University of Southern Queensland
School of Mechanical and Electrical Engineering

Design and Development of a Fibre Optic Microphone

A dissertation submitted by

James Ikin

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Abstract

Research into using optical fibres as the key components in a sensor has been of great interest to many over the past 50 years(Culshaw & Kersey 2008). Optical fibre sensors prove to have many advantages over conventional electronic sensors. Infact there are many enviroments where using an electronic sensor may prove to be to be ineffective or outright unuseable (Lee, Kim, Park, Eom, Myoung, Kim, Rho & Choi 2012). Unfortunately optical fibres encounter many other different disadvantages that electronic microphones do not. Therefore optical fibre sensors are still generally only designed and built for specific applications.

One of the optical fibre sensors that has had a great deal of research is the Fibre Optic Microphone (FOM), this particular area of optical fibre sensors is the focus of this dissertation. During the completion of this dissertation many different types of FOMs were investigated, however it soon proved to be too much effort to attempt to learn and categorize each different type. The shear amount of configurations, components and forms of modulating light was staggering.

Different physical effects were investagated during the projectwork, some examples of what was investagated included Fresnel Reflections, Acousto-Optic Effect and Interferometry. After the different types of FOMs were investigated and reviewed, several promising types of FOMs were chosen to be investaged further and constructed in order to evaluate their performance characteristics.

However due to time and equipment constraints it was not possible to get all of the different types of FOMs to work properly, in the end only one type of FOM was completed. This was the Helix Acousto-Optic Microphone.

The Helix Acousto-Optic sensor was then run through a series of tests in order to examine the performance characteristics. The sensor was placed into two different types of configurations, the first was just a basic sensor configuration and the second was a Mach-Zehnder interferometer configuration.

After the performance characteristics were examined it was evident that the Mach-Zehnder interferometer configuration proved to be the better of the two by a great margin.

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ENG4111/2 *Research Project*

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I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.
I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

James Ikin

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Signature

Date

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Chapter 1

Introduction

1.1 Brief History of Optical Fibre Sensing

Initial research into using optical fibres as a sensor started in the mid 1960s and led to the development to one of the first sensor designs using optical fibres known as the "Fotonic sensor" (Culshaw & Kersey 2008).

This "Fotonic sensor" operated by using half of the bundle of fibres to illuminate a vibrating surface and the other half of the fibres was used to recieve any reflected light.

The reflected light now held key information on how the surface was vibrating which could then be analysed at anytime to retrieve this key information. In other words, the light was modulated according to how the surface was vibrating. Later on in this text this concept will be reintroduced as a type of acoustic transduction and will be known as a lever type sensor.

Earlier on in that decade a man by the name of Elias Snitzer published a paper which had a theoretical description of an important type of optical fibre which had the special property of carrying light in only one waveguide mode.

This property required the use of an extremely small glass fibre core but at the same time greatly simplified the physical processes occuring inside the core, however this optical fibre also featured a high loss of light per meter limiting its usefulness.

The described fibre is now known as a single mode fibre (SMF) but it wasnt until a decade later when manufacturing processes greatly improved the quality of optical fibres for communication purposes. These improvements allowed the possibile applications of the SMF to open up greatly, one of which was the newfound application of building an interferometer with SMFs. This application is analysed in depth as one of the key types of optical fibre sensors later on.

Ever since these key events in material and optical science, the possible applications of optical fibres has opened up a very wide fields of research particuarly in using them as sensors and more possiblilities open up every day.

1.2 Advantages of Optical Fibre Sensing

Optical fibre sensors have been of great interest in many different fields and industries. This is due to the advantages that optical fibres provide in sensor design, some of the advantages include:

1. Immunity to Electro-Magnetic Interference .
2. High Accuracy in measurements.
3. Long distance operation is easily implemented due to low attenuation.
4. Resistant to chemical corrosion.
5. Ability to operate in harsh enviroments and high temperatures.
6. Sensors can be designed to be small in size and light in weight.

1.3 Objectives of this Project

This dissertation examines the use of optical fibre technology for the purpose of acoustic transduction. The key outcome of this project work is design, build and make recommendations as to how to make a simple inexpensive microphone from optical components. To achieve the key outcome of this project the following objectives had to be established.

The objectives of this project are:

1. Conceptually investigate different methods of sensing acoustic (sound) waves with optical fibres.
2. Analyse the physical effects that dictate how the acoustic waves are translated into light modulation.
3. Investigate the results of past research in optical fibre sensing to help evaluate the advantages and disadvantages of each method.
4. Evaluate each method of optical fibre sensing with a set of criteria, relating to the key outcome of this project.
5. Choose a select few methods of optical sensing.
6. Design, build and test each of the selected optical fibre sensors.
7. Assess and compare the performance characteristics of each FOM.
8. Make recommendations on improving each of the FOM sensor performances.

Additional objectives:

1. Investigate signal processing techniques to digitally improve the performance charateristics of each FOM
2. Investigate into multiplexing of the sensors.

Chapter 2

Introduction of Optical Fibres

This chapter will introduce a few key concepts about optical fibres, the first few are some of the physical phenonemon related to optical fibres and the final section will introduce the basic structures of two popular types of optical fibres.

2.1 Physical Phenonemon and Properties of Optical Fibres

The following sections will introduce the physical phenonemon that govern how optical fibres operate and other phenonemon that affect the optical fibres in different ways.

2.1.1 Refraction

When light encounters another medium that has a different refractive index at an angle, it undergoes the refraction inside the new medium. This effect of this is that the light that was transmitted into the new medium alters the direction that it is propagating in.

When the light transmits into the new medium the velocity that it travels at changes accordingly to refractive index of the new medium but the velocity of the light isn't the only part that changes. Since light is simplified to be a wave when the velocity changes, so does the wavelength of the light.

2.1.2 Refractive Index

The Refractive Index is a characteristic of transparent mediums and is related to the speed of light. When light is travelling through a transparent medium, its velocity is less than what it would be if it was travelling through a vacuum. The refractive index is simply just a ratio of the speed of light in a vacuum and the speed of light in that particular medium. (Wolfson 2012)

2.1.3 Optical Path Length

Optical path length is not the physical distance between two objects; it is instead the perceived length of the path from the point of view of the beam of light. The optical path length is simply the product of the actual path length and the refractive index of the medium the light is propagating through.

2.1.4 Total Internal Reflection

This phenonenom is similar to refraction but is related to reflection of the light. When the light propagating through the core of an optical fibre encounters the cladding of the fibre, the light will be reflected back into the core of the fibre instead of transmitting into the cladding. An example of total internal reflection is shown in Figure 2.1.

Total internal reflection only occurs when two criteria have been met, the first is that the cladding layer of the optical fibre must have a lower refractive index that the core and that the light hits the cladding layer at or lower than a special angle known as the critical angle. (Wolfson 2012)

The light will keep being reflected along the length of the fibre until it reaches the end face of the fibre, this phenonenom allows the light to travel from one location to another through the optical fibre with little attenuation.

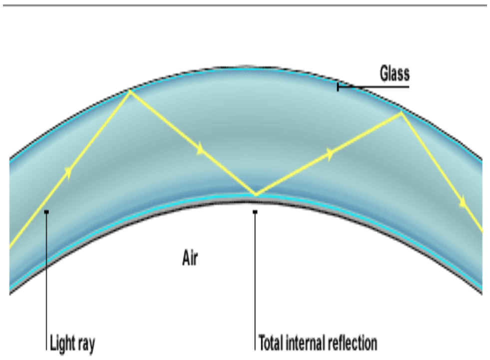

Figure 2.1: Light undergoing total internal reflection inside of an optical fibre (Sourced from http://www.bbc.co.uk/bitesize/standard/physics/)

2.1.5 Fresnel Reflections

The final phenonenom related to optical fibres is known as Fresnel reflections, this phenonenom occurs when light encounters medium with a different refractive index. It commonly happens when light at the air-glass interface enters or exits the fibre. (*Fresnel Reflection* n.d.)

The result of this phenonenom is that not all light is transmitted into or out of the fibre. Instead a small amount is reflected back, this is fresnel reflection. For an air-glass interface the amount of light that is reflected back is approximately 4

This phenonenom is useful when designing some of the fibre optic sensors as the air-glass interface of the optical fibre can then be considered a partial mirror. A diagram of a Fresnel reflection at the air-glass interface of an optical fibre is shown in Figure 2.2.

2.1.6 Birefringent Properties of Fibre Optic

When a materials refractive index depends on the direction of progagation of the light and its polarization. When light enters a material that exhibits birefringence, the resulting interaction results in the ray of light splitting into two different beams traveling different paths in the material. This is also known as double refraction.

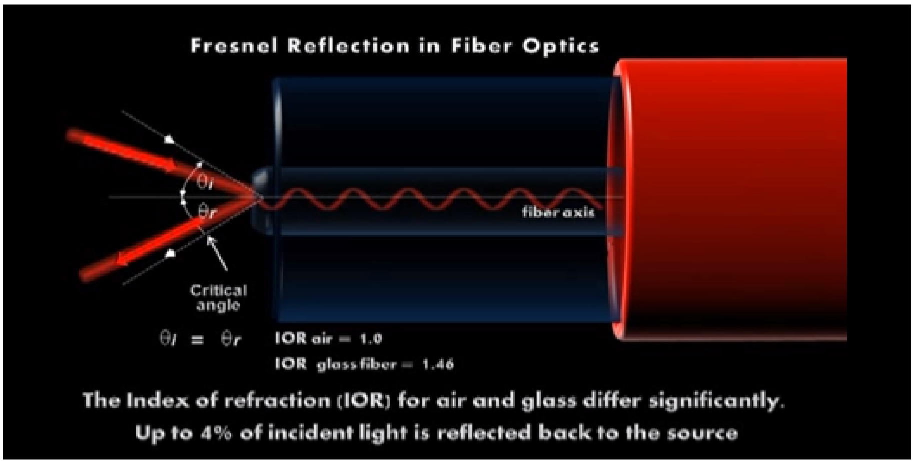

Figure 2.2: Represenation of a Fresnel reflection at the entrance of an optical fibre. (Sourced from exfo.com)

2.2 Structure of an Optical Fibre

This section will introduce the core component of this project which is the optical fibres themselves. There are two main types that can define optical fibre cabes, the first type is known as Single-Mode (SM) and the second is Multi-Mode (MM). Both types of optical fibres have been implemented in optical fibre sensors in many different ways.

The key difference between the two types of optical fibre is that the single-mode optical fibres generally have a core diameter of approximately 9 μm whereas multi-mode optical fibres have a core diameter in the range of approximately 50 μm (Miskovic 2008). The resulting differences in the core diameters directly correlates to the number of propagation modes that exist within the fibre. An diagram demonstrating the difference in the number of propagation modes is shown in Figure 2.3.

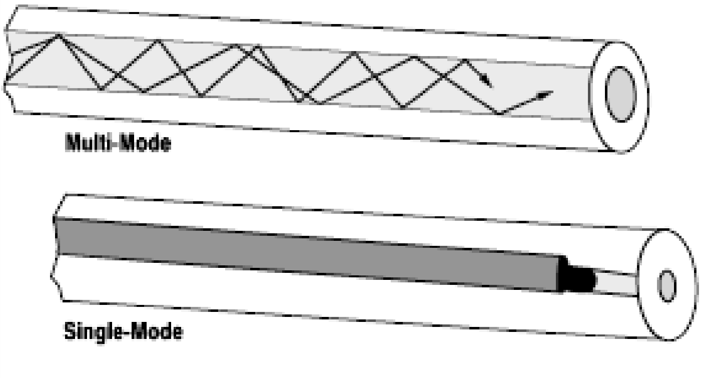

Figure 2.3: Difference in number of Propagation Modes. (ddp13fiberoptics.wordpress.com)

However due to the fact that MM optical fibres can have many different propagation modes, it is subjected to a physical phenonemon known as Modal Dispersion. Modal Dispersion affects the group velocity of the light travelling along the MM fibre, it is dependant on two characteristics of the propagating light. The first characteristic is the optical frequency of the light and the second is the propagation mode of the light. Therefore each ray of light travelling along different propagation modes will travel different distances, this means that at the end of the MM fibre each ray of light will arrive at different times.

This phenonemon becomes increasingly evident the greater the length of the optical fibre, this then restricts long distance operation of the MM optical fibre aswell as causing the recieved signal to become unnecessarily more complex.

Fortunately SM optical fibres are not subjected to modal dispersion, due to only having one mode. This results in the MM fibre to be considered to have an inferior performance to the SM fibre.

A general cross-section of a single-mode fibre is shown in Figure 2.4.

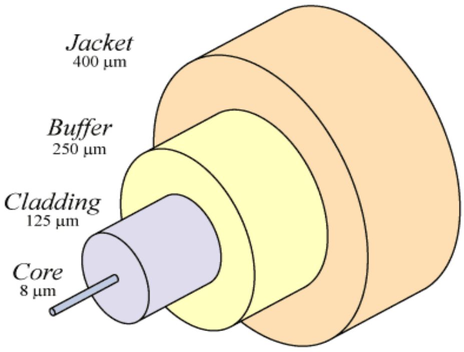

Figure 2.4: Cross-Section of a Single Mode Optical Fibre (Sourced from actewagl.com.au)

Chapter 3

Fundamentals of Acoustic Waves

In order to fully understand how any microphone works, several key concepts of what is being measured must be introduced. Therefore the first question that must be answered when learning about microphones is ”What is sound?”.

3.1 Fundamentals of Acoustic Waves

In order to fully understand how any microphone works, several key concepts of what is being measured must be introduced. Therefore the first question that must be answered when learning about microphones is ”What is sound?”.

3.2 The Mechanics of Sound

Sound can be visualised as a mechanical wave that travels through a medium (such as gases or liquids). Mechanical waves can be generated by any vibrating surface, these vibrations cause the surrounding propagation medium to temporarily compress or expand and this change in the medium is launched outward generating a longitudinal wave of pressure fluctuations.

Figure 3.1 is a visual representation of longitudinal acoustic wave travelling through a medium. Interestingly enough this was achieved by using a neon lamp that traced out the acoustic wave that was generated by the horn (Seen on the far left).

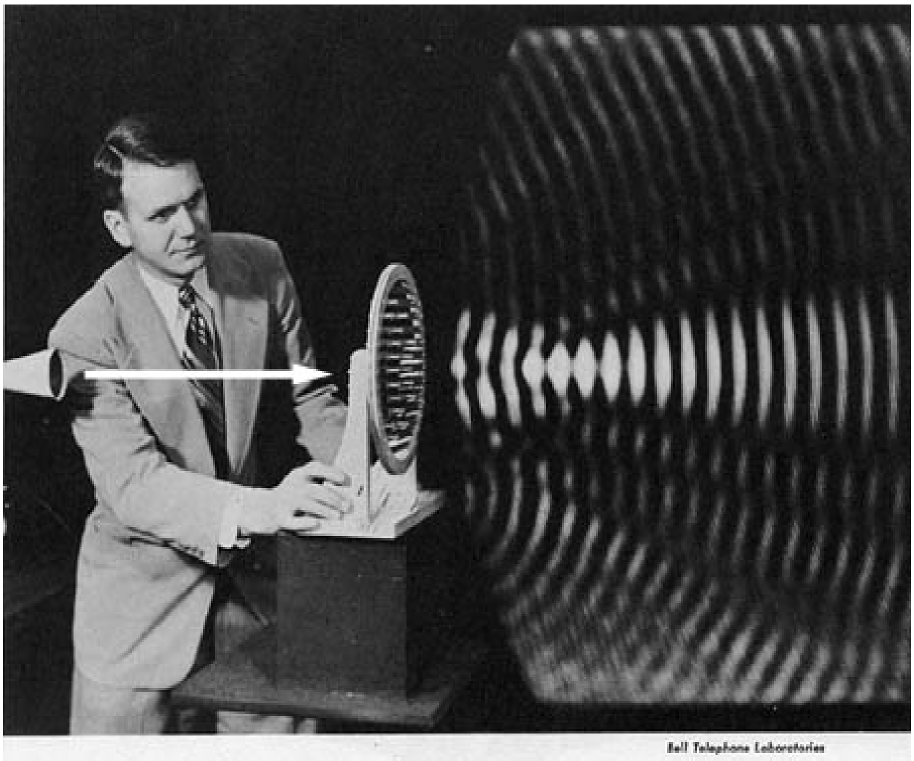

Figure 3.1: Visual representation of a longitudinal sound wave propagating. (irishacoustics.com)

3.2.1 Characteristics of Sound

Acoustic waves can also be visualized as a simple sine wave propagating through space, the terminology that describes a sine waves behaviour will also describe the properties of an acoustic wave. The properties of acoustic waves are:

Amplitude The amplitude of the acoustic wave can be described by either the maximum pressure change, relative to the mean pressure of the enviroment, or by the root mean square (RMS) of the maximum pressure change. Both descriptions of the amplitude are measured in Pascals (Pa).

Wavelength The wavelength is the distance that the wave travels in one cycle, it is generally measured in metres (m).

Frequency The frequency of an acoustic wave is the number of cycles of pressure fluctuations that occur in one second, measured in Hertz (Hz).

Velocity The velocity is the speed at which the sound is propagating through the medium, it is measured in metres per second (m/s). The velocity of the acoustic wave is also known as the speed of sound which is approximately 340 m/s at sea level.

contine to explain the following james!

Sound Power

Sound power is the total sound energy emitted by a source per unit time The total sound energy produced by a source over time is known as sound power, measured in Watts.

Sound Power is defined as the total sound energy radiated by the source in the specified frequency band over a certain time interval divided by the interval. In other words the total sound energy produced by a sound source over time is known as sound power, which is measured in Watts.

Sound Intensity

Sound intensity is a measurement of the sound power at a distance from the sound source, it is measured in Watts per metre squared.

A sound source produces the acoustic wave, which then propagates outwards. If the sound source is assumed to propagate in all directions equally, then the sound front is considered to be spherical. This results in the sound intensity to decrease correspondingly to the (1 on distance squared).

Sound Pressure Level

The human ear is capable of hearing an extremely wide range of sound pressure levels, the lower audible threshold of the human ear is approximately 20 μPa. This is why when your surroundings are quiet you are capable of hearing the faintest of noises The sound pressure level is related to the minimum audible level of a sound pressure that can be heard from the human ear. The minimum audible level of sound pressure is then taken to be a reference. When the sound is propagating outwards, the sound causes pressure variations accordingly to its characteristics. The pressure changes caused by the acoustic wave is then equivalent to the amplitude.

However in reality the sound encountered in our surroundings will not be of a single frequency, it will be a combination of lots of different frequencies with varying amplitudes

Chapter 4

The Acousto-Optic Effect

4.1 Acousto-Optic Effect

In the early 20th century a French physicist, by the name of Leon Brillouin, used light to analyse the refractive index of a medium (Solid, Liquid and Gases) while the medium is interacting with acoustic waves. When the acoustic wave interacts with the medium, the refractive index of the medium would undergo a small change and would cause light to scatter. The acoustic wave causes the medium to periodically compress, increasing the density of the medium and induces a mechanical strain, at that point of space, which then inturn causes a change in refractive index. Since the refractive index changes periodically, according to the acoustic wave, the medium that the light is travelling through behaves similar to a diffraction grating.

The original paper that was authored by Brillouin in 1922, was the first to give a theoretical explanation of the phenomenon known as Brillouin Scattering and gave birth to the field of Acousto-Optics.

The theory as derived by Brillouin is used in calculations regarding to the light deflection and the shift in frequency of the deflected light when the medium that the light is traveling through is being affected by acoustic pressure changes. These calculations primarily govern how todays acousto-optic equipment function.

An introduction to the acousto-optic effect is done by (Pollack 2002) where the author presents the physical interpretation of different types of acousto-optic effects and derives the mathematical equations that express the interaction of sound and light, from Maxwells equations and acoustic wave theory. The physical interpretation of the acousto-optic effect as communicated by (Pollack 2002) shows that when an acoustic wave is launched it causes a mechanical strain on the active medium. From the lights point of view on the affected medium, the acoustic wave can be represented by a wave of refractive index changes traveling at the speed of sound. Any incident light on the refractive index of the medium, as it changes, will scatter in a pattern that corresponds to the acoustic waves presence on the medium.

Two special cases of optical diffraction when the incident light is traveling through an acoustically modulated medium have also been theoretically examined. These special cases are known as Bragg scattering and Raman-Nath scattering. These cases are only met within certain conditions and occur simultaneously, which means there is no defined boundary between the two and should be seen as a sliding scale to identify which type of scattering is dominant.

Each case occurs within its own specified frequency range and the length of acousto-optic interaction. The special case of Raman-Nath scattering dominates at a relatively low acoustic frequency range, a short interaction length and the angle of incidence of the light does not matter. Typically the interaction length is less than 1cm and the frequency range is from DC (0 Hz) up to 10MHz. Bragg scattering occurs at much high acoustic frequencies (over 100MHz is typical) and the interaction length is larger (¿1cm). (n.d.)

Since Bragg scattering is used in conjunction very high frequency acoustic waves it is generally ignored for most micro-phonic applications but is instead used in other acousto-optic devices due to lower loss in light intensity. However it is essential to identify which type of diffraction is dominant so that qualitative calculations can be done accurately.

The Klein-Cook parameter equation is used for this identification. Each case is met under certain conditions when using the Klein-Cook equation. If Q¿¿1 then Bragg scattering is dominant and conversely if Q¡¡1 then Raman-Nath is the dominant type of diffraction. (n.d.)

Chapter 5

Introduction to Interferometry

5.1 Introduction to Interferometry

Interferometry is a family of techniques that analyse the interference patterns produced when two waves are superimposed onto each other. These waves can be optical, acoustic or even radio frequency; this allows measurement devices called interferometers to have a very high sensitivity. Interferometers are able to measure many different types of quantities such as small movements, time intervals, material surface structures and many more. (Wolfson 2012) This chapter introduces the basic concepts of interferometry needed to fully understand the interferometer configurations used later when testing FOM sensors and the expected received signal for them. Several interferometric configurations are introduced; the key interferometers examined are the Michelson, Mach-Zehnder and the Fabry Perot setups.

5.2 Basic Principles of Interferometry

Devices that use interferometry, as its operating principles, are known as interferometers. These devices can use almost any type of wave that can produce interference. Since interferometers can be used with light (Optical) waves, it is possible to have displacement measurements that are in the range of a fraction of a wavelength which is ideal when the expected changes in the fibre optic microphone setup are expected to be extremely small!

Interferometry uses the principle of superposition, when light waves are combined and the interference pattern of the combined waves will and the quantity of the measurement will show itself as a property of the interference pattern.

The core principle that interferometers are based on is superposition. Superposition is when two or more waves are superimposed onto each other, this superposition generates what is known as an interference pattern or an interferogram. The interference pattern then contains the properties of all of the original waves.

Most interferometers make use of only two different waves. One wave is used as a reference while the other wave has been slightly changed accordingly to what is being measured, when these two waves are combined they interfere with each other which creates the corresponding interference pattern. If the properties of the reference wave is known then with the proper analysis of the interference pattern the properties of the second wave can be determined and the quantity that altered the second wave can be calculated.

For example if the two light waves are of the same frequency, then when they combine the interference pattern will be dependant on the phase difference of the two waves and depending on the phase difference the superposition of the two waves will undergo constructive or destructive interference.

However this assumes that the intensity of the light of both the waves have been attenuated equally, which is often never the case.

5.3 The Michelson Interferometer

One of the most well known interferometer configurations is the Michelson Interferometer, as shown in Figure 5.1, the Michelson Interferometer is conceptually one of the most simple types of interferometers and is one of two configurations that use a dual path for sensing. (Michelson 1995)

Conceptual Explanation of how the Michelson Interferometer works:

The light originates at the source and propagates to the beam splitter, usually only a half silvered mirror, at which point the original light will be split into two

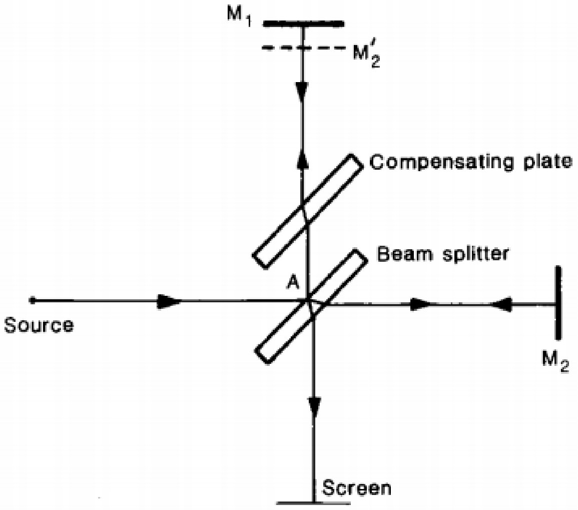

Figure 5.1: Diagram of a Michelson Interferometer, (P. Hariharan, page 21.3)

separate beams.

The two beams now travel their own separate paths and at the end of each of the paths is a highly reflective mirror. However each path may have two different lengths, the first path is the reference path so the mirror at the end of it is fixed in place and the length of this path is known. This makes the second path the measurement path, usually this path has a moveable mirror which defines the change in the path length.

However it should be noted that this may not always be the case, sometimes the lengths of the two paths may be equal but the medium which the light travels through may differ. In this case it is the measurement optical path length is different due to the differing medium.

The two beams are then reflected from their respective mirrors and recombined at the beam splitter where the combination of the two is then directed along another path to a screen. The interference pattern produced by the two beams will be completely dependant to the optical path length difference the two beams took and is viewed on the screen. An example of what can be seen on the screen is shown in Figure 5.2, this is the interference pattern from the two beams.

However one key limitation of using interferometry is that the optical path lengths of the two light paths most be very similar, this is because the light wave repeats itself similar to a sine wave and the consequence of this is that the difference in the optical path length must of the order of the wavelength of the light used. But this is also one

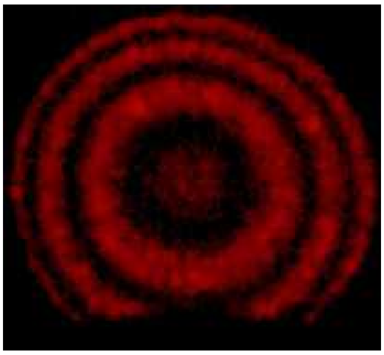

Figure 5.2: Interference fringes from a Michelson Interferometer using a He-Ne Laser, (phy.davidson.edu/interferometer)

of its key advantages since the wavelength of light can be extremely small allowing for the measurement of extremely small changes in the optical path length.

This limitation will impact on the Michelson Interferometer in Figure 5.1 since one path is only reflected of the beam splitter and the other must propagate through it. Which means the latter path will have a longer optical path, but this difference has already been considered and a compensation plate has been placed in the shorter reflected path to compensate for the difference between the two optical paths.

Therefore compensation plate in Figure 5.1 is there to compensate for the small difference in the optical path length caused when the original light splits into two. One beam of light is transmitted through the beam splitter and the other is reflected from it, the beam splitter usually has a different refractive index then the medium that the light traverses so the compensation plate compensates for this difference in the two paths.

The advantages of the Michelson Interferometer:

1. Simplest interferometer configuration
2. Easier to balance than other configurations
3. Low Temperature sensitivity
4. More reliable than other configurations

The disadvantages of the Michelson Interferometer:

1. Can only be operated in the reflection mode.
2. Is more vulnerable to random reflection interference phenomena in the optical path.
3. Requires a seperate path that is not must be isolated from the quantity being measured, this path is used as a reference.
4. The dual paths, reference and measurement, must be highly balanced to accurately understand and measure the received interference pattern.
5. Since the Michelson interferometer can only operate in the reflection mode, some issues may arise when the light is reflected back into the light source. If this issue is not properly addressed then it may cause instabilities in the optical cavity of the light source, which then causes the incident light from the laser to vary.

5.4 The Mach-Zehnder Interferometer

The Mach-Zehnder Interferometer is one of the more commonly used and researched configurations used when designing optical fibre sensors, this configuration is the second of the two that utilises a dual path for sensing. But the key difference between the Mach-Zehnder and the Michelson Interferometers is that the light in the Mach-Zehnder interferometer does not traverse the same path twice. Figure 9.3 shows a diagram of an optical fibre Mach-Zehnder Interferometer.

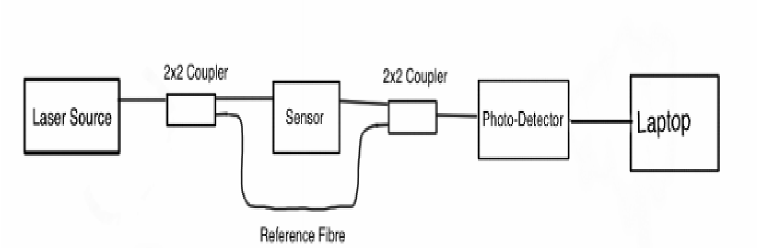

Figure 5.3: Mach-Zehnder Interferometric Configuration

Advantages of the Mach-Zehnder Interferometer:

1. The Mach-Zehnder configuration inherently does not allow any light to reflect back at any point. This then circumvents any feedback of light into the light

source.

Disadvantages of the Michelson Interferometer:

1. Can only be operated in the transmission mode.
2. Requires a seperate path that is not must be isolated from the quantity being measured, this path is used as a reference.
3. The dual paths, reference and measurement, must be highly balanced to accurately understand and measure the received interference pattern.

5.5 The Fabry-Perot Interferometer

The Fabry-Perot interferometer (FPI) was first described by Charles Fabry and Alfred Perot in 1897, in their paper. The paper introduced the relevant theory of the FPI when it used for precision measurement of small displacements. It also introduced the variables of the FPI and the effect they have on the recieved signal, some of the variables include the reflectivity and spacing of the mirrors as well as the wavelength of the light used.

Advantages of the Fabry-Perot Interferometer include:

1. Unlike the Michelson and Mach-Zehnder Configurations the Fabry-Perot Interferometer does not require a seperate reference path. This minimises any the effect that enviromental changes may have on the optical fibres since the light travels along only a single path.
2. The Fabry-Perot interferometer can be configured to act in either the transmission or reflection modes aswell as constructed as either an extrinsic or intrinsic sensor.
3. Relatively simple and inexpensive construction process. (Bremer, Lewis, Leen, Moss, Lochmann & Mueller 2012)
4. Can yield high mechanical strength and can operate in high temperature enviroments.

Due to the advantages of the Fabry-perot interferometer, it is widely used Disadvantages fo the Fabry-Perot Interferometer include

1. Similar to the michelson interferometer, if the fabry-perot interferometer is configured to operate as a reflection type sensor then issues may arise if any light is reflected back into the optical cavity.

Key Operating Principles of the Fabry-Perot Interferometer:

A diagram of a Fabry-Perot interferometer constructed with optical fibres can be seen in Figure 5.4. This particular FPI is designed to use extrinsic type sensing and is configured to operate in the reflection mode.

The light from the laser diode (1) is coupled into the optical fibre (2), when the light reaches the 2x1 Fibre Optic coupler (3) is coupled into the optical fibre (4) connected to the coupler. At this point the light from optical fibre (4) then propagates to the end of the fibre.

When the light from reaches the end of the fibre, the majority of the light is transmitted out of the fibre but a small fraction of the light will be reflected at the end of the fibre. The light that was reflected is now considered to be the reference wave. The transmitted light optical fibre then propagates to the mirror (5).

The mirror is moving back and forth, the movements of the mirror is determined by the measurand. The mirrors movement is on the same axis as the exiting light from the fibre and the mirror is parallel to the fibre. The mirror is parallel to the fibre so that the exiting light can be reflected back from the mirror and recoupled back into the fibre.

When the light reaches the mirror it is then reflected back into the optical fibre and partially transmitted through the mirror. The amount of light that is reflected or transmitted depends on the properties of the mirror.

Since the light from the laser source is continously pumped into the optical fibre and the mirror is being changed by the measurand, the light that is reflected back in to the optical fibre has been modulated to hold the information relevant to the mirrors movements and therefore the measurand.

The modulated light from the mirror and the light that was reflected at the endface of the fibre will then interfere with each other in the fibre, this produces the interference pattern.

The modulated light and the reference light will then interfere with each other in optical fibre (3) then propagate to the coupler and is transmitted into the final optical fibre. The resulting light from interference, then travels to the photodetector so that it may be converted from light to voltage or current so that the recieved signal can be easily sampled and viewed on a laptop.

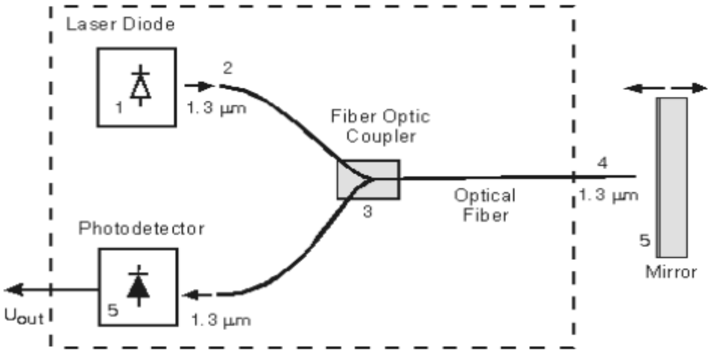

Figure 5.4: A Fibre-Optic Fabry-Perot Interferometer , (physics-animations.com)

Chapter 6

Types of Fibre Optic Sensors and Configurations

6.1 Types of FOM System Configurations

Many different configurations exist for fibre-optic microphones. The configuration used depends on different factors of the FOM sensor head and the type of received signal from the sensor head. The factors are listed below:

- The type of modulation at the sensor head.
- If the sensor is based on Intrinsic or Extrinsic sensing.
- If the sensor is setup for Reflection or Transmission of the modulated signal.
- The actual sensor head itself may restrict the freedom of choice.

Luckily most FOM sensors tend to use very similar configurations as a whole and only tend to differ slightly depending on the applications specifications.

6.2 Types of Modulation

As mentioned previously, knowing the type of modulation that the sensor uses is critical when designing the entire FOM system. There are three key types of modulation used, a the first type is Phase Modulation, the second is known as Intensity Modulation and the final type is known as Polarization Modulation.

Phase Modulation Phase modulation sensors are the most common configuration used in industry; these are generally based on optical Interferometry. As the name of this type of modulation suggests, sensors of this configuration change the phase of the incident light accordingly to the measurand and then combines with a reference light to create an interference pattern.

Sensors based on this type of modulation are generally regarded to have the highest performance and flexibility, this is due to the inherently high sensitivity interferometric sensors tend to exhibit. However these types of sensors, if not designed adequately, can be very prone to phase noise along the entire optical fibre path due to environmental changes in temperature and pressure.

Sensors that are based on phase/interferometric modulation have the following characteristics:

- They are known for having a high sensitivity. (Linero, Jalali, Joshi & Zuckerwar 1995)
- Susceptible to phase noise created along the fibre due to ambient pressure and temperature changes.
- Methods have been investigated to reduce the random phase change, but these make the sensors costly, more complex and generally impractical for many applications (Linero et al. 1995)

Intensity Modulation Intensity modulation, otherwise known as Amplitude Modulation, is categorized when the sensor head changes the intensity of the incident light correspondingly to the required measurand. Sensors that are based on intensity modulation tend to have simpler designs, more compatibility with optical or electronic components and generally have a relatively simple output signal. The simpler design and easy construction allow these types of sensors to be ideal candidates for sensing in harsh environments. However due to the simpler design of these types of sensors, they are not nearly as inherently sensitive as interferometric sensors.

Sensors based on Intensity/Amplitude Modulation have the following characteristics:

- Simpler design.
- Advantageous for Low frequency acoustic detection.
- Mechanical alignment is very critical and can limit its usefulness.
- The smallest and cheapest fiber optic sensors are intensity modulated. (Bucaro & Lagakos 2001)

Polarization Modulation Polarization Modulation is not as commonly used in optical fibre sensors when compared to phase modulation or intensity modulation. This type of modulation changes the polarization of the incident light according to the measurand signal, however this type of modulation can then be translated into either Intensity or Phase Modulation before the receiver.

The advantage of having the free choice to translate the original modulation to one of the other two types allows this type of sensing to be very versatile in its applications. But this type of modulation comes with several disadvantages; the first disadvantage is the cost of the optical components needed to use this type of modulation. In order to have accurate measurements the polarization of the incident light must be known, which means expensive optical components such as polarization maintaining fibres, polarization controllers and cross polarizers must be used. The second disadvantage is that there are few optical sensors that uses polarization modulation, so design choices can be very limited.

6.3 Extrinsic vs. Intrinsic Sensing

Extrinsic Sensing In fibre optic sensors the light propagates through optical fibres until it reaches the sensor head, at that point the light exits the optical fibre and interacts with the physical quantity to be measured. That is the actual transduction of the physical quantity occurs outside of the fibre, this is known as an extrinsic sensor or an open light path sensor.

Extrinsic sensing is commonly used when designing a fibre optic microphone, this is due to the fact that most sensor designs requiring the light to exit and interact with the sensor head. The most common types of FOMs that use extrinsic sensing are lever sensors, spliced core sensors and Fabry-Perot Interferometers.

Intrinsic Sensing Conversely to extrinsic sensing, Intrinsic sensing is when the physical quantity somehow effects the optical fibre itself, the entire sensing action occurs within the fibre and the light never leaves the fibre at any point.

Intrinsic optical fibre sensors are also fairly common, some key examples of intrinsic optical fibre sensors are gyroscopes, hydrophones and pressure sensors. These sensors typically rely on one of two physical phenomenon, the first is the Acousto-Optic effect and the second being micro bending of the fibre structure.

6.4 Reflection vs. Transmission

The terms Reflection and Transmission relate to the way that the light travels to and from the sensor head. If the modulated light is reflected back into the same optical fibre it originally travelled through then it is said to be a reflection type sensor and conversely if the modulated light travels through another optical fibre to the receiver then it is a transmission type reflector.

Reflection based sensors are very commonly used when building a FOM, a lever sensor requires the configuration to be reflection based and the Fabry-Perot interferometer is generally configured to be reflection based. A fibre optic sensor configured to operate in the reflection mode is show in Figure 6.1.

Transmission based sensors are also used fairly commonly, most types of FOM can be built using a setup configured for transmission and the general design of the entire FOM system can be very simple compared to systems based on reflection. A diagram of a transmission type sensor is shown in Figure 6.2.

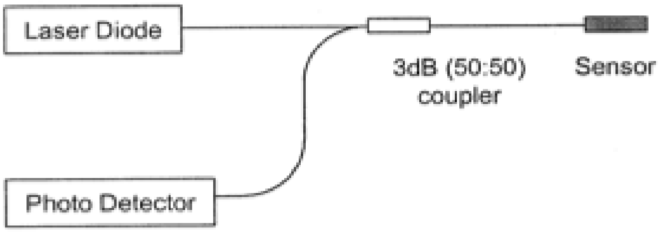

Figure 6.1: An example of a reflection type fibre optic sensor, this is the diagram of a Fabry-Perot Interferometer.

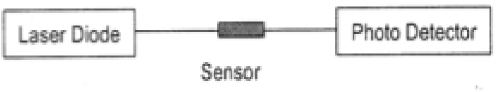

Figure 6.2: An example of a transmission type fibre optic sensor

Chapter 7

Review of Current Fibre Optic Sensors

7.1 Review of Current Fibre Optic Sensors

This chapter will introduce and analyse previously reported designs of microphones using optical fibre technology that were published over the past 50 years.

The following designs have been reviewed:

1. Fabry Perot Interferometer Sensor
2. Acousto-Optic Sensor
3. Spliced Fibre Core Sensor
4. Lever Sensor

7.2 Extrinsic Fabry-Perot Interferometer based Sensors

The Fabry Perot Interferometer (FPI) is a very popular configuration used in the designs of fibre optic microphones, this section will focus specifically on the extrinsic type of FPI.

Extrinsic Fabry-Perot Interferometers (EFPI) are very promising configuration for acoustic or vibration sensing, due to the ability to be able to sense extremely small changes in the phase of light. These phase changes can be of the order of a wavelength of light which means that sensors based on this can be extremely sensitive. This sensitivity of extrinsic Fabry-Perot interferometers, coupled with the other advantages of optical fibre technology are the main reasons it is no surprise that they are very commonly used in different industries as a microphone.

A typical design of an EFPI sensor was studied by (Zhou & Yu 2011) for the measurement of dynamic pressure fluctuations, the design can be viewed below in Figure 7.1. Although the intended application is dynamic pressure measurement, the author has also investigated the designed EFPI as an acoustic sensor.

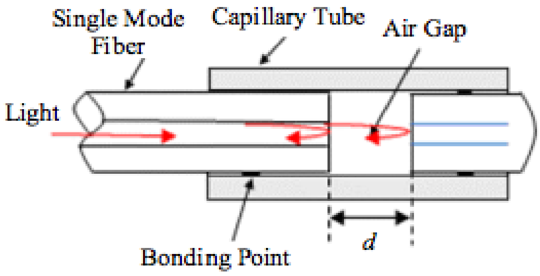

Figure 7.1: A schematic of a typical EFPI sensor, (Zhou, page 73)

Zhou & Yu (2011) implements several major improvements to EFPI sensors that have been developed previously, these improvements include a new method of constructing the sensor head through controlled thermal bonding techniques instead of using epoxy, Zhou & Yu (2011) noted that the use of epoxy would increase the sensors sensitivity to enviromental temperature changes and the use of thermal bonding technique would overcome the disadvantages that the epoxy introduces.

Another improvement in the design of an EFPI sensor was the implementation of a diaphragm instead of using another optical fibre as a mirror, a diaphragm based EFPI is shown in Figure 7.2. The typical sensor shown in Figure 7.1 is generally only suitable in detecting high frequency pressure variations but was insensitive to low frequency pressure variations. The Diaphragm based EFPI sensors however show a high sensitivity to the lower frequency pressure variations and a much wider frequency range. The final modification that was implemented by Zhou & Yu (2011) was the use of a low coherent light source, otherwise known as white light. Most EFPI sensors used a highly coherent light source instead because the light source offered a large dynamic range but these light sources have the disadvantage of generally having a higher cost. Low coherent light sources on the other hand are comparitively much cheaper but trade off overall sensitivity of the EFPI.

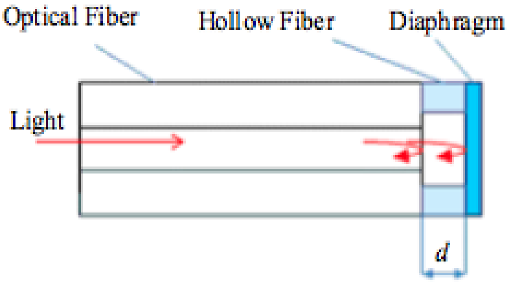

Figure 7.2: A schematic of a Diaphragm based EFPI sensor, (Zhou, page 74)

A unique example of these sensors is for the monitoring of airport ground traffic by using extrinsic Fabry-Perot acoustic and vibration sensors. These sensors are used as a part of the experimental surface movement guidance and control system to help manage the airport ground traffic (Furstenau, Schmidt, Horack & Goetze 1997). The acoustic EFPI sensor is to be used to distinguish the acoustic frequency spectrum of different aircraft; therefore the sensor must be sensitive and have a wide frequency range. The design of the EFPI acoustic sensor used to identify the frequency spectrum is shown in Figure 7.3.

The sensors used were designed with a low-coherence light source in mind, a technique of demodulation was also implemented to keep the signal stable and eliminate any signal fading when the environmental temperature variation is large. The demodulation technique used is called dual wavelength passive quadrature demodulation.

Furstenau et al.'s (1997) paper describes a new conceptual design of the Fabry-Perot interferometer acoustic sensor. Unlike the typical setup of a FP interferometer, which has the membranes movement parallel as the reflecting mirrors of the interferometer, the newer design has the membranes movement orthogonal/radial to the reflecting mirrors, see Figure 7.3. Since the membrane is orthogonal to the mirrors, when the membrane is displaced, by the acoustic wave, the attached mirror tilts with the membrane. As the acoustic wave moves the membrane back and forth, the gap between the two mirrors will increase or decrease with the wave.

Furstenau et al.'s (1997) EFPI acoustic sensor was initially tested using different sources of sound, these tests demonstrated that Furstenau et al.'s (1997) newer EFPI

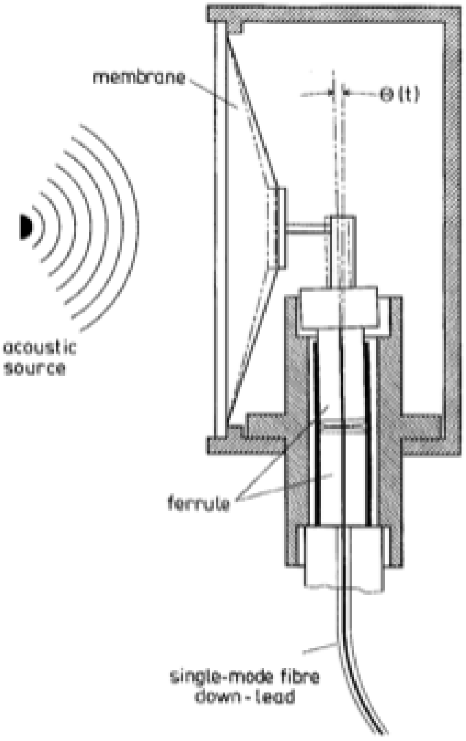

Figure 7.3: EFPI Acoustic Sensor, (Furstenau, page 139)

design exhibited behaviour comparable to a standard electronic microphone. Another experiment was set up where the EFPI acoustic sensor was to record the noise from different aircraft, the sensor proved to be sensitive enough to be able to distinguish the acoustic frequency spectra of the three different aircraft. The results also demonstrated that the acoustic EFPI sensor was able to distinguish between two near identical aircraft by the small differences in their respective low acoustic frequency spectrum.

This newer design has the advantages that is no longer requires a highly coherent light source, optical isolator or a sophisticated demodulation technique in order to get comparable results to an electronic microphone. The newer design of an extrinsic fibre optic interferometer is cheaper, less complicated and much more stable in environmental temperature variations.

Another acoustic sensor based on the EFPI is studied by (Malki, Gafsi, Lecoy & Mevel 1996), the FOM described in the paper is to become the primary microphonic element in a digital telephone. Since the FOM is to be used as a part of a telephone the frequency range required is from 300Hz to 3400Hz, which is the same as analogue phones.

The FOM designed for the digital telephone is similar to the typical design of

EFPI, however Malki uses a multimode fibre instead of a single mode fibre. Another difference is that the light source of the FOM is an LED with lower coherence. This difference in design allows the FOM to be intensity modulated based on the position of the membrane instead on relying on phase modulation and interference patterns.

The theoretical model presented in the paper is relatively simple when compared to a more traditional EFPI model. This appears to be due to the inclusion of the MMF and basing FOM on intensity modulation.

Malki et al.'s (1996) design offered a simple assembly at a low cost and the FOM was capable of transducing sound into telephone signals in the range of 300 to 3400 Hz. But Malki et al. (1996) notes that more research is required in the design of the membrane used in FOMs and that improvements in the acoustic behaviour, sensitivity performance and bandwidth are also required to make this FOM more comparable to already existing telephone systems.

7.3 Acousto-Optic Sensors

One of the simpler applications of the acousto-optic effect, when used in the design of a FOM was demonstrated by Culshaw, Davies & Kingsley (1977). This paper describes the acoustic pressure sensitivity of both single mode fibres (SMFs) and multimode fibres (MMFs) when being used as an acoustic sensor as a part of a FOM.

The variation in the refractive index of the SMF, caused by the acoustic pressure wave, causes the light to change its phase by a small amount inside of the fibre. However the acoustic wave is not the only component that is altering the phase inside of the SMF, in reality the length and refractive index will be varying continually. Variations in the environments temperature, ambient pressure and any stress induced on the fibre will alter the optical length and refractive index of the SMF. However these changes in the environment are not considered significant and generally vary slowly with time. (Culshaw et al. 1977)

The light source used in the experimental setup of Culshaw et al. (1977) FOM is coherent light; this is used so that the received signal is simple and so that no other physical phenomenon is interfering within the fibre causing a noise like signal at the receiver. If a non-coherent light source is used then every optical frequency present will be modulated but will appear as noise at the receiver.

To test this type of acoustic sensor, several experiments had been conducted in the optical data highway at the University College of London. Two configurations were used in the experiments, the first used a SMF as the sensor and the second experiment used the MMF as its sensor.

The results of the experiments show that the single mode optical fibre sensor is very sensitive to the acoustic waves and also highly linear in its frequency range but the MMF acoustic sensor was found to be less sensitive and less linear in its frequency range compared to the SMF.

The SMF demonstrates to be a very promising and simple acoustic sensor when compared to the MMF, but the MMF sensor is not as well understood as the SMF due to the process of acoustic sensing being a lot more complicated. Understandably the received signal from the MMF is also much more complex than the signal from the SMF, due to each individual fibre in the MMF being affected differently do to being spatially apart and each taking relatively different paths.

Some limitations of the SMF sensor were defined after an experimental and theoretical analysis. The main limitations found were due to the losses that occur in the fibre, the fibre carrying capacity and the fact that the acousto-optic effect is generally non-linear. However to simplify the theoretical analysis the non-linearitys of the acousto-optic effect was assumed to be linear over a small change in the refractive index, this was within a 1

The theoretical model, of the acoustic sensitivity of the SMF, derived by Culshaw et al. (1977) to be fairly close to the experimental results. Any difference in the model to the results is mainly due to the difficultly of theoretically expressing the non-linear properties of the acousto-optic effect.

Culshaw et al.'s (1977) and his team noted some interesting elements that had been found during the experimental analysis. If the optical power is increased at the source the overall sensitivity of the SMF sensor is increased, the fibre power capacity is the limit to this. If the optical power is approximately 1 Watt then for a 30-metre length of SMF, the sensor is able to detect acoustic power that is below the threshold of human hearing. However this effect itself is limited by the noise in the light source and by the receivers noise.

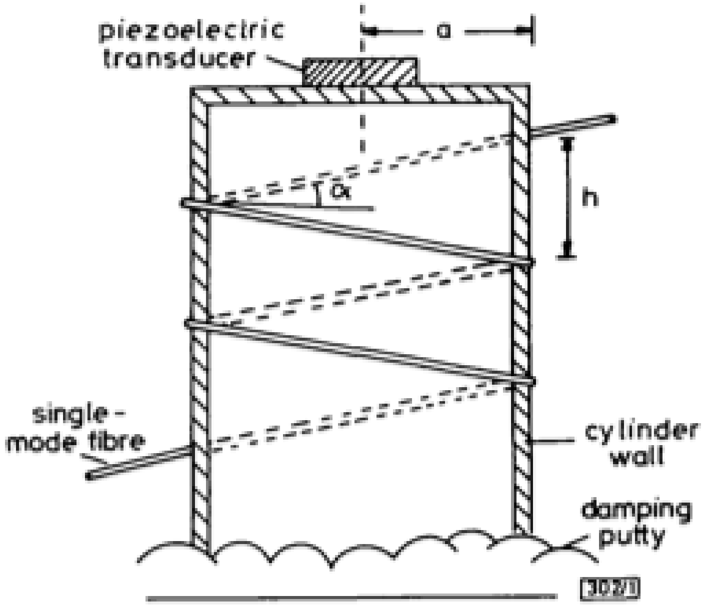

Figure 7.4: Schematic of an Acousto-Optic based FOM sensor, (Ji, page 1141)

Another method of constructing a FOM sensor based on the acousto-optic effect is demonstrated by using the bend induced birefringence properties of a single mode fibre, to shift the optical frequency of the propagating light when it is under the influence of an impacting acoustic wave was demonstrated by Ji, Uttam & Culshaw (1986).

The FOM was built by wrapping the single mode fibre around an aluminium cylinder, the radius of the cylinder is key to achieve bend induced birefringence. Once the fibre is wrapped helically around the cylinder, with a small enough radius, this section of the fibre becomes the key interaction region between the fibre and the acoustic wave. Figure 7.4 shows the Acousto-Optic sensor designed by Ji et al. (1986).

A piezoelectric transducer is attached to the end face of the aluminium cylinder and launches the acoustic wave along the cylinder. The wavefront of the acoustic wave is assumed to be parallel to the end face of the cylinder; this assumption allows the simple calculation of the angle between the acoustic wave and the helically wrapped single mode fibre. This angle is the key in determining the frequency shift of the light. Ji et al.'s (1986) Demonstrates that if the angle between the acoustic wavefront and the single mode fibre is at 45 degrees then the shift in optical frequency will be greatest which results in optimum operation.

The light source was linearly polarized before it travels through the birefringent fibre. When the polarized light enters the interaction zone, it undergoes double refraction and the optical frequency of the light shifts due to the bend induced birefringence.

If the acoustic wavefront is traveling in the same direction as the light, the optical frequency is shifted upwards and conversely if the acoustic wavefront is traveling in the opposite direction the optical frequency is shifted downwards.

The FOM sensor was placed in the sensing arm of a Mach-Zehnder interferometer arrangement, the shifted optical frequency from the acoustic sensor is then mixed with the original optical frequency of the laser source at the photo-detector. The mixed signal from the photo-detector is then viewed on a spectrum analyser to determine the difference of the original optical frequency to the shifted frequency. The frequency of the acoustic wave changes the how far apart the original optical frequency is to the frequency shifted sensor signal. This sensor results in having a very good discrimination when viewed on a spectrum analyser and the shift in optical frequency is extremely distinct. However the sensitivity or the acoustic frequency range is not shown for this type of FOM, so it is unknown if it would be a good acoustic sensor for the intended application.

7.4 Spliced-Core Sensor

Most fibre acoustic sensors use interferometric setups. These arrangements are generally very complex and can be extremely expensive for the intended application. However other configurations have been explored in order to build a low cost FOM.

One FOM has been constructed by simply splicing a single mode fibre with a multimode fibre and placing a thin membrane over the spliced section see Figure 7.5, also known as a hetero-core sensor (Sun, Semenova, Wu & Farrell 2010). The incident light travels through the multimode fibre and is then transferred to the single mode fibre at the spliced section. However not all light from the multimode fibre is transferred to the single mode fibre, some is lost in the cladding layer due to the diameter difference of the two fibres.

This spliced sensor will use the vibrations induced in the membrane, by an acoustic wave, to deform the spliced section of the sensor. This deformation will then change the amount of light loss in the spliced section between the single mode fibre and the multimode fibre. The received signal intensity corresponds directly to the vibration of the membrane, which in turn is caused by acoustic waves impacting the membrane.

The spliced fibre sensor was then experimentally tested with an acoustic frequency range from 300Hz to 20kHz to examine the performance of the sensor. The frequency response of the spliced sensor was compared to an electronic microphone and the spliced sensor proved to be both more sensitive and have a larger frequency range than the electronic microphone. (Sun et al. 2010)

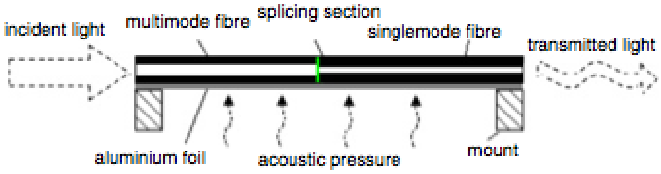

Figure 7.5: The Spliced Hetero-core sensor Schematic , (Sun et al.)

7.5 Lever Sensor

Optical fibre lever sensors have been theoretically and experimentally examined since optical fibres were first used as sensors. Nowadays, however when compared to most other types of sensors (Fabry-Perot, Acousto-optic and Fibre Bragg Gratings) they do not seem to have as much research interest but still prove to be one of the most versatile optical sensors available.

A fibre optic lever sensor designed for high temperatures was studied by Zuckerwar & Cuomo (1989). This sensor is reported to be able to withstand temperatures of up to 1093 degrees Celsius with a pressure range of 130 to 190 dB (0.01 to 10 psi), the reported frequency range of this lever sensor is up to 200kHz.

Zuckerwar & Cuomo's (1989) noted that fibre optic lever sensors showed many advantages when it was applied to sensing in high temperature environments compared to electronic microphones. The most notable of which was the limits of the sizes of the sensors, the electronic microphones where comparably large due to needing a pre amplifier at the microphone and that the lever sensor has an advantage in its bandwidth due to its principle of operation.

Another study of lever sensors at high temperatures was also been published by Linero et al. (1995), this paper also presents a theoretical model of the lever sensors behaviour along with experimental data to demonstrate the models accuracy.

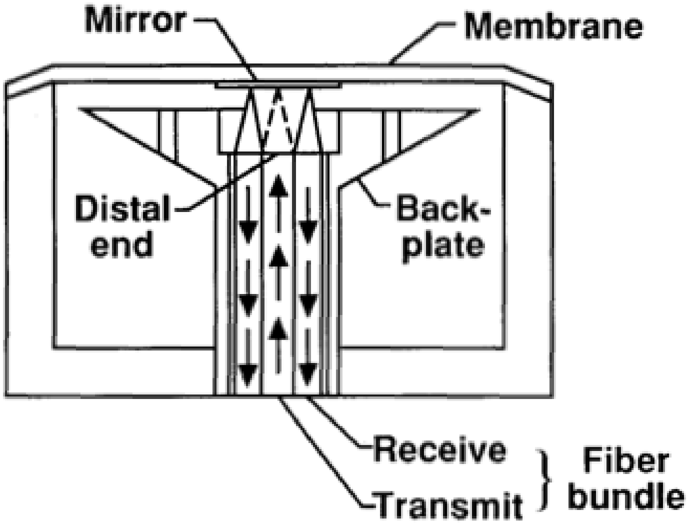

Figure 7.6: Schematic of the prototype lever sensor, (Zuckerwar et al.)

This optical fibre lever sensor from this study was designed to detect and measure acoustic pressure fluctuations in hypersonic flow fields under hostile environments. The fibre optic lever sensor was constructed into a probe like sensor, Linero et al.'s (1995) final design can be seen in Figure 7.5.

The sound pressure levels that this sensor was subjected to was in the range of 130-160 dB, similar to (Zuckerwar & Cuomo 1989). However Linero and his team reported that there sensor is able to operate at temperatures up to 538 (degrees C) and shows to have a very linear response across a frequency range of up to 100kHz.(Linero et al. 1995) also noted that the frequency response is theoretically in excess of 100kHz and is unaffected in the ambient temperature changes.

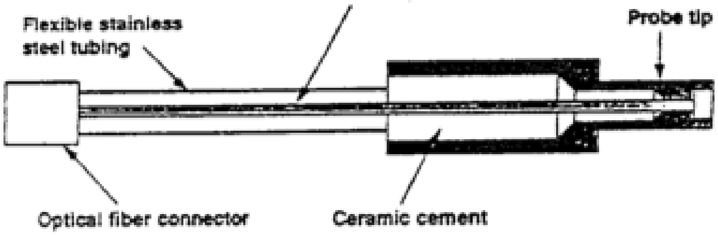

Figure 7.7: Schematic of a lever probe sensor , (Linero et al.)

Another lever sensor has been reported by Bucaro & Lagakos (2001), this sensor was designed and built as a part of a "Active Smart Acoustic Blanket" which is to be apart of a satellite payload to reduce the transmission of very high sound levels to the payload. The main requirement of this particular Lever sensor was that it had to be extremely light and small, this was so that it would keep the cost of a launch as low as possible.

The design used by Bucaro & Lagakos (2001) implements a multimode fibre as its collection system instead of using a single collection fibre, which requires an optical coupler, Bucaro & Lagakos's (2001) design can be seen below in Figure 7.8.

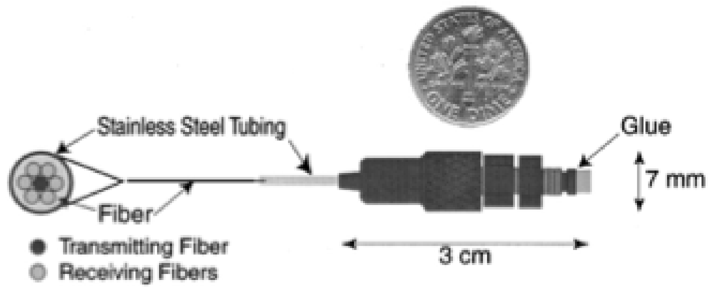

Figure 7.8: Schematic of a lever probe sensor , (Bucaro et al.)

The optimal separation of the sensing membrane to the optical fibres in Bucaro & Lagakos's (2001) FOM probe was between 180 and 250 mumetres and the single fibre probe had a separation that was less than 100u meters. The resulting FOM lever sensor weighed approximately 1.3g, has a minimum detectable acoustic pressure level of 0.016Pa per sqrt Hz and a linear response over its intended frequency range (50Hz to 2kHz).

Bucaro & Lagakos (2001) and his team compared their FOM probe, which used seven fibres in total, to a probe that only had one fibre acting as a transmitter and receiver for the modulated light. They found that there design was nearly five times more sensitive than the single fibre probe and the single fibre probe required more careful handling due to the short separation between the sensing membrane and the optical fibres.

This brings the conclusion that the more receiving fibres used in the lever sensor, the higher the theoretical maximum sensitivity and the distance of the optimum separation between the membrane and the fibres us increased, allowing a more reliable design.

7.6 Chapter Summary

This chapter of the dissertation evaluated different types of FOMs, after the analysis the following conclusions have been made about the selection of sensor types:

For Extrinsic Fabry-Perot Interferometer type FOMs:

- Can be designed and built to be extremely senstive.
- Frequency range and sensitivity is extremely good, it can detect small differences in frequency spectrums. (Furstenau et al. 1997)
- For performance comparable to a conventional electronic microhphone the EFPI does not require a sophisticated demodulation technique. (Furstenau et al. 1997)
- The use of epoxy in the construction of the EFPI sensor head will increase the sensors sensitivity to enviromental temperature and would cause unwanted noise. Instead thermal bonding is used to overcome this issue. (Zhou & Yu 2011)
- The use of a diaphram as the mirror instead of another fibre improves the sensitivity to lower frequency noise and improves the frequency range. (Zhou & Yu 2011)
- Both coherent and non-coherent light sources can be used with the EFPI, generally though non-coherent light sources are cheaper but at the sacrifice of reduced performance.

For Acousto-Optic type FOMs:

- Variations in the environments temperature, ambient pressure and any stress induced on the fibre will alter the optical length and refractive index of the SMF, however these changes in the environment are not considered significant and generally vary slowly with time. (Culshaw et al. 1977)
- If a non-coherent light source is used for this type of FOM, then every optical frequency present will be modulated but will appear as noise at the receiver. (Culshaw et al. 1977)

- Experiments show that single mode optical fibre is very sensitive to the acoustic waves and also highly linear in its frequency range. (Culshaw et al. 1977)
- Multi-Mode fibre was found to be less sensitive and less linear in its frequency range compared to the single mode fibre. (Culshaw et al. 1977)
- The Acousto-optic effect is generally non-linear but to simplify the non linearities of the acousto-optic effect was assumed to be linear over a small change in the refractive index, this was within a 1
- If the optical power is increased at the source the overall sensitivity of the SMF sensor is increased. Theoretically if the optical power is approximately 1 Watt then for a 30-metre length of SMF, the sensor is able to detect acoustic power that is below the threshold of human hearing. (Culshaw et al. 1977)

For Lever type FOM sensors:

- Lever type sensors have been designed and built to withstand temperatures of up to 1093 degrees Celsius with a pressure range of 130 to 190 dB (0.01 to 10 psi), the reported frequency range of this lever sensor is up to 200kHz. (Zuckerwar & Cuomo 1989)
- Fibre optic lever sensors showed many advantages when it was applied to sensing in high temperature environments compared to electronic microphones. (Zuckerwar & Cuomo 1989)

Chapter 8

Fibre Optic Microphone Sensor Designs and Prototypes

As it came clear from the literature review and the background theory the amount of different types and configurations of FOMs is absolutely staggering. Unfortunately due to the scope of this project only a small amount of FOM sensors can be built and tested.

This chapter will introduce the FOM sensor designs chosen to be constructed and tested in the laboratory.

The following designs were selected to be investigated further

1. Acousto-Optic Helix Sensor
2. Acousto-Optic Flat Sensor
3. Spliced Fibre Core Sensor
4. Extrinsic Fabry-Perot Interferometer Sensor

8.1 Acousto-Optic Helix Sensor

A diagram of the Acousto-Optic Helix is shown below in . The Acousto-Optic Helix is based on the sensor described by Ji et al. (1986). This was chosen because the construction is extremely simple, the required components were readily available in the lab and the design can be altered in almost anyway to examine the effects of the modifications.

However the Acousto-Optic Helix design used in this project will not use polarization as its form of modulating the laser light. Instead it will only be modulated by using the Acousto-Optic effect.

However Ji et al.'s (1986) design uses polarization as its form of modulation which cannot be implemented due to the lack of optical polarization components. Instead the Helix design used in this project will be relying solely on the Acousto-Optic effect to modulate the laser light.

As mentioned before this design has the added benefit that it can be altered in many ways, some possible modifications include:

- Increasing the seperation of the turns on the cylinder.

  The spacing of the turns will change the angle that the fibre is at on the cylinder, Ji et al. (1986) suggests that this angle changes the behaviour of the SMFs response. Specifically the induced birefringence but when the acoustic wavefront impacts the fibre at different angles the behaviour of the change in the refractive index would also differ.

- Changing the material and dimensions of the cylinder.

  Different materials and dimensions of the cylinder will alter the frequency response and acoustic sensitivity of the sensor. The amount of possiblilities of using different dimensions and materials is absolutely staggering.

8.1.1 Guide to Acousto-Optic Helix Sensor Operation

1. The wave front of the acoustic waves will impact on the front part of the sensor.
2. The acoustic waves will cause a small amount of mechanical strain on the SMF.
3. The mechanical strain then induces a refractive index change on the affected fibre at the front of the sensor.

4. Since the fibre is segmented by the acoustic wave, the fibre will then have refractive index gratings.
5. Fresnel reflections will then occur at the refractive index gratings, since the refractive index gratings will be proportional to the acoustic wave impacting the fibre.
6. The Fresnel reflections, from the refractive index gratings, will then modulate the transmitted optical power

8.1.2 Acousto-Optic Helix Sensor Construction Details

The Acousto-Optic Helix sensor was built using the following material:

- PVC (Polyvinyl Chloride) pipe was used as the cylinder. Its dimensions were.......
- A 2x2 Optical coupler was used as the sensing SMF. (Thorlabs: 10202A-50-APC)
- A small stand was used to hold the PVC pipe vertical.
- Blu-Tack and scotch tape were used to hold the cylinder vertical and hold the SMF onto the cylinder.

Initially a patch cord was used as the sensing SMF but the jacket proved to be a major issue. The jacket was far to thick and any pressure from the acoutic wave was absorbed in the jacket, therefore very little or no mechanical strain was on the fibre.

Instead a 3dB 2x2 Optical coupler from thorlabs was used, but by using this coupler the amount of useable optical power from the laser source is halved. To keep the sensor as simple as possible aswell as to avoid any unforseen effects, only two of the arms of the coupler are used as a part of the sensor. The other two arms had the ferrule caps on so as to avoid any light exiting the setup.

The SMF was carefully wrapped around the PVC pipe as many times as applicable, this ended up being as seven turns and the spacing between the turns was then kept to a minimum.

The Blu-Tack was used

8.2 Flat Acousto-Optic Sensor

The Flat Acousto-Optic sensor design is similar to the Helix sensor but instead of wrapping the fibre around a tube it will be placed along a flat surface, the design will be constructed similar to Murata, Ohkawa & Sato (2012). A diagram of the Flat Acousto-Optic sensor is shown in Figure 8.1. The red box in the middle of the diagram indicates the placement of a membrane but it is not essential.

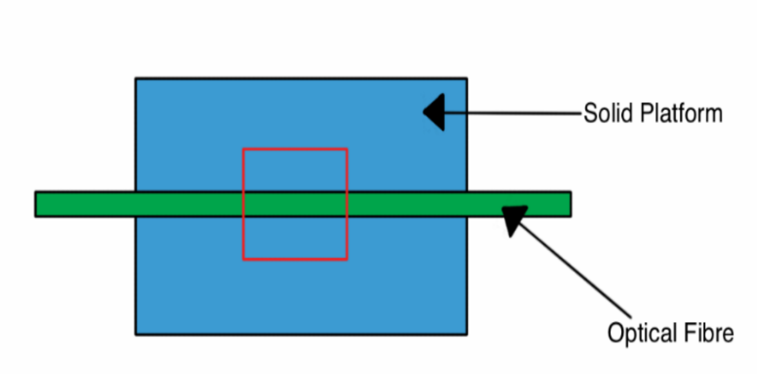

Figure 8.1: Simple Diagram of the Flat Acousto-Optic Sensor

Similar to the acousto-optic helix sensor, the design illustrated by Murata et al. (2012) uses the polarization of the light as the method of modulation. Instead the flat design will rely on the same physical mechanism as the Helix sensor, shown above, to modulate the signal using to the acousto-optic effect to change the refractive index of the fibre.

This design yields fewer opportunities when it comes to modifying the design than the Helix sensor. The only modifications possible would include:

- Changing the of membrane that is placed on the SMF.
- Changing the length of the SMF on the surface.

8.3 Spliced Fibre Core Sensor

The third design to be tested is the Spliced Fibre Core sensor shown in Figure 8.2. The inspiration for this sensor is from Sun et al. (2010) from the literature review, however there are a few key difference from the design used in this project and the design used by Sun et al..

Sun et al.'s (2010) sensor design uses two different types of fibres, one MMF and one SMF and the fabrication process of the sensor implemented a fusion splicer to fuse the two fibres together.

Whereas the design used in this project is limited by both the fabrication process and the available optical components. Unfortunately aquiring a fusion or mechanical splicer were not within the funds allocated to this project. Aquiring a MMF was also outside the grasp of this projects budget due to the fact that other optical components would also needed to be bought to use the MMF.

However the Spliced Fibre Core sensor used in this project will use only a ceramic mating sleeve (Thorlabs: ADAF1) to act as a mechanical splice.

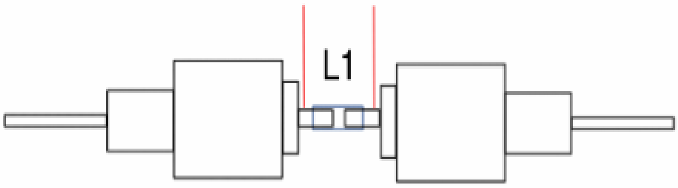

Figure 8.2: Diagram of the spliced fibre core sensor designed for this project.

8.4 Extrinsic Fabry-Perot Interferometer Sensor

The final sensor to be built for this project is the Extrinsic Fabry-Perot Interferometer sensor which is shown below, this design is similar to Furstenau et al. (1997). Ideally there will be little difference between Furstenau's but due to the lack of precise equipment it is very unlikely that the EFPI sensor will satisfy the quadrature condition. Due to this fact this EFPI design will likely have a different type of output based on the intensity of the signal instead of the phase.

Chapter 9

Evaluation of Fibre Optic Microphone Sensor Performance

Multiple experiments were performed in order to evaluate some of the performance characteristics of the selected Fibre Optic Microphone designs. The two main performance characteristics that were examined include the effect of the optical power on the microphones sensitivity and the effect of distance between the fibre optic sensor and the sound source.

9.1 Prototype Sensor and Configurations

Unfortunately due to time constraints only the Acousto-Optic Helix sensor was successfully built and tested. A picture of the prototype Acousto-Optic Helix sensor can be seen in Figure 9.1.

Figure 9.1: Prototype Acousto-Optic Helix FOM sensor

The experiments were then tested using only this sensor but it was used in two different types of configurations, the first is the basic configuration and the second was a Mach-Zehnder Configuration. Figure 9.2 and Figure 9.3 show the basic configuration and the Mach-Zehdner configuration respectively.

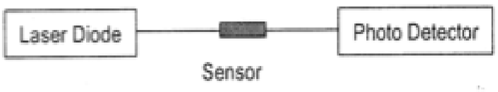

Figure 9.2: Basic Configuration of the Acousto-Optic Helix sensor

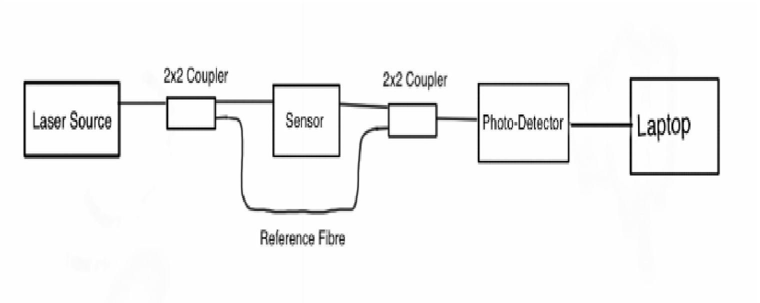

Figure 9.3: Mach-Zehnder Interferometric Configuration of the Acousto-Optic Helix sensor

9.2 Equipment used in the Experiments

A description of the equipment used to conduct both of the experiments is shown below, not included in the list is the equipment used for the sensors themselves. A photo of the equipment for the experiments is shown in Figure 9.4.

Light Source

The light source was a S1FC-1310 Fabry-Perot Benchtop Laser sourced from ThorLabs. The wavelength of the output laser is 1310 nm and the maximum output power is 1.5 mW.

Photodetector

The photodetector used to convert the light signal into an electrical signal is the inGaAs Fast PIN (RF) Amplified photodetector (Model: PDA8GS from ThorLabs) and was loaned from USQ.

Data Acquistion Device

The data acquisition device used to retreive the signal from the photodetector is known as the Labjack U6 and was loaned from USQ.

Sound Source

The sound source used for the experiments was just a generic computer speaker.

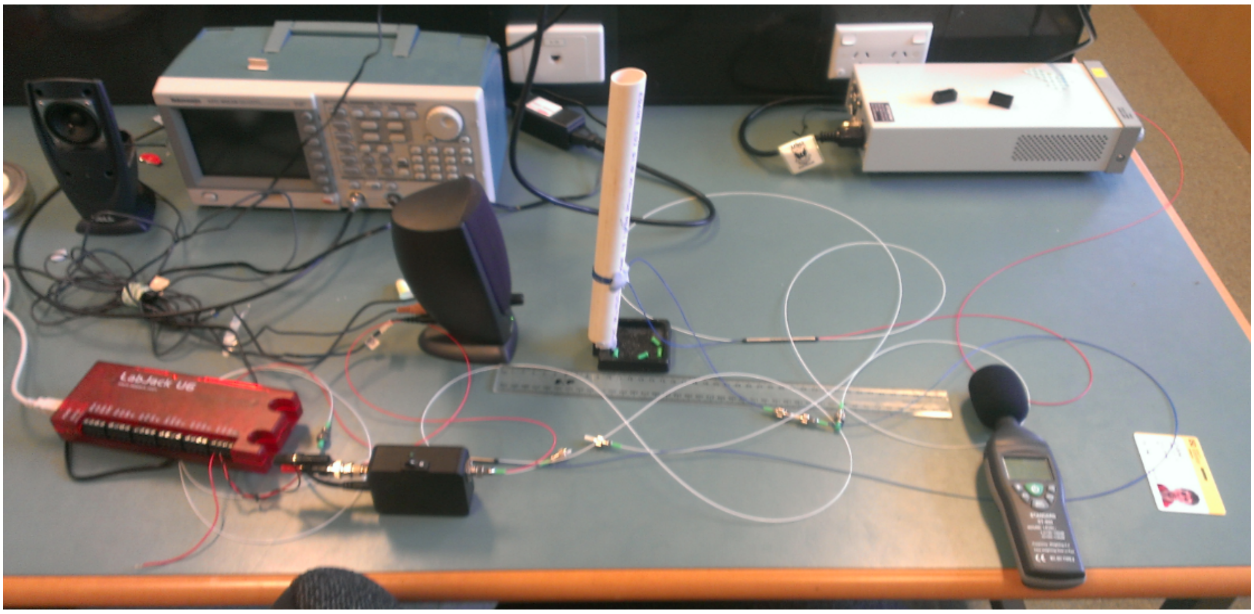

Figure 9.4: Setup of the Experimetns

9.3 Effect of Optical Power on Sensitivity

The purpose of this experiment is to see if the output optical power from the laser source has any effect on a FOM sensors sensitivity to the acoustic sound.

As suggested by Culshaw et al. (1977) if the optical power in the fibre is increased, so should the sensitivity of the sensor. But Culshaw et al. did not examine this effect on SMF and was not able to use more than 1 mW of optical power due to physical constraints of their components.

9.4 Effect of Optical Power: Experimental Setup and Considerations

For this experiment the equipment was configured exactly as follows:

1. The computer speaker was fed a 2kHz soundwave from a laptop, the speakers volume was held constant at 90dBa. The speakers volume was measured with the sound power level meter at a distance of 40cm.
2. The sound power level of the ambient room was measured to be 55dBa
3. The distance between the FOM sensor and the sound source was held constant for all experiments at 10cm.
4. For each rendition of the experiment, five samples were taken at each distance in 20 second intervals. Then for each distance the recieved signal is averaged so to show the expected signal.

9.5 Results of Optical Power Effect Experiments

After each test was completed, the recieved signal was analysed using MATLAB. The only analysis performed on the recieved signal was a Fast Fourier Transform (FFT), this then allowed the frequency spectrum of the recieved signal to be analysed.

Figure 9.5 and Figure 9.6 show a few of the FFT plots of the recieved waveforms from the Acousto-Optic Helix Sensor in the Basic and Mach-Zehnder Configurations respectively.

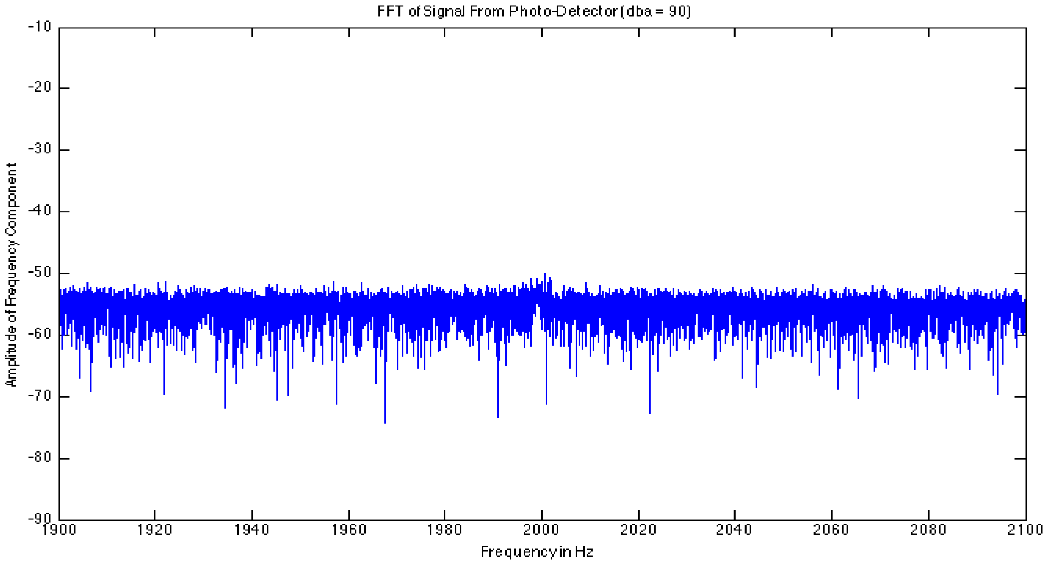

Figure 9.5: FFT of the Acousto-Optic Helix Sensor in the Basic configuration, output optical power was 1.0mW and the distance between the sensor and source was 10cm.

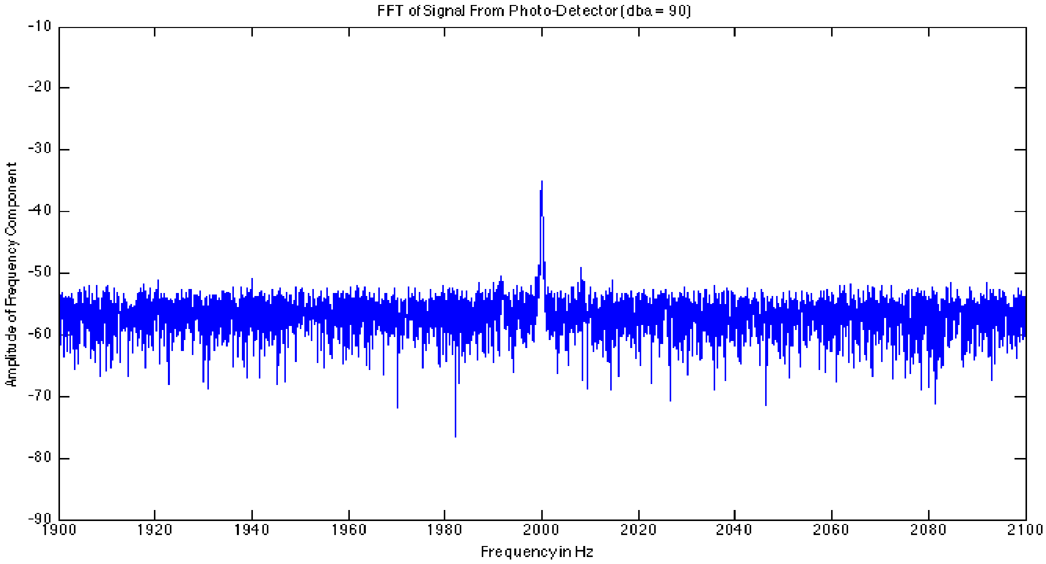

Figure 9.6: FFT of the Acousto-Optic Helix Sensor in the Mach-Zehnder configuration, output optical power was 1.0mW and the distance between the sensor and source was 10cm.

As mentioned in the preceding section, five intervals of the recieved signal were taken for each distance, the mean of all of the intervals for each distance were taken for both of the Acousto-Optic Helix configurations. The purpose of this was to show the expected signal from each sensor for each distance.

The results of the averaged intervals of the Acousto-Optic Helix sensor in the Basic and Mach-Zehnder interferometer configuration is shown in Figure 9.7 and Figure 9.8 respectively.

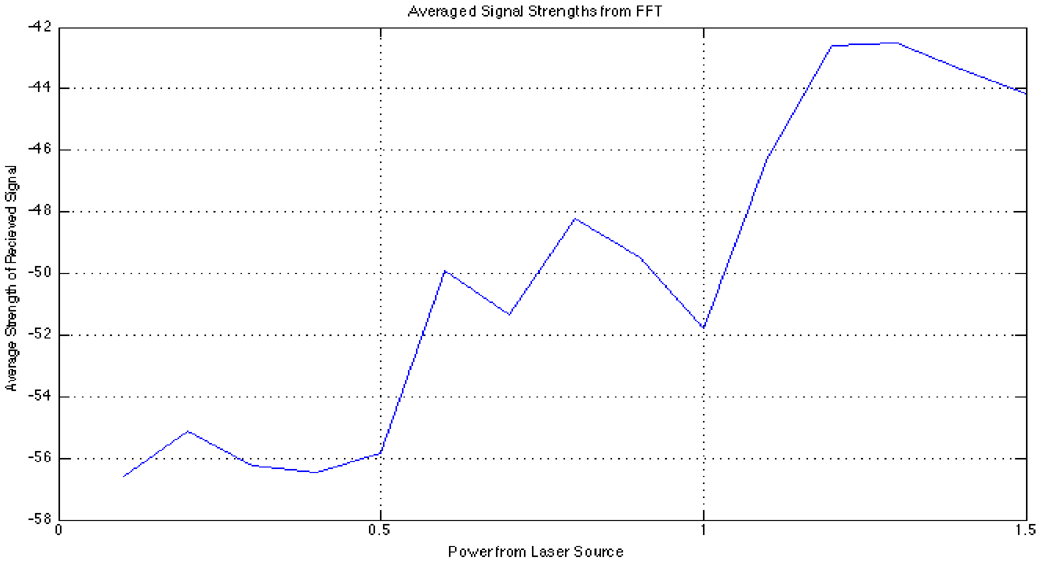

Figure 9.7: Results from the Acousto-Optic Sensor in the Basic Configuration, where the distance between the sensor and source is 10cm

9.6 Effect of Spatial Seperation of Source and Sensor

The purpose of this experiment is to attempt to evaluate the performance of the constructed fibre optic microphones across a small range of distances. A picture showing the total experimental setup can be seen below in Figure 9.4.

One of the conclusions from the review of different fibre optic microphones was that some physical phenonenom on the optical fibres demonstrated to be non-linear. In particular interest was the Acousto-Optic Effect.

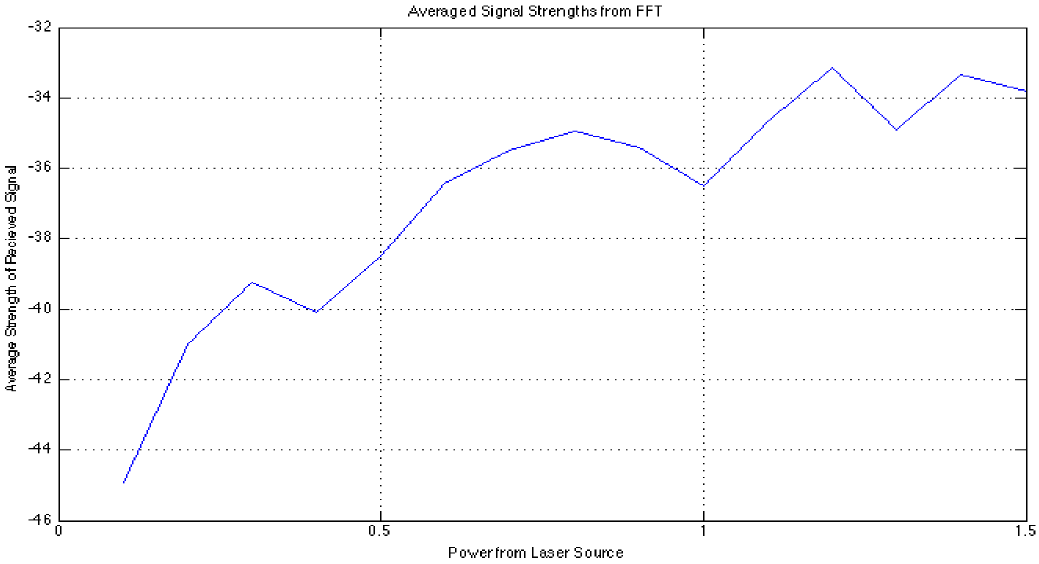

Figure 9.8: Results from the Acousto-Optic Sensor in the Mach-Zehnder Configuration, where the distance between the sensor and source is 10cm.

9.7 Spatial Seperation: Experimental Setup and Considerations

For this experiment the equipment was configured exactly as follows:

1. The computer speaker was fed a 2kHz soundwave from a laptop, the speakers volume was held constant at 90dBa. The speakers volume was measured with the sound power level meter at a distance of 40cm.
2. The sound power level of the ambient room was measured to be 55dBa
3. The output power of the laser source was set to 1mW and did not use any sort of external modulation to change the output of the laser.
4. The seperation between the speaker and the FOM starts at 5cm and increases to a distance of 40cm in 5cm increments.
5. For each rendition of the experiment, five samples were taken at each distance in 20 second intervals. Then for each distance the recieved signal is averaged so to show the expected signal.

9.8 Results of Spatial Seperation Experiments

After each test was completed, the recieved signal was analysed using MATLAB. The only analysis performed on the recieved signal was a Fast Fourier Transform (FFT), this then allowed the frequency spectrum of the recieved signal to be analysed.

Figure 9.9 and Figure 9.9 show a few of the FFT plots of the recieved waveforms from the Acousto-Optic Helix Sensor in the Basic and Mach-Zehnder Configurations respectively.

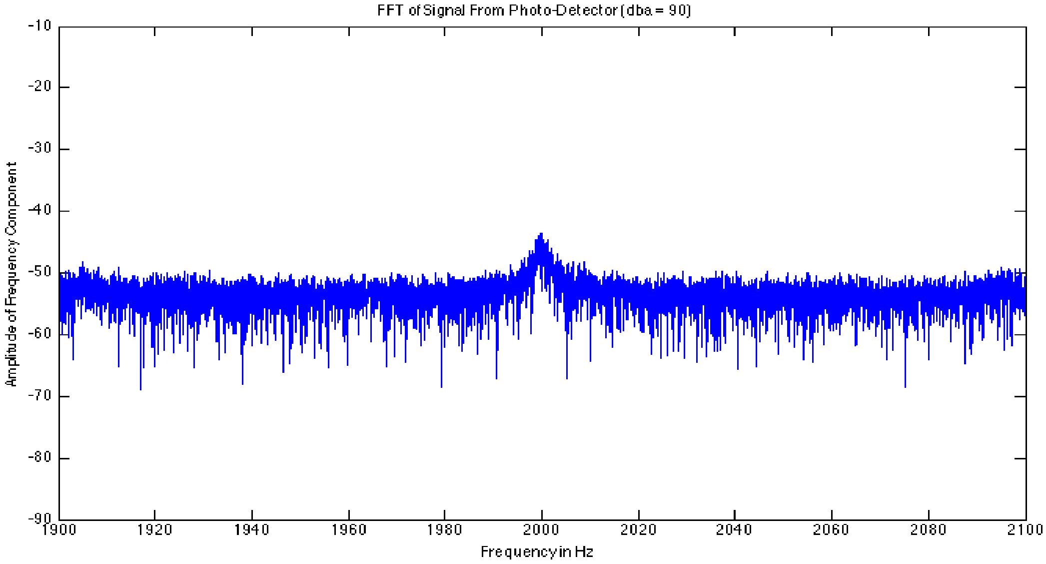

Figure 9.9: FFT of the Acousto-Optic Helix Sensor in the Basic configuration, seperation between the sensor and source was measured to be 10 cm

The results of the Acousto-Optic Helix sensor when the distance is held at 25cm and the output optical power was held at 1mW. The data samples were iterated five times for the Basic and Mach-Zehnder configuations is show in Figure 9.11 and Figure 9.12 respectively.

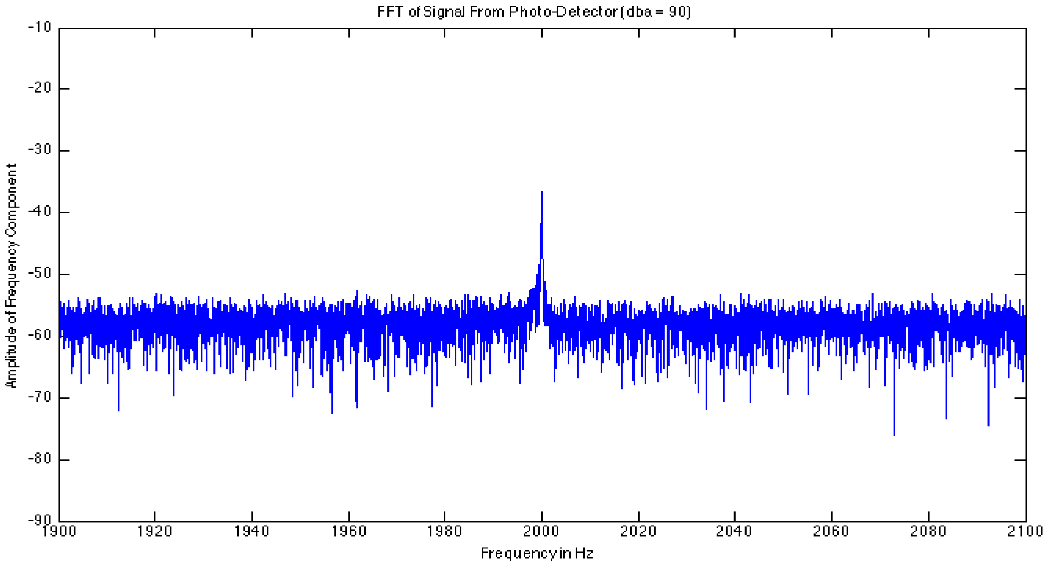

Figure 9.10: FFT of the Acousto-Optic Helix Sensor in the Mach-Zehnder configuration, seperation between the sensor and source was measured to be 10 cm

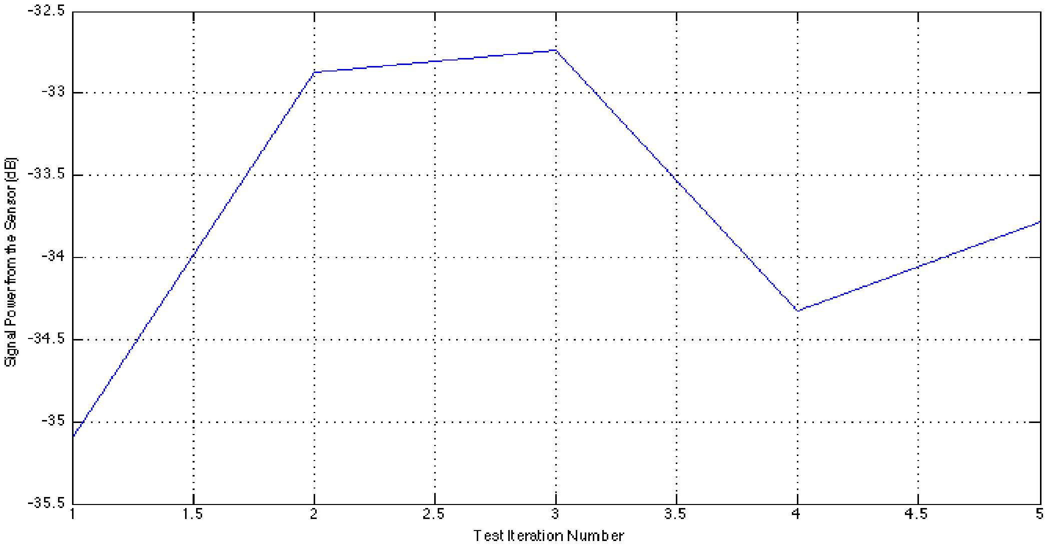

Figure 9.11: Results from the Acousto-Optic Sensor in the Basic Configuration when the distance and output optical power were both held at 25cm and 1mW respectively.

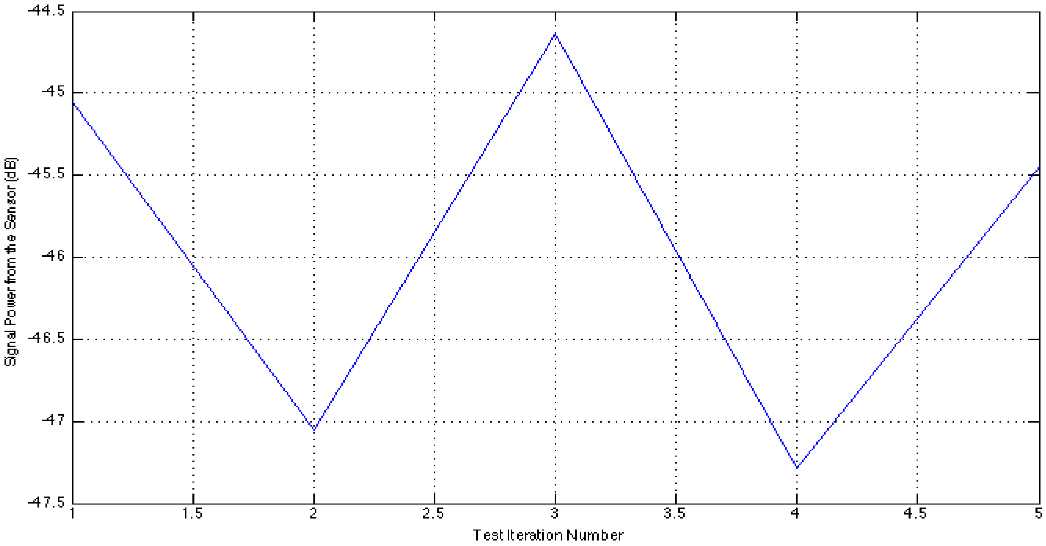

Figure 9.12: Results from the Acousto-Optic Sensor in the Mach-Zehnder Interferometer Configuration when the distance and output optical power were both held at 25cm and 1mW respectively

As mentioned in the preceding section, five intervals of the recieved signal were taken for each distance, the mean of all of the intervals for each distance were taken for both of the Acousto-Optic Helix configurations. The purpose of this was to show the expected signal from each sensor for each distance.

The results of the averaged intervals of the Acousto-Optic Helix sensor in the Basic and Mach-Zehnder interferometer configuration is shown in Figure 9.13 and Figure 9.14 respectively.

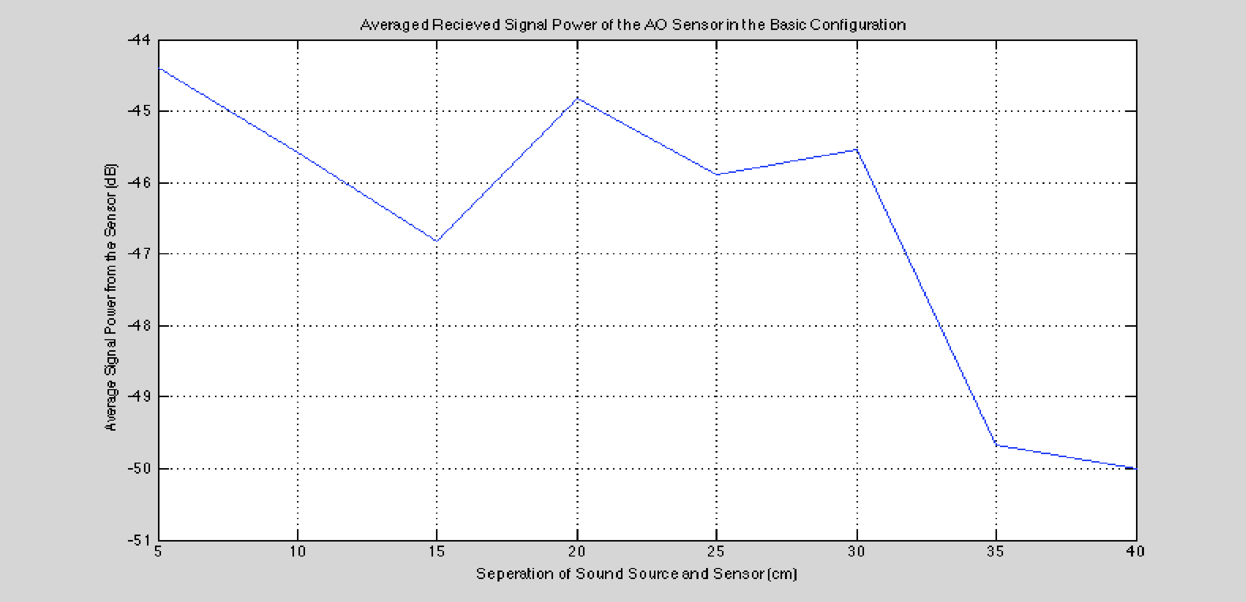

Figure 9.13: Results from the Acousto-Optic Sensor in the Basic Configuration

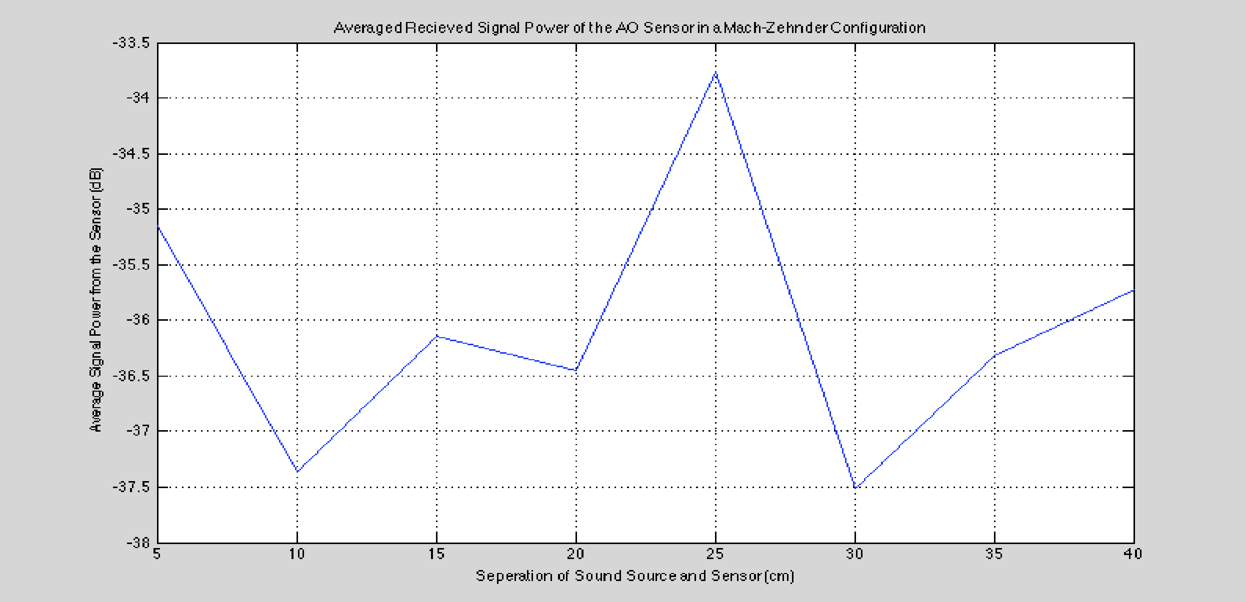

Figure 9.14: Results from the Acousto-Optic Sensor in the Mach-Zehnder Configuration

9.9 Discussion of the Results

From the FFT, the noise floor for all of the experiments was approximately -52 dB. If any of the FFTs of the data showed that the signal was at or very close to the noise floor it was considered to be unattainable.

Figure 9.7 and Figure 9.8 both indicate that as the output optical power of the light source increases, the sensitivity of the sensor in either configuration increases.

However the basic configuration needs atleast 0.75mW of optical power in order to for the sensor to be able to get a signal above the noise floor. But even at 0.1mW the sensor that is in the interferometric configuration is sensitive enough to be well above the noise floor.

Figure 9.13 shows that when the Helix sensor, in the basic configuration, increases its distance from the sound source the recieved signal strength of the 2kHz acoustic wave drops off very quickly. When the distance is at the maximum test distance (40cm) the signal has been attenuated so much that it almost isn't detectable.

However in Figure 9.14 when the Helix sensor is in the Mach-Zehnder Interferometer configuration, the recieved signal strength does not attenuate so quickly, at the maximum test distance the signal strength is at -35.75dB. The signal strength of the interferometer configuration at 40cm is far greater than the signal strength of the basic configuration at 5cm.

Figure 9.11 and Figure 9.12 demonstrates that when the distance and power were both held constant, the recieved signal from consecutive test iterations varied by only approximately 3-4dB. However these figures were taken when both the configurations were within there range to sense the acoutic waves. When the distance is increased so much so that the recieved signal is only just above the noise floor, the 3dB change could make the sensor inconsistantly transduce the signal.

Example FFTs of the sensor in both configurations are shown in Figure 9.5, Figure 9.6, Figure 9.9 and Figure 9.10. These figures show that the interferometric configuration yields a sharper and more obvious signal. This would make the interferometric configuration more suitable for signal processing techniques.

Chapter 10

Conclusions and Further Work

10.1 Conclusions from the Project Work

Unfortunately only the 5 objectives (Objectives: 1,2,3,5 and 6) of this project were fully accomplished, due to the the fact that many of the required components to build the sensors did not arrive until the end of the Semester 2 break and not enough time was left over to troubleshoot most of the selected sensors.

10.1.1 The Acousto-Optic Helix in the Basic and Interferometric Configurations

From the previous chapters discussion, it is very clear that the Acousto-Optic Helix and by extension any other similar sensors would benefit greatly when used in an Interferometry configuration. However only two performance characteristics were examined, more research and experimentation needs to be done in order to fully validate my conclusion.

10.1.2 The Extrinsic Fabry-Perot Interferometer and the Spliced Fibre Core Sensors

Unfortunately only the Acousto-Optic sensor was the only working sensor built. The other two sensors, Fabry-Perot and the Spliced Fibre Core, were constructed but due to time constraints there was not enough time to troubleshoot them to get them to work.

However, one possible reason as to why they did not end up working may be because of the ceramic mating sleeve used to hold the ferrules together. In the literature review the EFPI and the Spliced Fibre Core sensors had been constructed using special fabrication techniques. the ceramic mating sleeve could possible be to stiff and would then weaken any possible modulation of the sensors greatly.

In the case of the Spliced fibre hetero-core sensor from /citenameSun, they used a fusion splicer which would have the effect that at the point where the two fibres were fused there would have only been the outer layers of the optical fibre. Therefore their sensor would be more sensitive to acoustic waves.

10.2 Further Research and Development

Due to the large amount of different configurations, sensor designs and components. Many types of sensors were not even fully evaluated. There is still plenty of research left to fully cover the "Design and Development of Fibre Optic Microphones" topic.

One of the additional objectives of this project was to investigate into the signal processing aspects of fibre optics, much research has been done surrounding this topic and is a very promising prospect.

The other additional objective was to investigate multiplexing the sensors to make a microphone array, this object goes hand in hand with the previously mentioned one.

ENG 4111/2 Research Project

Project Specification

For:	James Ikin
Topic:	Design and Development of a Fibre-Optic Microphone
Supervisors:	Dr John Leis Dr David Buttsworth
Project Aim:	The purpose of this project is to investigate different methods of using optical fibre sensing with the aim of developing a Fibre Optic Microphone. Initially the project will investigate two different types of design of the fibre optic microphone. The first is the open light path technique where the light from the optical fibre exits the sensor and is reflected off a membrane that is vibrating due to acoustic pressure and is collected by another optical fibre. The second method is the closed light path where the light does not leave the optical fibre but instead is attenuated when pressure is applied to the sensor. After that a design will be developed and built with the intention of testing its suitability as an all optical microphone.

Program:

1. Research multiple methods of optical fibre sensing and signal processing techniques for data extraction.
2. Analyse and compare each method of sound sensing and data extraction for suitability.
3. Design a fibre-optic microphone using one or more of the design methods/techniques.
4. Test the design in the lab.
5. Analyse data from the experiments and evaluate the performance in terms of frequency response and sensitivity.

As time and resources permit:

1. Refine the design of the fibre optic microphone to yield better results in terms of frequency domain response, sensitivity and time domain response.

Agreed:

Student Name:	James Ikin
Date:	/3/2013

Supervisor Name:	Dr John Leis
Date:	/3/2013

Examiner/Co-Examiner:
Date:

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(n.d.).

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