are extremely robust and flame-resistant.

Multimode optical fiber, which enables the transmission of many light modes, has typically been used in fiber optic networks for mining. This type of fiber has a large amount of bandwidth and can handle Ethernet protocols across short distances. Additionally, it is more than equipped to accommodate applications for machine control and miner tracking technologies. Optical fibers need to be housed in strong cables that can maintain valuable transmission properties in order to function properly in mining environments.

This chapter provides a brief history of optical fibres for mine safety and data communication in mines. In addition, we will then explore how and why current technology plays a role in enhancing safety in mines. Furthermore, a detailed description of the layout of the thesis will follow outlining the information entailed in each chapter.

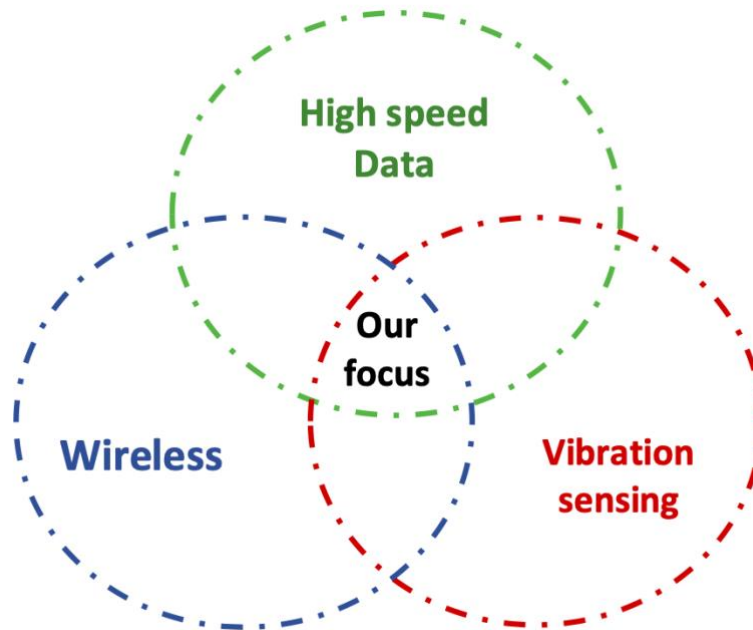
## **1.2 Data communication in mining and safety background**

The mining industry has contributed immensely to the development of current civilization. According to B.S. Dhillon, in his book “Mine safety: A modern approach” , the history of mining can be traced back to Egyptians who operated malachite mines. Over 6 billion tons of raw products are produced by the mining industry annually to date [1]. This means that the mining sector is a very lucrative industry for economic growth. However, each year thousands of miners die from accidents in mines all over the world. The risk of injury in a mine is six times greater when compared to general industries. This has made safety in mines a great concern for the mining sector for years. Over the years, the mining industry continues to upgrade its communications and monitoring infrastructure. Some implemented strategies have contributed to improved safety, meeting new federal requirements and maximizing their profitability. As companies invest in newer information technology infrastructure they are obligated to remain within the requirements of the Mine Safety and Health Administration's (MSHA) Mine Improvement and New Emergency Response Act in the United states of America [2]. Thus mine owners are looking for ways to leverage the capacity, capability of systems that are able to measure and monitor air exchange and communicate in real-time.

Optical fibre systems come highly recommended for applications in mining companies as a cost-effective network alternative to copper. They are able to provide world-class data communications solutions as well as other additional benefits. These include greater bandwidth for real-time voice, sensing capabilities, data and video applications. The need to measure and monitor can be coupled with the need to implement improved production efficiencies and use more advanced sensor technologies and IP cameras.

The aim of the work presented in this dissertation is to determine how to create a fast and effective converged data communication system using multimode fiber and multimode components. This multimode system would also work as a vibration sensor for seismic activities. This three in one component system is what brought about the concept of a converged photonic data and vibration sensing which incorporates 5G wireless connectivity. The wireless aspect is important for fast connectivity of miners and their devices for timely responses. Motivation to create the system with multimode components was the affordability of

multimode fiber. Furthermore, the vibration sensor will be polarization based due to the reliability of polarization based sensors. This is summed up on the diagram below;



**Figure 1.** Thesis objective

### **1.3 Outline of this thesis;**

Chapter one provided a brief history of optical fibres for mine safety and data communication in mines. In addition, it explored how and why current technology plays a role in enhancing safety in mines. An overview of what is to be expected from the rest of the thesis is also presented in this chapter.

Chapter two entails a detailed introduction to the basic operating system inside an optical fibre in terms of light propagation, material composition and the structure. The differences between the multimode and single mode are elaborated.

Chapter three focuses on the sensing capabilities of optical fibers. The principles by which these sensors are operated are discussed. Just as there are different types of optical fibers, there are different types of optical fiber sensors. For further clarification of different applications for these optical fiber sensors.

Chapter four gives a detailed study for the application of optical fiber technology in mining environments. Data communication in the mines is thoroughly introduced and its benefits are highlighted. Furthermore, some literature on vibrational applications of optical fiber sensors is elaborated.

Chapter five is the experimental and methodology chapter. Here a detailed explanation of the equipment used during this study is given. Furthermore, the experimental methods used are discussed.

Chapter six is the first experimental chapter where multimode data transmission systems were tested through lab experiments. This chapter focused on the characterization of the VCSEL's used in this study. Bit error rate was used for the transmission characterization properties.

Chapter seven comprises experiments conducted using polarization based sensors. A drilling experiment was conducted to test the efficiency of the designed sensor. Furthermore, a wireless system was tested for wireless transmission within the mine cavities using 5G speed.

This study primarily focused on the application of multimode optical fibers for data connection communication interlinks across short distances. The vision was for data transmission in a mining environment to help improve equipment efficiency and safety. In addition, the plan was to also to develop a distributed optical fibre sensor, using the same multimode fibre, which will be modified for applications in an underground mining set up. It will be safer and more productive to monitor, analyse, and manage the facilities and equipment used in mining by using fiber optics for dependable communications. The objective was to have a reliable geotechnical monitoring system that can alert underground workers in a timely manner in the event of any major geotechnical failure that is unanticipated, with special attention paid to monitoring threats to the surfaces posed by geological hazards from mining operations or naturally occurring incidents.

The novelty in this work was the use of multimode fiber for industrial application such as the mine. Additionally, the choice of a multimode VCSEL to ensure that this configuration was cost effective made these concepts worth considering. In an effort to further optimize the efficiency of the system, we introduce the concept of using that same multimode (MMF) as a vibration sensor. Which also adds a unique element to this work.

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## References

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- [2] B. Smith, 2020, Investigating fiber optic capabilities in the mining sector  
<https://www.azooptics.com/Article.aspx?ArticleID=1768>

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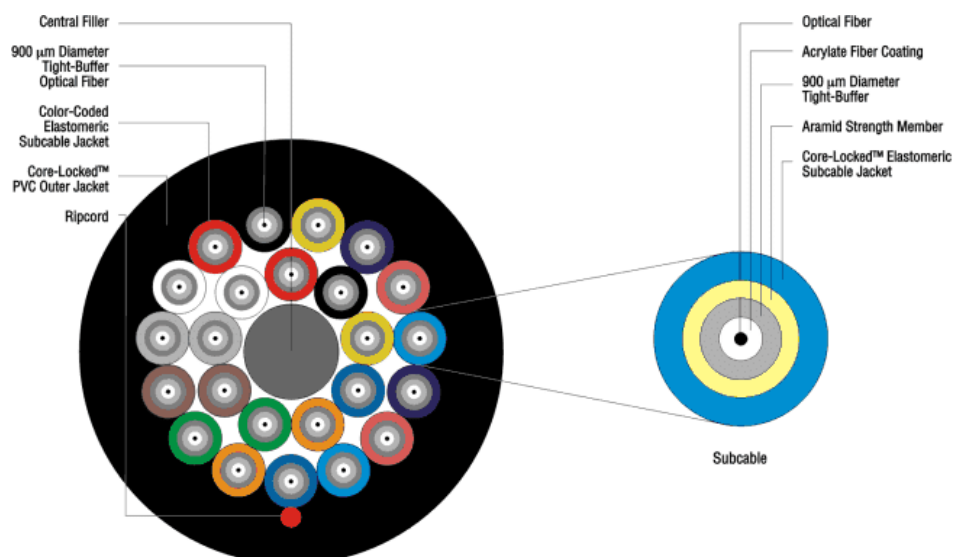
# CHAPTER 2

# Introduction to data communication concepts in fiber optics

## 2.1 Introduction to optical fibers

Since the invention of the telegraph and electromagnet, electrical wiring has been based on copper [1]. The copper metal has a wide range of properties that make it a great choice for various applications, such as electrical induction and network setups. All of those features are great for electrical applications, but when it comes to network and telecommunication applications, it turns out that copper is not necessarily the best or only option, and thus we come to the optical fiber.

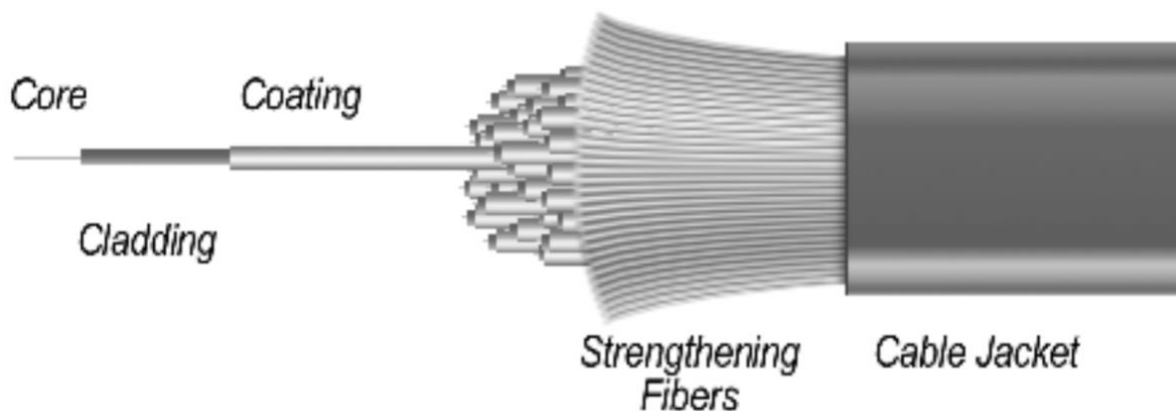
An optical fibre is a thin rod of high-quality glass or plastic that is used to transmit information using light [1]. It is about the diameter of a strand of human hair. These strands are bundled together in a protective sheath or cover and the entire assembly (the optical fibers and other parts inside the sheath) is often referred to as an optical fiber cable or just fiber. When bundled into an optical fiber cable, they are able to transmit more data over longer distances and faster than other mediums [1]. Figure 1 shows a multi-fiber cable cross-section which consists of a number of optical fiber wired stacked and condensed together to form a fiber cable. This is the usual set up for industrialized optical fiber cables.



**Figure 1.** shows the cross section of multiple optical fiber cables. Here we can see the outer polyethylene jacket, sub cable loose tube/jacket, filling compound and central filler membrane. [2]



Let us have a closer look inside an individual optical fiber wire. Figure 2 below shows the constituents of an optical fiber cable inside. The basic structure of an optical fiber consists of three main parts; the inner core, the cladding, and the coating or buffer [3]. The fiber core is the actual glass cylindrical rod through which light propagates. This core is made up of dielectric material which help guide the propagating light according to certain specifications.



**Figure 2.** This image shows the labelled composites of an optical fibre [2]

Surrounding the core is a dielectric glass or plastic material called the cladding which has a specific index of refraction. The index of refraction of the cladding material must be less than that of the core material so that when light from the core strikes the boundary with the cladding at an angle greater than the critical angle, it will be reflected back to the core by total internal reflection [3]. The cladding protects the fiber from absorbing the surface contaminants. Other functions include decreasing scattering loss at the surface of the core and decreasing loss of light from the core into the surrounding air.

The coating or buffer material layer covers the cladding and is typically made from a type of plastic. The buffer helps to protect an optical fiber from physical damage. This material is elastic in nature and prevents abrasions [3]. The coating is also covered by strengthening metallic fibers twisting around to form a protective shield. These are held together by a cable jacket which makes them feasible for industrial use.

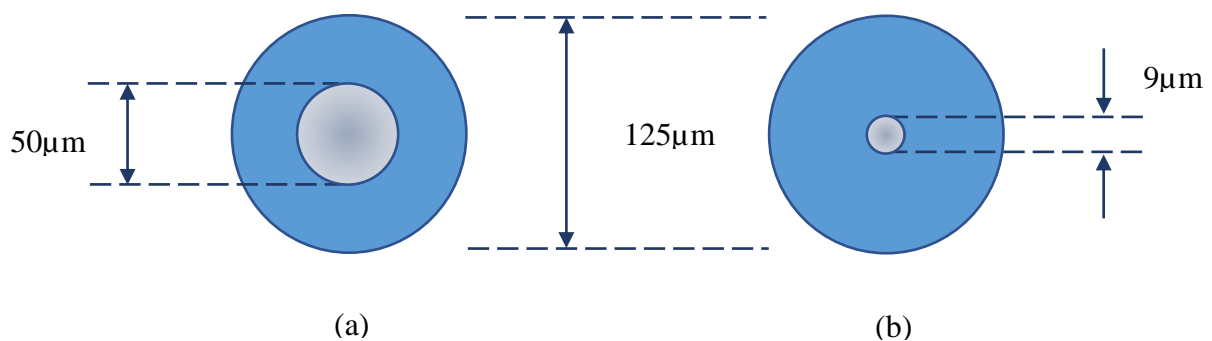
Optical fiber technology is associated with data transmission using light pulses travelling along the fiber which is usually made of plastic or glass. Metal buffering wires were preferred for

transmission in optical fiber communication as signals travel with minimal damages [3]. However, optical fibers are unaffected by electromagnetic interference making them a better alternative. This technology provides homes and businesses with fiber-optic internet, phone and TV services.

Fibre is built in such a way that minimal light is absorbed by the glass or plastic core. Light going through one end undergoes repeated total internal reflection, even when the fibre is bent, and emerges at the other end. The fibers are factory designed to facilitate the propagation of light along the optical fiber relative to the requirement of power and distance of transmission. The functioning principles of light will be discussed in the section to follow. Find the discussed different types of optical fibers.

## 2.2 Single mode vs multimode fiber

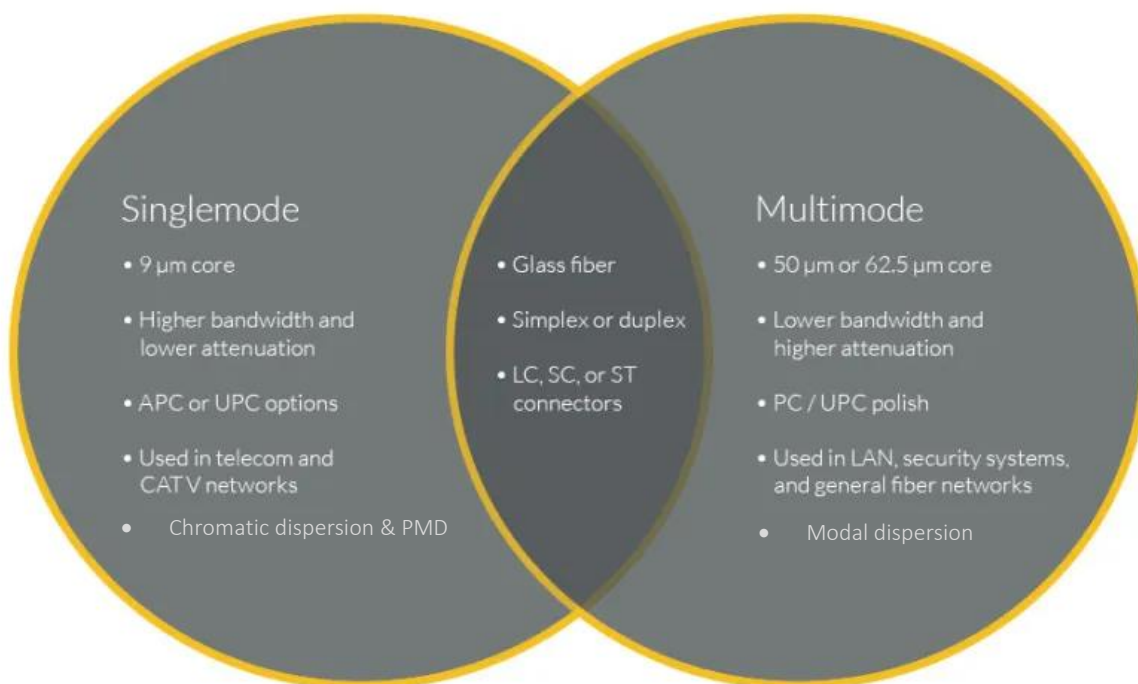
Single mode means that one light mode can propagate at a time through the fiber. Technobyte.org perfectly summarises the definition of light modes as electric field distributions in free space, waveguide or optical resistors. In contrast, multimode means multiple modes can be propagated simultaneously. There are many differences between single mode and multimode fiber optic cable. However, the major differences can be seen in the diameter of the fiber core, the wavelength and light source used, the bandwidth, the colour of the sheath, as well as the cost. The fiber core diameter of single mode fiber is much smaller than the fiber core diameter of multimode fiber.



**Figure 3.** The images show the cross-section of a multimode (a) and single mode (b) optical fiber. Here we can distinctively see the differences in the core diameters. The overall fiber diameter is the same for both[16]

The core properties of a single mode fiber vs those of a multimode fiber are displayed in figure 3 above. From the diagram we can note the differences in the core diameter, with the core of a multimode fiber being more than 5 times that of a single-mode fiber.

The core diameter for a single mode fiber is typically 9  $\mu\text{m}$ . Multimode fibers have core diameters of about 50  $\mu\text{m}$  and 62.5  $\mu\text{m}$ , which allows them to have higher light gathering ability and simplify connections. The diameter of the cladding of both the single mode and multimode is 125  $\mu\text{m}$ . Attenuation in the multimode fibre is much greater than in the single mode fibre due to its larger core diameter. For single-mode fibers, the usual loss values for intrinsic attenuation are roughly 0.40 dB/km at 1310 nm and 0.30 dB/km at 1550 nm. The values are slightly higher for multimode fibers, averaging 3.50 dB/km at 850 nm and 1.50 dB/km at 1300 nm. The core for single mode fibers is extremely narrow such that the light passing through these optical fibre cables is incapable of reflecting multiple times. Therefore the attenuation in a single mode fiber is kept minimal. Figure 4 below summarizes some of the most important differences properties with multimode and single mode fiber while highlighting the apparent similarities.



**Figure 4.** The illustration shows common features between single mode fiber and multimode fiber. Both are incompatible and cannot be mixed between two endpoints. The optics are also incompatible.

When choosing single mode or multimode fibers, distance is the most important consideration. Multimode fiber is typically installed between 300 meters and 400 meters within a data centre. Single mode fibers can be installed between 10 kilometres and 80 kilometres or even further. To install at such distances, installers must utilize the appropriate optics (namely, the laser transmitters, photodiode receivers, wavelength division multiplexing (WDM) splitters, couplers, attenuators etc.). For transmission distances up to 550 meters in data centre applications, multimode fiber is the best option, while for distances above 550 meters, single mode fiber is the best option. Besides the distance, total cost of ownership (TCO) should also be considered. Most importantly, choosing the correct fiber for the network is the intelligent choice.

## **2.3 Basic theory of light**

A light wave is an electromagnetic wave which propagates through the vacuum of outer space. Light waves are produced by vibrating electric charges [3]. For sources of light in nature, objects are either generating light or else reflecting it. With some of the major generators of light being light emitting diodes, lasers, fluorescent lamps, flames and the sun. The sun emits a form of energy known as electromagnetic radiation which travels through as electromagnetic waves [3]. Light waves are characterized by their frequency, wavelength and velocity. These characteristics of light can be distributed in an electromagnetic spectrum.

As can be seen on the electromagnetic spectrum below, visible light represents a narrow band between ultraviolet light (UV) and infrared energy (heat). It is these light waves that stimulate the retina of the eye, resulting in the sensation of sight [4]. The frequency and the length of these waves make light distinct from other forms of energy on the electromagnetic spectrum.

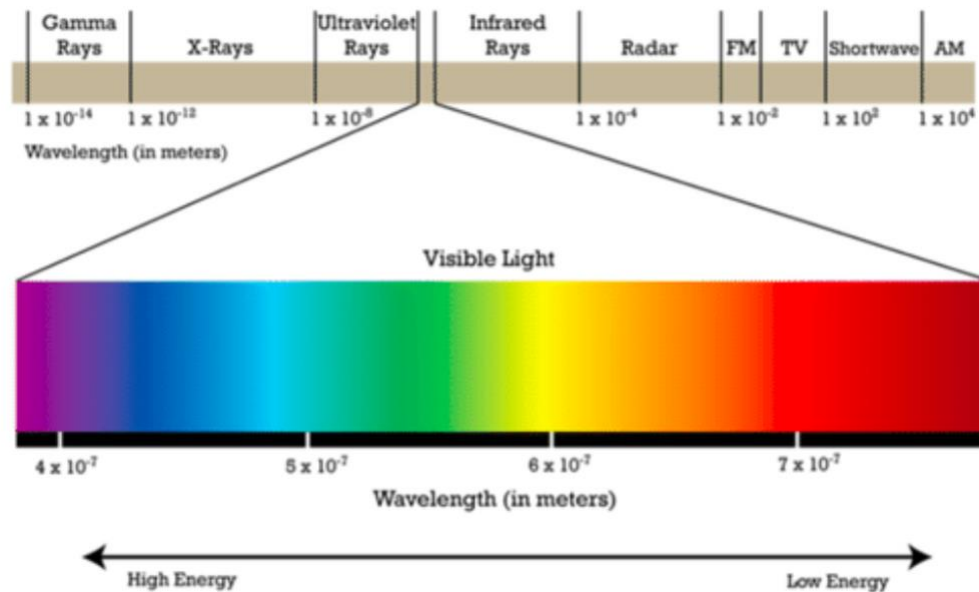
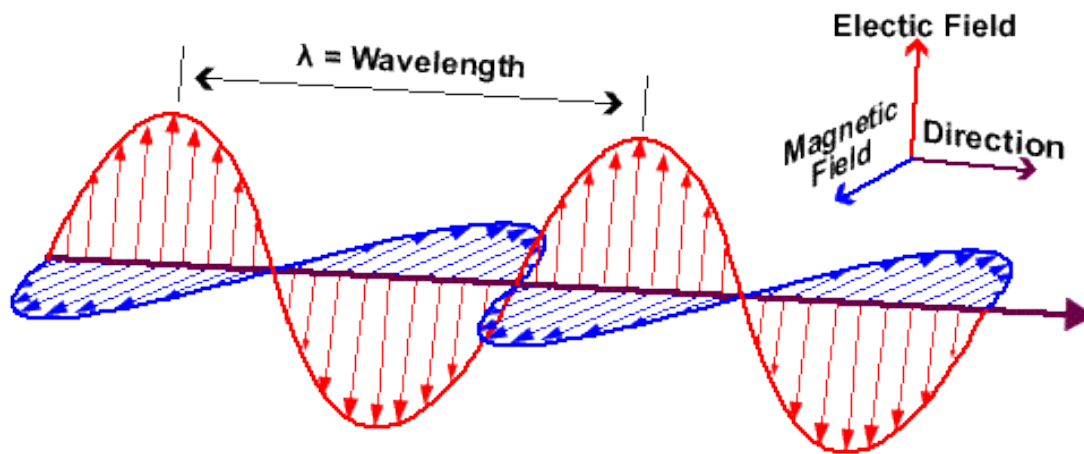


Figure 5: An image of an electromagnetic spectrum with wavelengths in meters. This entire spectrum of electromagnetic waves includes low energy waves up to very high gamma rays. [4]

Electromagnetic radiation is a form of energy that is composed of two oscillating fields. An electric field and a magnetic field, each of which has a direction and an amplitude. Both fields, electric and magnetic, are oriented at precisely  $90^\circ$  to one another within an electromagnetic wave. Basically, the electric field and the magnetic field move in opposite directions (by definition, at the speed of light). If we consider them in three dimensions, the electric field would be oriented on the y-axis, and the magnetic field on the x-axis. The direction of travel would be along the z-axis [4].

The electromagnetic waves carry the electromagnetic radiation energy from one position to the next in a rope-like fashion as displayed in figure 6 below.

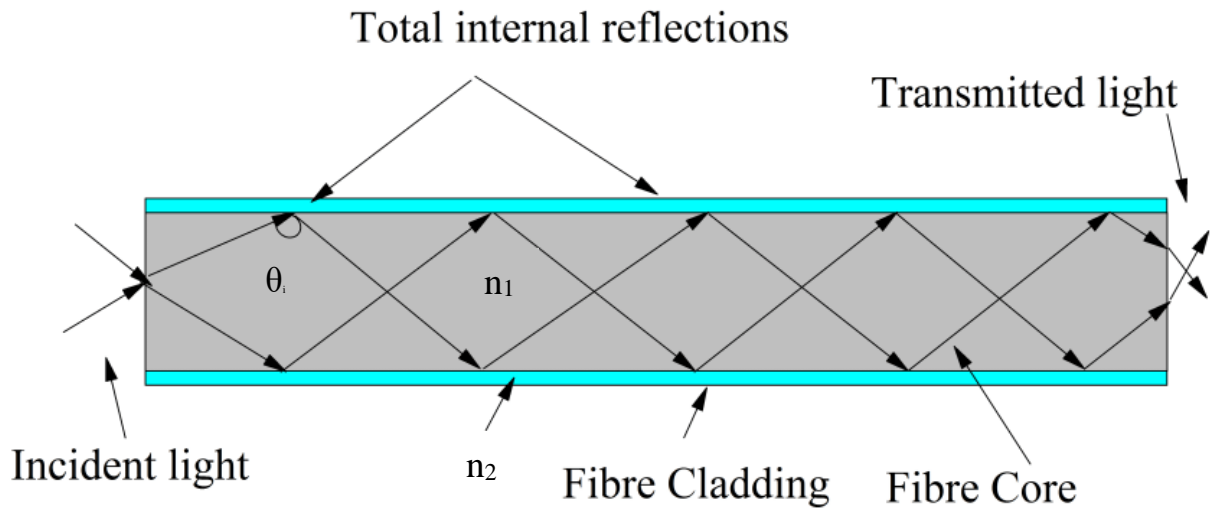


**Figure 6.** The Structure of an Electromagnetic Wave. Electric and magnetic fields are actually superimposed over the top of one another.

The best way to understand this would be to compare it with wave motion observed in water that is more practical. If we observe a leaf floating in a pool of water where there are waves, we notice that it moves up and down in one place. Rather than moving across, waves move vertically, and particles occupy vertical space as they move, so wave motion is at 90 degrees or transverse to the wave propagating. It is the same thing with electromagnetic waves, as opposed to sound waves, in which the oscillation is in the same direction as the wave propagating.

## 2.4 Total internal reflection

The light-guiding principle along the fiber is based on the “total internal reflection”. The angle at which total internal reflection occurs is called the critical angle of incidence. At any angle of incidence, greater than the critical angle, light is totally reflected back into the glass medium (see Figure 7). The critical angle of incidence is determined by using Snell's Law. Optical fiber is an example of electromagnetic surface waveguide [5].



**Figure 7.** Image of total internal reflection where  $n_1$  = core and  $n_2$  = cladding [17]

When light propagates from the middle of a refractive index  $n_1$  to the centre of a lower refractive index  $n_2$ , it generates a reflection, which we term total internal reflection. The angle at which the light enters is given, and the light is reflected when  $n_1$  is greater than  $n_2$ . T. L Singal defines the critical angle,  $\theta_c$  as the minimum possible angle of incidence at which if a light ray is incident at the intersection of two different mediums [17]. This can be expressed in the following equation

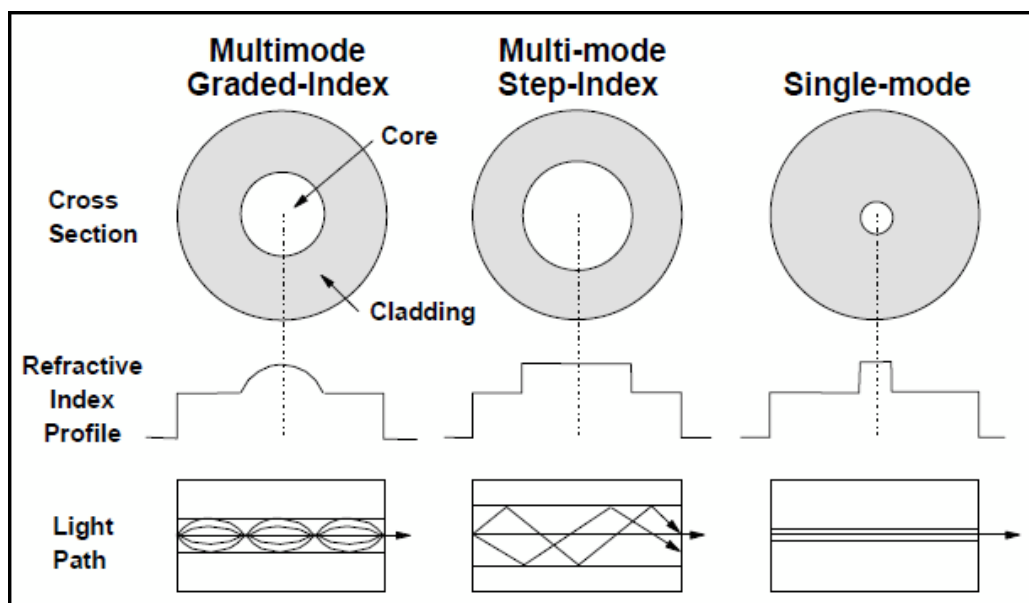
$$\sin \theta_c = n_2 / n_1 \quad ; \quad \text{for } n_1 > n_2$$

One of the requirements for total internal reflection is when light enters with an incidence angle larger than the critical angle  $\theta_c$  [5]. The pathways taken by rays in an optical fiber with a stepped refractive index varies based on the angles of their proximity to the axis, i.e., the difference in media results in a difference in time to reach the end point, and this index influences the pace of data transfer in optical fibers. [5] Single medium (single mode) counts for zero as the rays descend downward, while multimode carrying rays are carried in the high position, allowing for classification of the number of media in the fibers. In addition to the diameter of the core and the wavelength of the light, the number of modes is determined by the numerical aperture of the fiber and the acceptance angle.

## 2.5 Propagation of light in multimode fiber

Light traveling on a multimode fibre is limited to a relatively small number of possible paths [5]. These paths are referred to as modes. Modes have two classifications namely radiation modes and guided modes. Where radiation modes carry energy out of the core and guided modes are restricted to the core and propagate energy along the fiber to transport power and information [5].

When light propagates along a particular path within an optical fibre, the wavefront must stay in phase with itself. Meaning that the wave or light ray should be in phase at corresponding points. Thus there must be an integer multiple of wavelengths between points of reflection between the core and the cladding. Thus it can be assumed that if we have this restriction on the paths that can be taken then there will be a finite number of possible paths. Figure 9 illustrates different types of fiber properties allowing light to propagate differently. A step-index fiber is one that has a uniform refractive index within the core and a significantly lowered refractive index at the core-cladding contact due to the lower refractive index in the cladding [5]. Graded index multimode fiber is a kind of optical fiber where the refractive index is higher at the core's axis and gradually falls as it approaches the core-cladding contact [5].



**Figure 9.** Propagation of Light in Multimode Fiber. Light is bound within the fibre due to the phenomena of “total internal reflection” which takes place at the interface between the core of the fibre and the cladding [11]



Arguably the most important property of modes is that all of the propagating modes within a fibre are orthogonal. It is only if the fibre is perfectly regular, with no faults, perfectly circular, uniform refractive index, then there would be no power transfer or interference between one mode and another. This forms the basic reason for the restriction that corresponding points along the path of a mode must be in phase. Without them, destructive interference between modes could occur and the wave would not propagate. [5]

Another feature of light propagation in a fibre is that an optical fiber may be wrapped or bended around corners. In cases where the bend radius is not extremely tight, the light will follow the fibre and may propagate without loss due to the curves or bends. This can be credited to the previously described phenomena of “total internal reflection”. As a ray of light enters the fibre, it bounces off the interface between the core and the cladding with a lower refractive index, guiding the light ray along the fibre. It can be concluded that the light is “bound” within the fibre. [5]

## **2.6 Signal impairments**

When a short pulse of light from a source like a laser or an LED is delivered through a narrow fibre, it is modified (degraded). It will emerge weaker, dispersed in time ("smeared out"), and warped in other ways, depending on the distance. In [5], the following causes are used to elaborate on the reasons for signal impairments:

### **2.6.1 Attenuation**

Because all glass absorbs light, the pulse will be weaker. Impurities in the glass can absorb light, but the glass as a whole does not absorb light at the wavelengths of interest. Furthermore, differences in the regularity of the glass produce light scattering. The quantity of scattering and the rate of light absorption are both influenced by the wavelength of the light and the properties of the glass. Scattering accounts for the majority of light loss in contemporary fibers.

### 2.6.2 Dispersion

When a pulse of light is spread out during transmission on the fibre, it is called dispersion. A short pulse develops longer and eventually merges with the pulse behind it, making dependable bit stream recovery impossible. There are several types of dispersion, each of which functions differently, but the three most important are outlined below:

#### *i. Material dispersion (chromatic dispersion)*

Rather than a single narrow wavelength, lasers and LEDs create a range of optical wavelengths (a band of light). Because different wavelengths have distinct refractive index properties, each wavelength will move at a different speed through the fibre. As a result, some wavelengths arrive ahead of others, causing a signal pulse to disperse (or smears out).

#### *ii. Waveguide dispersion*

The form and index profile of the fibre core generate waveguide dispersion, which is a very complex phenomenon. However, careful design can manage this, and waveguide dispersion can even be utilized to prevent material dispersion, as will be seen later. Because light moves through a single-mode fiber core and cladding at an effective speed that is between that of the materials making up the core and cladding, waveguide dispersion results. The effective velocity, or waveguide dispersion, changes with wavelength, which causes the waveguide dispersion to occur.

#### *iii. Modal dispersion*

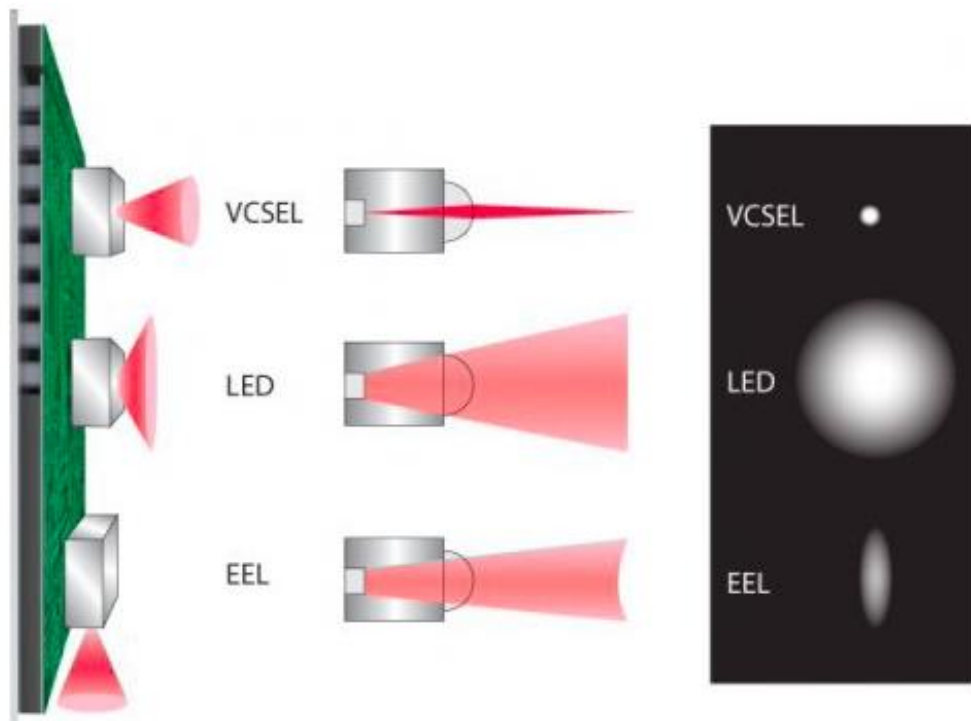
When light travels through multimode fibre, it can take many different routes or "modes" as it travels through the fibre. Figure 9 on page 15, under the name "Multimode Step-Index," illustrates this. Each mode's distance travelled by light differs from the distance travelled by other modes. Parts of a pulse (rays or quanta) can adopt several distinct modes when it is transmitted (usually all available modes). As a result, some pulse components will arrive before others. With increasing distance, the difference between the arrival time of light in the quickest mode and the slowest option becomes noticeable.

#### *iv. Noise*

The term "noise" is typically used to describe any erroneous or unwanted interruptions that obscure the signal being received in a communication system. One of the major advantages of fiber optical communications is that noise from outside the system is not picked up by the fiber. However, noise from within the system might cause a variety of problems. In single-mode fiber, mode partition noise can be a concern, and modal noise is a phenomenon in multimode fiber [6].

### **2.7 VCSELS (Vertical Cavity Surface Emitting Laser)**

Vertical Cavity Surface Emitting Lasers (VCSEL) provide a wide bandwidth, single mode operating in the C-L bands, wavelength turnabilities, direct modulation convenience, and low drive current energy efficiency. VCSELs are suited for high-speed optical communication networks across short distances [6]. Due to their wafer level testing capability, intrinsic single longitudinal mode, low threshold currents, and low power consumption, surface-emitting lasers (VCSELs) generating at 1.55 m are particularly promising laser sources for low-cost telecommunication systems [7].



**Figure 10.** Comparison of VCSEL vs LED vs EEL [10]

As depicted in Figure 10, VCSELs are semiconductor-based devices that emit light perpendicular to the chip surface. As an example, a micro-electromechanical systems (MEMS) tuneable VCSEL is illustrated. VCSELs were created as a low-cost, low-power alternative to edge-emitting diodes, primarily for high-volume datacom applications. The advantages of VCSELs quickly became apparent, and they became the preferred light source over edge-emitters in many applications. VCSELs have better output beam quality and single-mode operation in comparison to edge-emitting sources.

Tuneable VCSELs based on MEMS are particularly appealing since wavelength tuning is continuous and controlled simply by applying a voltage to the MEMS structure [8]. Unlike other tuneable lasers like multi-section distributed Bragg reflectors (DBRs) the emission wavelength control over time just requires a closed loop on the voltage to compensate for any aging effects. The laser's operability in a real network arrangement is greatly enhanced by its ease of adjustment [9].

### 2.7.1 Industrial applications for VCSELs

VCSELs, like many lasers, are employed in optical communications as transmitters in single optical fibers and multimode fibers in both short- and long-range free-space communication links. Long-wavelength communication technologies, such as those used in metro systems, storage networks, and fiber-to-home communications, are the most commonly used of all communication technologies. There are a number of applications for VCSEL and below is a list of examples

#### i. Communications via light

VCSELs can be modulated with frequencies well into the gigahertz region because to the short resonator round-trip time. This makes them suitable as transmitters for optical fiber communications. VCSELs are used in conjunction with multimode fibers for short-range communications. A data rate of 10 Gbit/s, for example, can be achieved over a few hundred meters.

#### ii. Mouse for Computers

Computer mice are an example of an application that was developed later yet has a huge market volume. A laser mouse using a VCSEL as the light source can achieve great

tracking precision while consuming little power, which is critical for battery-powered devices.

### iii. Gas Detection

Gas sensing with wavelength-tuneable infrared VCSELs is another popular use. Optical oxygen sensors are particularly important since GaAs-based VCSELs can detect an absorption line at 760 nm, whereas longer-wavelength VCSELs that may detect water vapor, methane, or carbon dioxide require more development before being widely employed.

There are many other applications for this innovative technology but the above stand out. These include but are not limited to optical clocks and laser pumping.

## 2.8 Polarization in optical fibers

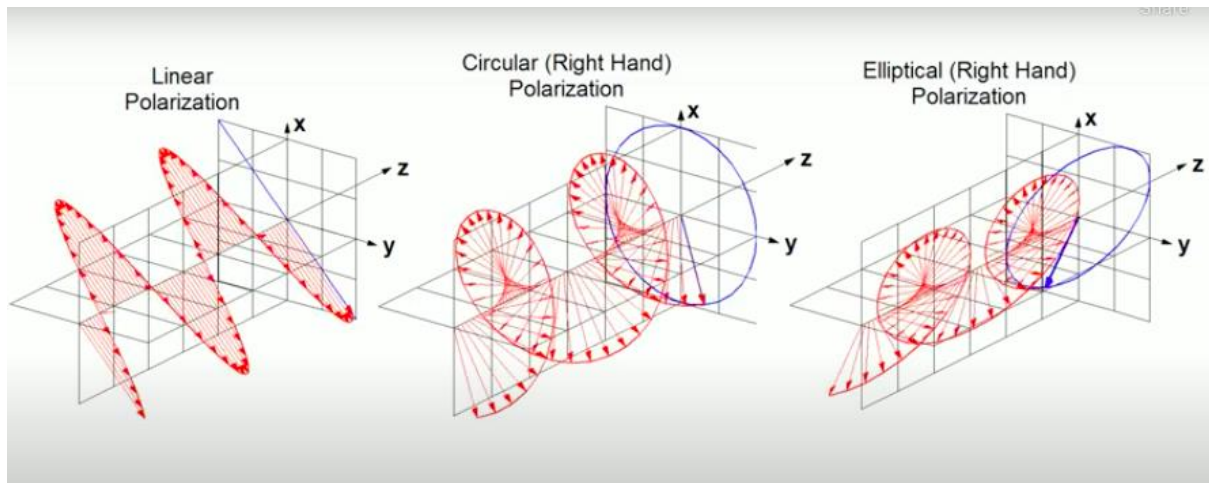
Polarization, the vectorial aspect of light, is a core topic in physical optics that is the subject of much fundamental research today. It is an important dimension in studies of light in all of its complexity, as well as in the interaction of light fields with matter. Polarization is also an important component in applications such as metrology, sensing, communications, and display technologies. New technologies, materials, and devices, such as liquid crystals, have advanced our understanding of the subtle ways in which vector fields interact with matter, creating at the same time new ways to harness the properties of light. All polarized light is an elliptical polarization state in general, with linear and circular polarization states being exceptions. Laser light has a high degree of polarization (DOP), which is extremely close to unity.

### 2.8.1 Polarized light and unpolarized

When we refer to the polarization of light, we refer to one of the fundamental aspects of a light wave; that is, the polarization is defined to be the description of the vibration of the electric field's oscillation [12]. In a transverse plane (a plane perpendicular to light's propagation direction), polarized light wave signals flowing in fiber or free space are represented by electric and magnetic field vectors that are at right angles to one another.

The pattern etched out in the transverse plane by the electric field vector as a function of time is used to describe polarization. Namely these are linear, circular and elliptical polarization as

shown in the image below. The images show the electric field as a function of distance, where as time passes, the pattern moves towards the observer.



**Figure 11.** Classifications of polarization [13]

### 2.8.2 Degree of polarization and Polarization coordination system

The degree of polarization (DOP) of a light wave might affect its utility in a given application. The light from a standard light bulb is completely unpolarized, making it suitable for non-fiber optics engineers' regular tasks. The nearly perfect polarization of light from a diode laser presents both opportunities and constraints in sensor and telecom applications. A light emitting diode (LED) can create polarized light in the range of 10% to 20% [14].

The superposition of a fully polarized and a totally unpolarized light wave can be used to describe partially polarized light. The following equations explain the degree of polarization (DOP):

$$DOP = \frac{P_{pol}}{P_{pol} + P_{unp}} \dots\dots\dots (1)$$

Where  $P_{pol}$  and  $P_{unp}$  are the intensity of polarized light and unpolarized light, respectively. When  $DOP = 0$ , light is said to be unpolarized, and when  $DOP = 1$ , it is totally polarized. Intermediate cases correspond to partially polarized light.

Unpolarized light of a particular intensity can be easily represented as an electric field vector that occupies arbitrary orientations in the xy-plane from instant to moment. Within the physical context of a specific measurement or application, the random reorientation just needs to be rapid enough to escape detection.

This qualifier is important to note because there are applications in telecommunications and optical sensors where fully polarized light is polarization-scrambled at a high enough rate to appear unpolarized within the lifetime of carriers in an optical amplifier or the bandwidth of optical instrumentation.

### 2.8.3 Poincare sphere and Stokes parameters

The stereographic projection created by the Greek astronomer Hipparchus transferred the points or positions on a celestial sphere onto a plane, and this is where the core idea of the Poincare sphere originates. Poincare proposed the exact opposite, i.e. projecting a plane onto a sphere[15].

In the realm of fiber optics, the Poincaré sphere is now heavily utilised. A single arc can connect any two polarization state values shown on the surface of the Poincare sphere, and the difference in azimuth and ellipticity between the two states can be determined using spherical trigonometry. This makes predicting the polarization state of light after interaction with a polarizing element as well as determining the azimuth and ellipticity of the polarizing element required to achieve a desired polarization state much easier. The state's Cartesian coordinates are represented by the Stokes parameters ( $S_1$ ,  $S_2$ ,  $S_3$ ) (see the table below).

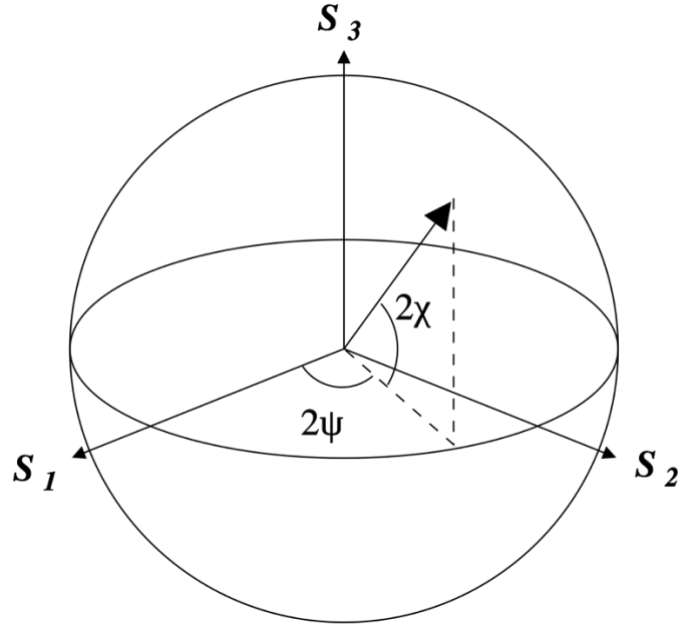
#### Cartesian to Poincaré Sphere Coordinates [15]

$$S_1 = \cos(2\chi) \cdot \cos(2\psi)$$

$$S_2 = \cos(2\chi) \sin(2\psi)$$

$$S_3 = \sin(2\chi)$$

These equations are equations that relate to the cartesian coordinates (x,y,z) to the spherical coordinates (1,  $\psi$ ,  $\chi$ ) for the point on the Poincaré sphere of unit radius. The longitudinal lines in the Poincare sphere represent the elliptical angle  $\chi$  and the latitude lines represent the orientation angle  $\psi$ .



**Figure 12.** Poincare sphere of unit radius and its cartesian coordinates. The spherical coordinates of the point P are  $P(\psi, \chi)$ .

Mapping polarization states to the Poincaré sphere uses a method similar to locating points on an Earth map using latitude and longitude. Two angular values (azimuth and ellipticity) and a radius are used to specify the coordinates of points inside and on the surface of the Poincaré sphere. Polarization ellipse representation of the polarization state is used to calculate azimuth and ellipticity parameters. A light's polarization determines its radius, which is approximately equal to one at perfect polarization. In addition to the Poincaré sphere, the polarization ellipse can also be used to observe the evolution of polarization.

## 2.9 Bit Error Rate (BER)

The bit error rate, or BER, is a key metric for assessing the performance of data networks. The crucial parameter for transmitting data from one point to another, whether via radio/wireless or cable telecommunications, is how many errors will occur in the data at the remote end. As a result, Bit Error Rate, or BER, is applicable to a wide range of applications, including fiber optic lines, ADSL, Wi-Fi, cellular communications, IoT networks, and many more [14]. Even though the data lines may use a variety of technologies, the fundamentals of calculating the bit error rate are the same. A limited amount of faults in transmitted data can be found and fixed



using the forward error correction (FEC) approach without the need for retransmission. In this approach, the sender additionally includes an error-correcting code in the data frame. The additional redundant bits are used by the receiver to execute the appropriate checks. If it determines that the data is error-free, it runs the code that creates the real frame to rectify any faults. Before sending the message to the upper layers, it then eliminates the unnecessary bits.

A bit error rate is the rate at which errors occur in a transmission system, as the name implies. This can be easily translated into the number of errors in a string of a specified length. The definition of bit error rate can be expressed in the following way:

$$\text{BER} = \frac{\text{Errors}}{\text{Total number of bits}}$$

There is a chance that errors will be introduced into the system when data is transmitted across a data link. If errors are introduced into the data, the system's integrity may be jeopardized. As a result, it's important to evaluate the system's performance, and the bit error rate, or BER, is an excellent way to do so.

The average likelihood of incorrect bit identification is essentially what the BER states. Therefore, a BER of  $10^9$  indicates that, on average, 1 out of every  $10^9$  bits is read wrongly. Receiving  $10^9$  pulses would take time if the system were operating at 100 Mb/s, or 108 pulses per second.

$$10\text{s} \sim \frac{10^9}{10^8} \dots\dots\dots (3)$$

This is the typical time for an error to occur. On the other hand, if the BER is  $10^{-6}$ , an error would typically happen every 0.01 seconds, which is unacceptable.

BER evaluates the whole end-to-end performance of a system, including the transmitter, receiver, and the medium between them, unlike many other types of evaluations. In this

approach BER, can be used to test the real performance of a system in use, rather than just the component pieces.

### 2.9.1 Factors affecting bit error rate

It is clear that the BER can be influenced by a variety of circumstances. It is feasible to optimize a system to deliver the needed performance levels by modifying the factors that can be controlled. This is usually done during the design stages of a data transmission system so that performance characteristics can be tweaked during the early stages of the design.

#### *i. Interference:*

The levels of interference in a system are usually determined by external variables and cannot be altered by system design. However, the system's bandwidth can be customized. The level of interference can be lowered by lowering the bandwidth. However, limiting the bandwidth restricts the amount of data that can be transmitted.

#### *ii. Boost transmitter power:*

It is also feasible to increase the system's power level to increase the power per bit. This must be balanced against other considerations such as the influence of increasing the power output on the size of the power amplifier, overall power consumption, and battery life, among others.

#### *iii. Reduce bandwidth:*

Reducing the bandwidth is another way to lower the BER. As a result of the lower levels of noise received, the signal to noise ratio will improve. Again, this reduces the amount of data that can be processed.

#### *iv. Lower order modulation:*

Lower order modulation schemes are possible, but they reduce data throughput. To get a desirable BER, all possible elements must be balanced. Normally, it is not possible to meet all of the needs, thus some compromises are necessary. Even if the BER is lower than ideal, additional trade-offs can be made in terms of the amounts of error correction inserted into the data being communicated. While more redundant data must be provided with higher degrees

of error correction, this can assist disguise the consequences of any bit errors, lowering the overall BER.

The BER, is a fundamental metric used in selecting which connection characteristics should be employed, including everything from power to modulation type, in many communications systems.

## **2.10 Summary**

In this chapter, the important features of any fibre transmission system were discussed. These include the physical properties of the fiber, its shape, thickness, refractive index, and absorption spectrum and the different light's used in terms of wavelength for different optical fibers. The work shows that there are different factors that affect the operating system in an optical fiber. Thus we also discussed forward error correction which can be used to ensure proper signal transmission. In the following chapter, chapter 3, we explore the sensing capabilities of optical fibers.

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# CHAPTER 3

# OPTICAL FIBER SENSING

## 3.1 Introduction

As the name indicates, an optical fiber sensor is a device that measures physical quantities and converts them into signals that can be read by an observer or analysed by an instrument. This means that the device that senses or reacts to any physical, chemical, or biological condition is known as a sensor. As an example, a thermocouple detects temperature and converts it into current or voltage. Information is displayed either analogically or digitally.

The discovery and development of optical fiber sensors began in the 1970's. Several laboratories and research groups have entered this field during the past decades, contributing to rapid progress in this field. Optical fiber research focuses on many disciplines including photoacoustic, strain, vibration, temperature and fluid level studies. This technology offers unparalleled flexibility due to its dielectric nature, meaning they can be used even in stressing environments with outstanding results [1].

Fiber optic research has aligned with sensor technology developments, and has been heavily reliant upon technology related to optoelectronics and fiber optic communications [2]. Some industries often use fiber optic components developed for fiber optic sensor applications. The development and subsequent mass production of components to support these industries has often led to the development of fiber optic sensor technology. Consequently, fiber optic sensors are great candidates to replace traditional sensors as component prices decrease and reliability has drastically improved since discovery [1].

Findanboyly K *et al* report on their paper about fiber optic sensors and their applications. They elaborate on how fiber optic sensors are excellent candidates for monitoring environmental changes as they offer many advantages over conventional electronic sensors. The advantages are listed below:

- Geometric versatility since they can be configured in arbitrary shapes, including composite materials, with little interference due to their small size and cylindrical geometry
- Inability to conduct electric current
- Immune to electromagnetic interference and radio frequency interference

- Lightweight
- Robust, more resistant to harsh environments
- Increased sensitivity over existing techniques
- Multiplexing capability to form sensing networks
- Remote sensing capability
- Multifunctional sensing capabilities such as strain, pressure, corrosion, temperature and acoustic signals

With so many advantages, this deems optical fibers as reliable sensors. To date, fiber optic sensors have been widely used to monitor a wide range of environmental parameters such as position, vibration, strain, temperature, humidity, viscosity, chemicals, pressure, current, electric field and several other environmental factors [3]. The majority of the applications for these sensors are in remote sensing. Light can be detected using optical sensors, usually in a specific region of the electromagnetic spectrum (ultraviolet, visible, and infrared). The photoelectric effect causes the sensor to transform the detected light's wavelength, frequency, or polarization into an electric signal.

In this chapter, an overview of fiber optical sensors is presented. Section 3.2 explains the principle of operation of optical fiber sensors. The different types of optical fiber sensors and their respective applications are then explored for clarity.

### **3.2 Optical fiber sensor operational principles**

Fiber optic sensors work by the environment and physical effects modulating some parameters of fiber optic systems such as wavelength, polarization, phase, etc. The result is a change in the optical signal characteristics at the receiver. In an optical fiber, light will be redistributed as a result of Rayleigh, Brillouin or Raman scattering after being launched into a fiber from a light source using electromagnetic waves. If temperature, strain, vibration, and acoustic wave changes are transferred to, mostly via direct contact with some types of special glues to the optical fibers, the scattered signal in the fiber will be modulated by these physical parameters [4]. Through measuring the changes in the modulated signal, fiber sensors can be realized. Therefore, the principle of operation for optical fiber sensors is a change in the power or other properties of the light signal which propagates through the fiber due to a particular perturbation [4]. By measuring the time delay of the speed of light in the presence of temperature or stress

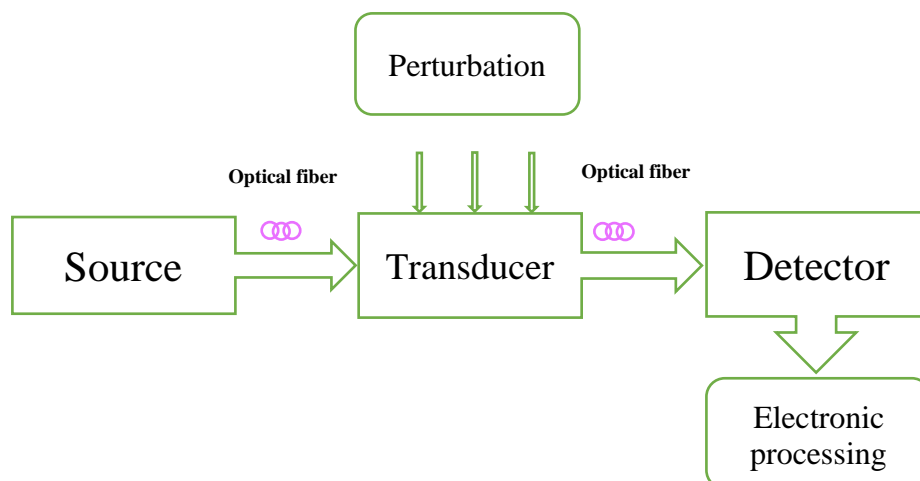


changes along the optical fiber, the modulated signal can be localized along the fiber based on the pulse width of the input light:

$$\Delta z = \frac{\tau c}{2n_{\text{eff}}} \dots\dots\dots (1)$$

Where  $\tau$  and  $c$  are the time constant and the speed of light respectively, and  $n_{\text{eff}}$  is the effective refractive index of the fiber, which is associated with the group the index. The factor of 2 is the time it takes for pumped and scattered light to travel from the source to the receiver. Optical time domain reflectometer (OTDR) test sets based on Rayleigh scattering commonly use pulse width-defined spatial resolution. Since Rayleigh scattering is an elastic scattering process without frequency shift and the pulse spectral width is within the range of MHz, we can ignore the variation in the group index and the phase index within the spectral width. For fibers with differing frequency shifts due to Brillouin (GHz) and Raman (THz) scattering, the variation of phase and group indices is not negligible. Especially for fibers with high chromatic dispersion (CD) and PMD with separate Stokes components in the fast and slow axes, particularly over long fiber lengths (>10km) [4].

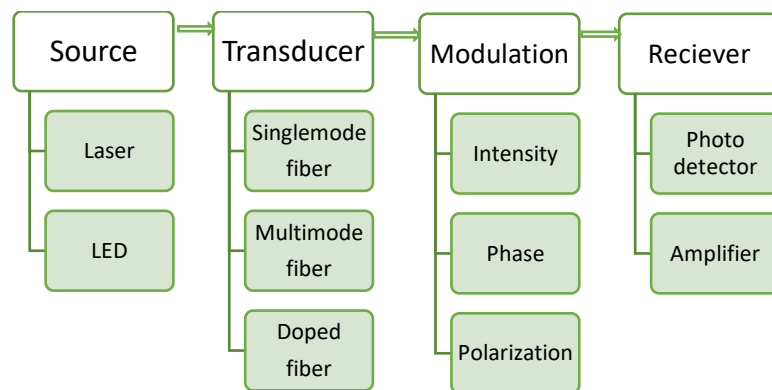
Optical fiber sensors are ideal for insensitive conditions, such as low light, high vibration, extreme heat, wet and unstable environments [5]. These sensors can be conveniently placed in small areas and can be positioned correctly wherever flexible fibers are required. Using a device called optical frequency-domain reflectometry, you can calculate the wavelength shift. The time delay of an optical fiber sensor which may be due to impairments, is determined using a reflection time-domain or optical time domain reflectometer [5]. Presented in figure 1 below is the basic components of an optical fiber system consisting of an optical source, optical fiber, a modulator, an optical detector and an electronic processor.



**Figure 1.** Basic constituents of an optical fiber sensor

The light source acts as the carrier of the signal or embedded data, which can be an LED or laser. The perturbation is the disturbance to be detected by the system. The perturbation can either be in the intensity, phase or polarization of the transmitted light. The transducer is the optical fiber connection system which is made up of an interconnection of the selected optical fiber (single mode, multimode or doped). The optical fiber acts as the sensing device of the perturbed signal. The detector is responsible for interpreting the optical signal and thus converting it into an electronic signal for the electronic processing.

The above information can be summarized below:



**Figure 2.** Functioning structure of an optical fiber sensor

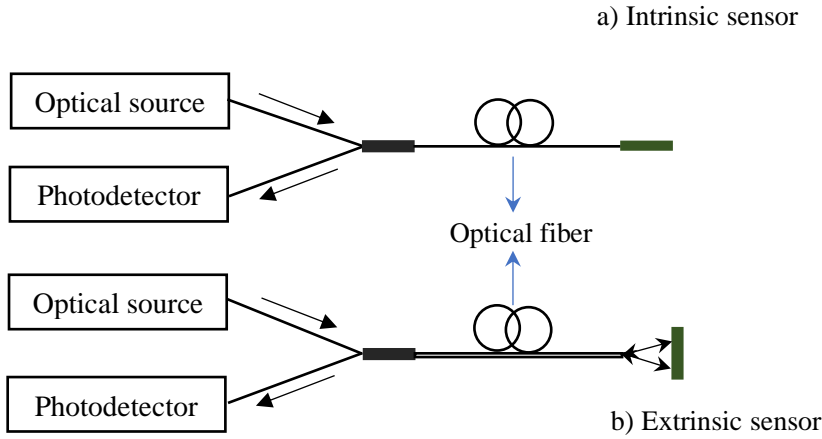
Therefore from this schematic we can see the components of an optical fiber sensor and how they link to one another.

### 3.3 Types of optical fiber sensor systems

Generally, fiber optic sensors can be classified according to how they make use of the optical fiber. These sensors can be classified into intrinsic and extrinsic sensors based on their functional properties.

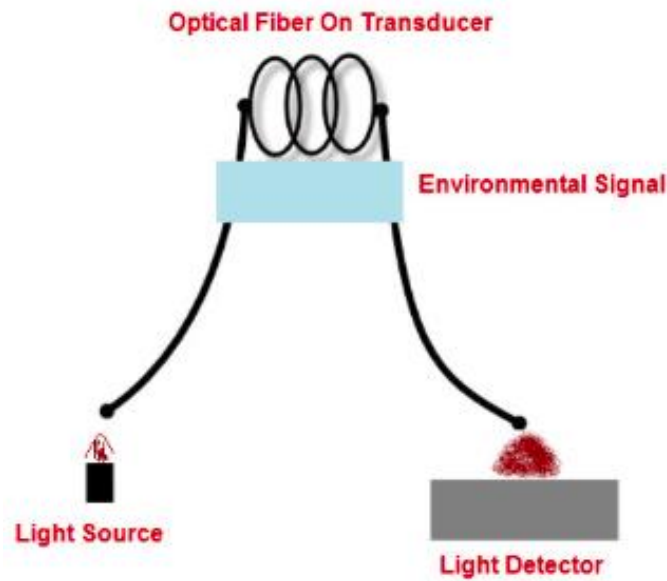
#### 3.3.1 Location based classification

Based on the sensing location, optical fiber sensors can be classified as either intrinsic sensor or extrinsic sensors. Let us have a look on the schematic representation for a better idea of the concepts before we elaborate further.



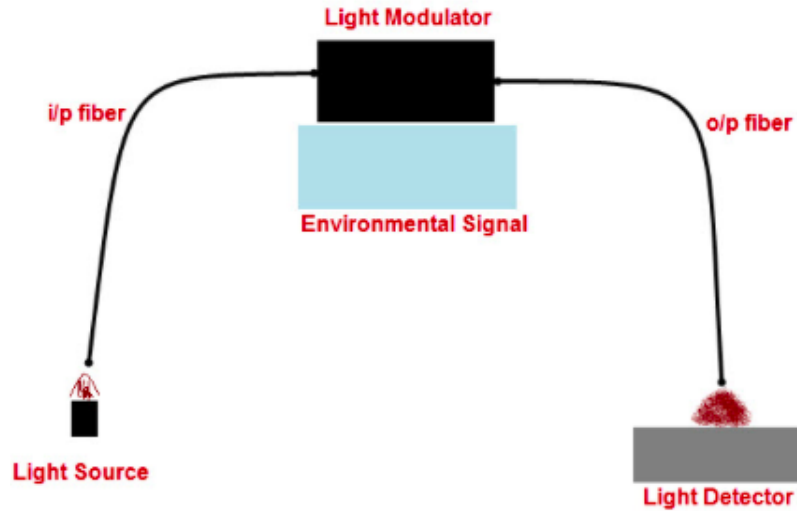
**Figure 3.** Typical orientation of an optical fiber sensor with an a) intrinsic sensor arrangement and b) extrinsic sensor arrangement

*Intrinsic* optical fiber sensors are based on the fact that a light beam propagating through the optical fiber is modulated by an external environment either directly or through changes in the optical path length due to the environment itself [5]. While the light is guided through the fiber, the optical signal is modulated. Meaning the fiber itself modulates the propagating light in response to the measurand field. In principle, the light does not leave the fiber except at the detection end (the output). As a result, this involves measuring-induced excess loss in the sensor fiber region. Measuring-dependent scattering, fluorescence, differential modal propagation, and optical length have all been used in various sensor systems reported to date. The physical perturbation (variable of interest) in intrinsic sensors increases the characteristics of the optical fiber, thus modifying the properties of the light carried by the fiber. Intrinsic optical fiber sensors can either use fiber interferometers (FIG), Fiber Bragg Gratings (FBG), or Long Period Fiber Gratings (LPFGs). They can also use special fibers (doped fibers) designed to be sensitive to various perturbations [5]. Figure 4 gives a example of a schematic of an intrinsic optical fiber sensor.



**Figure 4.** Intrinsic optical fiber sensor

*Extrinsic* optical fiber sensors are composed of optical fibers that lead up to and out of a black box that modulates the light beam passing through it in response to an external environment factor [5]. In this case, the light leaves the fiber, passes through some external transduction elements, and is then recoupled back into a fiber. The fiber is simply used to carry light to and from an external optical device where the sensing takes place. On [6], the authors write that an optical fiber is simply used to guide light to and from a location where an optical sensor head is located. The sensor head is often an external component that is built with miniature optical components, which modulate the properties of light as a result of physical perturbations in the environment. Thus in this configuration, one fiber transmits optical energy to the sensor head. Following modulation, the light is coupled back via a second fiber, which is then guided back to the optical detector. It is this principle that explains optical sensors relying on transmission of intensity. The most notable example of this type of sensor is the inside temperature measurement of aircraft jet engines, which uses a fiber to transmit radiation to an external radiation pyrometer. Figure 5 gives an example of a schematic of an extrinsic optical fiber sensor.

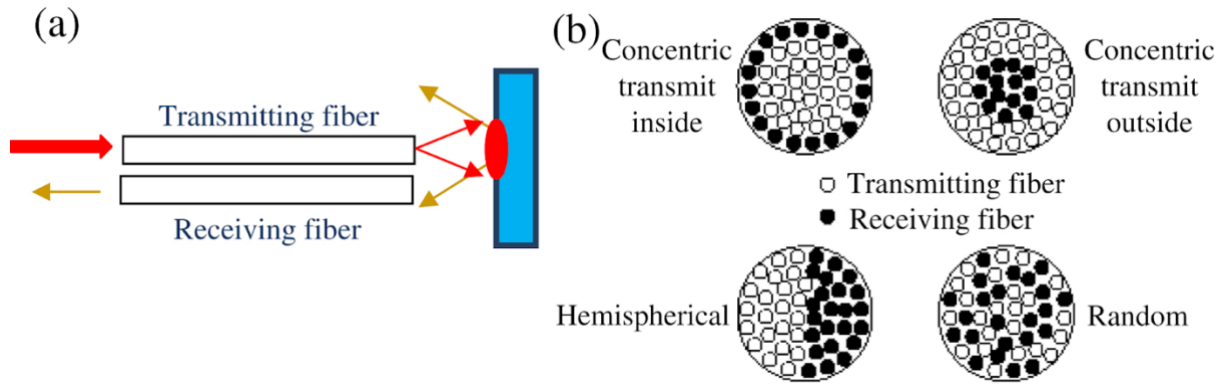


**Figure 5.** Extrinsic optical fiber sensor

### 3.3.2 Operation based classification

#### *i. Intensity based sensor*

Fiber optic intensity sensors rely on signals that undergo some loss. These devices rely on an apparatus to convert what is being measured into a force that bends the fiber in the process of attenuating the signal [7]. Other methods of attenuating the signal are absorption or scattering. Intensity-based sensors often use multimode, big core fibers since they require more light. From the work done in [7] we learn that sensors of this type respond to environmental perturbations by detecting variations in the light intensity. There are a variety of concepts associated with intensity modulation, such as transmission, reflection, and micro bending. A fiber can be integrated with a reflective or transmissive target in order to accomplish this. In addition to the three primary concepts, there are a number of other mechanisms that can be used independently or as a part of a combined approach. The simplicity of their application, low cost and multiplexing possibilities work as their prime advantage. Meanwhile, the fact that a referencing system needs to be used to ensure accuracy (which may be due to intensity variation of the light) can be quite a drawback in these types of sensors [8].



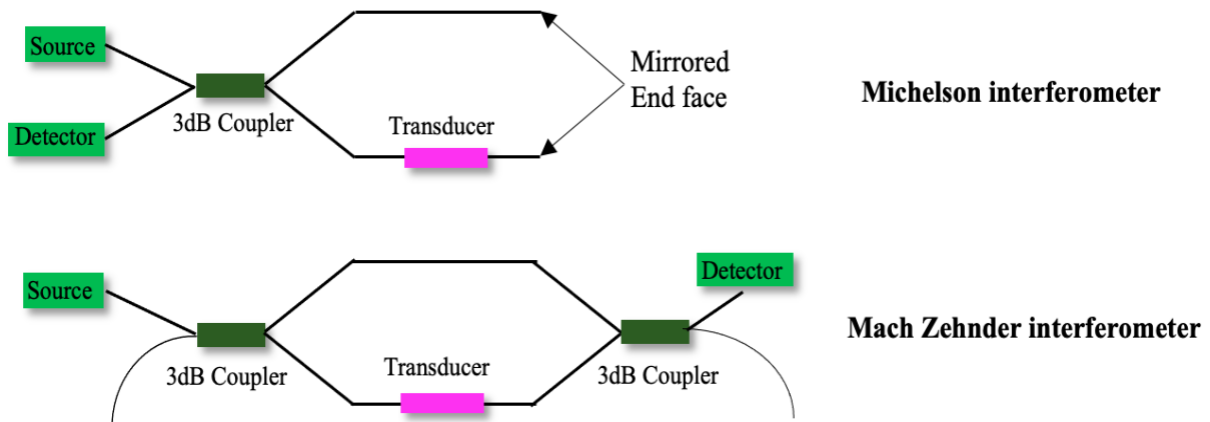
**Figure 6.** An example of a fiber optic intensity sensor for measuring distance. (a) A two-fiber sensor that displays the subject and the underlying logic (b) Different fiber bundle sensor head geometries, taken from with permission [11].

The figure shown above gives an idea about the functioning principle of the light intensity sensor. From figure 6 we can notice how this arrangement makes the fiber work as a vibration sensor. In the event of a vibration there will be a perturbation in the light which is inserted from one end to another thus creating an intelligent technique for measuring the vibration amplitude. Figure 6 also show how proximity and light intensity in the optical fiber sensor contribute to the accuracy of vibration sensing. Despite their many advantages, these sensors have numerous limitations due to the variable losses in the system that do not occur in the environment. These losses include those due to splices, micro bending and macro bending, as well as those related to connections at joints. Examples include the intensity-based sensor, the microband sensor, and the evanescent wave sensor.

## ii. Phase based sensors

A sensor of this type compares the phase of light in a sensing fiber to the phase of light in a reference fiber using an interferometer. These sensors are usually equipped with a coherent laser light source and two single-mode fibers. Specifically, the laser light is split and injected into the reference and sensing fiber [9]. Where one beam is exposed to the sensing environment which is used as a reference. Light traveling through a sensing fiber experiences a phase shift if it is exposed to an environmental perturbation. Once the two split beams are recombined, then they get in the way with each other by interference. An interferometer detects this phase shift. Optical sensors use four types of interferometric configurations: the Mach-Zehnder, Michelson, Fabry-Perot, and Sagnac. The most widely used acoustic sensing configuration is

the Mach-Zehnder interferometer. Optical fiber sensors using phase-modulation are often more accurate than sensors using intensity-modulation.



**Figure 7.** Phase based sensor schematics

The types of phase based sensors schematics are shown on figure 7 above, where a Mach Zehnder and Michelson interferometer are shown. In terms of similarity, the Michelson Interferometer is often considered to be the folded Mach Zehnder interferometer. There is only one optical fiber coupler necessary for a Michelson interferometer configuration. The optical phase shift measured per unit length of the fiber is doubled since light passes twice through the sensing and reference fibers. As a result, the Michelson essentially has a better sensitivity. Another notable advantage of Michelson sensors is the fact that the source and source detector modules need only be connected via a single fiber. However, a good-quality reflection mirror is needed for the Michelson interferometer.

### *iii. Polarization based sensor*

Polarization sensors are based on changes in the birefringence of single-mode fibers [9]. As polarization state of the light field is defined as the direction of the electric field component of the light field. There are three different types of polarization states of the light field: linear, elliptical, and circular. A linear polarization state implies that the electric field direction stays in the same direction during the propagation of light. When the elliptical polarization state is present, the direction of the electric field changes during the propagation of light. Electric field vectors end in an elliptical shape, which is why this form of light is called "elliptical polarized light" [9].

When an optical fiber experiences stress or strain, its refractive index changes. As a result, there is an induced phase difference between different polarization directions. This phenomenon is referred to as photoelasticity. In addition, the refractive index of a fiber subjected to a certain strain or stress is called induced refractive index. According to the direction of applied stress or strain, the induced refractive index changes. Therefore, different polarization directions are induced to have phase differences. In other words, the optical fiber acts like a linear retarder when it is exposed to an external perturbation, such as stress or strain. This means that the external perturbation can be detected by detecting the change in output polarization.[9] The optical configuration for the fiber optic sensor based on polarization is shown in Figure 8.

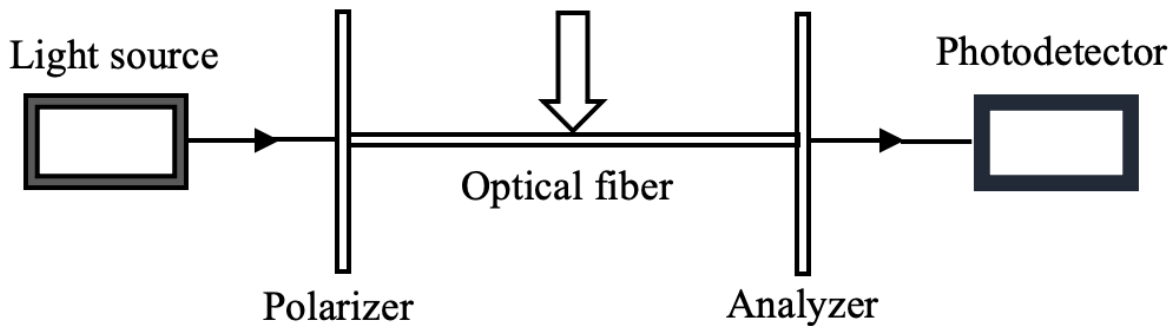


Figure 8: Polarization based fiber optic sensor.

It is created by polarizing the light coming from a light source using a polarizer. This could be a piece of fiber that maintains polarization, but this was not the case for the work done in this thesis. For this work, an extended piece of multimode fiber is used to launch the polarized light, similar to figure 8. This fiber segment serves as a sensor fiber. The phase difference between two polarization states changes in response to an external perturbation like stress or strain. The output polarization state is subsequently modified in accordance with the perturbation. As a result, the external perturbation can be found by examining the output polarization state at the fiber's exit end [12].



### 3.4 Optical fiber sensor applications

The fiber optic technology was already showing promise in the areas of industrial and environmental sensing before fiber optics became popular in the telecom industry. Researchers are now developing safe and precise fiber-based measuring instruments, such as gyroscopes, thermometers, hydrophones, and chemical monitors, based on decades of research. Fiber optic sensors are in fact finding applications in nearly every field, including railroads, bridges, industrial ovens, and waste-disposal systems. This versatile technology is also experiencing growth in fiber sensing, which uses fiber optics for sensing applications in industrial and environmental. There are a few ideas that have made the leap from the laboratory to the highly competitive sensor market. In fact, fiber optics were used in sensing applications several years before fiber optics were used in communications networks. It was introduced in the mid-1960s with the introduction of the "Fotonic" sensor, a bundle-based device that measures distance and displacement, particularly in the machine tool industry. In spite of its imperfection, the Fotonic was a highly anticipated technology, capturing the imagination of researchers for years. Table 1 tabulates some primary applications for the different types of optical fiber sensors.

**Table 1:** Principal application areas for optical fiber sensors

<b>Intensity-based sensors</b>	<b>Interferometric-based sensor</b>
Temperature	Strain
Pressure	Pressure
Force	Acoustic fields Magnetic fields Electric fields Rotation
Strain	(gyroscope) Acceleration Vibration
Torque	Velocity Temperature
Flow	Flow
Liquid level	Current
Position (displacement) Vibration	
Turbidity (oil pollution) Refractive index Chemical	
Radiation	
Humidity	

3.4.1 There are also some disadvantages which are reported on [12], and they are as follows:

- i. Fiber-optic sensors have a low output and, therefore, only become viable when they are used with electronic control systems.
- ii. Precise measurement with fiber optic micro bend sensors is difficult. This is because of inherent variations in the system such as the light loss between the ends of the fiber and the electronic emitters and detectors. However, a simple variable output is easy to achieve.

### **3.5 Mining applications for optical fibres**

A modern and efficient mine uses innovative control methods and increased mechanization to ensure optimum productivity. When fiber optics are used for reliable communications, safety as well as production efficiency will be improved. These fibers will allow mining equipment and facilities to be monitored, analysed, and controlled. Communication must move faster and more reliably as volumes grow, distances increase, performance increases, and demands on operating safety grow. The use of fiber optic communication systems ensures top production standards and safety standards while allowing for the integration of real-time data from environmental and equipment sensors.

Changing from copper wire to fiber optic systems for signal transmission is a necessity due to safety, harsh environmental conditions, and bandwidth requirements. For mining operations with many different gases, a real-time monitoring system is necessary to measure carbon monoxide, methane, hydrogen sulphide and other gases continuously. In underground mines, diesel engines are used more frequently. Because of this, engine emission levels must be monitored continuously in real-time using defined thresholds. System architectures that are designed to respond to input instantly or with a slight delay are called "real-time" operating systems. In simple terms real time refers to distinct process control and feedback mechanism embedded within systems for accurate measurement result in minimum time. Therefore, the implementation of optical fiber advancements in technology has helped improve safety, product quality and processes improvement providing lowest lifetime cost per tin in mining, preparing and processing.

A number of sensors are required in coal mine safety monitoring, for instance Raman scattering based fiber optic distributed temperature sensors (DTS) for hot spot detection and early warning of coal combustion, strain and load sensors for rock stress monitoring, pressure sensors for underground water and monitoring [10]. On the other hand, methane sensors are by all means the most demanding to prevent explosion and fire within cavities. Statistics shows that in cases where a coal mine work face is 600 m below the ground level, rock burst becomes phenomena [10]. This is a direct result of abrupt stress release and can cause burst out of thousands of tons of coal and rock into the tunnels or work face. It is therefore useful for such instances that optical fiber accelerometers are used for detection of rock breakage and fracture.

### **3.5 Summary**

The aim of this chapter was to introduce optical fiber sensors to give some literature background on terminology and concepts. The operating principles of these sensors were explored. We can note that the various kinds of optical fiber sensors have different operating principles. This depends primarily on the function for which the sensor will be used i.e. intensity or phase. Many uses for these optical fiber sensors are provided for clarification. Mining applications are particularly highlighted due to the inspiration of the work done on this thesis. In chapter four, the proceedings of the aim of this thesis experimentally are discussed.

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# CHAPTER 4

# **Optical fiber-based data transmission and vibration sensing in mining**

## **4.1 Introduction to data communication in mining environment**

Monitoring of the environment in underground coal mines has always been mandatory to ensure safe working conditions for miners. The underground condition needs to be quickly detected and accurate location references provided to the workers to evacuate them from the dangerous zone should be developed as part of an active communication and information network. The implementation of real-time data in mine cavities has moved far beyond the point of convenience and is now essential for any operation looking to improve productivity and promote maximum health and safety. The importance of data and real-time information has also increased the ability to transfer these data throughout the entire mining environment, in real-time, and it has become a focal point of modern mining to create and maintain this infrastructure.

Due to the strides in technology made by the mining industry, fiber optics cables of greater durability are now available, allowing "smart mines" to flourish. Mines that have embraced these technologies have experienced incredible gains. Mining companies can increase productivity, keep workers safe, be more profitable, and even protect the environment by utilizing specialized fiber optic solutions.

### **4.1.1 Smart mines and green mining**

Prior to recent innovations, harsh mining conditions prevented fiber optics and other smart technologies from being used in mines. However, fiber sensors are about to lead the industry into a new era. The growth rate for smart mining market is projected to be worth \$23.6 billion by 2027 according to Allied Market Research [1]. A growth that will be driven by the increase in demand and use of the smart mining concepts.

More consumers are becoming eco-conscious, so there is a push for mining to become more sustainable. Green mining technologies can help companies like mines meet these sustainability demands. According to this case study [1], computer technologies, remote sensing, and other innovations can help reduce the environmental impact of mining operations. Making it obvious that smart and green mines are the future of the mining industry, and for

many good reasons. Therefore, efficient Communication technologies can help mines become more productive, safer, profitable, and environmentally friendly.

#### 4.1.2 More data results in more productivity and safety

Many industry leaders are concerned about the decrease in productivity that the mining industry has seen in the past decade. But it appears that smart mining is turning the tide for the industry, largely due to this development. Immense amount of data can now be collected using fiber optic sensors which is used to understand the land lay out amongst other things. The ability to see the rock face clearly provides with the ability to make better decisions, optimizes drilling and blasting, which in turn makes them more productive.

Since the implementation of fiber optic communication systems, safety has become the one of the top focal areas in the mining industry, aimed at making it possible for days with no accidents. For example, worksite simulators contribute to making the mining industry safer. As an alternative to training additional employees, the mining sector can use simulations to demonstrate what should be done during an emergency. Another game-changing innovation are the prospective smart helmet. There is no longer a need to use canaries for signalling carbon monoxide poisoning. Currently in some countries, workers helmets come with integrated carbon monoxide sensors. Should a certain amount of carbon monoxide be detected by the sensor out of a specific range, the appropriate people will be alerted, and lives can be saved. Other examples of ways that optical fiber technology contribute to making the mining industry safer include self-driving vehicles, rescue, and radio frequency identification (RFID) communication [13].

#### 4.1.3 Better profit margins

The introduction of optical fiber-based communication innovative technology in the mining industry will lead to a lot of growth in the sector. There have been lots of projections that intelligent sensors alone would add \$34 billion in value to the mining industry by 2025. This expansion is exactly what many mining firms require right now, especially in the face of economic headwinds. As more information on smart mining becomes available, it becomes evident that fiber optic sensors and other technical breakthroughs will become increasingly important to mining companies.

## 4.2 Vibration detection in mine cavities

As the degree of automation rises, early detection of malfunctioning equipment in mines becomes increasingly important. The amplitude of the vibration signal on fundamental frequency grows when the functioning condition of the equipment varies from normal to malfunction conditions, as measured by an optical fiber vibration sensor positioned on the surface of a mine. As the functioning condition of the equipment changes, so does the frequency spectrum of the vibration signal. With good repeatability, high diagnostic accuracy, and dependability, the mine monitoring system based on the fiber vibration sensor may further implement effective monitoring and malfunction diagnostic of the mine working circumstances. A broadband noncoherent light source is employed in standard optical time domain reflectometry (OTDR) to detect anomalies along the length of an optical cable by evaluating the intensity of the Rayleigh backscattered signal [2]. The typical OTDR, however, does not provide phase information for the returning light. Fiber optical sensor technology for distributed parameter detection ranges from interferometry-based systems to phase-OTDR and polarization-OTDR systems based on Rayleigh and/or Brillouin scattering, using either to coherent or direct detection methods.

### 4.2.1 Microseismical monitoring

Modern technology has made oil exploration and production possible. Hydraulic fracturing is the primary technology underpinning this sort of production, in which a mixture of water, sand, and chemicals is injected into the earth to break apart the rock and liberate trapped oil and gas. Several investigations [3] have found a link between local earthquakes caused by induced microseismical activity and nearby hydraulic fracturing. A distributed acoustic sensing (DAS) device installed in the wellbore can detect the magnitude and location of micro-seismic events in the surrounding area, which can help with oil and gas production optimization and earthquake prediction [4]. To capture vibration data during and after hydraulic fracturing operations, fiber-optic distributed vibration devices can be put both on the surface and in the borehole. These data can then be used to predict any probable generated earthquakes in the area using existing earthquake prediction systems. In underground mines, integrated distributed antenna systems and distributed temperature sensing systems can be used to monitor the local



environment, stress-induced rock movements, and microseismical occurrences to assure mine safety and operations [5].

#### 4.2.2 Real-Time monitoring

Subsea well operation and maintenance are considered costly and high-risk investments. As a result, even though subsurface engineering and geoscientists promote added value, innovative technologies such as fiber-optic technology in subsea applications are rarely utilized. Information on down-hole flowing and shut-in pressures, build-up or drawdown pressure, time-lapse production profile, flowing and static down-hole temperatures, multiphase flow rate, and water or gas breakthrough is required for risk reduction in subsea wells [6]. Temperature, pressure, and vibration across the length of the well are the data kinds. These needs can be satisfied by designing and implementing subsea-specific hybrid fiber-optic sensing systems that are both dependable and cost-effective.

Fiber-optic distributed sensors that are permanently installed allow consumers the option of continuous real-time monitoring without the need for new installations. Fiber-optic sensing systems, particularly in borehole measurements, provide the following advantages over other technologies: (1) no down-hole electronics, which reduces failure rates, and (2) relatively low mass of the sensing element (fiber-optic cable with supporting structure), which improves equipment vibration tolerance and hence reduces noise in obtained data [7].

#### 4.2.3 Geohazard monitoring

Landslides, soil erosion, levee failures, and ground subsidence account for a large portion of today's recurring geohazards [6]. Time-lapse monitoring of soil levees and embankments can help avoid the supporting structure from collapsing. Temperature measurements inside the levee, both local and spread, are acknowledged as an important technique for detecting water-flow changes across the levee. Temperature readings employing distributed temperature sensing (DTS) systems have been demonstrated to be useful in detecting leakage in levees [8]. Another valuable measure for detecting any potential structural collapse is strain field fluctuations within the soil levees and embankments. A significant evaluation method for averting any potential soil levee and embankment-related geohazard is real-time monitoring of minor displacements with fine spatial resolution and high sensitivity [9]. For strain and temperature measurement, two distinct DSS (distributed strain sensing) and DTS systems are

traditionally employed. A Divot system can potentially detect both strain and temperature simultaneously in those applications, eliminating the requirement for two separate systems.

### **4.3 Wireless data transmission**

Mobile computing and hardware advancements have enabled the deployment of more efficient functions on mobile devices while also reducing their size and weight. Mobile device usage is low in underground mining sites due to tight safety rules. Several wired [10] and wireless communication technologies are currently available that meet the minimal data broadcast speed and range requirements to enable distant mining operations and advanced monitoring systems. The fundamental benefit of wireless communication is mobility within a restricted area. Wireless technologies can be utilized in underground mines to assist the mobility of humans and machines in hazardous working environments. Heavy gear can easily destroy traditional cable connectivity in certain regions, and it may not be able to keep up with the required expansion of operating areas.

As a result, wireless sensor networks (WSNs) have proven valuable for detecting and monitoring critical data such as in-situ stress and strain, air quality, and data from underground mine machinery. To monitor the rock conditions in mining operations, long-term in situ stress and strain monitoring devices are required. Although numerical modelling methods are faster, actual measurements from sensors placed around the areas of interest can provide more precise stress and strain measurements of the surrounding rock.

#### **4.3.1 Wireless sensor networks**

The effective monitoring of natural phenomena that represent a safety risk to humans in underground mining operations can help to improve environmental health and safety. Rock movement owing to stress, temperature and ventilation imbalances, and smoke and air quality issues are all potential hazards [11]. In shallow coal mines, the rate of increase in horizontal stresses as depth increases is greater than the rate of increase in vertical stress, hence in situ stresses generally increase with depth. The rate of rise in horizontal stresses, on the other hand, reduces as depth increases. As a result, there could be a lot of variation in the in-situ stress test data due to unique variances in the strength and deformation moduli of strata in different geological settings and coal areas [12].

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## 4.4 Summary

Underground mines will become deeper and more sophisticated in structure in the near future. This needs ongoing worker safety and productivity improvements. Communication systems, which are critical for the safe operation of underground mines and the prevention of potential accidents and losses, are one area where improvements might be made.

With its innovative uses, fiber-optic sensing technology has revolutionized distributed multi-parameter measurements in a variety of industries. The oil and gas industry has emerged as a leader in developing distributed sensing technology for energy exploration, reservoir integrity monitoring, and production optimization. In this chapter the three main focal areas of this thesis where outlined to emphasize the motivation of this work.

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# CHAPTER 5

# Experimental and methodology

## 5.1 Introduction

The following chapter will entail a detailed discussion of the techniques adopted in this work together with their operating principles. The respective experimental setups for the different experiments will be shown and explained. The BER method used for ensuring accurate measurements will also be discussed.

## 5.2 Equipment used for experiments

### 5.2.1 Laser source

The work conducted in this thesis was done using two laser sources. The first was a distributed feedback (DFB) laser for the polarization-based sensing. The most stable single-frequency tuneable laser configuration is DFB. For predefined wavelengths, the DFB laser provides a high signal to noise ratio (SNR), minimal temperature sensitivity, intrinsic fiber compatibility, single mode operation, and is simple to construct. For direct detection and wavelength division multiplexing (WDM) schemes, this makes it the most appealing optical source [1]. DFB lasers in the C-band were used in this study. Figure 1 below shows the Thorlabs WDM laser with 8 channels, which was used in the experiments.



**Figure 1:** Thorlabs WDM laser with 8 channels

The second of these is a vertical cavity surface emitting laser (VCSEL) used for the data transmission. VCSEL arrays are substantially easier to package than a comparable edge-emitter bar-stack due to the ease of manufacturing and heat-sinking technology. Existing silicon industry heat-sinking methods can be used to remove heat from very high-power arrays. As a result, the cost of the high-power module will be considerably decreased. This makes VCSELs a potential replacement for many expensive industrial lasers. In figure 2 both with a centre wavelength around 850nm. LEDs have a very broad spectral output which causes them to suffer chromatic dispersion in fiber, while lasers have a narrow spectral output that suffers very little chromatic dispersion

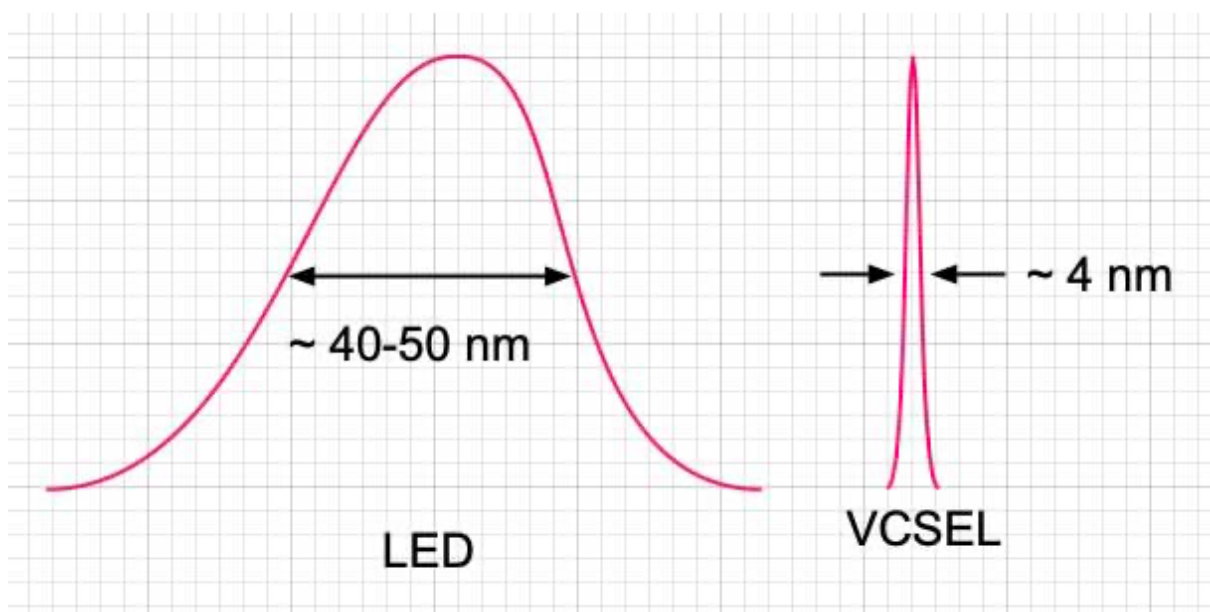


Figure 2: Comparison of spectral output of a LED and a VCSEL

### 5.2.2 Spectrum analyser

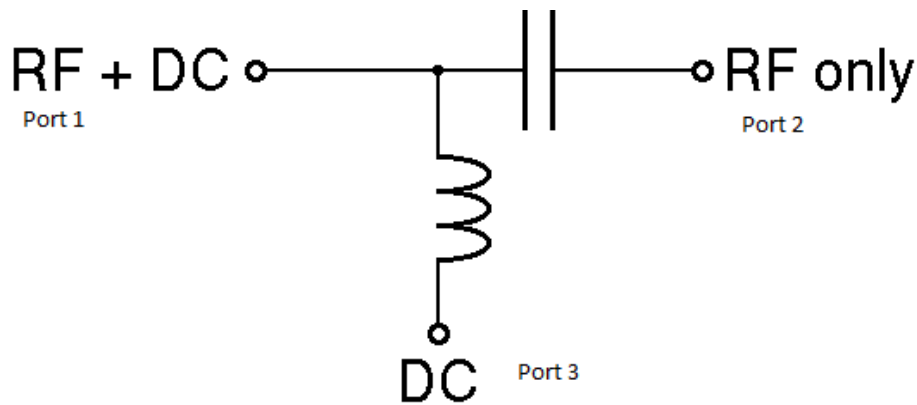
Spectrum analysers are a very effective way of quickly and accurately testing phase noise, and they can be considerably easier and more accurate than other types of electronic test tools. Poor phase noise performance can result in more data errors, but it can also cause interference to users on other channels, therefore it's becoming more important as a criterion on many radio frequency (RF) devices. Routines are frequently included into the software of these electronic test tools to make testing even easier. When compared to alternative approaches using various



types of test equipment, the spectrum analyser not only makes it easier to obtain phase noise data, but it is also usually more accurate.

### 5.2.3 Bias T

A Bias T is a diplexer with an ideal capacitor that permits alternating current, AC, while blocking direct current, DC, bias and an ideal inductor that blocks AC while allowing DC. To power remote antenna amplifiers or other devices, a bias tee is used to inject DC power into an AC signal. It is commonly installed at the coaxial cable's receiving end to send DC power from an external source to the coaxial cable that leads to the powered device. this is displayed at figure 3 below.



**Figure 3:** Bias T schematic

### 5.2.4 Optical modulator

An optical modulator is a device that can be used to manipulate a light property, most commonly a laser beam. Depending on the type of light being controlled, intensity modulators, phase modulators, polarization modulators, spatial light modulators, and other names for modulators may be used.

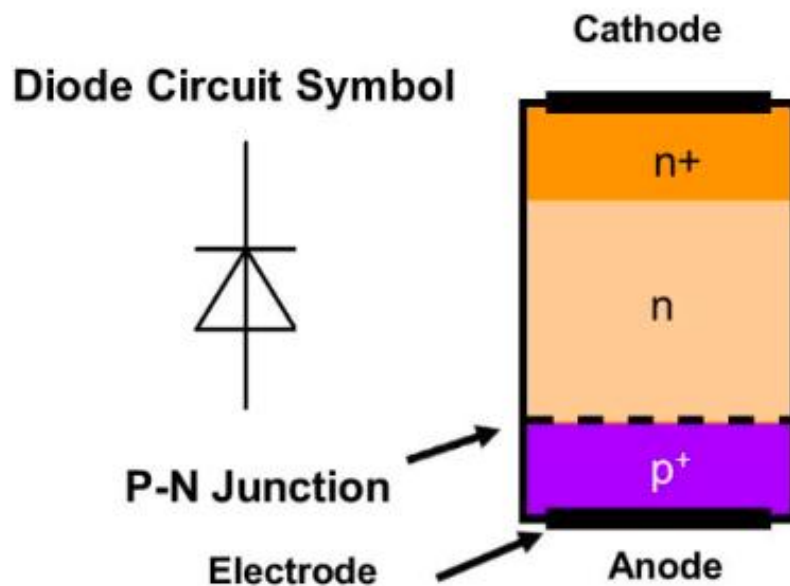
For this work, a Mach- Zehnder modulator was used. The amplitude of an optical wave is controlled via a Mach-Zehnder modulator. Two waveguide interferometer arms are created from the input waveguide. When a voltage is put across one of the arms, the wave travelling through that arm undergoes a phase change. The phase difference between the two waves is translated to an amplitude modulation when the two arms are recombined [2].

### 5.2.5 Variable optical attenuator (VOA)

VOAs have two main applications, one is levelling the output signals for enhancing the intensity of multiple photonic signals in an erbium-doped fiber amplifier (EDFA) while maintaining a consistent amplifying ratio, even when the number of signals or intensity changes. Because the amplifying ratio varies, the performance of the communications system decreases. The optical signal intensity can change depending on the route when optical add drop multiplexing (OADX) and optical cross connect (OXC) are used in the optical network. The strength of the nonuniform signal must be levelled. The arrayed VOA is preferred when using VOAs for each wavelength in a WDM system [3].

### 5.2.6 PIN photo diode optical receiver

PIN photodiode is a light detector that can convert optical signals to electrical signals. Photodetectors and photovoltaic cells use them, while PIN photodiodes are used in fiber optic network cards and switches. These diodes can be used in RF protection circuits and as an RF switch. The PIN photodiode can also detect photons from X-rays and gamma rays.



**Figure 4:** Basic structure of PIN diode

Figure 4 shows the working principle structure of a PIN diode. There are no charge carriers in the layer between the P and N regions because any electrons or holes have merged. The depletion area of the diode acts as an insulator because it lacks charge carriers. A PIN diode has a depletion region, but if the diode is forward biased, the depletion region is not there. The carriers then enter the depletion region, and the current flow begins as the two carrier types collide.

The PIN diode operates on the same principles as a regular diode. The key difference is that in a reverse biased or unbiased diode, the depletion area is greater because it generally exists between both the P and N regions. The P region of any PN junction diode has holes because it has been doped to ensure that it has most holes. Similarly, the N-region has been doped to accommodate more electrons.

#### 5.2.6 Coherent receiver: lab buddy



**Figure 5:** 40 / 100 Gbps Coherent Receiver Lab Buddy

The Coherent Receiver Lab Buddy shown in figure 5 helps have made enhancing optical front end easier. The Lab Buddy is more versatile than any other O/E converter on the market today since it can be used with over 30+ equipment. The Lab Buddy delivers device specific voltages, factory set current limitations, and appropriately sequenced biasing for optical receivers. These devices typically have a universal power supply with 50/60 Hz, 110/ 220 VAC. The built-in receptacle connector receives optical input power from the user's fiber optic cable. A coaxial connector provides RF output to an oscilloscope. Spectrum analysers, network analysers, oscilloscopes, and RF power meters, to name a few, can now have optical front ends. Modern models of this device are portable enough to tote from lab to lab.

### 5.2.7 Function generator

The function generator employed in this work was Beckman Industrial's FG2A function generator, as depicted in figure 6. It was used to generate sinusoidal waveforms of various frequencies that powered the vibration producer, causing variations in the state of polarisation of the light travelling through the core of the optical fiber sensor.



**Figure 6:** Function generator

### 5.2.8 Vibration source

The vibration source used in this work was the Euro Tec 17S 035 411 speaker. The speaker was connected to the function generator during the study which enabled us to drive the speaker. This was mainly done by varying the frequency. The speaker used in the experiment is shown in figure 7.



**Figure 7:** Vibration source speaker

### 5.2.9 Poynting Antennae

Antennae are metallic devices used for radiating or receiving radio waves. They are mostly used for transmitting communications, with the transmitting antenna used to transfer information and the receiving antenna used to receive data at the receiver end. For this work a pointing antenna was used. The antenna used in the experiment is shown in figure 8 below.



**Figure 8:** Poynting sensing antenna

### 5.3 Data transmission configuration

This part of the work studied the ability of the VCSEL to transmit high speed photonic data. This was done by using the bit error rate (BER) method to quantitatively measure its performance for photonic transmission.

#### 5.3.1 Bit error rate (BER)

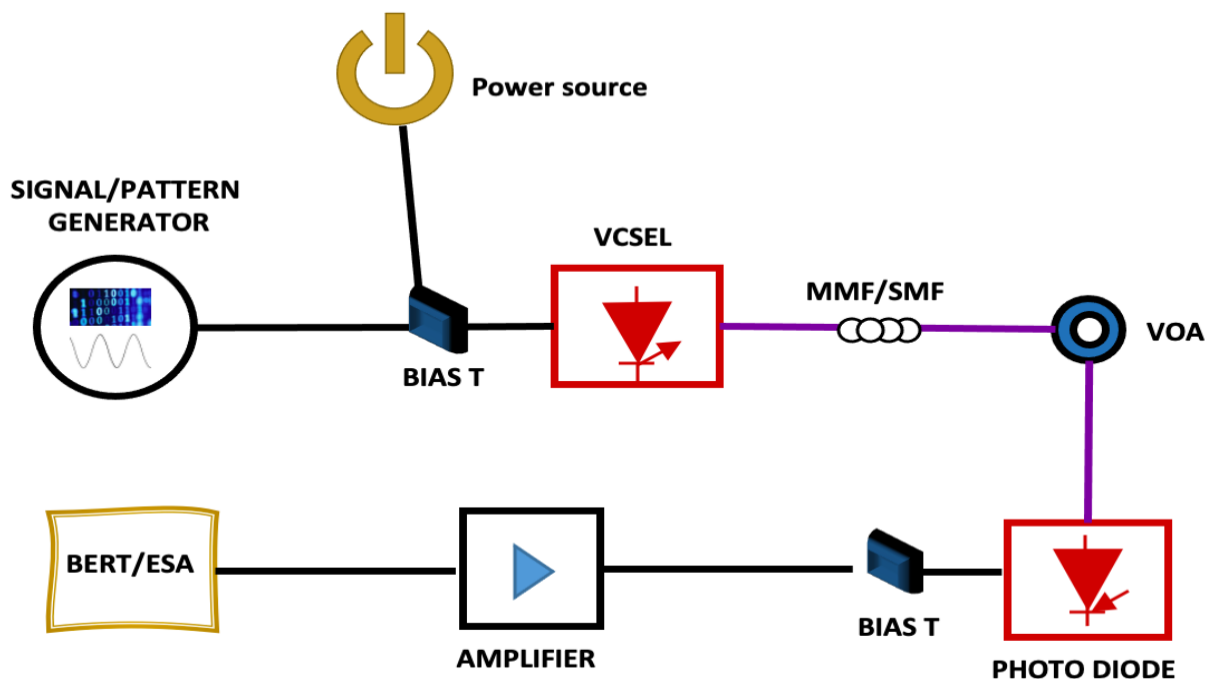
A BER is the rate at which errors occur in a transmission system, as the name implies [4]. This can be easily translated into the number of errors in a string of a specified length. As previously mentioned, the definition of bit error rate can be expressed in the following way:

$$\text{BER} = \frac{\text{Errors}}{\text{Total number of bits}}$$

If the medium between the transmitter and receiver is good and the signal to noise ratio is strong, the BER will be very low - perhaps inconsequential and have no influence on the entire system. However, if noise is present, the BER may need to be considered.

Bit errors in fibre optic networks are caused by flaws in the components that make up the link. The optical driver, receiver, connections, and the fiber itself are among them. Bit mistakes can also be introduced due to optical dispersion and attenuation. Noise could also be introduced into the optical receiver. These are typically photodiodes and amplifiers that must respond to every minute changes and, as a result, may have high noise levels. Any phase jitter in the system, which might change the sampling of the data, is another significant factor for bit mistakes.

The BER, is a fundamental metric used in selecting which connection characteristics should be employed, including everything from power to modulation type, in many communications systems.



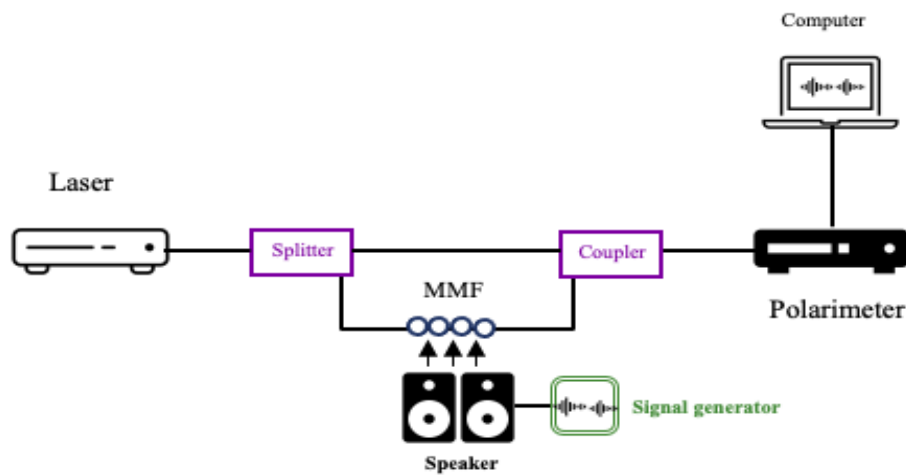
**Figure 9:** Experimental set up for data transmission using multimode fiber and multimode components.

In the laboratory, the above schematic was used for the experiment. The multimode VCSEL was connected to the pattern generator through a bias tee. The bias tee was connected to a power source to power it up. A 100m long multimode fiber was then connected to the spectrum

analyser. To convert the optical signal to electrical, a PIN (photo diode) had to be connected. It was also connected to its own bias tee. Due to dispersions and attenuation the signal, an electrical amplifier had to be used to amplify the signal.

## 5.4 Vibration sensing configuration

As we will report on the experimental results, this setup is that of the polarization based sensor, which is meant to mimic the slightest vibrations that would be experienced in a mine cavity. Using a speaker as a vibration source, a polarization-based sensor experiment was successfully completed. A laser was employed as a light source in the figure below, and it was transmitted via an optical splitter to help create an interference for the goal of boosting sensitivity. Because the interference changes the birefringence of the fiber, this happens. The change in birefringence leads to a shift in light polarization. As a result, the sensitivity is increased.



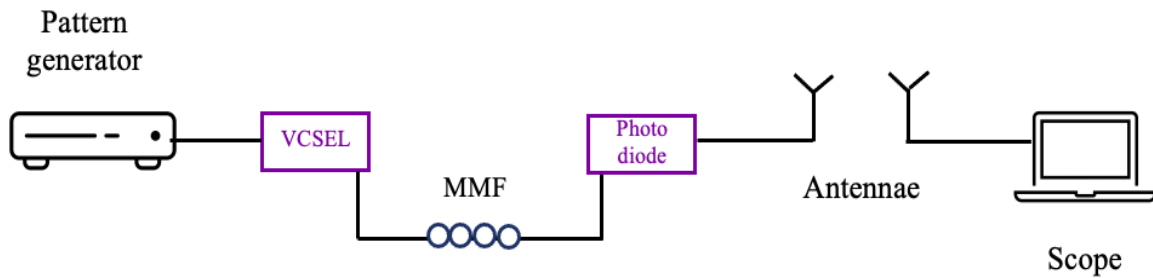
**Figure 10:** Experimental set up for polarization sensor using a speaker as the vibration source.

Studying the behaviour of the fiber with more intense vibration, a drill was then introduced to the experiment. The behaviour of the fiber was then studied and reported where the frequency response was studied in the experimental results chapter.



## 5.5 Wireless transmission configuration

This section explores a wireless communication system for underground mines focusing on data transmission. The fundamental benefit of wireless communication is mobility within a restricted area. This means less risk of workers tripping on wire cords.



**Figure 11:** Experimental set up for wireless transmission

As seen on figure 11, data was transmitted using the X-Bert which was connected to the multimode VCSEL. During a BER test the system is given a unique digital pattern. Utilizing a data pattern that mimics the data sequences most likely to lead to system problems is crucial. It is frequently used to replicate a variety of bit patterns using a pseudo-random binary sequence (PRBS). The PRBS sequence, which repeats after a predetermined number of bits, is a "random" sequence of bits. A typical pattern has a length of  $10^{23}-1$  bits. An error detector compares the output of the link under test to the known input. The error detector counts the errors and then compares them to the amount of bits sent.

For this work, the data was successfully transmitted through the antennae that were 1 m apart. Depending on the strength of the antennae used this proves useful for quick and reliable data transmission from the cavity to the control room.

## 5.6 Summary

The primary goal of this chapter was to provide an overview of the methodologies and equipment used in conducting our research tests. The employment of a BER technique to determine the accuracy of the signal was discussed. In addition, the basic theory underpinning the functional working principle of the primary optical components used was unpacked. We

also assessed the performance of VCSEL as a data transmitter for high-speed data. In addition, we illustrate how a vibrating speaker can be used to predict the performance of the multimode fiber as a vibration sensor in mining applications.

## 5.7 References

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# CHAPTER 6

# Multimode VCSEL characterization and high-speed 5G photonic transmission

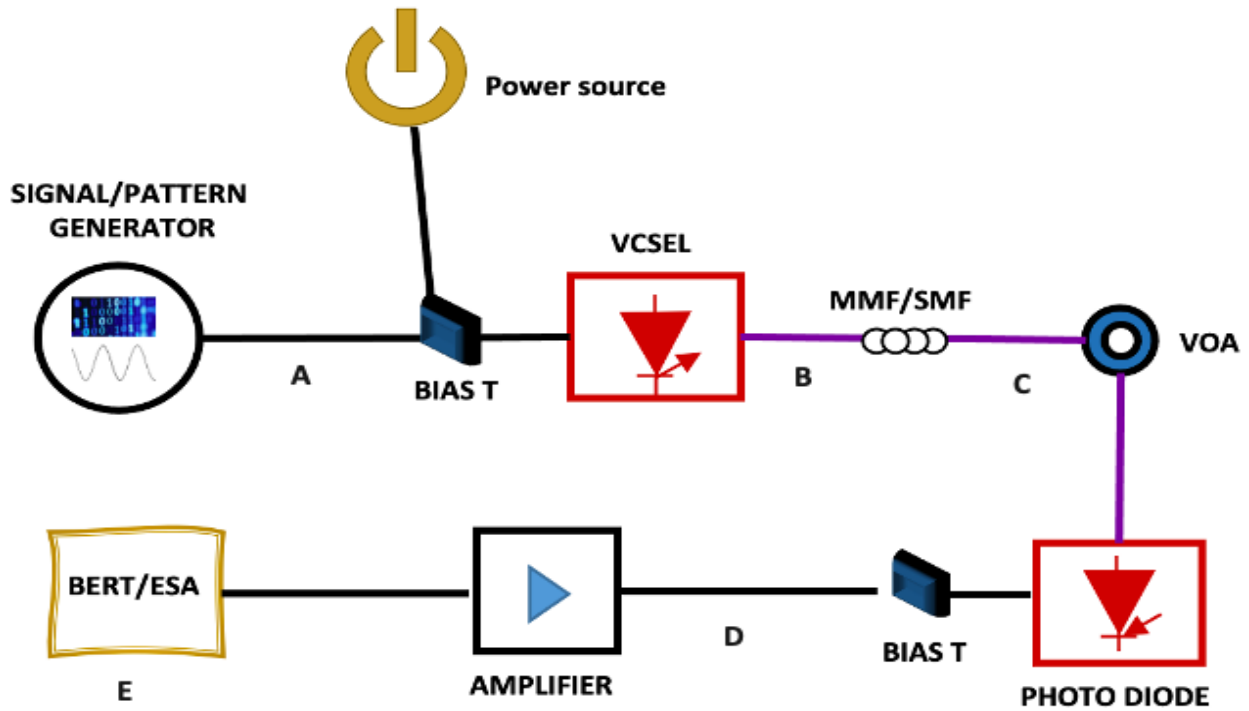
## 6.1 Introduction

Multimode VCSEL lasers have sparked interest to be an excellent candidate to substitute existing external cavity lasers, owing to their cost effectiveness and easy adaptability to existing equipment. In this chapter, the objective is to characterize the multimode VCSEL to investigate its important properties. These properties include central wavelength, output power, modulation bandwidth, spectrum and threshold current. The properties will initially be observed without any data transmission and then further to add some data transmission to then look at the transmission penalties. The VCSEL characterization is important since the multimode VCSEL will be later used in more complicated transmissions later in this study.

## 6.2 Experimental configuration

This experimental procedure is for the characterization of the multimode VCSEL at various points in a transmission system. The points are shown in the figure below: point B, characterization of the multimode optical fiber at point C, observing the functioning of the photodiode at point D and then further do a BER test upon addition of data transmission.

The schematic above in figure 1 shows the representation of the experiment performed for this work. An 850 nm multimode VCSEL was directly modulated using a 10 Gbps  $2^7-1$  non-return-to-zero pseudorandom binary sequence (NRZ PRBS) from a programmable pattern generator (PPG). A VOA is placed after the optical fibre in order to acquire the BER for the data transmission. An RF amplifier had to be used because the peak to peak has to be greater than the minimum requirements, so that the X-BERT and/or scope can be able to pick up the signal or data that was initially transmitted. The PRBS intensity modulated optical signal was subsequently transmitted over 100 m OM4 multimode fibre. The attenuation of the fibre was 2.2dB /100m. The transmitted optical signal was detected using a positive-intrinsic-negative (PIN) photodiode (PD) optimised for 850 nm.

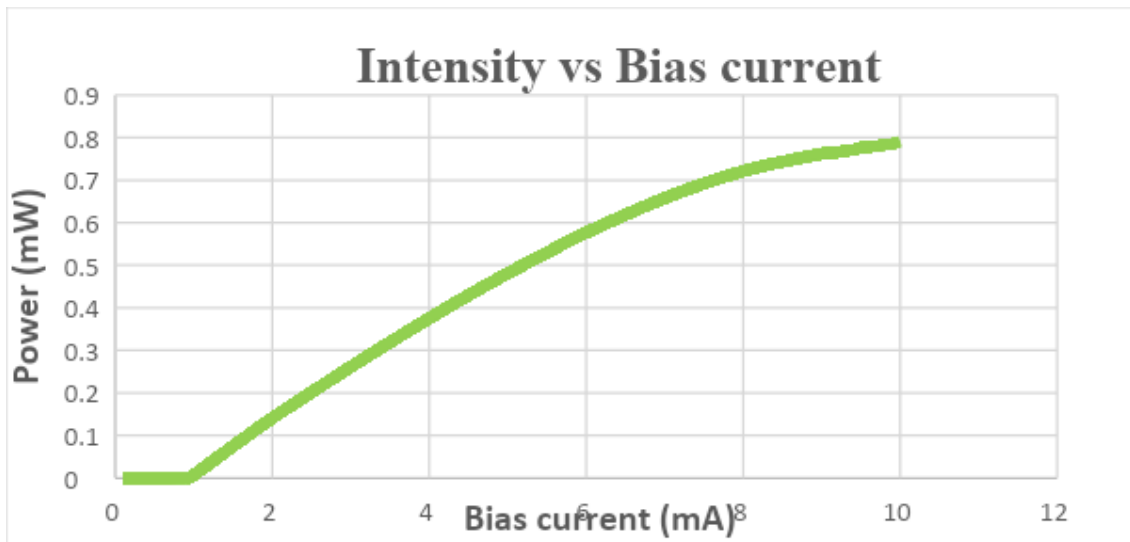


**Figure 1:** Experimental procedure for VCSEL characterization and BER testing

At point A in Figure 1 the eye diagram of the resultant electrical signal after the high-speed photodiode was analysed by using an Agilent Infinium 86100 A high bandwidth oscilloscope with 10 GHz bandwidth in the time domain. Data transmission was also quantitatively measured through the BER performance for photonic transmission. The performance of the wireless antennae transmission was quantitatively investigated using the high bandwidth oscilloscope.

### 6.3 Analysis of results

The following graph shows optical output power vs bias current for the purpose of looking at threshold current, maximum output power and determining where the best point to bias the VCSEL. It is essential for us to be sure that the VCSEL is working properly by looking at these characteristics and there after confirming with the expectations set by the data sheet.



**Figure 2:** An illustration of the optical output power of a multimode VCSEL as a function of bias current.

The characterization of an unmodulated 850 nm multimode VCSEL is shown on figure 2 above with the optical power as a function bias current. The maximum optical power was observed to be 0.8 mW, which can help in estimating how far the signal can travel relative to the loss of the optical fiber.

The length based on fibre loss and receiver sensitivity can be estimated using calculations. However, please note that this will be an optimistic length, since it doesn't take into account phenomena's like modal dispersion. This is another reason why the transmission experiment was done.

### Calculation;

0.8 mW is - 0.97 dBm optical power

Receiver sensitivity is ~ -6 dBm

Therefore:

$$\text{POWER BUDGET} = -0.97 \text{ dBm} - (-6 \text{ dBm}) = 5.03 \text{ dBm}$$

And the fibre loss is 2.2 dB /100 m.

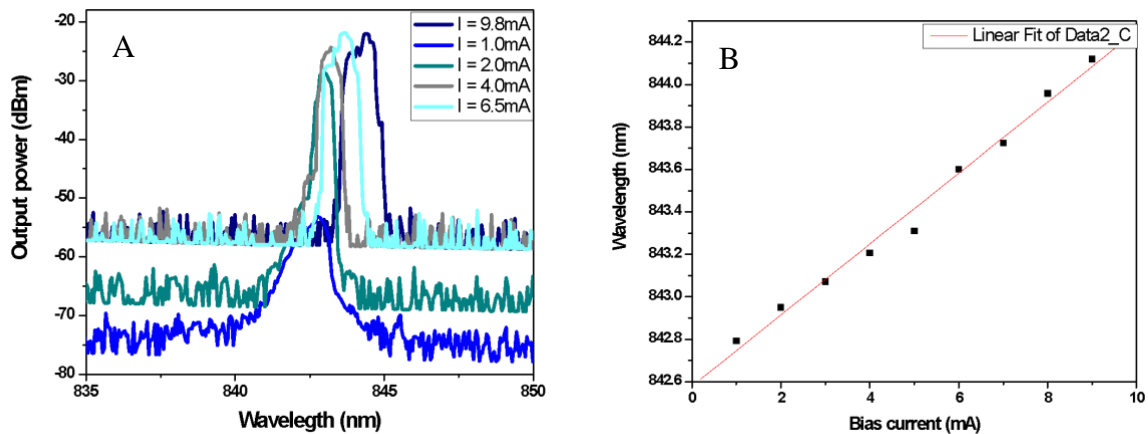
Thus;

$$\text{Maximum Reach} = 5.03 \text{ dBm} / (2.2 \text{ dBm per } 100 \text{ m}) = 228 \text{ m}$$

Therefore, the signals power starts at -0.97 dBm and then it goes through the fiber until such a time that it reaches -6 dBm. At that point it can no longer work, meaning it is only allowed to lose about -5 dBm maximum.

Upon addition of the modulation, current at the zero-level was measured to be 0.9 mA and 9 mA for the one level. There was a significant difference between these values which indicates that the extinction ratio was relatively large and so we can clearly distinguish between the one and the zero level. When the VCSEL was first turned on the VCSEL bias current was initially set to the midpoint of 5.61 mA. When modulation was added then the bias was changed between 0.9 mA and 10 mA. This information is useful as we were able to determine that we have a linear region in the graph. This is the best region to operate the VCSEL to attain the maximum swing so as to get a big extinction ratio.

The maximum current for this 850 nm multimode VCSEL was specified at 10mA. The lasing threshold current is seen to be around 1 mA. The VCSEL was biased at 5.5 mA before adding the PRBS modulation in the transmission experiment. (say why this was chosen) The maximum output power of the VCSEL was -0.97dBm.



**Figure 3:** A) indicates the spectrum results for the optical power at different bias currents (B) shows the trend in the change in wavelength with bias current.

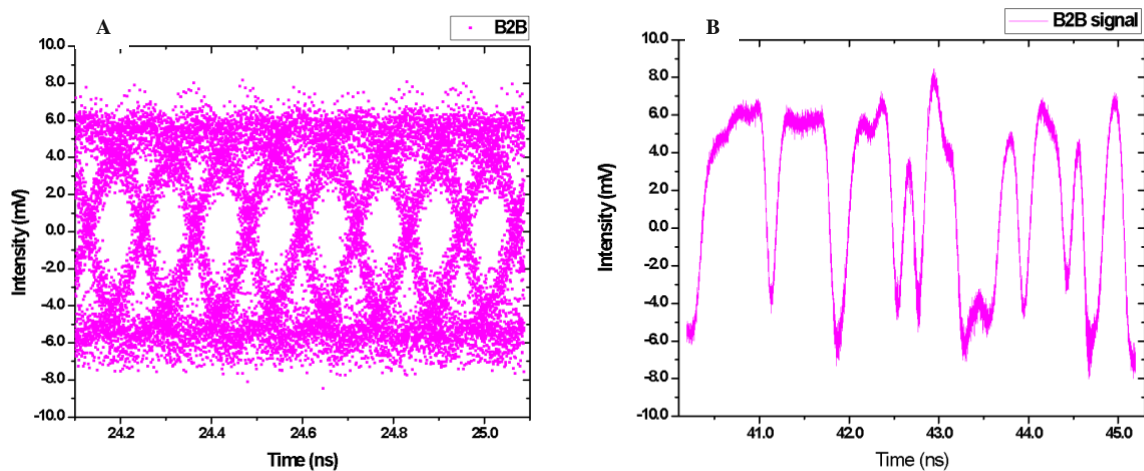
Figure 3A above illustrates the optical spectra of an unmodulated multimode VCSEL as the bias current changed. The full width half maximum (FWHM) for 1 mA, 2 mA, 4 mA, 6.5 mA and 9.8 mA were found to be 0.16 nm, 0.05 nm, 0.04 nm, 0.09 nm and 0.08 nm, respectively. FWHM by definition refers to the width of an optical signal at half of its maximum intensity. This value refers to the bandwidth of the light source operations at 50% capacity. The boarder peaks in the spectrum are an indication that they have more wavelengths as compared to the

thinner peaks. These boarder peaks are potentially problematic as they have susceptibility to distortions, which are due to chromatic dispersions because of the different spectral components of a pulse travel at different velocities. It is therefore advisable to try and bias the VCSEL around an operating region with the thinner peaks for more accurate usage of the VSCEL.

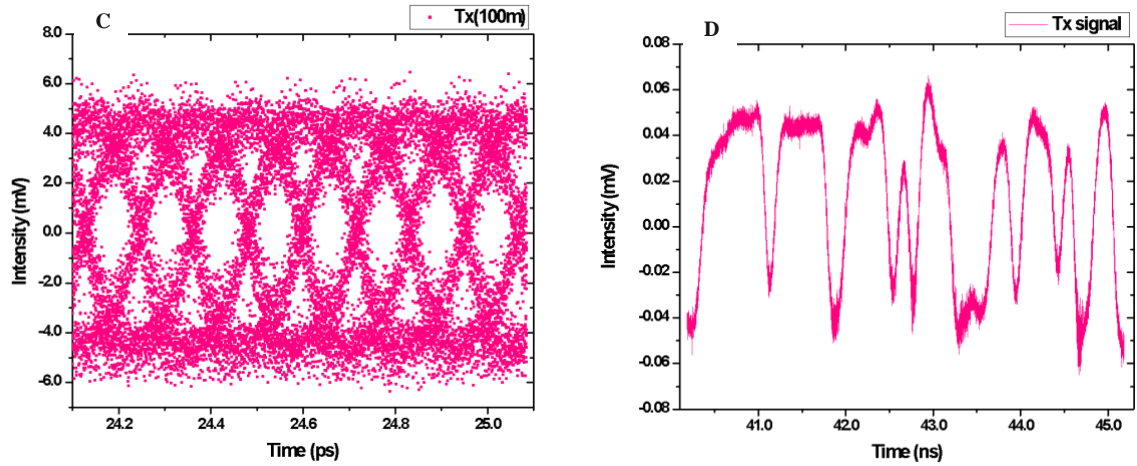
Figure 3B shows a plot of how much the wavelength changes with increasing bias current. The line of best fit shows that the wavelength and the bias current have a generally linear relationship. The gradient of this line was calculated to be 0.175 nm/mA signifying that the relationship between the wavelength and bias. Therefore, for every 1 mA the wavelength changes by 0.175 nm. This plot of wavelength vs bias current and its gradient would be important to know in cases whereby a WDM system was implemented where we would want to tune the bias such that each VSCEL cannel has a different wavelength.

### 6.3.1 Addition of data transmission to the network

The previous section considered static characterization of the unmodulated VCSEL. We now proceed to optimally bias the VCSEL and add modulation. This analysis was acquired upon adding high speed 10Gbps data transmission to the network with the VCSEL and multimode optical fiber present at point E in the experimental set up. The focus for this part of the experiment was to check the electrical signal, add the VCSEL and observe the effects of the multimode optical fiber. BER measurements were also acquired in order to study how the optical fiber affects the data transmission over the 100 m fiber.



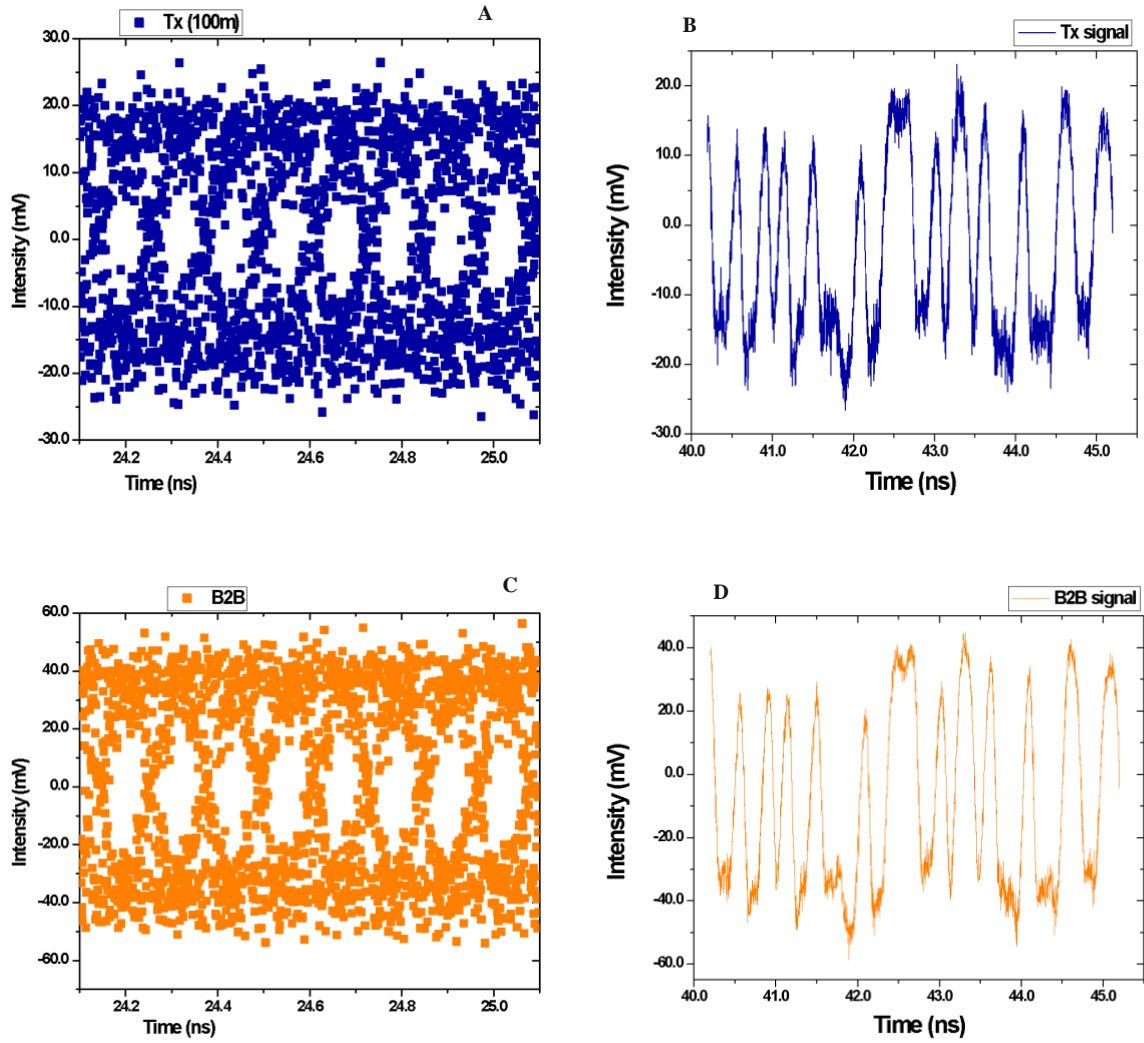




**Figure 4:** A and B are Electrical back to back signals. C and D show the electrical signal in the presence of a 100m optical fibre without the multimode VCSEL.

A digital electrical signal from the signal generator was observed in the X-BERT receiver. This part was for the purpose of knowing how the signal looks like prior modulation so as to have a reference signal. Figure 4B above shows how the signal appears without any transmission and its corresponding eye diagram can be seen next to it in figure 4A. An eye diagram is created on an oscilloscope display by repetitively sampling the digital signal from a receiver and placing it into the vertical input of the scope while the data rate triggers the horizontal sweep. In communication it is used to visually assess the performance of a system in operation [1]. The eye diagrams describe the super positioning of the multiple bits on top of one another. This super positioning gives an overall picture from which we can tell how open the ‘eye’ is, thus helping us distinguish the decision threshold.

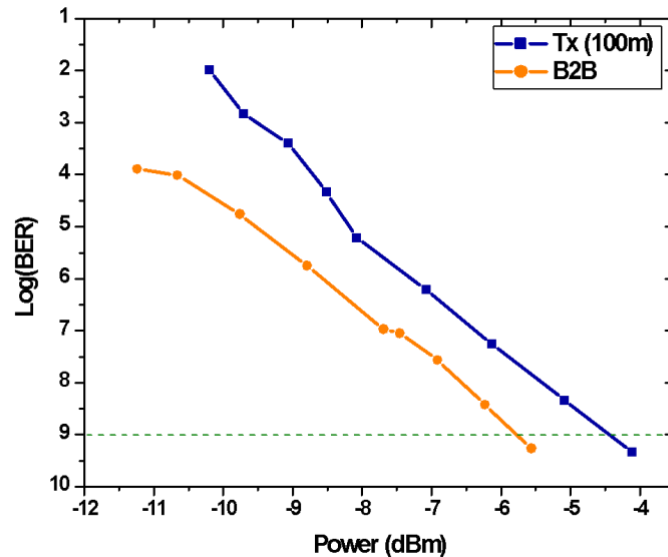
Transmission is then introduced to the network where the signal undergoes an opto-electrical conversion, and this signal transmission is shown in figure 4D with its corresponding eye diagram in figure 4C. These are the observed perfect signal transmission giving an idea of what to expect when a multimode fiber is introduced. The eyes are perfectly open indicating successful data transmissions with minimal signal distortions, as it is easy distinguish between the ones and zeros of the digital signal.



**Figure 6:** The graphs above show the signals in the presence of the optical data.

The pattern that the bits make were observed in the time domain on Figure 6. Eye diagrams for the back to back and the transmission signals are presented in Figure 6. The bit pattern has been wrapped after ever eight bits. The eyes appear in both cases, with an error free decision threshold evident mid-level. The right-hand eye on figure 6 appears only slightly closed in comparison to the back-to-back eye. This corresponds to the small modal dispersion penalty of only 1.6 dB, as seen from figure 7. By definition, the power penalty is defined as the received optical power difference in dB with and without signal impairments at a specified BER (conventionally  $10^{-9}$ ), from measured BER versus optical power curve. Therefore, 1 dB power penalty means that a system with signal impairments requires 1 dB more optical power at the receiver in order to achieve the same BER performance compared to the system without

signal impairments [2]. For the system/network used in this work, the power penalty was in an acceptable range, especially when we consider the fact that this is a system with multimode components.



**Figure 7:** Bit Error Rate (BER) of back-to-back (B2B) and transmitted (Tx) signal over 100m MMF. The BER measurements were attained by variation of power relative to the log bit error rate.

The BER results for experiment were quantitatively measured with PBRs at 10 GB/s are illustrated in Figure 7. The BER is obtained from a bit-for-bit comparison between the transmitted and received signal. BER measurements are quantitative since they count the number of errors in a string. This is done by doing the bit-to-bit comparisons for what was sent and what was received. A VOA was placed between the 100 m fibre and photo diode to study how does the BER differ with respect to the receiver optical power. Figure 7 illustrates a plot for the back to back and transmission signal through the 100 m multimode fibre. The back to back signal is represented above with lower power than the transmission signal represented in blue. The receiver sensitivities for the back to back and transmission signals were found to be -5.9 dBm and -4.3 dBm respectively. The difference between these two values is the power penalty, which is mainly due to the fibre impairments. In this case the power penalty was found to be 1.6 dB, introduced mainly by modal dispersion in the optical fibre. Modal dispersion occurs in multimode fibre since various modes follow unequal paths of propagation through the fibre.

## 6.4 Summary

In this chapter, the multimode VCSEL was successfully characterised to find its optimal bias current. This was done in order to be able to properly use the VCSEL for transmission. The VCSEL optimal operating region at 5.5 mA and the maximum optical power was observed to be 0.8 mW, indicating how far the signal can travel relative to the loss of the optical fiber. From the values of the FWHM it can be observed that the boarder peaks were due to prevalence of multiple wavelengths, while around the operating region the peaks were relatively thinner. The power penalty was found to be 1.6 dB, introduced mainly by modal and chromatic dispersion in the optical fibre.

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- [2] S. Lee, A.E. Willner, in *Encyclopaedia of Modern Optics*, 2005

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# CHAPTER 7

# **Polarization-based vibration sensing over a multimode fibre**

## **7.1 Introduction**

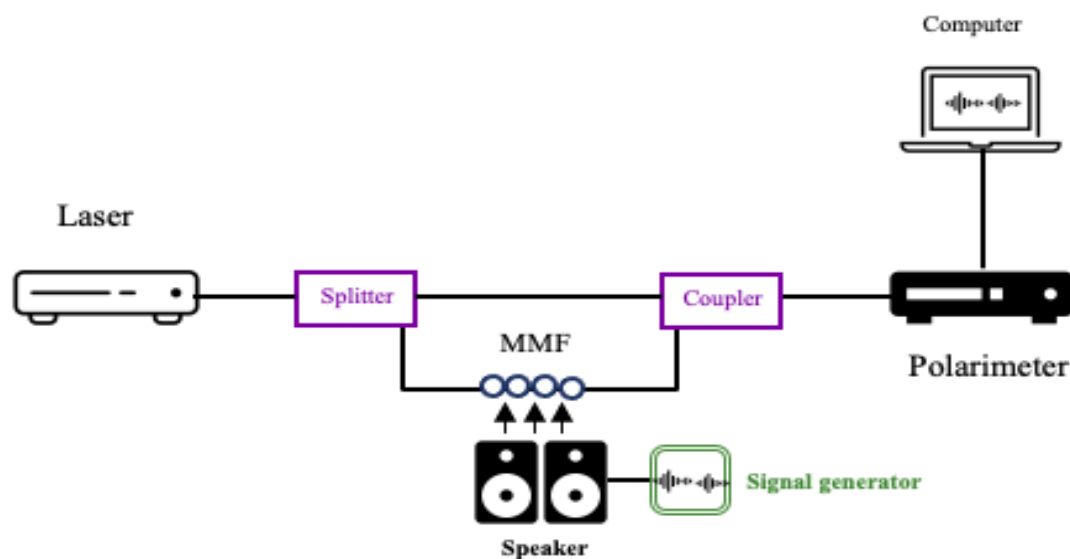
Optical fibres have revolutionized sensor innovation in many industries. This is due to the fact that optical fibres are highly sensitive. Other incredible characteristics of the optical fibre include that they are very light and flexible, they are not affected by electromagnetic interference (EMI) and can be used as distributed sensors, as opposed to point sensors. This makes them reliable because any small change in the fibre leads to a change in its birefringence. The alterations in the birefringence then lead to a change in some properties of the light propagating through the optical fibre.

The monitoring of vibrations using optical fibre sensors relies on techniques such as polarisation and/or phase OTDR. In this work, a multimode optical fibre was used for the monitoring of vibrations from a speaker. A interferometric/ Mach Zehnder experimental set up was built up using multimode fibre. A known frequency reference from the speaker and the polarimeter was used to conduct the experiment. The fibre sensor was characterized and then optimized at different frequencies. For the analysis of the results , a code was then written to perform the DSP. This was done in order to find the frequencies from the sensed data.

The performance of different optical fibres was also compared, for the purpose of studying the sensitivity response of a single mode sensor to that of a multimode sensor. After the characterization and comparison, an application test was then performed on the experimental set up that was built. This was done by using a drill on different material (wood, metal and plastic) to be able to tell what the developed multimode sensor would be able to detect from the material vibrations.

## 7.2 Experimental configuration

In the experiment, an interferometric set up was implemented to help increase the sensitivity of the polarization-based sensor to vibrations. This type of set up include a splitter and coupler that form the interferometer in the set up. The light is split into two paths, one to the MMF and the other to the coupler. As the light recombines in the coupler a high pulse is created due to the overlap in the light waves. This overlap is responsible for the increase in sensitivity of the sensor. This functions on the superposition principle which is implemented on an interferometric set up. Interferometry is a measurement method which uses the phenomenon of the interference of light. It makes use of the principle of superposition for the combination of waves. This happens in such a way that the combining of light waves will cause the results of their combination to have some meaningful property that is diagnostic of the original state of the waves[1]. The tools used are referred to as interferometers due to their functioning. They operate by merging two or more sources of light to create an interference pattern. The interference pattern can be measured and utilized for analysis in relevant fields.



**Figure 1:** Mach Zehnder experimental set up for the vibration sensor with optical fibre sensing the vibration from a speaker at specified frequencies.

A polarization-based sensor experiment was successfully conducted using a speaker as a source of vibration. In figure 1, a laser was used as a laser source, it passed through an optical splitter to help create an interference for the purpose of increasing the sensitivity. This occurs

because the interference causes a change in the birefringence of the fibre. The alteration of the birefringence in turn causes a change in the polarization of the light. Thus leading to an increase in the sensitivity. The other by-product of this set is that the rest of the equipment can be protected from receiving too much power at a go.

A signal generator is tuned with frequencies ranging from 50 Hz to 1 KHz. The generated frequencies produced vibrations on a speaker which was attached to the multimode fibre. The vibrations induced by the speaker change the properties inside optical fibre, specifically the birefringence. The light travelling through the fibre then interacts with the polarization in the fibre and thus changing the polarization states. These changes are then detected by the polarimeter as signals of the vibration sensor.

### 7.3 Analysis of results

The Stokes polarization parameters are represented by the parameters S0, S1, S2 and S3 for a plane wave [1]. These set of parameters are useful in defining the polarization state of an electromagnetic wave. Stokes parameters were first introduced in optics by Sir George Gabriel Stokes in 1852. These parameters are real quantities and are simply the variable observables of the polarization ellipse, and consequently, the optical field [2,3].

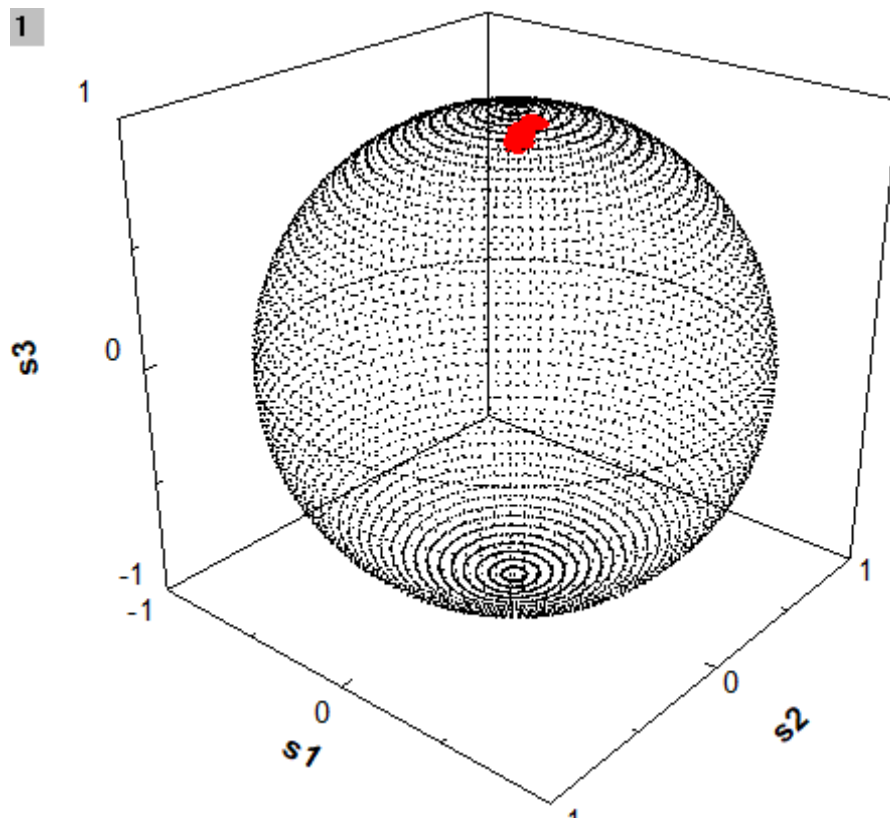
A state of polarization is represented by a point on the Poincare' sphere. The longitude,  $2\psi$ , on the sphere determines the PA of linear polarization,  $PA = \psi$ . Similarly, the latitude,  $2\chi$ , determines the axial ratio of the polarization ellipse,  $T = \tan \chi$ : right-hand circular,  $T = 1$ , corresponds to the north pole,  $2\chi = \pi/2$ , and left-circular,  $T = -1$ , to the south pole,  $2\chi = -\pi/2$ . Points in between the pole and the equator represent elliptical polarizations. In terms of the Stokes parameters, it is convenient to write  $q = Q/I$ ,  $u = U/I$ ,  $v = V/I$ , so that the degree of polarization is  $r = (q^2 + u^2 + v^2)^{1/2}$ . It is only the polarized part that can be represented by a point on the Poincare' sphere,

$$q/r = \cos(2\chi) \cos(2\psi),$$

$$u = \cos(2\chi) \sin(2\psi),$$

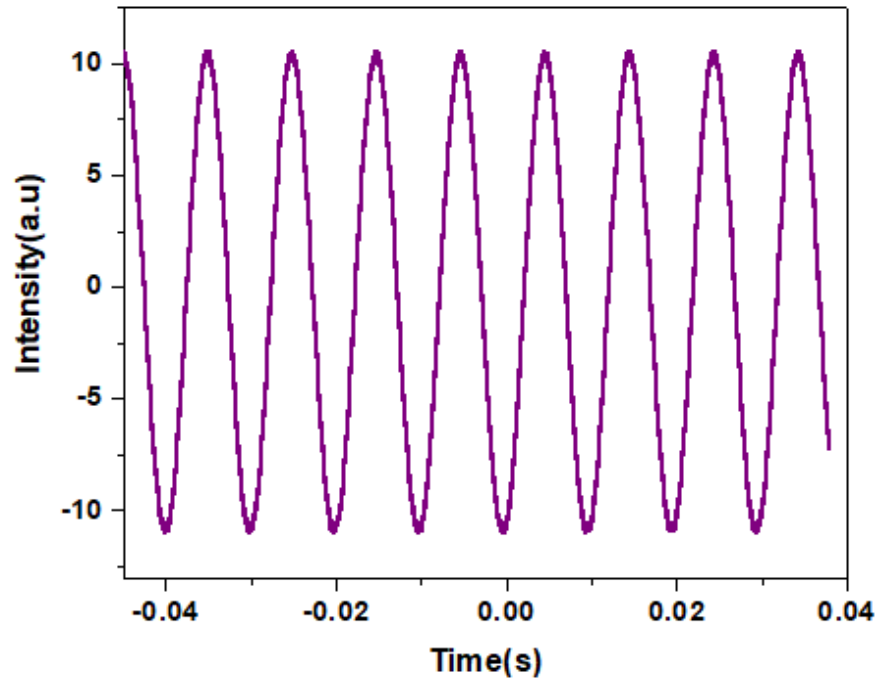
$$v/r = \sin(2\chi) \quad [4]$$





**Figure 2:** Poincare sphere with Stokes parameters. A state of polarization is represented by a point on the Poincare sphere on the diagram.

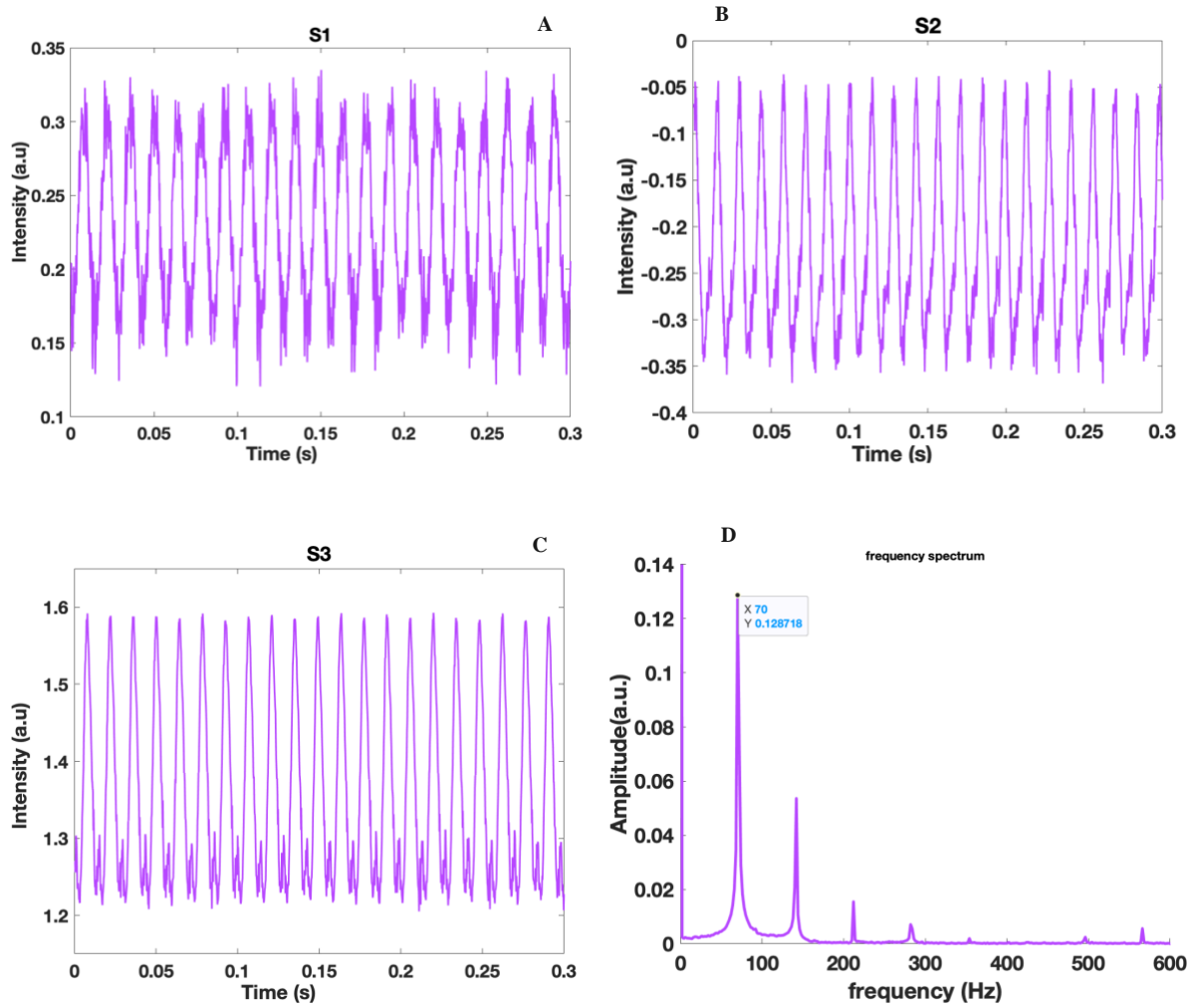
Figure 2 shows a Poincare sphere with its Stokes parameters. The interpretation works in such a way that when there is a perturbation, certain point in the Stokes parameters will move along the axis due to changes in polarization of the light. The states of polarisation are represented by a point while continuous evolution of the state of polarisation is represented by a continuous arc on the sphere as shown in figure 2. In this case the light is orthogonally polarized because it is at 90 degrees and so the state of polarization remains unchanged.



**Figure 3:** The above sine waves represent the intensity of reference signal in the time domain.

The signal in figure 3 was recorded before the sensor was subjected to vibrations. This graph gives us a good notion of what our signal should look like. The introduction of a disturbance is expected to cause variations in the signal.

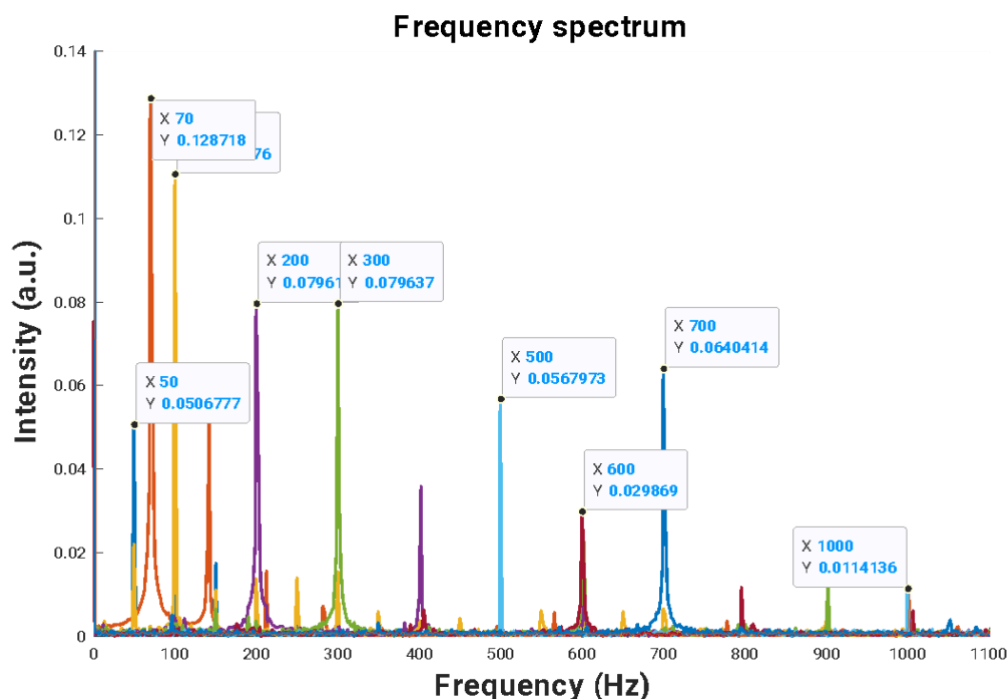
A speaker with an induced frequency of 70Hz was studied in this part of the experiment. A signal generator was connected to the speaker and the time signal was measured. The states of polarization are characterized by means of Stokes parameters namely  $S_0$ ,  $S_1$ ,  $S_2$  and  $S_3$ .  $S_0$  represents total intensity while  $S_1$ ,  $S_2$  and  $S_3$  represent the Cartesian coordinates of a point [5]. Figures 3a,3b and 3c show the acquired sine wave for  $s_1$ ,  $s_2$  and  $s_3$  respectively. A fast Fourier transform (FFT) was then performed on the data to confirm the corresponding frequency that the polarimeter detected from the speaker vibration. Figure 3 also shows the measured frequency spectra detected using the proposed polarization based optical fibre sensor with a single vibration source. The fundamental frequency of the vibration, as well as the higher and lower order harmonics are clearly visible.



**Figure 4:** Sine wave of speaker vibrating at a frequency of 70Hz for S1, S2 and S3 and FFT of S3 showing the detected frequency. Because they are the same/ similar we look in one S3 frequency spectrum.

A speaker with an induced frequency of 70Hz was studied in this part of the experiment. A signal generator was connected to the speaker and the time signal was measured. The states of polarization are characterized by means of Stokes parameters namely S0, S1, S2 and S3. S0 represents total intensity while S1, S2 and S3 represent the Cartesian coordinates of a point [5]. Figures 3A, 3B and 3C show the acquired sine wave for S1, S2 and S3 respectively. A FFT was then performed on the data to confirm the corresponding frequency that the polarimeter detected from the speaker vibration. Figure 3D also shows the measured frequency spectra detected using the proposed polarization based optical fibre sensor with a single vibration source. The fundamental frequency of the vibration, as well as the higher and lower order harmonics are clearly visible.

The experiment was repeated for 50 Hz, 100 Hz, 200 Hz, 300 Hz, 500 Hz and 1000 Hz. In figure 4 below, the frequency spectrum of the different measured frequencies is shown. The multimode optical fibre sensor was able to precisely detect the generated frequency from the speaker. However, the intensity of the peaks were observed to dwindle as higher frequencies were approached. This may be because of the response of the speaker. The speaker could possibly not be optimized for specific frequencies. As a result, when the higher frequencies are sent to the speaker then the speaker makes smaller vibrations. this does not contradict wit this experiment as we were only interested in vibrations at no specific frequency.



**Figure 5:** Above we see the frequency spectrum at the different frequencies measured out during the experiment.

The graphs shows the intensities of the frequencies that were detected by the sensor. The accuracy and precision of the sensor is evident in the precise detection. Multiple frequencies where measured to show the best operating frequency of the sensor to be used.

Table 1. shows what frequency was acquired and the percentage error. The experimental results illustratively shown in table 1 clearly corresponded to the set frequencies assigned on the frequency synthesizer. All vibrational frequencies were experimentally measured to within errors less than 0.02%.

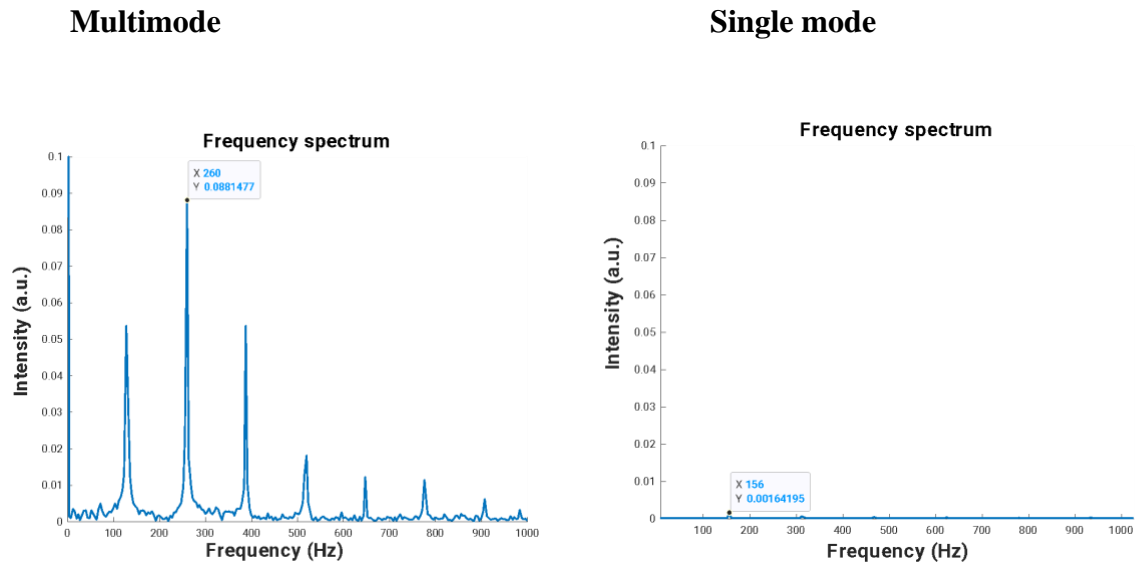
**TABLE 1:** Tabulation of values

<b>Set frequency (Hz)</b>	<b>Acquired frequency (Hz)</b>	<b>Percentage error (%)</b>
50.00	50.01	0.02
70.00	69.99	0.01
100.00	99.98	0.02
200.00	200.00	0.002
300.00	300.01	0.002
500.00	499.99	0.002
1000.00	999.98	0.001

The experimental results of the sensing experiments has shown that the multimode polarization sensor works well for picking up vibration signals. All measured frequencies from the speaker correspond well with the set frequencies. Also in the previous chapter, data transmission was experimentally shown to be operational for this same multimode fiber. Therefore in the following part of this work we will explore and experimentally demonstrate a converged system where the data transmission and vibration sensing will be done at the same time.

### 7.3.1 Comparison between MM with SM turns at 77Hz

A lot of decisions come into play when installing fiber optic cabling. One of the most important questions is whether to install single mode or multimode. This decision has huge implications for the network's distance, bandwidth, and budget. Therefore, it is important to understand the differences between these two types of fiber optic glass. An experiment to observe and highlight the differences between the multimode and single mode fiber was conducted. In particular, the focus was to observe how efficiently each optical fiber performs as a vibration sensor. This is determined by the sensitivity of the different optical fibers.



**Figure 6:** 40 coils of naked multimode and single mode fiber placed on a vibrating speaker

The results attained above show how the vibration sensor was able to successfully detect feasible frequency peaks for the multimode fiber. However, when compared to a single mode fiber of the same length, the peaks did not have the same intensity. The single mode peaks were smaller than the ones observed in the multimode vibration sensor. This may be owed to the fact that a single mode fiber has one path or mode in an optical fiber whereas, the multimode optical fiber has multiple pathways for the light to travel inside of it. For this reason, the light inside a multimode fiber behaves like that of the light inside an interferometer. Meaning for the experimental schematic adopted in this work favours a multimode fiber set-up over the single mode fiber set up.

As previously studies, using an interferometer proved to result in greater sensitivity, where the light is split into two paths that interfere at the receiver. It would thus not be unreasonable to expect that MMF would be a more sensitive sensor. It can be assumed then that an optical fiber sensor based on an interferometer structure is capable of being used for monitoring a vibration reliably.

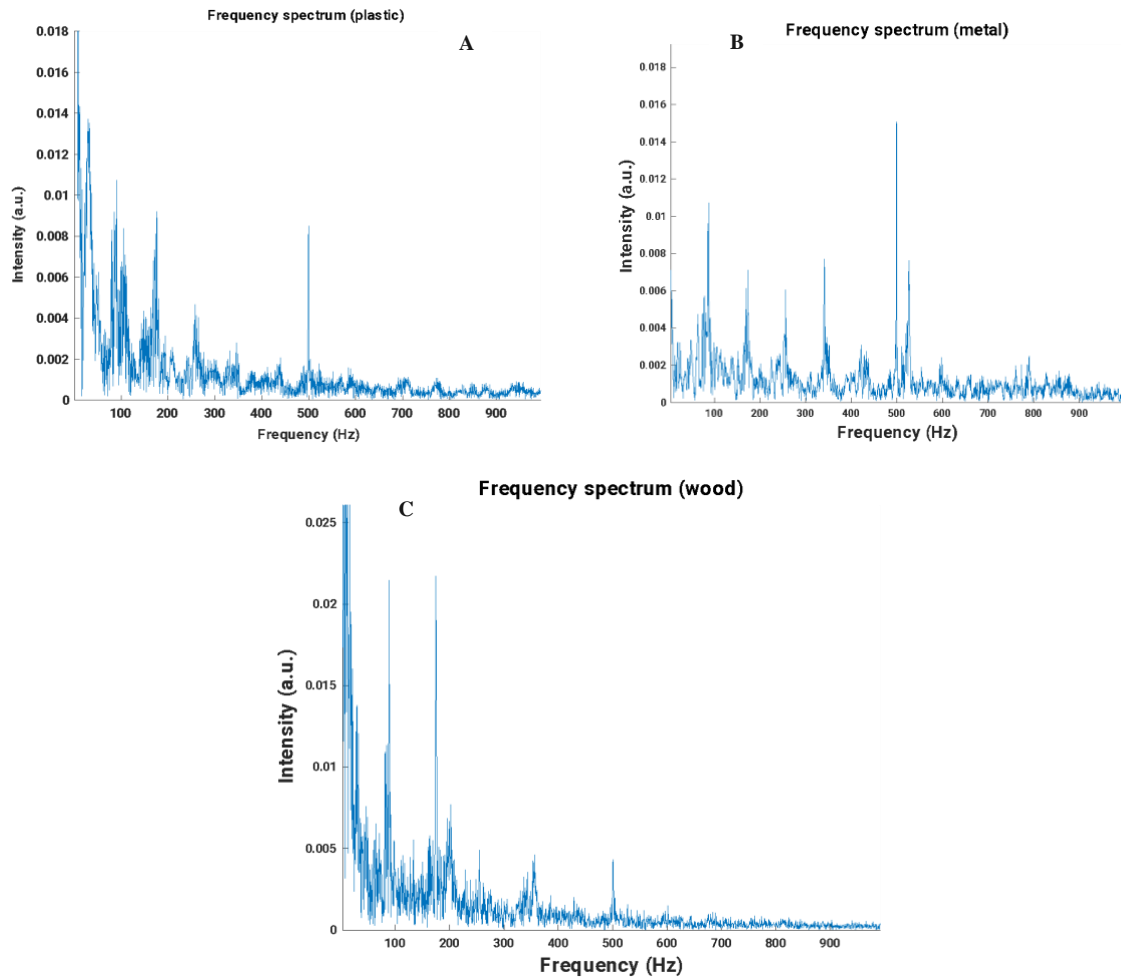
Different sensors will have different sensitivities and this depends on the type of fiber as well as the following features;

- i. The weight/ thickness of the fibre as it bounces on the speaker
- ii. The cabling/packaging of the fibre and sensor
- iii. How long the fibre is (because the longer it is the more chance there is for the changing birefringence to affect the light)
- iv. The number of “light paths” in the fibre and interfering at the receiver

These are all factors that were taken in consideration while proceeding with this experiment. The following results will demonstrate how the single mode behaves as compared to the multimode optical fiber.

### **7.3.2 Drilling experiments**

The following work explores a drilling experiment to find an application for the sensing experiment conducted above. A drill was placed on top of different material, with the intension to observe weather the sensor would be able to tell the difference between the individual material. The optical fibre was placed at different positions in the material to find the optimal position, thus exploring accuracy.



**Figure 7:** Sensing experiment for wood, metal, and plastic

A drill experiment was experimentally demonstrated. The results on figure 7 show the frequency spectrum the different material upon vibration. The frequency distribution ranges from about 40 Hz to 500 Hz for all the material. The drilling results for the wood show a peak distribution with high intensity peaks at 100 Hz and 200 Hz. In the case of metal and plastic, the high intensity peaks were observed to be at 500 Hz with metal having the greater intensity. This observation can be explained by, when drilling into wood the vibration were more stable and relatively slower. However when drilling into plastic and metal the materials were more shaky resulting in having more frequency peaks as compared to wood. The resonant peaks for wood were at 100 Hz and 200 Hz with not distinct peaks after. Plastic had resonant peaks at 500 Hz and metal also has a resonant peak at 500 Hz with a greater intensity.

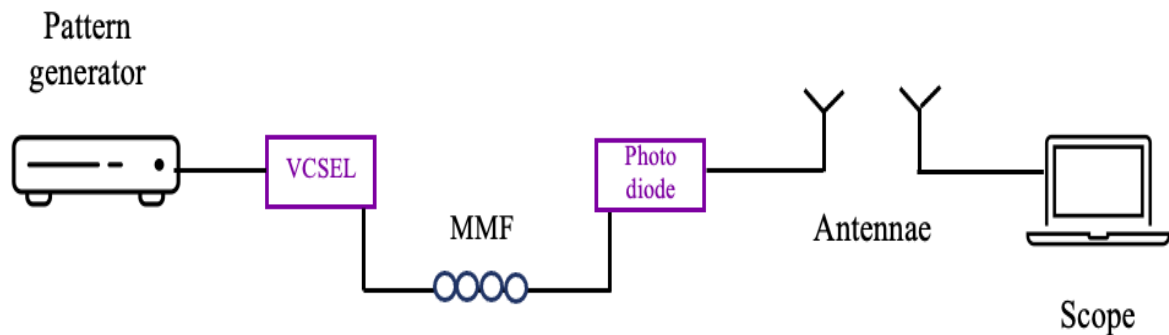
Looking at the area under the curves, the peaks of the lower frequencies for wood and plastic were observed to have more power since they had a large area under the curve. The power



seemed to decrease for wood and plastic as frequencies got higher. The power distribution for metal was more evenly distributed in general. The drill experiment was successful as we were able to observe different frequency behaviour for the different material.

#### 7.4.1 Wireless transmission

This part of the experiment focussed on wireless measurements where it was demonstrates how the wireless signals can be transmitted and/or received at multimode nodes. In the experiment, two Omni directional antennas were used. The antennas were placed 1m apart for the duration of the experiment and high-speed photonic data was thus transmitted. During the experiment the frequency was transmitted starting from 0.5 Ghz to 3 Ghz.



**Figure 8:** Experimental set up for wireless transmission

The results in Table 3 show that wireless transmission was found to be optimal at a frequency of 1.7 GHz. The signal was observed to dwindle, and the SNR decreases as we switched to higher (2 GHz) and lower (1.4 GHz) frequencies. The combined results suggest that a 10 Gbps multimode mode fibre feed could be implemented to drive 10 or more wireless antennae, each transmitting at a bit rate of up to around 1 Gb/s.

**Table 3:** Sinusoidal wave tabulation at 1.4 GHz, 1.7 GHz and 2.0 GHz for wireless transmission with antennas 1m apart.

Frequency (GHz)	Back-to-back	Transmission
1.4		
1.7		
2.0		

The objective for this part of the experiment was to determine whether wireless transmission could provide 5G connectivity for machinery and users within mining cavities. With the above results, this was proven to be possible.

## 7.4 Summary

A polarization based sensor was explored and experimentally demonstrated in this chapter. The work done here shows that the 850 OM4 multimode fibre was successfully able to detect vibrations from the speaker. The comparison between the multimode and single mode fibre shows that a multimode fibre is a more sensitive sensor due to light acting like an interferometer. The drill experiment was successful as we were able to observe different frequency behaviour for the different material.

## 7.5 References

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# CHAPTER 8

## 8.1 Thesis conclusion

In this dissertation, we presented a study for multimode optical fibre for converged vibration sensing and 10 Gbps photonic data with 1.7 GHz wireless transmission for mining applications. The objective for this study was to create a multimode converged system that was able to transmit high speed reliable data. This would occur simultaneously with the fiber being able to act as a vibration sensor for seismic activities in mining cavities. A high speed wireless transmission system was then suggested within the cavities to avoid lost connections.

The introduction of an advanced modulation to boost the transmission rate was proven to be very advantageous for higher bits. To build vibrational and load-stressing optic fiber sensors, a thorough grasp of interferometric sensing technology is required. The developed multimode fiber sensor was then tested for usability in the mining industry using a fully functional experimental setup that validated optical properties of the MMF that can be altered for sensing vibrations and strain.

A system was designed, implemented and experimentally tested for simultaneous data transmission and vibration sensing in the mining environment. It was demonstrated that photonic transmission at 10 Gbps over 100 m of multimode fiber was excellent for establishing connections between underground mine cavities. Using the same multimode fiber, we also built precise vibration sensing in the frequency range of 50 Hz to 1 kHz. The suitability of 1.7 GHz multimode antennas for wireless data communication inside cavities was demonstrated. The suggested technology has the potential to increase productivity, decrease costs, and increase safety in mining applications.

## **8.2 Future work**

The concept of a converged multimode data transmitting and vibration sensing system would be beneficial for many environments. For future work I would suggest testing the system out in the mine cavity in real time and seeing the actual response. Also, it would also be interesting to observe whether this multimode system would function properly for set-ups where a data transmitting fiber can be a pressure, temperature or motion sensor.

## **9. Research paper output**

For this work, a SATNAC conference paper was the peer reviewed output.

Reference:

V. Shumane, J. Jena, R. Karambera, S Wassin, A. Leitch, T. Gibbon, Multimode Optical Fibre for Converged Vibration Sensing and 10 Gbps Photonic Data with 1.7 GHz Wireless Transmission for Mining Applications, 2021

## 10. Appendix 1



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