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THE DESIGN AND APPLICATION OF OPTICAL SOURCES
FOR DISTRIBUTED FIBRE SENSING SYSTEMS

by

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This thesis investigates pulsed optical sources for distributed fibre sensing applications. Such sensors operate on the optical time domain reflectometry (OTDR) principle, and the source requirements depend on the desired sensing range, spatial resolution and nonlinear thresholds.

A number of Q-switched Erbium-doped fibre lasers at 1.5\(\mu\)m optimised for high peak powers and short pulse widths were designed and constructed. Experimental results were compared and contrasted with theoretical predictions.

The successful development of high peak power Q-switched fibre lasers at 1.5\(\mu\)m enabled the generation of broadband Stokes-shifted Raman pulses at the wavelength region of 1.65\(\mu\)m, with approximately 1.4W peak power and 45ns pulse width. Using both the 1.5\(\mu\)m and 1.65\(\mu\)m pulses, a novel technique referred to as delayed Raman amplification was demonstrated to increase the range of an OTDR sensor operating at 1.65\(\mu\)m. An increase in sensing dynamic range of 17.5dB was achieved. A Raman-based distributed temperature sensor was also developed using the 1.65\(\mu\)m source, and had a spatial and temperature resolution of 10m and 4\(^\circ\)C respectively, over a 10km sensing range. Both the OTDR and distributed temperature measurements potentially allow losses and temperature to be monitored in active communication links operating at 1.5\(\mu\)m.

A narrow linewidth amplified and gated semiconductor DFB source was constructed and its suitability for two spontaneous Brillouin-based distributed sensors investigated. The first sensor was a high spatial resolution distributed temperature sensor with a 35cm spatial resolution. The second sensor was a combined distributed strain and temperature sensor which used two Mach-Zehnder interferometers in series as filters to measure the Brillouin intensity and frequency shift. Temperature and strain resolutions of 4\(^\circ\)C and strain resolution of 290\(\mu\)\(\varepsilon\) were accomplished over a 15km sensing range.

Finally, investigations into using pulsed fibre sources compared to a semiconductor DFB source were performed. Both unidirectional Q-switched fibre ring lasers and short fibres Bragg grating lasers with stable and narrow linewidths were demonstrated. A stable, robust and high output power DFB Erbium/Ytterbium fibre laser was eventually selected to perform simultaneous strain and temperature measurements.
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Glossary

AOM Acousto-optic Modulator
ASE Amplified Spontaneous Emission
CRN Coherent Rayleigh Noise
CW Continuous Wave
DFB Distributed Feedback
DOFS Distributed Optical Fibre Sensor
DPMZ Double-pass Mach-Zehnder
DSS Distributed Strain Sensor
DTS Distributed Temperature Sensor
EDFA Erbium-doped Fibre Amplifier
EMI Electromagnetic Interference
ESA Excited State Absorption
FBGL Fibre Bragg Grating Laser
FWHM Full Width Half Maximum
LMA Large Mode Area
LPR Landau-Placzek Ratio
OFS Optical Fibre Sensor
OTDR Optical Time Domain Reflectometry
PZT Piezo-electric Transducer
SPMZ Single-pass Mach-Zehnder
WDM Wavelength Division Multiplexer
CHAPTER ONE

INTRODUCTION

1.1 Overview

1.1.1 Optical Fibre Sensors

Whilst developments in optical fibre technology have played a vital role in the telecommunications industry, the use of optical fibres is greatly expanding the fields of instrumentation and sensors. Optical fibre sensors (OFS) may be classified into extrinsic or intrinsic sensors [1]. If the variation in light propagation caused by the measurand occurs outside the fibre, it is classified as an extrinsic sensor. In intrinsic sensors, the influence on the propagation of light occurs whilst the light is travelling down the sensing fibre.

OFS have become increasingly popular due to the properties of fibres and unique design possibilities offered by the sensor itself. In particular, silica-based OFS have several advantages over other types of sensors [2]:

1) No interference with the external environment and chemically passive; important for high voltage or medical applications.
2) A high level of immunity from electromagnetic interference (EMI).
3) The attractive geometry of fibres. They are small, lightweight and compact, allowing flexibility in designing a whole range of sensors.
4) Capable of high sensitivity and large bandwidths.
5) The high reliability, durability and low component cost has provided an impetus for the development of commercial sensors.
1.1.2 Distributed Optical Fibre Sensors

A distributed optical fibre sensor (DOFS) allows continuous monitoring of the measurand as a function of distance down the fibre. This unique capability allows a single length of fibre to be used as opposed to an array of discrete sensors placed at specific points which utilises multiplexing schemes (quasi distributed optical fibre sensors).

There are many applications that require the distinct capabilities of distributed sensors. Some examples of their use are in:

1) Chemical/Process industries: the use of DOFS enables the monitoring and control of ovens, reactors and alarm systems.
2) Electrical industries: long range power cables can be monitored to prevent hot spots in power transformers and power cables from causing total destruction, rendering a potentially huge financial loss. They can also be used in real time thermal rating of power cables, which allows the current along the cable to be varied depending on the cable temperature.
3) Structural monitoring: a range of sensors may be used in large structures such as roads and dams to monitor weak points and defects before the structure fails, and in smart structures where the measurement of strain and temperature allows continuous monitoring of buildings, bridges and aircraft.

1.2 Objective and Outline of Thesis

The principal objective of this research is to first examine various novel pulsed sources, and issues pertaining to the use of these sources in distributed optical fibre sensors (DOFS), and then demonstrate their applications to distributed measurements such as attenuation, temperature and strain variations. With respect to these distributed sensors, the research aims to administer the fibre-based sources to increase the performance of the sensors in terms of sensing range, spatial resolution, measurand resolution, sensor operating wavelength and simultaneous parameter measurements. The current optical time domain reflectometry (OTDR) systems for splice/attenuation loss measurements typically operate with a range of tens of
kilometres using relatively long pulses (1µs), which results in low spatial resolution. Furthermore, they operate in the 1.5µm wavelength region which renders them inappropriate for monitoring active communication links. There is therefore interest in developing an OTDR system which may potentially achieve a dynamic range over 100km or more with a high spatial resolution (<10 metres), and possibly operate at a wavelength region different from that used by data transmission. An OTDR system demonstrated recently operating at 1.6µm reported measurements up to 20km with a spatial resolution of 100 metres[3]. In terms of distributed temperature sensors, the performances of both Brillouin and Raman-based systems have been improved in the recent years. Although commercially Raman-based sensors operate with a high spatial resolution of 1m over a 5km sensing range[4], the capability of distributed sensors based on Brillouin scattering to perform simultaneous measurement of both temperature and strain with low signal attenuation due to fibre losses is expected to result in Brillouin-based sensors substantially surpassing the range offered by Raman-based sensors. For the purpose of short to medium range monitoring of temperature, efforts have been made to reduce the spatial resolution, with the latest efforts demonstrating strain measurements with a spatial resolution of 0.4m but over a sensing length of 2.8m[5]. Efforts will be made in this research to perform sub-metre spatial resolution measurements for temperature with a much longer sensing range of >1km. By launching counter-propagating signals into both ends of the sensing fibre and measuring the Brillouin loss, the Brillouin frequency shift can be measured. It was demonstrated the Brillouin loss signal dependence on temperature at a distance of 22km over a 51km length may be measured[6]. However, there has only been limited literature describing Brillouin-based systems which truly measures distributed temperature/strain, one such demonstration was performed by Parker et. al with a spatial resolution of 40 and sensing range of 1200m[7]. With respect to this work, this research will also focus on efforts in performing simultaneous strain and temperature measurements for a sensing length >10km with a temperature resolution < 5°C, strain resolution <200µε and spatial resolution of 10m using narrow linewidth pulsed sources.

Chapter 2 provides an understanding of DOFS operating on the concept of optical time domain reflectometry (OTDR). In order to develop distributed temperature
sensors (DTS) and distributed strain sensors (DSS), the concept of basic OTDR is extended to utilise spontaneous Raman and Brillouin scattering. This chapter also provides a review of previous work in the field of DOFS. The current trend in DOFS is to be able to increase temperature and strain resolutions whilst maintaining a high spatial resolution. However, the maximum power that may be launched down a sensing fibre is limited by the onset of either stimulated Raman and Brillouin scattering, or self phase modulation accompanied by distortion of backscattered traces. The threshold powers for sensors as a function of different spatial resolution and sensing ranges and how these determine the characteristics of pulsed sources for each application are discussed.

Chapter 3 describes the operation of Q-switched fibre lasers and fibre amplifiers. A historical perspective of Q-switch lasers is briefly presented. The Erbium system is then described followed by a mathematical model of its behaviour in amplifiers and Q-switched lasers. A discussion of various Q-switching methods is also provided, followed by experimental investigation of the effects of varying fibre and cavity parameters such as fibre core size and mirror reflectivities with a view to optimise the laser performance.

In Chapter 4, the design of Q-switched lasers has been extended to generate a pulsed source operating in the wavelength region of 1.65µm. This source was utilised for two distributed sensing measurements at pump wavelengths of 1.65µm; an extended OTDR system using Raman amplification and a distributed temperature sensor. In a 1.65µm wavelength OTDR system, the use of overlapping signals from the 1.65µm source and a 1.55µm source enabled a novel method for increasing the dynamic range to 100km through a delayed Raman amplification process to be implemented. The 1.65µm Q-switched source has also been experimentally demonstrated for a 1.65µm distributed temperature sensor that allows the possibility of temperature monitoring in live optical transmission lines.

Chapter 5 describes experimental work of distributed fibre sensing that was performed using an amplified pulsed distributed feedback (DFB) semiconductor laser diode
source. The first sensor developed was a distributed temperature sensor with a high spatial resolution of less than 50cms at the operating wavelength of 1.5µm. This was achieved by using a source with a short pulse width and sufficient energy to generate the required backscattered signals. The second experiment was the development of a combined temperature and strain sensor. Issues governing the amplified pulsed DFB source and filtering requirements for both the Brillouin and Rayleigh backscattered signals are described. Two Mach-Zender interferometers in series were utilised as filters in the final design, providing a method of obtaining independent strain and temperature measurements by measuring both the Brillouin intensity and frequency shift variations.

Chapter 6 examines various novel fibre laser designs to compare their performances with the DFB semiconductor laser as sources for distributed strain and temperature sensing. A review of various cavity designs such as fibre ring cavities and short cavity in-fibre Bragg grating lasers is provided, followed by results from the experimental work. A combined strain and temperature sensor was demonstrated using one of these narrow linewidth sources.

Chapter 7 concludes and summarises the findings of preceding chapters. In this final chapter, the overall conclusions of the research are provided, and future directions in this field of study are outlined.

The work described in this thesis consists primarily of the author’s own research, with collaborations and discussions with other members within the Optoelectronics Research Centre at the University of Southampton. Materials used from other sources to illustrate or explain a particular topic are referenced.
1.3 References


CHAPTER TWO

DISTRIBUTED OPTICAL FIBRE SENSING SYSTEMS

2.1 Introduction

In a distributed fibre sensor, a measurand imposes a variation in the interrogating signal as a continuous function of distance, with its accuracy limited by the sensor’s spatial resolution. There are many methods available for performing distributed sensing, with the current techniques of optical time domain reflectometry (OTDR) being the most popular. In these sensors, a pulse of light is transmitted down the fibre and the light which is backscattered within the numerical aperture of the fibre is measured. The time between sending the pulse of light into the fibre and detecting the backscattered light provides a measure of the distance along the fibre. The physical characteristics of the backscattered light can provide valuable information on fibre parameters such as optical attenuation, temperature and strain. The scattering mechanisms and their dependence on various measurands can be classified into that of Rayleigh, Raman and Brillouin scattering, each of which will be described in the following sections.

2.2 Rayleigh Scattering

Rayleigh scattering results from random inhomogeneities of the density and compositional variations that are frozen into optical fibres during the fabrication process. These variations cause refractive index fluctuations, resulting in a fraction of the scattered light lying within the numerical aperture of the fibre being guided in the opposite direction to that of the incident light. It is an elastic scattering mechanism because there is no difference in the frequency between that of the incident light and the backscattered light. Rayleigh scattering is an intrinsic loss mechanism, and in the low-loss region of an optical fibre, Rayleigh scattering forms the dominant loss. It
exhibits a wavelength dependence proportional to $1/\lambda^4$ and the scattering coefficient is given by [1]:

$$\gamma_R = \frac{8\pi^3 n^8 p^2 k T \beta_T}{3\lambda^4} \left[ \beta_T - \left( \rho v_A^2 \right)^{-1} \right]$$

(2-1)

where $\lambda$ is the optical pump wavelength, $n$ is the refractive index, $p$ is the average photoelastic coefficient, $v_A$ is the acoustic velocity of glass, $\rho$ is the density of glass, $\beta_T$ is the isothermal compressibility at the fictive temperature $T_F$ and $k$ is the Boltzmann constant.

In an OTDR sensor, the backscattered light decays exponentially with distance/time as the pulse travels down the sensing fibre due to Rayleigh scattering. This backscattered power detected back at the input of the fibre as a function of time $t$ is given by the relation [2]:

$$P_R = \frac{1}{2} P_{in} W_o \gamma_R \nu_g S \left( \exp^{-\nu_g \gamma t} \right)$$

(2-2)

where $P_{in}$ is the input optical power, $W_o$ is the input pulse width, $\nu_g$ is the group velocity of the pulse in the fibre, $\gamma_R$ is the Rayleigh scattering coefficient and $S$ is the capture fraction of the backscattered signal within the numerical aperture. It is assumed that the sensing fibre consists of negligible variations in fibre geometry and composition.

OTDR systems based on Rayleigh scattering have been successfully exploited commercially as a fibre diagnostic tool for the detection of fibre attenuation and damage. However, with conventional silica fibres as sensing fibres, these systems are unable to perform measurements related to measurands such as strain and temperature. A demonstration of using Rayleigh backscattered measurements for distributed temperature sensing has however been performed using liquid-core fibres [3].
2.3 **Raman Scattering**

To appreciate the origin of Raman scattering, an outline of vibrational modes in molecular structure is required. In a unit cell that contains two different kinds of atoms, or two similar atoms occupying non-equivalent positions, there exist two separate groups of vibrational modes. In an acoustic mode, the motion may be described as two ions in the cell moving in phase with one another, although neighbouring cells may be 180° out of phase, whereas in an optical mode, the motion is such that two ions within a basic cell are moving 180° out of phase with each other.

The name optical mode arises because in crystals, these modes generate electrical polarisation and can therefore be excited by light, with the incident light being strongly absorbed. From the dispersion relation derived from the harmonic equation, it can be found that these optical modes lie at frequencies higher than that of the acoustic branches and the dispersion is much weaker [4]. It is these optical modes which cause the inelastic Raman scattering process. The peak of Raman gain in fused silica occurs at 440cm⁻¹ (approximately 13THz for the pump wavelength of 1.5µm) away from the wavelength of the incident light [5].

In silica glass, Raman scattering occurs over a wide range of frequencies. This is due to the fact that the molecules in a glass lattice are non-crystalline or amorphous in nature, leading to different vibrational energies for different groups of molecules within the glass structure. Figure 2-1 illustrates the process of both Stokes and anti-Stokes Raman scattering. With an incident photon of energy $h\nu_0$, the molecule in energy level $E_1$ is excited to the virtual state $E_3=E_1+ h\nu_0$, and decays to states $E_2$. The emitted Stokes photon has a lower frequency than the incident photon. In Raman anti-Stokes scattering, the photon is excited from initial energy state $E_2$ to virtual state $E_4$, and decays to energy level $E_1$. The emitted anti-Stokes photon has a higher frequency than the initial photon frequency. The population density of states $E_1$ and $E_2$ are governed by the phonon distribution that varies with increasing/decreasing temperature. It is this thermal sensitivity which permits the use of Stokes/anti-Stokes Raman backscattered signals in distributed temperature sensing systems. The
The probability of the anti-Stokes Raman scattering is smaller than the Stokes scattering because the molecule loses energy requiring that it is in an excited state initially, causing a smaller backscattered power than the corresponding Stokes Raman scattering.

It is possible to obtain an absolute temperature measurement by taking the ratio of the Stokes to anti-Stokes components. From the temperature dependence of the spontaneous Raman scattering, the temperature sensitivity can be expressed by:

\[
\frac{1}{R(T)} \frac{\partial R(T)}{\partial T} = \frac{hc\nu_{R}}{kT^2} \quad (2.3)
\]

![Figure 2-1: Process of Raman Stokes/anti-Stokes scattering](image-url)
where $c$ is the velocity of light in vacuum, $T$ is the temperature and $\hat{\nu}_R$ is the separation between the pump and scattered wavelengths expressed in wavenumbers. In silica fibres, the percentage change in intensity due to temperature variations using $T=293K$ and $\hat{\nu}_R = 44000m^{-1}$ is approximately 0.8%/K.

2.4 Raman-based Distributed Sensing Systems

Although Rayleigh scattering based systems using liquid core fibres are capable of performing distributed temperature sensing measurements, spontaneous Raman scattering based systems have the notable benefit of using reliable and cheap conventional silica fibres as the sensing element. This has resulted in Raman-based distributed sensors being developed rapidly into commercial reality. The attractiveness of Raman-based sensors is enhanced from the relative ease of separating the Rayleigh and Stokes/anti-Stokes components due to their wide frequency difference (~13THz).

In the initial demonstration of such a Raman-based sensor, a pulsed argon-ion laser was used as the pump to obtain the anti-Stokes/Stokes backscattered light. The anti-Stokes-Stokes ratio then provided an absolute temperature measurement, after a correction was made for the different attenuation at the anti-Stokes and Stokes wavelengths [7]. Further research into Raman-based systems aimed at achieving both better temperature resolutions and higher sensing spatial resolutions, has resulted in improvements from a 7.5m spatial resolution [8] down to 1m [9] with a temperature resolution of 1°C.

There are also applications that require a very high spatial resolution (<0.5m) over a reasonable sensing range, such as the monitoring of hot spots in steam pipes in power plants. The technique based on digital detection schemes using photon counting has been utilised in Raman-based distributed temperature sensors to achieve both a high spatial resolution combined with a reasonable temperature resolution [10]. Although a spatial resolution of 10cm and temperature resolution of 5°C was achieved, the experimental set-up lacked the versatility to allow sensing over a longer range due to the high repetition rate of the Nd:YAG mode-locked laser.
2.5 Brillouin Scattering

In the case of Brillouin scattering, it is acoustic phonons that participate in the scattering process. Spontaneous Brillouin scattering results from the interaction between an incoming incident light wave or pump wave and thermally generated acoustic waves in the medium. A periodic modulation of the dielectric constant and hence refractive index in the medium is generated due to the density variations produced by the acoustic wave in the material. Only when the incoming optical wave is phase matched to the acoustic wave, Bragg reflection occurs satisfying Equation (2-4) and results in spontaneous Brillouin scattering:

\[ 2n\lambda_A \sin \theta = \lambda_p \]  

(2-4)

where \( n \) is the refractive index in the fibre, \( \lambda_A \) and \( \lambda_p \) are the acoustic and pump wavelengths respectively, \( \theta \) is the angle between the incident and scattered light, as shown in Figure 2-2. Only a small fraction of the incident wave is converted to the scattered light with a shifted frequency (~15dB smaller than the corresponding Rayleigh signal).

\[ \lambda_A \]

\[ \lambda_p \]

\[ \lambda_i \]

\[ \lambda_2 \]

\[ \theta \]

\[ \theta \]

Travelling acoustic wave

Figure 2-2: Process of Brillouin scattering from an acoustic wave

From Equation (2-4), the Brillouin frequency shift is equal to the acoustic frequency \( \nu_a \) and is dependent on the pump wavelength and scattering angle. It has the expression:
\[ v_n = \frac{2nv_a}{\lambda_p} \sin \theta \]  \hspace{1cm} (2-5)

where \( n \) is the refractive index, \( v_a \) is the acoustic velocity, and \( \lambda_p \) is the pump wavelength. In optical fibres, only scattering in either the forward and backward directions is guided. As a result, the Brillouin frequency shift is maximised when the light is scattered in the backward direction or 180° with respect to the direction of incident wave and Equation (2-5) becomes:

\[ v_B = \frac{2nv_a}{\lambda_p} \]  \hspace{1cm} (2-6)

The frequency shift of the backscattered signal is approximately three orders of magnitude smaller than for Raman scattering corresponding to the much smaller acoustic phonon energy involved in Brillouin scattering. Using typical values for silica fibres of which \( n = 1.46 \) and \( v_a = 5960 \text{ms}^{-1} \), the shift is approximately 11.2GHz for a pump wavelength of 1550nm wavelength, which makes separation of the Brillouin from the Rayleigh signal more difficult.

The Brillouin scattering coefficient has a similar form to the Rayleigh scattering coefficient \[ ] , and is given by:

\[ \gamma_B = \frac{8\pi^3 n^2 p_1^2 kT (\rho v_s^2)^{-1}}{3\lambda^4} \]  \hspace{1cm} (2-7)

where the variables are defined as in Equation (2-1). However, there is a fundamental difference from Rayleigh scattering in that Brillouin scattering is caused by thermally generated acoustic waves, and it is this that provides the temperature and strain dependence.
Essentially, there are three fundamental parameters of Brillouin scattering which
needs to be considered for distributed strain and temperature measurements; the
Brillouin natural linewidth $\Delta \nu_B$, the Brillouin frequency shift $\nu_B$ and the Brillouin
scattering coefficient. Unless otherwise stated, strain as described in the ensuing
discussions refers only to the longitudinal strain induced by stress along the fibre
length $[11]$. The Brillouin natural linewidth $\Delta \nu_B$ provides a measure of the phonon lifetime. It has
been demonstrated that this linewidth does not vary with strain and exhibits only a
small temperature-dependence of approximately -0.1MHz/K $[12]$, and would
therefore be of limited use for strain or temperature variation measurements.

The Brillouin frequency shift variation with temperature and strain follows from
Equation (2-6). Although there is a linear increase in refractive index with increasing
temperature or strain as can be found in values taken from Wray and Neu $[13]$, it is
the contribution from the variation of acoustic velocity that dominates the variation in
Brillouin frequency shift. Using data from Bansal and Doremus $[14]$, approximations
to the change in the Brillouin frequency shift due to acoustic velocity with strain and
temperature may be evaluated. These shifts range from 10.978GHz to 11.026GHz
over 1000$\mu$e of applied strain, and from 10.978GHz to 11.66GHz over a temperature
increase of 1000K. It has also been experimentally determined that the frequency shift
increases linearly with strain $[15]$ and temperature $[16]$:

$$\nu_B(\varepsilon) = \nu_B(0)[1+C_S \varepsilon] \quad (2-8)$$

$$\nu_B(T) = \nu_B(T_R)[1+C_T(T-T_R)] \quad (2-9)$$

where $C_S$ and $C_T$ are the proportional constants of strain and temperature respectively.
Unlike the variation of Brillouin frequency shift, the variation of the scattering
coefficient with temperature due to the acoustic velocity is minimal, with a variation
of less than 1% for the temperature range from 290K to 500K. As a result, any
changes in the scattering coefficient can be considered to be caused primarily by its
direct dependence on temperature. The temperature sensitivity of the scattering coefficient has been experimentally and theoretically determined to be approximately 0.3%/K at the wavelength of 1.5\(\mu\)m\[17\]. There is a slight variation in the scattering coefficient with applied strain, due to the change in fibre elastic properties\[18\].

2.6  Brillouin-based Distributed Sensing Systems

There have been reports on distributed sensing systems utilising the Brillouin frequency shift with strain\[15\] and temperature\[16\] variations for over a decade. The main approaches can generally be classified as either the Brillouin amplification/loss technique or the Brillouin OTDR backscatter technique.

2.6.1  Brillouin Amplification/Loss Technique

The technique of Brillouin amplification/loss was first described by Horiguchi \textit{et al}. for distributed strain measurement in 1990\[19\] and was also known as the Brillouin Optical Time Domain Analysis (BOTDA). The principle is based on the interaction between a pulsed source and a counter-propagating continuous wave (CW) source. In a Brillouin amplification system, the pulsed source acts as a pump wave at a frequency \(\nu_2\), and the energy is transferred from the pulse to the counter-propagating CW probe wave at \(\nu_1\) provided the difference between the two waves is equal to the Brillouin frequency shift, \(\nu_B\). The initial probe signal acts to seed the transfer of energy from the pump wave to the probe wave and becomes a stimulated process, when both these waves interfere to reinforce the presence of the acoustic wave modulating the material dielectric constant. The intensity of the BOTDA signal is then detected and processed as a function of time, allowing regions for which there is significant interaction between the pump and probe waves to be determined. If the frequency difference between the two lasers is known, it is possible to determine the frequency shift due to variations in either temperature or strain.

Several methods have been demonstrated to improve the technique of BOTDA. An increase in the sensing range of a Brillouin amplification system has been achieved by utilising a 1.55\(\mu\)m wavelength source in conjunction with Erbium-doped fibre
amplifiers (EDFA) as compared to earlier systems based at 1.32\(\mu m\) [20]. A second technique employed the Brillouin loss mechanism [21]. In this case, the pulsed source acted as the probe wave and the CW wave was the pump wave. Again, there will be a transfer of energy between the two waves if their frequency difference is the same as the Brillouin frequency shift. However, the pulse was now amplified rather than depleted. For distributed measurements over long sensing fibre distances, the Brillouin loss method is favoured over the Brillouin gain technique, particularly if the majority of the sensing fibre is at a constant strain/temperature. In such a situation, the higher frequency pump pulse energy will be rapidly transferred to the lower frequency CW signal, whereas in the case of Brillouin loss, the energy is transferred from the lower frequency CW signal to the higher frequency pump signal. Recently, there have been efforts to operate a pump-probe Brillouin amplification system by single-ended measurements using a single laser source. Probe pulses were generated by modulating a Mach-Zehnder electro-optic modulator (EOM) at the frequency of the Brillouin shift for a pulse duration, and the pump pulse was created by gating a laser source signal. Amplification occurs when the probe and pump pulses overlap at a specific location along the sensing fibre, and this process may be repeated for every position along the sensing fibre [22].

### 2.6.2 Brillouin Backscatter Detection Systems

Early Brillouin backscatter detection measurements were performed using coherent self-heterodyne detection, otherwise known as the Brillouin Optical Time Domain Reflectometry (BOTDR). This was performed using a fibre pigtailed laser diode source, Erbium-doped fibre amplifiers and a frequency translator circuit [23]. In this scheme, a coherent source was divided into both a signal and reference circuit. In this scheme, a coherent source was divided into both a signal and reference circuit. The CW probe was pulsed and then translated in frequency whilst being amplified to reduce losses until a frequency shift approximately equal to the Brillouin frequency shift was achieved. The spontaneous Brillouin backscatter signal was then mixed with the local reference oscillator signal and the heterodyne beat frequency is down converted in frequency such that it lies within conventional heterodyne receiver bandwidths.
In this research, another form of backscatter technique is utilised whereby distributed sensing measurements are made using the Landau-Placzek ratio. This technique was first used to measure the temperature variation profile in a length of conventional silica sensing fibre[17]. This direct detection technique determines the temperature profile along a length of optical fibre by measuring the intensity of the Brillouin backscattered light that is captured within the numerical aperture of the fibre. To compensate for variations in intensity due to local attenuation in the sensing fibre such as splice and bend losses, the measurement is normalised using a Rayleigh reference signal which is insensitive to temperature [17] and strain [24]. The ratio of the Rayleigh signal to the Brillouin signal is then calculated and this is known as the Landau-Placzek ratio (LPR). Using Equations (2-1) and (2-7), the LPR may be expressed as:

$$\text{LPR} = \frac{\gamma_R}{\gamma_B} = \frac{T}{T} \left( \rho v_B \beta_T - 1 \right)$$  

(2-10)

By measuring the Brillouin frequency shift as well as the intensity variations in the backscattered signal using the LPR, both temperature and strain variations can be separately resolved. Equation (2-11) shows the relationship between the change in Brillouin frequency shift and backscattered power with strain and temperature:

$$\begin{bmatrix} \Delta v_B \\ \Delta P_B \end{bmatrix} = \begin{bmatrix} C_{v\text{e}} & C_{v\text{T}} \\ C_{P\text{e}} & C_{P\text{T}} \end{bmatrix} \begin{bmatrix} \Delta \varepsilon \\ \Delta T \end{bmatrix}$$  

(2-11)

where $\Delta v_B$ is the Brillouin frequency shift, $\Delta P_B$ is the Brillouin backscattered power, $\Delta \varepsilon$ is the strain applied to the sensing fibre and $\Delta T$ is the temperature variation of the fibre. The constants have previously been determined to be $C_{v\text{e}} = 0.048 \text{MHz}/\mu\varepsilon$ and $C_{v\text{T}} = 1.1 \text{MHz}/K$ [25] for the Brillouin frequency shift dependencies on strain and temperature, and $C_{P\text{e}} = 0.32\%/K$ [17] and $C_{P\text{T}} = -9.03 \times 10^{-4}\%/\mu\varepsilon$ [24] for the Brillouin backscatter power dependencies on strain and temperature at a pump wavelength of 1.5µm. The two variables which are variations in strain and
temperature can be resolved by taking the inverse matrix of the above equation provided \( C_{\nu \epsilon}C_{\rho T} \neq C_{\nu \epsilon}C_{\rho \epsilon} \), thereby allowing simultaneous distributed temperature and strain monitoring of practical structures. This technique was utilised by Parker et al. to demonstrate a combined strain and temperature sensor over a range of 1200m in 1997 \[25\].

2.7 Comparison between Raman-based and Brillouin-based Distributed Sensors

There is currently a strong motivation to pursue research in Brillouin-based sensors as compared to Raman-based sensors. This is attributed to several advantages which Brillouin-based distributed fibre sensors offer over Raman-based sensors. The most important advantages are:

1) Distributed sensing based on Brillouin scattering allows the ability to perform simultaneous strain and temperature sensing, whilst spontaneous Raman scattering is essentially insensitive to strain variations.

2) The Brillouin backscattered signals are almost two orders of magnitude larger than the Raman backscattered signals, resulting in the ability to perform backscattered measurements with a higher signal-to-noise ratio using Brillouin scattering for equal amounts of launched pump powers in spite of the lower temperature sensitivity of the Brillouin signal.

3) The small frequency separation between the Brillouin backscattered signal and the Rayleigh signal (~11GHz for 1550nm pump source) facilitates computation of optical fibre attenuation.

4) Measurements of the Brillouin backscattered signal may be made with both the pump and backscattered signals lying in the low-loss third telecommunications window.

5) Operation at the low loss wavelength around 1.5\( \mu \)m allows incorporating the use of Erbium-doped fibre amplifiers (EDFA) for optical pre-amplification of the backscattered signals.
However, there are also some disadvantages of Brillouin-based systems compared to Raman-based systems:

1) Due to the small frequency separation between the Rayleigh and Brillouin signals, a narrow linewidth source is needed to allow the Brillouin signal to be resolved from the Rayleigh signal.

2) For Brillouin-based systems, a narrow bandwidth optical filter has to be designed to separate the Rayleigh from the Brillouin signal, whereas simple filters (bulk filters/wavelength division multiplexed couplers) are used for Raman-based systems.

3) The narrow linewidth sources used in Brillouin-based systems generate Coherent Rayleigh Noise (CRN) which degrades the measurand resolution. This issue is addressed in Chapter 5.

Although the initial motivation behind the investigation of spontaneous Brillouin scattering for sensing purposes was to enable a combined strain and temperature distributed sensor, the advantages offered by Brillouin-based measurements have proved to be of practical significance. As a result, distributed temperature sensors based on spontaneous Brillouin scattering have provided improved performance over Raman-based sensors for certain applications.

### 2.8 Nonlinearity Thresholds

In designing an OTDR-based distributed fibre sensor, it is desirable to launch the highest energy possible down the sensing fibre to obtain a large backscattered signal. Although recent advances have led to the availability of high peak power sources, the maximum peak power which can be launched down the sensing fibre is limited by the need to avoid nonlinear effects, such as stimulated Raman scattering, stimulated Brillouin scattering and self-phase modulation. In silica fibres, the presence of an intense time-varying electromagnetic field gives rise to a time-varying electrostrictive strain, and is capable of generating acoustic waves in the fibre. The presence of the acoustic waves would then modulate the optical dielectric constant of the fibre and
cause a fraction of the pump photon energy to be reflected in the opposite direction. The exchange of energy between the pump and probe waves to generate the Brillouin signal occurs with a frequency difference equal to the acoustic frequency. When both the Stokes shifted signal and the incoming pump signal interfere to reinforce the acoustic wave, stimulated scattering occurs. For stimulated Raman scattering, the role of molecular vibrations substitutes that of acoustic vibrations.

2.8.1 Stimulated Raman Scattering

When the input pulse pump power approaches a certain threshold, stimulated Raman amplification will occur and the pump power is transferred to the Stokes signal. The threshold power at which this effect occurs has been defined as the input pump power at which the output Stokes power equals the residual pump power at the fibre output [26] and can be expressed by:

$$P_0^{\text{th}} = \frac{16 \cdot A_{\text{eff}}}{L_{\text{eff}} \cdot g_R}$$ \hspace{1cm} (2-12)

The effective area is calculated to be approximately 60μm² for conventional silica fibres [27], and the effective length is given by:

$$L_{\text{eff}} = \frac{1}{\alpha_p} \left[ 1 - \exp(-\alpha_p L) \right]$$ \hspace{1cm} (2-13)

where $\alpha_p$ is the absorption of the pump pulse in the sensing fibre and $L$ is the length of the sensing fibre. As the pump and Stokes wavelengths are separated by a large frequency difference (~13THz), another effect becomes dominant and modifies the effective length of Equation (2-12) for short pump pulse widths (<40ns). This effect arises from dispersion and causes the pump and Stokes pulses to separate after a certain distance down the sensing fibre and the two pulses cease to interact [28]. This distance is given by:
where \( W \) is the pulse width, \( D \) is the fibre dispersion coefficient (17 ps km\(^{-1}\) nm\(^{-1}\)) and \((\lambda_s-\lambda_p)\) is the wavelength separation between the pump and Stokes light. The consequence of this effect is that the stimulated Raman threshold increases significantly for short pulses. This may be seen in Figure 2-3 (a), where the peak threshold power increases to 2.5 W for a pulse width of 10 ns, for a sensing range of 20 km. The dotted lines extending from Figure 2-3 (a) are used to minimise the discontinuity at the point where the walk-off length or effective length is dominant in determining the threshold peak power.

![Figure 2-3: Threshold peak power for stimulated Raman process for various pulse widths for (a) 20 km of fibre (b) 2 km of fibre](image)

However, if the sensing range considered is short (less than 3 km), the effective length then dominates in Equation (2-12) as can be seen in Figure 2-3 (b). As a result, the threshold peak power remains constant at 7.9 W even for short pulse widths, for a sensing range of 2 km.
2.8.2 Stimulated Brillouin Scattering

When the incident light beam is of a high intensity and narrow linewidth, a much stronger backscattered signal due to the reinforcement of the acoustic waves by the process of electrostriction between the pump beam and the thermally generated acoustic waves occurs and is known as stimulated Brillouin scattering. The expression for the threshold power for stimulated Brillouin scattering effects is similar to that for stimulated Raman scattering \[26\] and is expressed as:

\[
P_{th}^{B} = \frac{2\cdot A_{eff}}{L_{eff} \cdot g_{B}}
\]

where \(A_{eff}\) is the effective fibre cross-section area, \(L_{eff}\) is the effective interaction fibre length and \(g_{B}\) is the Brillouin gain coefficient. However, in the case of Brillouin scattering, the effective length is given by half the pulse width, as both the pump wave and Brillouin backscattered wave are counter-propagating. For input pulses with narrow linewidths and pulse widths greater than approximately 400ns, stimulated Brillouin scattering occurs prior to stimulated Raman scattering. This is due to the increased interaction length between the counter-propagating pulses and the large magnitude of Brillouin gain coefficient \((5 \times 10^{-11} \text{m/W})\) compared to the Raman gain coefficient \((1 \times 10^{-13} \text{m/W})\). For many applications where a spatial resolution of less than 10m is required (pulse width of 100ns), stimulated Raman scattering will occur at lower pulse powers than stimulated Brillouin scattering.

2.9 Choice of DOFS Operating Wavelengths

There has been intense research of DOFS which has used operating wavelengths of 1.0\(\mu\)m and 1.5\(\mu\)m. The use of a specific wavelength depends on several factors. The dominant advantage of 1.5\(\mu\)m systems lies in the fact that the signals lie in the low-loss attenuation window, which is in the order of 0.2-0.3dB/km. At lower wavelengths, the Rayleigh scattering increases, and attenuation of signals reach as high as 1dB/km at 1.0\(\mu\)m.
Considering a source input of 500mW and pulse width of 30ns for a sensing range of 20km, the Rayleigh backscattered signals using both 1.0µm and 1.5µm pump sources are shown in Figure 2-4, ignoring non-linear effects. The backscattered power using a 1.0µm source is seen to be approximately 6 times higher than that using a 1.5µm source at the front end of the sensing fibre, but quickly suffers a higher signal attenuation and beyond 3km, the backscattered Rayleigh signal is higher for the 1.5µm source.

![Graph showing Rayleigh backscattered signals for a sensing range of 20km using a 0.5W peak power pulse and 30ns pulse width at a pump wavelength of (a)1.0µm and (b)1.5µm](image)

**Figure 2-4**: Rayleigh backscattered signals for a sensing range of 20km using a 0.5W peak power pulse and 30ns pulse width at a pump wavelength of (a)1.0µm and (b)1.5µm

However, taking into account the maximum amount of input power permitted prior to stimulated Raman scattering which is the dominant nonlinear effect for using 30ns pulses, Figure 2.5 shows the backscattered plots for both these wavelengths again. The maximum backscattered power achieved using a 1.0µm pump source is now only approximately 3.5 times more than that using a 1.5µm pump source, using a maximum pump power of 0.77W at 1.0µm and 1.18W at 1.5µm.
Figure 2-5: Rayleigh backscattered signals at the threshold of nonlinear effects for a pump wavelength of (a) 1.0μm and (b) 1.5μm

Regarding detector technology, there are issues related to the photoreceiver sensitivity/gain that limits the sensing range, and the bandwidth that limits the minimum spatial resolution of the sensor. Previously, shorter wavelength sensors (operating at 1.0μm) have benefited from the low noise Silicon technology as compared to Germanium detectors. However, detector technology for near infrared wavelengths has shifted towards using Indium Gallium Arsenide (InGaAs) materials. Currently, examples of optical receivers operating at both 1.0μm and 1.5μm are able to reach noise equivalent powers (NEP) as low as 3.3pW/√Hz and 2.5pW/√Hz for both wavelengths respectively, for a receiver bandwidth of 125MHz[29]. As a result, receivers at both these wavelengths have comparable performances.

Another effect that needs consideration before selecting the operating wavelength is dispersion. A pulsed source with a broad bandwidth will undergo temporal pulse broadening as it travels down the sensing fibre. At the operating wavelengths of 1.0μm and 1.5μm, typical fibre dispersion values are 40ps/(km.nm) and 17.5ps/(km.nm) respectively[30].
For spontaneous Brillouin scattering based sensing systems, the backscattered Brillouin signals generated are very close to the pump wavelength, and can therefore be assumed to have similar dispersion. For spontaneous Raman scattering based systems, the detected anti-Stokes signal will be generated at wavelengths of 0.95µm and 1.43µm using pump sources of 1.0µm and 1.5µm, leading to dispersion parameters of 52ps/(km.nm) and 15ps/(km.nm) respectively [30].

The parameters for pulse broadening due to fibre dispersion using pump wavelengths of 1.0µm and 1.5µm are given in Table 2-1 for the pump wave travelling down the sensing fibre, and Brillouin, Raman and Rayleigh backscattered signals. The broadening is calculated for sensing ranges of 1km and 30km at the wavelength of 1.5µm, and for 1km and 3km at the wavelength of 1.0µm due to the high fibre attenuation at this wavelength. The source bandwidth considered in the case of Rayleigh and Raman scattering is 5nm, whereas a narrow linewidth of 0.025nm was used for calculating the Brillouin backscattered dispersion. The Brillouin backscattered signal is assumed to have a similar broadening as that of the pump wave, neglecting the small broadening of the Brillouin natural linewidth (~50MHz).
<table>
<thead>
<tr>
<th>Scattering mechanism</th>
<th>Typical Bandwidth</th>
<th>Pump Operating Wavelength</th>
<th>Sensing Range</th>
<th>Dispersion (Outward travelling pulse)</th>
<th>Dispersion (Backscattered signal)</th>
</tr>
</thead>
<tbody>
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<td>Brillouin scattering</td>
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<td>1km</td>
<td>1x10^{-3} ns</td>
<td>1x10^{-3} ns</td>
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<td></td>
<td></td>
<td>3km</td>
<td>3x10^{-3} ns</td>
<td>3x10^{-3} ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5µm</td>
<td>1km</td>
<td>4.375x10^{-4} ns</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30km</td>
<td>13.12x10^{-3} ns</td>
<td>13.12x10^{-3} ns</td>
</tr>
<tr>
<td>Raman scattering</td>
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<td>1.0µm</td>
<td>1km</td>
<td>0.2 ns</td>
<td>0.26 ns</td>
</tr>
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<td>3km</td>
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<td></td>
<td>1.5µm</td>
<td>1km</td>
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<td>0.075 ns</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>30km</td>
<td>2.625 ns</td>
<td>2.25 ns</td>
</tr>
<tr>
<td>Rayleigh scattering</td>
<td>5nm</td>
<td>1.0µm</td>
<td>1km</td>
<td>0.2 ns</td>
<td>0.2 ns</td>
</tr>
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<td>3km</td>
<td>0.6 ns</td>
<td>0.6 ns</td>
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<tr>
<td></td>
<td></td>
<td>1.5µm</td>
<td>1km</td>
<td>0.0875 ns</td>
<td>0.0875 ns</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>30km</td>
<td>2.625 ns</td>
<td>2.625 ns</td>
</tr>
</tbody>
</table>

**Table 2-1: Pulse broadening for different pump wavelengths for the pump signal, Brillouin and Raman backscattered signals**

From Table 2-1, it is observed that for both 1.0µm and 1.5µm operating wavelengths, the Brillouin backscattered signals have encountered negligible dispersion even at sensing ranges of 3km and 30km respectively. However, the broadband source used to obtain the Rayleigh reference signal causes a total dispersion (forward travelling and backscattered signals) of 1.2ns and 5.2ns for the maximum sensing ranges considered at 1.0µm and 1.5µm respectively. This implies that the spatial resolution is limited to approximately 0.12m for 1.0µm Brillouin-based sensors and approximately 0.52m at 1.5µm. For Raman-based sensors, the spatial resolution limitation is relatively similar to that for the broadband source used to obtain the Rayleigh reference signal. This indicates that using 1.5µm sources, the sensor spatial resolution are almost identical for both Raman and Brillouin-based systems, achieving a high spatial resolution and low signal attenuation.
2.10 Conclusions

This chapter has provided an outline of the different scattering mechanisms of Rayleigh, Raman and Brillouin scattering and their use in distributed sensing applications. Characteristics of the sensor requirements are limited by factors such as the maximum source peak power prior to the onset of nonlinear effects, sensor spatial resolution as dictated by the source pulse width and sensor operating wavelengths. Distributed sensing systems based on various detection techniques have also been described, and their use in strain and temperature measurements. It is the purpose of this thesis to describe work that has been performed to develop sources for distributed temperature and strain sensing, and long range OTDR sensors.
2.11 References


[9] York Sensors Ltd, DTS 80 system


CHAPTER THREE

ERBIUM-DOPED FIBRE AMPLIFIERS AND Q-
SWITCHED LASERS

3.1 Introduction to Fibre Amplifiers and Lasers

Optical amplifiers were first developed to compensate for the loss caused by fibre attenuation whilst avoiding the need for electronic repeaters. Adopting systems that incorporate electronic repeaters limits the operating bandwidth to tens of gigahertz due to the need to convert the signal from the optical to electronic domain to amplify the signal, and then convert back to the optical signal. In the 1980’s, interest shifted from using semiconductor laser amplifiers to fibre-based amplifiers due to practical problems such as coupling losses, polarisation sensitivity and interchannel cross-talk encountered in semiconductor amplifiers. The development of the Erbium doped fibre amplifier (EDFA) proved to be a successful active fibre device, due to the broadband gain of the Erbium ion in the glass host[1] and the operating wavelength of 1.55 µm corresponding to the low loss transmission window of standard silica fibres.

Although the early use and research of EDFAs have focused on optical communication applications, amplification of a signal source is also useful in long range distributed fibre sensing. This is particularly true if narrow linewidth signal sources are required in sensing applications, as the majority of available sources typically have continuous wave (CW) powers of a few mW or less. The operation of a sensing system requires pulsed signals as explained in Chapter 2, therefore modulation of the CW source is necessary. This provides additional justification for the use of EDFAs due to the relatively high losses of an external modulator and its associated optics. The successful use of EDFAs as an amplification medium has also led to the development of fibre lasers.
The first fibre laser was demonstrated in 1961 using a Nd-doped fibre with a 300-µm core diameter[2]. One main advantage provided by fibre lasers is efficient lasing due to the guided nature and small dimensions of the gain medium. This allows a high concentration of pump intensity with low pump powers and long interaction lengths of guided light. The fibre geometry also allows efficient heat dissipation in the fibre core. However, fibre laser research soon concentrated on the Erbium-doped fibre laser (EDFL), which operated at 1.55µm corresponding to the wavelength for minimum attenuation in silica fibres, and was first demonstrated in 1986[3]. The attraction for EDFLs has increased with the production of reliable pump sources at the excited state absorption (ESA) free wavelength of 980nm[4] which is discussed in more detail in the following section. EDFLs provide an attractive approach for the development of both narrow linewidth and broadband sources for fibre sensing applications, and has the advantages of being compact and fibre compatible.

The long metastable lifetime of Erbium ions (~10ms)[3] makes it ideal for energy storage as compared to the lifetime of Neodymium ions (~250µs)[6]. This energy storage capability may be efficiently utilised in Q-switched lasers. Q-switched fibre lasers play an important role in fibre sensing applications, providing pulses with high power and short pulse widths, without the need of further amplification with an EDFA. The development of broadband Q-switched lasers is described later in this chapter. Another important objective of utilising EDFLs for fibre sensing applications lies in the development of narrow linewidth sources for the purpose of strain sensing based on Brillouin scattering. Previous work on Brillouin intensity-based distributed temperature sensing has used Q-switched sources which require linewidths smaller than the frequency separation (~11GHz at 1.5µm) between the generated Rayleigh and Brillouin backscattered signals [7]. In developing a combined Brillouin-based distributed strain and temperature system that requires accurate measurements of the Brillouin frequency shift, the required linewidth has to be of the order of few tens of MHz. The work relating to the development of narrow linewidth sources is discussed in Chapter 6.
3.2 **Erbium-silica Systems**

This section describes two types of Erbium-doped fibres, a conventional Erbium-doped fibre and a large mode area Erbium-doped fibre. A comparison in terms of amplifying and Q-switching operation characteristics using both these fibres is made.

3.2.1 **Erbium-doped Fibres**

Erbium is a member of the Lanthanide series in the Rare-Earths (Lanthanides and Actinides) of the periodic table. It has an electronic configuration which can be expressed as [Xe] 4f\(^{11}\) [8]. When Erbium is doped in silica glass fibres, it becomes triply ionised with the removal of two outer 6s electrons and an inner 4f electron.

An Erbium-doped fibre system incorporates relatively efficient pumping bands at the wavelengths of 514nm, 650nm, 807nm, 980nm and 1480nm [9]. However, there are two particularly attractive pumping wavelengths at 980nm and 1480nm due to the virtually excited state absorption (ESA) free property of these bands. Furthermore, commercial development offers a wide range of high-power semiconductor pump lasers at these wavelengths. As a comparison of efficiencies, pumping at 980nm offers a gain versus input pump power of 11 dB/mW [10] whilst pumping at 1480nm gives 6.3 dB/mW [11]. By pumping at 1480nm, stimulated emission occurs at the pump wavelength, which reduces the pump efficiency at 1480nm as compared to pumping at 980nm. This is particularly undesirable for the operation of Q-switched lasers. This has led to the choice of using 980nm pump lasers for the ensuing experiments. In addition, the current generation of 980nm pump lasers includes a range of miniature and compact fibre-pigtailed semiconductor laser diodes, which has made these more attractive as pump sources.

If we consider the excited state absorption (ESA) free pump at the wavelength of 980nm, the energy used will excite the Erbium atoms to the \(^{4}I_{11/2}\) energy level whereby atoms in this level has a lifetime of approximately 3.0µs [12]. These atoms will then undergo nonradiative relaxations to the \(^{4}I_{13/2}\) energy level. The \(^{4}I_{13/2}\) metastable energy level has a relatively long lifetime (\(~10\)ms) [12]. Figure 3-1
illustrates a simplified energy diagram for the three-level Erbium-silica system. In Erbium-doped fibres, charge distribution in the glass host generates a permanent electric field called a ligand field. This field induces a Stark effect, which results in the splitting of energy levels to what are known as manifolds, consisting of energy sublevels. However, it is still valid to consider each of the energy levels as a single discrete level due to the effect of thermalisation, which maintains a constant population distribution within the manifolds.

Figure 3-1: *Energy diagram of the Erbium-doped fibre system including pumping levels*
3.2.2 Large Mode Area Erbium-doped Fibres

In conventional Erbium-doped fibres, the maximum achievable gain is limited by the saturation of the amplified spontaneous emission (ASE) [13]. An expression for the saturation power that can be extracted from a fibre is defined as [14]:

\[
I_{\text{sat}} = \frac{\hbar \cdot \nu}{\sigma \cdot \tau_2} \text{ W/m}^2 \tag{3-1}
\]

where \(\sigma\) is the stimulated emission cross section and \(\tau_2\) is the lifetime for the excited state transition and \(\nu\) is the pump frequency. The saturation intensity is defined as the input power that would reduce the gain to half its small signal value. To increase the energy storage in the Erbium fibre, it is possible to either increase the Erbium ion concentration or increase the core volume of the fibre. The disadvantage of increasing the Erbium concentration is the effect of clustering of dopant ions in the fibre which leads to a co-operative up-conversion process which will decrease the pump efficiency [15]. Recently, an analysis through numerical modelling suggested that the energy storage in Erbium fibres can be increased with the design of a fibre with a large mode area [16] as opposed to standard fibres with an area of approximately 60 \(\mu\)m\(^2\).

There are two primary benefits of using a large mode area fibre as a gain medium. With a larger core area, more dopant ions per unit length of fibre can be incorporated. A larger core area will also lead to a reduction in the ASE gain saturation. Secondly, the increase in core area leads to a higher threshold for non-linear effects, which transfers the signal energy to higher wavelengths. A large area fibre will thus lead to fibre amplifiers and lasers with increased saturation intensity.

However, using a large core area fibre causes incompatibility with other fibre devices and presents difficulties during fusion splicing. To achieve single-mode operation, the fibre is designed with a low numerical aperture (NA) and this increases the sensitivity of the fibre towards bend losses.
3.2.3 Erbium-doped Fibre Amplifiers

With the introduction of conventional and large mode area Erbium-doped fibres, it is now useful to appreciate the use of both these fibres as gain media in amplifiers and in Q-switched lasers. This section introduces the modelling of Erbium-doped amplifiers to understand their behaviour, such as varying the fibre and dopant parameters. The amplifier model is then extended to incorporate Q-switching behaviour, and to evaluate the optimum properties for achieving high peak power and short Q-switched pulses.

The model was performed using coupled rate equations with the equations for EDFAs described by Giles and Desurvire [17]. Properties of pump absorption, population inversion, signal and amplified spontaneous emission (ASE) evolution along the length of Erbium-doped fibre are considered. The use of this amplifier model is then incorporated with Q-switching behaviour to predict the performance of Q-switched Erbium-doped fibre lasers with various cavity parameters.

Briefly, the population inversion needed for a gain medium to exist is achieved by pumping. The ions in the pump band then decay non-radiatively into the metastable level. Ions in the metastable level can then reach the ground state either by spontaneous or stimulated emission processes. If a signal with the wavelength that lies within the gain curve of the Erbium, this will be amplified by the process of stimulated emission. Spontaneous emission generates a noise-like broad spectrum that is also amplified along the Erbium-doped fibre and is referred to as amplified spontaneous emission (ASE).

Several assumptions were made in modelling the Erbium-doped amplifier:

1) As the laser amplifier was considered to be pumped at 980nm, any loss of pump efficiency due to excited state absorption (ESA) is disregarded. During ESA, the pump photon is not absorbed from the ground level, but from the excited level which happens to closely match the pump photon energy $h\nu_p$. As a result, ESA reduces the pumping efficiency to create the desired population inversion.
2) The pumping rate of ions from the ground state to reach the metastable level is much faster than the lifetime of the metastable level, hence the population inversion was considered to exist predominantly between the metastable level and the ground level.

3) The wavelength dependencies of the absorption and emission cross-sections are neglected.

### 3.2.3.1 Equations Governing the Amplifier Behaviour

Equations (3-2) and (3-3) based on the analysis of Giles and Desurvire[17] describe the rate of change of population densities in the upper and lower levels of the Erbium system. The first term describes the spontaneous emission; the second term describes the pumping process, whilst the third and fourth terms describe the stimulated emission and absorption rates respectively.

\[
\frac{dN_1(z,t)}{dt} = A_{21}N_2 - P_p \frac{\sigma_{13} \eta_p}{\hbar \nu_p A} N_1 + (P_a^+ + P_a^- + P_s) \frac{\sigma_{21} \eta_s}{\hbar \nu_s A} N_2 - (P_a^+ + P_a^- + P_s) \frac{\sigma_{12} \eta_s}{\hbar \nu_s A} N_1
\]

(3-2)

\[
\frac{dN_2(z,t)}{dt} = -A_{21}N_2 - P_p \frac{\sigma_{13} \eta_p}{\hbar \nu_p A} N_1 - (P_a^+ + P_a^- + P_s) \frac{\sigma_{21} \eta_s}{\hbar \nu_s A} N_2 + (P_a^+ + P_a^- + P_s) \frac{\sigma_{12} \eta_s}{\hbar \nu_s A} N_1
\]

(3-3)

The corresponding variation of ASE, pump and signal powers are also considered along the length of the Erbium fibre, which are given by Equations (3-4), (3-5) and (3-6):

\[
\frac{dP_s^\pm(z)}{dz} = \pm P_s^\pm \eta_s (\sigma_{21} N_2 - \sigma_{12} N_1) \pm 2 \sigma_{21} N_2 \eta_s h \nu_s \Delta \nu \pm \alpha_s P_s^\pm
\]

(3-4)

\[
\frac{dP_p(z)}{dz} = -P_p \eta_p \sigma_{13} N_1 - \alpha_p P_p
\]

(3-5)
\[
\frac{dP_s(z)}{dz} = P_s \eta_s (\sigma_{21} N_2 - \sigma_{12} N_1) - \alpha_s P_s
\]  
(3-6)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_1, N_2)</td>
<td>Population Densities of Upper and Lower lasing levels (m(^{-3}))</td>
</tr>
<tr>
<td>(A_{21})</td>
<td>Spontaneous decay rate from the metastable level (s(^{-1}))</td>
</tr>
<tr>
<td>(P_p, P_s)</td>
<td>Pump Power &amp; Signal Power (W)</td>
</tr>
<tr>
<td>(P_a^\pm)</td>
<td>Forward and Backward ASE powers (W)</td>
</tr>
<tr>
<td>(\sigma_{21}, \sigma_{12})</td>
<td>Signal emission and absorption cross-sections (m(^2)/ion)</td>
</tr>
<tr>
<td>(\sigma_{13})</td>
<td>Pump absorption cross-section (m(^2)/ion)</td>
</tr>
<tr>
<td>(\eta_s, \eta_p)</td>
<td>Signal and Pump overlap factors</td>
</tr>
<tr>
<td>(\nu_s, \nu_p)</td>
<td>Signal and Pump frequencies (s(^{-1}))</td>
</tr>
<tr>
<td>(\Delta\nu)</td>
<td>Equivalent ASE Bandwidth (GHz)</td>
</tr>
<tr>
<td>(A)</td>
<td>Effective Core Area ((\mu)m(^2))</td>
</tr>
<tr>
<td>(\alpha_p, \alpha_s)</td>
<td>Pump and Signal Attenuation (m(^{-1}))</td>
</tr>
</tbody>
</table>

**Table 3-1**: Definitions for symbols used in the mathematical description of rate equations

Table 3-1 shows the definitions of constants and symbols used to describe Equations (3-2) to (3-6). The parameters in this model were then evaluated along the length of Erbium fibre, considering that there is no initial signal present (\(P_s=0\)) and pump power of 50mW. This is the case when the model is later used to evaluate the Q-switched laser performance in Section 3.3. Figure 3-2 shows the values of population inversion density of the upper and lower levels in the system as a function of distance along the length of Erbium-doped fibre. At the near and far ends of the Erbium-doped fibre, the population inversion has been depleted due to the presence of both forward and backward ASE.
Figure 3-2: Variation of the population density of the upper and lower levels along a length of Erbium doped fibre using a pump power of 50mW

It can be observed that the development of ASE in the Erbium-doped fibre can cause a decrease in population inversion, hence a decrease in the effective gain. In practical situations, various techniques have been used to minimise the effect of gain depletion due to ASE. For example, the use of an optical isolator in a co-propagating pump configuration between two sections of gain medium reduces the immense build-up of backward travelling ASE. This is also known as using a midway isolator and was first demonstrated in 1991 [18]. In pulsed signal applications such as in OTDR whereby cascaded amplifiers are required, it is also possible to gate the pulsed signal for the duration of the pulse whilst preventing the ASE from saturating the subsequent amplifier. In another configuration, the signal through an initial amplifier could be filtered by a narrowband filter such as a fibre Bragg grating, before being amplified further, whilst once again preventing the ASE from saturating the second amplifier. This technique is utilised in achieving a high peak power pulse for the experiment described in Chapter 5.
3.3 Q-switching in Fibre Lasers

As mentioned in Chapter 1, Q-switched lasers are ideal as sources for distributed fibre sensing. The gain medium for Q-switched fibre lasers discussed in the following work is based on the Erbium-doped silica system. The potential of these sources is enhanced by the simplicity of diode-pumped operation, producing a compact, all solid-state device.

3.3.1 Q-switched Operation

The method of Q-switching enables light pulses with high intensity and short duration to be extracted from a laser cavity. Q-switching is a process whereby the finesse or ‘Q’ of the laser cavity is initially lowered and laser oscillation is prevented. During this period, the gain medium is pumped and energy is stored. Once sufficient population inversion has been achieved, the finesse is suddenly raised to a high value within a short period of time. This results in the gain being much larger than the threshold, and a rapid build-up of lasing photons occurs. As the population inversion is rapidly exhausted, lasing only occurs for a short period of time.

3.3.2 Modelling of Q-switched Laser Performance

The mathematical model used to describe the Erbium-doped amplifier system, may be extended to account for the pulse build-up process [19], thereby allowing theoretical values for peak power and pulse width to be obtained.

The model developed for the Q-switched laser is based on a Fabry-Perot type cavity as shown in Figure 3-3. The cavity consists of a Erbium-doped fibre gain medium with length \( L_{\text{fibre}} \), an optical switch which provides the Q-switching, two cavity mirrors, and a passive optical cavity with length \( L_{\text{air}} \).
Specific assumptions made in the model to simplify calculations were:

1) The duration of Q-switching is typically of the order of a few photon lifetimes as compared to the metastable state lifetime, and so it is assumed that the effect of pumping is negligible on the population inversion.

2) Any excited state absorption (ESA) processes for the pumping process is neglected.

3) There are no additional etalons formed between the optical components.

4) The rise/fall time of the Q-switching element is fast compared to the cavity round-trip time.

We begin by considering the increase in the number of photons within the cavity. In one cavity round trip, the number of photons will encounter both gain and loss, which will result in the number of photons becoming:

\[
\left( R_1 R_2 e^{-a_{max} L_{max}} \right) N_p \]  \hspace{1cm} (3-7)
Table 3-2 provides a list of symbols and their descriptions in describing the Q-switching process in the ensuing discussion.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n_{th})</td>
<td>Threshold Population Inversion</td>
</tr>
<tr>
<td>(N_p)</td>
<td>Number of photons inside the cavity</td>
</tr>
<tr>
<td>(R_1, R_2)</td>
<td>Reflectivity of Laser Mirrors</td>
</tr>
<tr>
<td>(A)</td>
<td>Cross-sectional area of fibre</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>Gain coefficient /unit length</td>
</tr>
<tr>
<td>(\gamma_{th})</td>
<td>Threshold gain coefficient/unit length</td>
</tr>
<tr>
<td>(\alpha_{fibre})</td>
<td>Attenuation of fibre /unit length</td>
</tr>
<tr>
<td>(\alpha_{sw})</td>
<td>Attenuation of Q-switch element</td>
</tr>
<tr>
<td>(L_{fibre})</td>
<td>Length of gain medium (fibre)</td>
</tr>
<tr>
<td>(\tau_{RT})</td>
<td>Cavity round-trip time</td>
</tr>
</tbody>
</table>

Table 3-2: List of parameters used to describe the Q-switching behaviour

The rate of change per round trip of the number of photons, that is the total number of photons after one round trip minus the number from the initial condition will then be:

\[
\frac{dN_p}{dt} = \left( \frac{R_1 R_2 e^{2L_{fibre} (\gamma - \alpha_{fibre})} - 1}{\tau_{RT}} \right) N_p \tag{3-8}
\]

It is also known that the threshold gain occurs when the gain equals the cavity losses, so that:

\[
R_1 R_2 e^{-(\alpha_{fibre} L_{fibre} + 2\alpha_{sw})} = e^{-2\gamma_{th} L_{fibre}} \tag{3-9}
\]
By using Taylor series expansion, the exponential terms in Equation (3-9) is simplified. From Appendix A, the first fundamental equation for Q-switching is then derived as:

$$\frac{dN_p}{dT} = N_p \left( \frac{n}{n_{th}} - 1 \right) \quad (3-10)$$

This states that if the gain of inversion is larger than the threshold value, the number of photons will increase with time. The second fundamental equation for Q-switching behaviour is also briefly discussed in Appendix A. In this equation, each increase in photon corresponds to a decrease by a factor of 2 in the population inversion:

$$\frac{dn}{dt} = -2N_p \frac{n}{\tau_p n_{th}} \quad (3-11)$$

In addition, the value of \((n_i-n_f)/n_i\) provides information regarding the fraction of the initial inversion that is converted to laser energy:

$$\left( \frac{n_i - n_f}{n_i} \right) = 1 - \exp \left[ - \left( \frac{n_i - n_f}{n_{th}} \right) \right] \quad (3-12)$$

The peak power from the laser is equal to the stored energy within the cavity multiplied by the fraction lost by output coupling per round trip divided by the time taken to complete the round trip:

$$P_0 (\text{max}) = \frac{\hbar u N_p (\text{max}) (1 - R_1)}{\tau_{RT}} \quad (3-13)$$
Another important feature of the Q-switch pulse is its pulse width. Although an exact solution can be obtained by locating the full width half maximum (FWHM) of the pulse profile, a very close approximation can be given by the total output pulse energy divided by the maximum output peak power:

\[
\Delta t = \frac{W_o}{P_o(\text{max})}
\] (3-14)

One useful trend which is observed during the design of Q-switched lasers is the variation of peak power and pulse width with various Erbium-doped fibre lengths. It has been demonstrated experimentally that there is an optimum length which yields the highest output peak power. Below this optimum length, there is less energy stored within the gain medium, requiring more round-trips to build-up and deplete the inversion, resulting in a wider pulse width. For a longer fibre length, the pulses have a longer round-trip time causing a drop in peak power.

By extending the amplifier model described earlier by incorporating Q-switching behaviour, another useful trend emerges that involves the variation of peak power and pulse width with different output coupling reflectivities. Figure 3-4 illustrates the theoretically calculated performance of a Q-switched Erbium-doped fibre laser, for various output reflectivity values whilst maintaining a constant 95% reflectivity for the other mirror. The values are calculated for a fixed Erbium-doped fibre length of 1.2m.
Figure 3-4: Theoretical plot of Q-switched peak power and pulsewidth for various output mirror reflectivities.

The final values obtained from the model consist of constraints limited by assumptions regarding the various parameters:

1) In the model, excited state absorption (ESA) within the pumped Erbium-doped fibre was neglected. In practice, this is not entirely true, as green fluorescence from the fibre is still observed, indicating that the pump efficiency is less than the calculated figure.

2) It is still difficult to verify the accuracy of measuring parameters such as dopant concentration, absorption/emission cross-sections and pump/signal overlap factors.

3) In practical Erbium-doped fibres, high Erbium ion concentration leads to clustering of ions which induces co-operative upconversion when the fibre is pumped.

4) The model assumes a uniform dopant profile within the core of the Erbium-doped fibre. However, fibres consist of a non-uniform dopant profile, leading to a population inversion different from theoretical predictions.
3.4 Techniques for Active Q-switching of Fibre Lasers

Before exploring the performance of experimentally constructed Q-switched fibre lasers, a short summary of common \[20\] and more recent techniques is given describing the principal characteristics of practical devices that are available for actively varying the loss within a laser cavity.

3.4.1 Mechanical Devices

An early method of Q-switching a fibre laser cavity is by using a mechanical chopper driven by a motor. This method allows Q-switching with a very high extinction ratio and virtually no insertion loss when the switch is in the high-Q state. Despite the advantages above, this technique is not favoured in many Q-switched fibre lasers due to the extremely slow switching speed of the chopper, typically between 7-10µs. Q-switching can also be achieved by mounting one of the cavity mirrors on a rotating motor. As with the chopper method, the rotating mirror technique is slow for Q-switching applications.

3.4.2 Electro-optic Modulator (Pockels cell)

The electro-optic effect, such as the Pockels effect, may be used for Q-switching. The Pockels cell consists of an optical medium such as KDP or Lithium Niobate, such that the distribution of electrons within the cell is distorted when an electric field is applied across it. This results in an induced change of refractive indices and hence an induced birefringence. A polarised light wave propagating through the cell will then encounter a change in polarisation depending on the applied electric field on the cell.

There are several ways to insert the Pockels cell into the cavity as the switching element, depending on the cavity configuration. In a standing-wave cavity, the Pockels cell is inserted between a polariser and one of the cavity mirrors. When a voltage is applied to the cell, such that it behaves as a quarter-wave plate, the cavity is in low-Q state. Switching is achieved by alternating the voltage on and off. In a travelling-wave cavity, the cell is inserted between two crossed polarisers and modulation of the signal is also achieved by alternating the applied voltage on and off.
Electro-optic Q-switching has the fastest Q-switching speed (~4ns) compared with other Q-switching techniques. In addition, it has a high extinction ratio (95-99%), good pulse to pulse stability, no frequency shift in the Q-switched pulses and the cell has a low insertion loss. However, the use of the cell imposes a high design cost, and the switch operates with high-switching voltages (0-5kV) producing severe electrical interference.

3.4.3 Acousto-optic Modulator (Bragg cell)

The acousto-optic modulator (AOM) is a device that utilises the acousto-optic effect as a means to diffract incoming laser light. A RF signal is applied to the piezoelectric transducer bonded to one side of the Bragg cell creating acoustic waves across the cell (Figure 3-5). This produces a periodic change in the refractive index of the cell caused by mechanical strains accompanying the acoustic wave, and it is this periodic modulation in refractive index which causes the diffraction of the incoming wave.

![Acousto-optic modulator (AOM)](image)

**Figure 3-5**: Acousto-optic modulator (AOM)

Still having a relatively fast switching time (~50-100ns), the AOM can also operate at a wide range of repetition rates. However, the extinction ratio is relatively poor being
only 60%. The AOM may be used either in zero order or first order mode of operation, in which either the undiffracted or diffracted beam respectively is used as the output. If the AOM is used in the zero order mode operation for a Q-switched laser, there is a comparatively less loss during the low-loss state as compared to the case when the AOM is used in the first order operation. This is because in first order operation, there is an increase by a factor of the square of diffraction efficiency compared to zero order operation. However, operating in first order provides substantial prevention of CW lasing during the high-loss state of the Q-switch.

### 3.4.4 All-Fibre Modulators

The convenience of an all-fibre modulator in fibre lasers was first demonstrated in 1993 [22]. This modulator consisted of a side-polished coupler with a piezoelectric overlay and was operated by coupling the evanescent field to vary the loss in the fibre. This technique avoids the loss incurred using bulk intracavity switching elements, which requires light to be coupled out of the fibre and back into the fibre. Potentially, this modulation may provide a robust solution in practical systems. Results of Q-switched pulses at 1.5µm with 400W of peak power and 15ns pulse width were reported using 100mW of pump power at 980nm.

An alternative all-fibre switch has been described in which two fibre Bragg gratings operating as the mirrors of the cavity are strained [23]. Q-switching operation was achieved by applying varying stress to the Bragg grating using a piezoelectric transducer (PZT). As the reflection spectrum of fibre Bragg grating 2 moves towards that of fibre Bragg grating 1 (Figure 3-6), the reflectivity overlap between both gratings increases thus decreasing the cavity loss (Q increases) resulting in the Q-switched pulse output. With a pump power of 26mW and a repetition rate of 1kHz, an optical pulse with a peak power of 2.1mW and pulse width of 2.46µs was achieved.
3.5 Experimental Results of Q-switched Fibre Lasers

Using the calculated Q-switched results from the developed model of Erbium-doped fibre lasers, experiments were performed to verify the predicted performance. In the following section, the performance of pigtailed diode-pumped Q-switched fibre lasers with respect to the variation of peak power and pulse width for different output mirror reflectivities are analysed. In addition, a large mode area Erbium-doped fibre was utilised to construct a high peak power Q-switched laser.

3.5.1 Optimisation of Q-switched Fibre Laser Performance by Varying Output Mirror Reflectivity

3.5.1.1 Introduction

To optimise the performance of a Q-switched fibre laser, it is convenient to utilise a Sagnac fibre loop reflector as one of the cavity mirrors of a fibre laser\cite{24} for two reasons. Sagnac fibre loop reflectors exhibit fibre compatibility with the Erbium-doped fibre gain medium, which avoids coupling loss both within and external to the laser cavity. More importantly, the use of a Sagnac loop reflector enables a continuous variation of reflectivity as a mirror by varying the fibre birefringence within the loop. The following section therefore provides a description and operating principle of a
Sagnac fibre loop reflector. This is followed by the experimental results obtained from a Q-switched laser for different output coupling reflectivities.

3.5.1.2 Sagnac Fibre Loop Reflectors

A schematic diagram of a Sagnac fibre loop reflector is shown in Figure 3-7. Connecting the two ports 3 and 4 of the coupler forms the Sagnac loop. Suppose that light is launched from port 1 and that the coupler has a cross coupling coefficient of $K_{x,y}$ for $x$ and $y$ polarisation respectively.

Figure 3-7: Illustration of a fibre Sagnac loop reflector showing the coupling ports

The effect of propagating through the loop is described by combining the Jones matrices. The input signal is coupled across and through the coupler:

\[
\begin{pmatrix}
E_{3n} \\
E_{4n}
\end{pmatrix} = \sqrt{1 - \gamma} \begin{pmatrix}
\sqrt{1 - K_n} & i\sqrt{K_n} \\
i\sqrt{K_n} & \sqrt{1 - K_n}
\end{pmatrix}
\begin{pmatrix}
E_{1n} \\
E_{2n}
\end{pmatrix}
\]

(3-15)

where $n=x,y$ for both $x$ and $y$ polarisation, and $E_{1n}$, $E_{2n}$, $E_{3n}$ and $E_{4n}$ describes the fields for ports 1, 2, 3, 4 respectively, $K_n$ is the coupling coefficient and $\gamma$ is the coupler loss. Both the fields $E_{3n}$ and $E_{4n}$ then travel around the Sagnac loop in opposite directions while experiencing the birefringence properties of the loop described by Jones matrices $J_C$ and $J_A$, representing clockwise and anti-clockwise directions of the fields.
\[
\begin{pmatrix}
E'_{3x} \\
E'_{3y}
\end{pmatrix} = J_C \begin{pmatrix}
-E_{3x} \\
E_{3y}
\end{pmatrix} e^{-\alpha L} = \begin{pmatrix}
J_{xx} & J_{xy} \\
J_{yx} & J_{yy}
\end{pmatrix} \begin{pmatrix}
-E_{3x} \\
E_{3y}
\end{pmatrix} e^{-\alpha L} \quad (3-16)
\]

\[
\begin{pmatrix}
-E'_{4x} \\
E'_{4y}
\end{pmatrix} = J_A \begin{pmatrix}
-E_{4x} \\
E_{4y}
\end{pmatrix} e^{-\alpha L} \begin{pmatrix}
J_{xx} & J_{xy} \\
J_{yx} & J_{yy}
\end{pmatrix} \begin{pmatrix}
-E_{4x} \\
E_{4y}
\end{pmatrix} e^{-\alpha L} \quad (3-17)
\]

where the prime denotes the fields travelling in the opposite directions from its original directions. The signal waves then propagate back into the coupler by recombining through ports 3 and 4. The reflectivity evaluated at port 1 is given by:

\[
R_{11} = (1 - \gamma)^2 e^{-2\alpha L} K (1 - K) \Gamma \quad (3-18)
\]

where \( \Gamma \) is the expression which is dependent on the birefringent properties of the loop (Appendix B). For the case of Jones matrix representing the birefringence property of the Sagnac loop being symmetric, the second half of the expression for \( \Gamma \) can be simplified to \( 4|J_{xx}|^2 \). Figure 3-8 shows a plot of reflectivity against the birefringence factor \( |J_{xx}|^2 \) for various coupling ratios \( K \).

**Figure 3-8:** Plot of reflectivity against degree of birefringence for \( |J_{xx}|^2 \) for different coupling ratios of (a)0.1 (b)0.15 (c)0.3 (d)0.5 (e)0.7
In conclusion, it is predicted that with a coupling ratio of 50% whereby the intensity passing through both arms of the coupler are equal, it is possible to obtain a coupler reflectivity variation from 0% to 100% by varying the birefringence properties of the loop, assuming that coupling losses are minimal.

3.5.1.3 Experiment

An experiment was conducted to determine the optimum reflectivity of a Sagnac loop mirror to achieve maximum Q-switch peak power pulses. The experimental configuration is shown in Figure 3-9, consisting of a Q-switched laser with a Sagnac loop as the output mirror. The Sagnac loop was spliced to a 50/50 coupler that enabled coupling from a CW DFB laser diode light. The DFB laser signal was initially launched into the Sagnac loop to determine the reflectivity of the mirror and then switched off before evaluating the Q-switched performance characteristics with various output mirror reflectivities. The birefringence property (governed by the Jones matrices in Equations 3-16 and 3-17) of the Sagnac loop was controlled by varying the positions of the wave plates of the fibre polarisation controller until a particular reflectivity was obtained.

**Figure 3-9**: Set-up of Q-switch laser and monitor laser for determining loop mirror reflectivity
3.5.1.4 Results

Using the experimental set-up in Figure 3-9, the Q-switched pulse characteristics for different output mirror reflectivities are shown in Figure 3-10. It can be seen that for the particular length of Erbium-doped fibre, the highest peak power was achieved for the mirror reflectivity of approximately 20%. The lower peak powers obtained experimentally compared to the theoretical predictions in Figure 3-4 may be due to several factors involving the assumptions made in Section 3.3.2. In the practical case, the factors which lead to a reduction of pulse storage energy will lead to a lower peak power in the Q-switched pulse.

![Figure 3-10](image)

**Figure 3-10**: Plot of experimentally obtained Q-switch peak power and pulse width for different output mirror reflectivities

By replacing the Sagnac loop mirror with the polarisation controller with a fibre Sagnac mirror consisting of a 95/5 splitting ratio coupler, a fixed reflection intensity of approximately 19% may be obtained. This is sufficiently close to provide an efficient Q-switched laser. Using such a laser, pulses with peak powers of 108W and 25ns pulse width were obtained, shown in Figure 3-11. The shorter pulse width results from the shorter length of the Sagnac loop. As a result, Q-switched broadband lasers constructed experimentally later were based on the design that utilised such a coupler.
3.5.2 A High Power Q-switched Erbium Fibre Laser Incorporating a Large Mode Area Fibre

3.5.2.1 Introduction

Using the large mode area Erbium-doped fibre described in Section 3.2, it is predicted that a higher peak power and relatively short Q-switched pulse may be achieved, due to the increased energy storage in the erbium doped fibre for a given pump power.

To maintain single-mode operation of the fibre, the normalised frequency \( V \) has to satisfy the condition \( V < 2.405 \), and

\[
V = \frac{2\pi}{\lambda} a (n_1^2 - n_2^2)^{1/2}
\]

\[
= \frac{2\pi}{\lambda} a \text{ (NA)}
\]  

(3-19)
where $a$ is the core radius, $\lambda$ is the operating wavelength of light, $n_1$ and $n_2$ are the core and cladding refractive indices respectively and NA is known as the numerical aperture. If the core area of the fibre is increased then the NA has to be reduced. The fibre used throughout this experiment had a step-index profile with a core radius of 7.3$\mu$m and an NA of 0.08 from preform measurements, which produced a mode field radius of approximately 8.1$\mu$m. This then corresponded to a mode field area of 208$\mu$m$^2$, whereas the mode field area of a typical Erbium-doped fibre is 60$\mu$m$^2$. The Erbium concentration of this fibre was 4000ppm.

3.5.2.2 Experiment

Initially, the estimation for the far field mode patterns for both the conventional and LMA Erbium-doped fibres were determined. The patterns were measured for the full width half maximum intensity of the light for both fibres. The experimental set-up is as shown in Figure 3-12. A screen was positioned 220mm from the fibre and an infrared vidicon camera was used to view the far field patterns. The NA could then be calculated by using the trigonometric formula of Equation (3-20) with the variables illustrated in Figure 3-12.

$$
NA = \frac{A/2}{\left(\frac{A}{2}^2 + D^2\right)^{1/2}} = \frac{A}{(A^2 + 4D^2)^{1/2}} \tag{3-20}
$$

![Figure 3-12: Experimental set-up for far field measurement](image-url)
Using the large mode area Erbium-doped fibre, a Q-switched laser was constructed. The schematic set-up of the Q-switch experiment is as shown in Figure 3-13. The pump source was an Argon pumped Ti-sapphire laser with output powers up to 1.2W at 980nm. This pump was launched into the LMA fibre through a 980/1530nm dichroic filter, and the output of the laser was also obtained from this end. The far end of the 63cm large mode area Erbium-doped fibre was angle polished at 16° to prevent the 4% Fresnel back reflections. Although the fibre had a low NA making the fibre sensitive to bend losses, this was not a major problem due to the short length used. The Q-switching medium used was an acousto-optic modulator (AOM) and the output was focused on a 99% reflectivity mirror at 1530-1550nm. Due to the low diffraction efficiency of the AOM, zero order operation produced the optimum results.

![Figure 3-13: Experimental configuration for large mode area Q-switch laser experiment](image)

### 3.5.2.3 Results

The mode field diameter measurements for both the conventional and large mode are Erbium-doped fibres are shown in Figure 3-14 and Figure 3-15 respectively. The full width half maximum (FWHM) values were 35.5mm and 67.7mm, corresponding to NA values of 0.08 and 0.15 for both the LMA and conventional fibres respectively. This was in good agreement with preform measurements. The far field patterns
obtained shown also indicate that the propagation of light in both fibres still satisfy the single transverse mode operation.

![Far field pattern for large mode area Erbium-doped fibre](image1.png)

**Figure 3-14:** Far field pattern for large mode area Erbium-doped fibre

![Far field pattern for conventional Erbium-doped fibre](image2.png)

**Figure 3-15:** Far field pattern for conventional Erbium-doped fibre

Various output characteristic measurements were made with the Q-switched operation of the laser. The output pulse profile is as shown in [Figure 3-16](image3.png), with a peak power of approximately 4kW and a pulse width of 11ns at a repetition rate frequency operation of 500Hz.
The output peak power and pulse width variation with repetition rate is shown in Figure 3-17. The fall off of peak power at higher frequencies is due to the finite recovery time of the population inversion, which is limited by the lifetime of the metastable level of the Erbium ions. Although this lifetime is typically 10-12ms for Erbium ions, the depletion of the population inversion due to ASE will effectively reduce this lifetime to approximately 1ms, which corresponds to 1kHz for repetition frequency.

Figure 3-17: Variation of peak power and pulsewidth with repetition rate
The variation of pulse energies with increasing launched pump powers is shown in Figure 3-18, with an estimate of launch efficiency of 50%. At high pump powers, there is a saturation effect for the output pulse energies, which is due to the increase of ASE powers for higher pump powers, thus clamping the gain and the output pulse energies. For an estimated launch pump power of 600mW, the output pulse energy is 50\(\mu\)J.

![Figure 3-18: Variation of net gain with input power](image)

### 3.6 Conclusions

This chapter has explored the mechanism of Q-switching in fibre lasers for producing high peak power, short duration optical pulses suitable for OTDR sensing. Mathematical models were also developed to predict the behaviour of these lasers, initiating from an analysis of Erbium-doped fibre amplifiers using the rate equations. The results from the model were used to show the variation in laser performance to confirm that a large mode area fibre could be used to generate higher energy pulses. A model of the Sagnac loop reflecting mirror was also generated to show that the loop reflectivity is dependent on the birefringence factor between the two counter-propagating waves. Experiments were carried out to verify that the results of the model were able to predict the experimental Q-switching behaviour. Using a polarisation controller to vary the degree of birefringence, the optimum reflectivity of a Sagnac loop mirror suitable for Q-switched operation was determined. By removing
the polarisation controller, a Q-switched laser with the output Sagnac loop mirror constructed from a 95/5 coupler provided a reflectivity of 19%. This resulted in output pulses with 108W peak power and 23ns pulse width at 1.5µm. The use of the novel large mode area Erbium-doped fibre geometry has resulted in the demonstration of a Q-switched laser with high peak powers of 4kW and 11ns pulse width. The relatively short pulse width has resulted from the cavity being comparatively short, consisting of only the doped fibre and the length needed to insert the modulator. Although this laser realises high peak power and short pulse outputs, there is still a need to accomplish better compactness and fibre compatibility before its full potential is realised. Table 3-3 shows the comparison of Q-switch pulse profiles between lasers using a conventional Erbium-doped fibre and large mode area Erbium-doped fibre.

<table>
<thead>
<tr>
<th>Fibre Type</th>
<th>Conventional Erbium-doped fibre</th>
<th>Large Mode Area Erbium-doped fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power</td>
<td>108W</td>
<td>4000W</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>25ns</td>
<td>11ns</td>
</tr>
<tr>
<td>Typical Q-switch laser cavity length</td>
<td>140cm</td>
<td>80cm</td>
</tr>
</tbody>
</table>

**Table 3-3**: Comparison of Q-switch laser pulse characteristics using conventional Erbium-doped fibre and large mode area Erbium-doped fibre
3.7 References


CHAPTER FOUR

GENERATION OF PULSED SOURCES AT 1.65µm AND THEIR APPLICATIONS IN DISTRIBUTED SENSORS

4.1 Introduction

In Chapter Two, the mechanisms of Rayleigh, Raman and Brillouin scattering were described. Combining this knowledge with the ability to construct a variety of high peak power, short pulse width Q-switched fibre lasers allows the design of high performance distributed sensors. Important parameters for such sensors include the length of sensing range that is predominantly dependent on the peak pulse power of the source, and the sensing spatial resolution that is dependent on the pulse width of the source.

Although interest has focused on the 1.5µm region for long range systems, there is increasing interest in operating distributed sensors at a different wavelength region. These systems may be incorporated for use in monitoring of links used for live optical data transmission using the conventional C-band Erbium-doped fibre amplifier (EDFA) systems at 1.5µm. By allocating a co-propagating wavelength different from the communication wavelength, potentially useful systems can be developed for monitoring of defects, attenuation and sudden temperature or strain rises along an active transmission fibre.

Another use for increasing the operating wavelength of OTDR sensors arises from the installation of future telecommunication networks. With the expectation of an extremely rapid market growth in data transmission, there is a need to extend the capabilities of current transmission systems. Although Dense Wavelength Division Multiplexing (DWDM) schemes utilising the conventional Erbium band (C-band) are currently being deployed extensively, it is forecasted that there will soon be extensive
use of the long-band in EDFAs (L-band) for telecommunication purposes to extend the bandwidth capabilities. These amplifiers operate in the 1560-1620nm wavelength region. In conventional single mode silica fibres, the degree of light confinement decreases as the wavelength of operation increases. As a result, transmission links operating at the higher wavelength region are more susceptible to bend losses than the conventional 1.5μm transmission, which forms a critical design issue in components such as fibre joint housings and tight bends within structures. OTDR diagnostic tools operating at 1.6μm will therefore become essential.

This chapter describes a recently developed source operating at 1.65μm [1] and demonstrates its use for a number of distributed sensors. The source exploits the high peak powers available from Q-switched lasers operating at 1.5μm combined with Raman amplification. Raman gain in silica fibre has a large frequency bandwidth, with its peak around 13THz away from the pump wavelength. The method of generating pulsed sources at the wavelength region of 1.65μm is first described, followed by the demonstration of two applications using this source; a long-range OTDR system based on a delayed Raman amplification technique and a Raman-based DTS system.
4.2 1.65μm Pulsed Fibre Laser Sources

The main difficulty in generating pulsed fibre laser sources at the wavelength region of 1.65μm is due to the fact that there is currently no suitable gain medium for doped fibres at this wavelength. Although semiconductor laser diodes have been developed at this wavelength, the output power available from these lasers is limited to a few mW [2]. To increase the signal power levels at 1.6μm, attempts have been previously reported using a Raman fibre amplifier (RFA) [2]. The pump source consisted of a 1546nm laser diode amplified by an EDFA to 1.4W peak power which was then synchronously coupled with a low-power 1662nm laser diode signal into a 20km Raman generation fibre. The highest peak power achieved for this set-up was 200mW with pulses of 100ns duration at the wavelength of 1662nm.

In this work, the configuration that was used for generating 1.65μm pulsed sources for the following experiments utilised a single Q-switched fibre laser source operating at 1.5μm and avoids the need for electronic synchronisation of two sources.

4.2.1 Experiment

The experimental configuration for the generation of 1.65μm pulse signal is shown in Figure 4-1. A 1.5μm Q-switched fibre laser was constructed which had the AOM operating in first order to achieve high-Q state. A Sagnac loop mirror was used, which consisted of a 95/5 coupler with two arms spliced together, providing a mirror reflectivity of 19%. The pulse signal at 1.53μm had a peak power of 100W and pulse width of 34ns was generated, as shown in Figure 4-2.
The output of this 1.5\(\mu\)m laser was then fed into one of two Raman generation fibres, one of which was 1km and the other 2km long. The frequency spectrum of the signal emerging from the Raman amplifier was measured using a Fourier Transform Infrared Spectrophotometer (Perkin-Elmer System 2000 FT-IR). As the laser was operated in a pulsed condition, frequency harmonics from the laser could generate spurious peaks in the Fourier Transform conversion of the measurement in the Spectrophotometer. Measurements therefore had to be taken for different repetition rates of the laser and
the results averaged. Figure 4-3 (a) and (b) shows the resulting spectrum for measurements made for the two Raman generation fibres.

![Figure 4-3](image)

**Figure 4-3:** The wavelength spectrum obtained at the end of the Raman generation fibre for (a) 1km generation length (b) 2km generation length

It can be seen from (a) that up to approximately 1km, there is still some residual signal at the first order Stokes wavelength and some signal generated at the second order Raman Stokes wavelength. As the generation fibre is increased to 2km, it is apparent from (b) that almost all the first order Stokes generated energy has been transferred to the second order Raman Stokes signal. As a result, depending on the required wavelength of operation for specific applications, the Raman generation fibre length is adjusted appropriately. As the following experiments required the source to operate at the wavelength region of 1.65µm, the Raman generation fibre has to be significantly less than 1km. An earlier source performed by a colleague demonstrated that the optimum length was between 300 and 600m, for an input peak pulse power of 96W and pulse width of 20ns [1].
In the current experiment, the pulses from the 1.53µm Q-switched laser (Figure 4-1) were launched into a Raman generation fibre length of 390m, for generation of the first order Stokes signal whilst minimising the transfer of energy to higher order Stokes signals. The pulse was filtered from the residual pump by incorporating a bandpass filter centred at 1.65µm with a 3dB bandwidth of 25nm. The resulting pulse had a peak power of 1.4W and pulse width of 45ns, as shown in Figure 4-4.

![Temporal profile of 1.65µm pulse](image)

**Figure 4-4: Temporal profile of 1.65µm pulse**

There is a slight depletion of the 1.65µm pulse at its peak, indicating that it is just on the threshold limit of further generating the second order Stokes signal. In conclusion, pulses at 1.65µm have been successfully generated with a single laser source in a simple configuration. The use of this source for sensing applications is now described in the following sections.
4.3 An Extended Range OTDR System Based on Raman Amplification

4.3.1 Introduction

The first experiment utilising the 1.6\(\mu\)m source laser demonstrates a novel method for increasing the dynamic range of a distributed sensing system. The method operates by providing amplification of the signal or probe pulse within the sensing fibre rather than before the sensing fibre. To demonstrate this principle, the experiment was carried out using an OTDR system operating at 1.65\(\mu\)m. The system used a Q-switched Erbium doped fibre source to generate pulsed signals in the 1.6\(\mu\)m wavelength region using Raman gain at the Stokes wavelength. As mentioned in Section 4.2, the initial limitation of 1.65\(\mu\)m OTDR systems rested in the limited power available from 1.65\(\mu\)m semiconductor laser diodes. The use of Raman amplification to amplify a 1.66\(\mu\)m laser diode pulse by 24.8dB has recently been reported [4]. However, the signal was amplified before being launched down the sensing fibre. The approach described here differs in that Raman amplification of the 1.65\(\mu\)m signal pulse by a 1.53\(\mu\)m pump pulse is provided some distance from the front end of the sensing fibre, and is referred to as delayed Raman amplification. With this method, the OTDR system operates with the Raman pump pulse and the OTDR pulse both maintained just below their respective stimulated Raman thresholds at the front end of the fibre. The gain experienced by the OTDR pulse is achieved during the overlapping process of the two pulses within the sensing fibre.

The ability to achieve a greater dynamic range with this system may be explained as follows. Consider initially the situation in which both the pump and OTDR probe pulses have the same pulse width and peak powers, the depletion of the pump pulse at some distance along the sensing fibre will double the energy of the probe pulse. As such, the amplification achieved depends on the amount of energy available to amplify the probe pulse, which is determined by the peak intensity and pulse width of the pump pulse. Due to the large difference in pump and probe pulse wavelengths, these pulses will travel at different velocities down the sensing fibre through the contribution of dispersion. By introducing an initial time delay between these pulses.
as they are launched down the sensing fibre, Raman amplification occurs within the sensing fibre during the period of overlap between the pulses.

The stimulated Raman threshold of the pump pulse limits the amount of energy that may be launched down the sensing fibre. Although the OTDR pulse width is limited by the system spatial resolution requirements, the pump pulse width may be considerably larger. This enables a large amount of energy to be transferred to the signal pulse. This process of amplification is achieved without significant noise penalty as a result of the directionality of the Raman gain, and is therefore ideally suited for backscattered measurements. In addition, this OTDR system operating at the pump and Stokes wavelengths of 1.53\(\mu\)m and 1.65\(\mu\)m respectively minimises the fibre attenuation during propagation as these wavelengths are in the low loss window of silica-based optical fibres, providing an ideal system for long lengths of sensing fibre.

### 4.3.2 Theoretical Modelling of the Delayed Raman Amplification Process

A model was developed to analyse Raman amplification of a 1.65\(\mu\)m pulse, representing the signal pulse in an OTDR system, by a 1.53\(\mu\)m pump pulse. The two pulses are launched in the single mode sensing fibre with a time delay, \(\Delta t\), between the pump and signal pulse. The distance from the front end of the sensing fibre to where the two pulses overlap is governed by the fibre dispersion parameter D and the initial time delay between the two pulses.

To provide data for the computer simulation, both the intensity profiles of the pump and signal pulses were measured experimentally and sampled at 200 equally spaced segments. The overlapping gain process was modelled by incrementing one pulse with respect to the other by one segment at a time and calculating the depletion of the pump pulse and Raman amplification of the signal pulse with the following pair of coupled equations [5]:

\[
\begin{align*}
\frac{dI_p}{dt} &= - \alpha I_p + \frac{G}{\gamma} I_s \nonumber \\
\frac{dI_s}{dt} &= \frac{G}{\gamma} I_p - \alpha I_s
\end{align*}
\]
\[
\frac{dP_s}{dz} = \left( \frac{g_R}{A} \right) P_s P_p - \alpha_s P_s 
\] (4-1)

\[
\frac{dP_p}{dz} = -\left( \frac{g_R}{A} \right) \left( \frac{\omega_p}{\omega_s} \right) P_s P_p - \alpha_p P_p 
\] (4-2)

where P is the optical power in the fibre and the subscripts p and s refer to the pump and Stokes shifted 1.65\(\mu\)m probe pulses respectively; \(\alpha\) is the absorption constant of the fibre; A is the effective cross-section area, and \(g_R\) is the nonlinear Raman gain constant at 1.53\(\mu\)m. An illustration of the overlapping process is shown in Figure 4-5.

![Figure 4-5: Process of overlap between the pump (1.53\(\mu\)m) and signal (1.65\(\mu\)m) pulses](image)

The backscattered Rayleigh signal generated by the 1.65\(\mu\)m pulse was then computed with a spatial resolution of 100 metres. Assuming that the Raman gain constant has a value of 9.2 x 10^{-14} m/W at a wavelength of 1.064\(\mu\)m [6], and is inversely proportional to the pump wavelength [7], the Raman gain constant at a pump wavelength of 1.53\(\mu\)m is given by:
\[ g_R = \left( \frac{1.064}{\lambda_p} \right) \times (9.2 \times 10^{-14}) \]

\[ = 6.4 \times 10^{-14} \text{m/W} \]  

(4-3)

The effective cross-section area was assumed to be 60µm², which is a typical value of conventional silica fibres.

Using this model, the backscattered trace profile using the values pump and signal pulses in the experimental set-up of Section 4.3.3 was evaluated. With an initial time delay of 35ns between the pump and signal pulses, the backscattered trace is superimposed on the experimentally measured backscattered trace shown in Figure 4-9.

4.3.3 Experiment

The source used for this experiment consisted of a 1.5µm Q-switched Erbium-doped fibre laser. This source produced pulses of 110W, 28ns pulse width and at a repetition rate of 800Hz. To generate both the pump and OTDR pulses into the sensing system, the configuration as shown in Figure 4-6 was used. The pulses from the Q-switched laser were divided through a 90/10 coupler. The light in the 90% arm was used to generate the 1.65µm pulses through a process of stimulated Raman process along 300metres of conventional telecommunications grade silica fibre. The generated 1.65µm pulses were then separated from the residual 1.53µm pump pulses with a narrow band pass filter centred at a wavelength of 1.65µm, producing pulses of 1.0W peak power, pulse widths of 18ns and a 3dB optical bandwidth of 25nm. The process of Raman amplification within the sensing fibre occurs when the 1.53µm pulses from the remaining 10% arm and 1.65µm pulses overlap due to fibre dispersion. The delay between the two pulses before the overlap can be adjusted and was controlled by varying the length of the fibre on the 10% arm of the coupler. The two arms were then recombined utilising a 66/34 wavelength division multiplexer (WDM), biased to receive the maximum backscattered signal.
A convenient definition of the dispersion is in terms of the relative delay in picoseconds between two optical frequencies per nanometre wavelength separation and per kilometre travelled, that is:

\[
D(\text{ps/nm.km}) = \frac{2\pi c}{\lambda^2} \frac{\partial}{\partial \omega} \left( \frac{1}{v_g} \right) \quad (4-4)
\]

As the operating wavelengths of both the pump and OTDR pulses are in the anomalous-dispersion regime for standard telecommunications fibre, a pulse at the wavelength of 1.53\(\mu\)m travels faster than a pulse at the wavelength of 1.65\(\mu\)m. The 1.53\(\mu\)m pulse in the 10% arm was therefore adjusted such that it was propagating behind the 1.65\(\mu\)m pulse at the front end of the sensing fibre, and would overlap at some distance along the fibre determined by the delay between the two pulses. The 1.65\(\mu\)m pulse was then amplified by the process of Raman amplification as the 1.53\(\mu\)m pulse passed through it.

**Figure 4-7** illustrates the experimental data for the time domain pulse profiles of both the pump and signal pulses at the front end of the sensing fibre and at the end of the sensing fibre after 100km. The dispersion parameter, D, can be calculated. From the relative positions of the pulses, D is calculated to be approximately 17\(\text{ps/km.nm}\), which is in good agreement with dispersion values at these wavelengths [8].
4.3.4 Results

The experiment was performed using a sensing fibre length of 100km, consisting of several drums of standard telecommunications fibre spliced together. The oscilloscope traces for the Rayleigh backscattered signals without and with Raman amplification are shown in Figure 4-8 (a) and (b) respectively with 4096 averages taken using a digital oscilloscope. The experimental results indicated an increase in dynamic range of 17.5dB for the OTDR trace at the amplification peak within the sensing fibre. It can be observed that without Raman amplification, the backscattered Rayleigh trace reaches the noise floor at approximately 80km whilst with Raman amplification, a clear backscattered trace is obtained for a range exceeding 100km. In addition, the splice point after 80km down the sensing fibre can still be clearly observed in the amplified signal.
Figure 4-8: Rayleigh backscattered trace at 1.65 µm (a) without Raman amplification and (b) with delayed Raman amplification.

Figure 4-9: Comparison of amplification process between (a) Theoretical analysis (b) Experimental results.

Figure 4-9 denotes a comparison between the experimentally obtained results and the computed OTDR using experimental pulse powers. The rise in the backscattered signals at approximately 17.5 km demonstrates Raman amplification of the probe pulse as a result of the overlapping process. The small difference between the two...
rates of Raman amplification in the experimental and calculated curves may be attributed to the uncertainty in determining the exact Raman gain constant. The step-like losses in the experimental curve are due to splice losses and were not included in the model. In selecting the appropriate initial delay between the pump and probe pulses which determine the overlap down the sensing fibre, several issues have to be considered. The overlap between pump and probe pulses should not occur too near at the front end of the sensing fibre, as energy may be wasted in the amplified probe signal generating a higher order Stokes signal. On the other hand, the overlap should not occur too far down the sensing fibre because the pump pulse may then interact with a longer effective length of fibre and generate its own Stokes shifted signal. One possible approach in achieving a high dynamic range is to generate pump and probe pulses with different pulse widths by using different sources. The delay between the pump and probe pulses could then be minimised whilst allowing a long interaction/overlap time between the pulses as they travel down the sensing fibre.

Further experiments were carried out as the peak pump power levels were increased in steps from 1.0 to 5.0W. The results of the OTDR traces are shown in Figure 4-10. It can be observed that the peak amplification is increased as the peak pump power level is increased. The resultant net gain for the OTDR system with varying peak pump power levels from 1.0 to 5.0W is shown in Figure 4-11. This net gain is calculated in the linear region after the amplification process, which is beyond 60km. Although there is a net gain for each of these peak powers, it is evident there is a net reduction in the rate of increase of net gain with increasing peak pump power levels. This is due to the 1.65µm probe pulse generating higher order Stokes signals and transferring its energy to other frequencies. With the higher gain achieved with more pump power, the backscattered signal at 1.65µm is increased allowing a higher dynamic range in the OTDR sensor.
**Figure 4-10:** Backscattered Rayleigh signals with increasing pump powers of 1 to 5W.

**Figure 4-11:** Net gain achieved by amplification process with increasing pump powers with 850mW pump power.
4.4 Raman DTS System at 1.65µm

4.4.1 Introduction

In this section, a Raman DTS system operating at the wavelength of 1.65µm is demonstrated. Optical fibre temperature sensors based on spontaneous Raman scattering in the wavelength region of 1.5µm have been the subject of research for a number of years [9][10][11]. Previous Raman-based systems typically operate with a pump light in the wavelength region of 1.5µm and sensors cannot be used in active optical transmission systems. By utilising the 1.65µm pulsed source which has been described in Section 4.2, it is possible to operate a DTS system by launching the 1.65µm pulsed source down the sensing fibre and obtaining the upshifted anti-Stokes spontaneous Raman backscattered signal. In an OTDR system with pump pulses launched at 1.65µm, both the backscattered signals generated from the anti-Stokes scattering from these 1.65µm pulses and Rayleigh backscattered signals generated from the data information signals will be in the wavelength region of 1.5µm. However, the OTDR anti-Stokes backscattered trace consists of an exponentially decaying backscattered signal compared to the near-constant backscattered trace due to the summation of Rayleigh scattering from every bit of the high frequency data information signal.

4.4.2 Experiment

A schematic diagram of the experimental set-up is shown in Figure 4-12. The Stokes 1.65µm pulses generated after the 390m telecommunications fibre were separated from the residual 1.53µm pump pulses by a band-pass filter (FWHM 25nm) centred at 1.65µm, to produce pulses with 1.5W of peak power and 40ns pulse width. The broadband nature (25nm) of these pulses is ideal for OTDR as coherent effects are reduced to a minimum. The pulses were then launched into the sensing fibre through a 1.6µm/1.5µm wavelength division multiplexer (WDM). The sensing fibre was 10.1km in total, consisting of four sections of standard single-mode telecommunications fibre, D1, D2, D3 and D4 spliced together with lengths of 8.6km, 500m, 500m and 500m respectively. Section D3 was placed in an oven and heated to 59°C. The Raman
The backscattered signal was measured using an InGaAs PIN detector in conjunction with a transimpedance amplifier with a bandwidth of 3MHz and sensitivity of 11mV/nW. The detected signal was electrically amplified with a 30dB gain amplifier and averaged 219 times. A narrow bandpass filter (FWHM 25nm) centred at 1.53μm was placed before the detector to filter the anti-Stokes signal from the backscattered Rayleigh signal. This filter had a transmission of 80% at 1.53μm.

**Figure 4-12:** Experimental configuration for Raman DTS system at 1.6μm

### 4.4.3 Results

The Raman backscattered measurements are shown in Figure 4-13. Figure 4-14 shows in detail the three sections of 500m test fibres indicating the splice positions. The plot also shows three sections of fibres (500m each) at a distance of 8.6km from the front end of the sensing fibre. The plot shows a clear rise in the Raman signal indicating the heated section. It can be seen that a measurement with the signal being well above the noise floor can be made for the range exceeding 10km.

This signal cannot be used to provide an absolute temperature value due to its dependence on fibre attenuation and splice/bend losses. To accurately predict temperature changes the Raman signal has to be referenced to the temperature-independent Rayleigh signal that must therefore be measured with the same spatial
resolution. The ratio of the Rayleigh and Raman signals provides a temperature dependent signal which is independent of splice/bend losses and corrected for fibre attenuation. Figure 4-15 shows this ratio for the same three sections of test fibres. The r.m.s. noise on the ratio was measured to be $2.2 \times 10^{-3}$, which corresponds to a temperature resolution of $4^\circ$C. The spatial resolution was measured to be 10m, which was limited by the detector bandwidth of 3MHz. Using the Raman anti-Stokes temperature sensitivity of $0.8 \% \text{K}^{-1}$ [10], the temperature change was calculated to be 36K, and this was in agreement within the experimental accuracy of the measured fibre temperature change. In practice, signal dispersion degrades the sensing spatial resolution, if a system with a long sensing range is required. This places a limiting factor in Raman-based distributed sensors described in Chapter 2. This effect was demonstrated in a 1.5µm distributed sensor, whereby the high spatial resolution of 1.6m at the front end of the sensing fibre was degraded to 6.5m after 30 km [11].

Figure 4-13: Raman backscattered signal for the full length of sensing fibre
Figure 4-14: Raman backscattered signal at the end of sensing fibre illustrating the heated section

Figure 4-15: Ratio of Rayleigh to Raman backscattered signal, compensating for splice and attenuation losses
4.5 Conclusions

A simple and compact Q-switched source at 1.53µm has been utilised to produce a high peak power pulsed source at 1.65µm. This source was then used for demonstration of a 1.6µm OTDR system. Combining this source with the use of the residual pump power at 1.5µm, amplification to the signal pulse at some distance down the sensing fibre through Raman amplification was provided. This technique has demonstrated a substantial increase in the dynamic range for sensing. Although this technique has only been demonstrated for an OTDR system based on Rayleigh backscattered measurements, it has wide applications for other forms of distributed measurements, such as distributed strain and temperature measurements based on Brillouin and Raman scattering processes. The ability to achieve the limiting threshold value of the amplified signal pulse at some distance down the sensing fibre will enable a new range of extended range distributed sensors to be developed.

This 1.65µm source was also demonstrated for use in a spontaneous Raman based DTS system. This allows existing live optical transmission cables to be used to also monitor distributed temperature. The pulsed source produced 1.4W peak power at 1.65µm with a pulse width of 45ns for repetition rates less than 1kHz. A temperature resolution of 4°C with a spatial resolution of 10metres for a range of over 10km was demonstrated. Further improvements in temperature and spatial resolution could be obtained by increasing the available peak power of 1.65µm sources. Since a backscattered trace is required, such a system is presently confined to unrepeated and unamplified communication links.
4.6 References


CHAPTER FIVE

BRILLOUIN-BASED DISTRIBUTED FIBRE
TEMPERATURE AND STRAIN SENSING

5.1 Introduction

In Chapter 2, the theory and principles behind the use of Brillouin scattering and the Landau-Placzek ratio for accurately performing distributed temperature and strain measurements were described. In this chapter, experimental realisation of spontaneous Brillouin-based distributed fibre sensors is described initially using a semiconductor distributed feedback (DFB) laser diode as a narrow linewidth source. Two distributed sensors are described; a distributed temperature sensor (DTS) with a high spatial resolution and a long-range combined distributed strain and temperature sensor. The problems encountered using this source are outlined in this chapter and prompted an investigation into achieving ultra narrow linewidth pulsed sources which is then described in Chapter 6. An optical filtering system based on fibre Mach-Zehnder interferometers was used to separate the Brillouin signal from the Rayleigh signal and to measure both the spontaneous Brillouin backscattered signal intensity and frequency shift variations.

In some applications, there is a need for fine monitoring of structures over a short sensing range which requires sub-metre spatial resolution, such as in vessels and aircraft. Several methods for temperature sensing using Raman scattering have been proposed in the past, which achieved metre-order spatial resolution. In the case of Brillouin scattering, a novel method using direct-frequency-modulation of a tuneable laser diode and electro-optic modulator (EOM) demonstrated a remarkable sensing spatial resolution of 45cms for a 7.8-metre sensing range \[1\]. For combined distributed strain and temperature sensors, long-range measurements are also useful in the power and oil industries, and structural monitoring.
Each experimental component for the sensing systems is described and discussed, and
the experimental results for both strain and temperature measurements are also
illustrated. In the combined distributed strain and temperature sensor, the results are
compared and contrasted with theoretical predictions. It has been shown that the
Brillouin backscattered intensity and frequency shift exhibit both strain and
temperature dependence [2][3][4][5]. By measuring both these parameters, strain and
temperature information can be resolved independently.

5.2  Spontaneous Brillouin-based Distributed Temperature Sensor
with Sub-metre Spatial Resolution

5.2.1  Variation of Brillouin Gain Spectrum with Source Pulse width

It has been suggested that the time-domain pulsed approach is unsuitable for
Brillouin-based distributed measurements of sub-metre resolution [1][6]. As the
length of the pump pulse width is decreased, the Brillouin gain spectrum no longer
remains constant [7]. The Brillouin gain curve spreads out to match the bandwidth of
the pulsed pump source and the peak gain decreases.

Previous methods of pulsed Brillouin sensing measured the variations in the Brillouin
frequency shift. In these systems, the minimum detectable change in Brillouin
frequency shift can be expressed by [8][9] (Appendix C):

$$\delta\nu_B = \frac{\Delta\nu_B}{\sqrt{2} (\text{SNR})^{0.25}}$$  \hspace{1cm} (5-1)

whereby $\Delta\nu_B$ is the natural Brillouin linewidth and SNR is the electrical signal-to-
noise ratio. When a short pulse width pump source is used (to achieve a high spatial
resolution), the resulting linewidth is the convolved spectral distribution of the natural
Brillouin linewidth and the pulsed source linewidth, and replaces $\Delta\nu_B$ in Equation (5-
1). This implies that to maintain high frequency shift sensitivity for high spatial
resolution measurements, the SNR has to be increased. However, the method of
measuring the spontaneous backscattered intensity in the ensuing experiment avoids
some of the problems associated with measuring the Brillouin frequency shift using very short pulses. There have been recent attempts to perform high spatial resolution structural monitoring using the counter-propagating pump and probe waves and Brillouin loss technique \[10\]. The strain was evaluated by obtaining the Brillouin frequency spectrum and fitting a peak function. However, there is a limitation on the system in the inability to measure the laser frequency accurately used to resolve the Brillouin frequency shift.

5.2.2 Development of Short Pulse Width Source for Distributed Temperature Sensor

Prior to conducting a distributed temperature sensing measurement with high spatial resolution accuracy, it was first necessary to develop a pulsed source with a short pulse width (<5ns) with a linewidth of less than approximately 3GHz. This linewidth limitation is required to ensure a high rejection of the Rayleigh signal from the Brillouin signal as both signals are separated with the use of Mach-Zehnder interferometers. Although the narrow linewidth operation of Erbium-doped Q-switched lasers has been demonstrated, it is difficult to achieve pulse widths less than 5ns.

One possible approach to obtain short pulse width sources is to design a mode-locked fibre laser. By designing a mode-locked fibre laser with its cavity length comparable to the sensing fibre, it is potentially possible to obtain a short pulse width source with sufficient energy suitable for distributed temperature sensing (DTS). Experiments were conducted by constructing an Erbium-doped actively switched mode-locked fibre laser in a ring configuration. The laser was pumped with a 100mW laser diode at 980nm, and an AOM was used for cavity loss switching for the cavity length of ~2km. Pulses with peak powers of 63mW and 22ns pulse width were achieved. It is believed that the difficulty in achieving shorter pulse widths is due to the cavity instabilities. Although shorter cavity mode-locked fibre ring lasers may achieve shorter pulse widths, extra synchronisation would be required to gate the pulses such that only a single pulse travels down the sensing fibre for each measurement.
As it seemed problematic to attain pulse durations less than 5 ns using a mode-locked fibre ring laser without any feedback stabilisation circuits, an amplified pulsed DFB semiconductor laser diode source was investigated as an alternative source. Figure 5-1 illustrates the experimental configuration of this source. To generate the required high peak power, narrow linewidth signal, a CW semiconductor distributed feedback (DFB) laser (Nortel LC155GC-20A) with an output power of 2.5 mW was used. This was externally modulated to reduce spectral chirp by using a LiNbO$_3$ electro-optic modulator (EOM) (IOAP-MOD9082A 2.5 Gb/s amplitude modulator at 1550 nm). The modulator takes the form of a Mach-Zehnder interferometer waveguide. In this modulator, there are two input ports (a DC bias port and a modulation port), whereby voltages can be applied to modulate/pulse the CW DFB laser signal. The sum of voltage levels applied at both input ports determines the optical transmission level through the Mach-Zehnder transfer function by controlling the relative phase difference between the two optical paths. For this experiment, as it was required to pulse the CW signal from the DFB laser diode, the applied DC bias voltage was set such that minimal light was transmitted. A pulse generator then provided an electrical pulse to the modulation port, providing the required increase in transmission through the EOM for the duration of the pulse. A polarisation controller was included prior to the modulator to provide efficient coupling of the DFB laser signal into the EOM.
This signal pulse was then amplified using an EDFA (EDFA1) and the residual ASE noise was filtered by an in-fibre Bragg grating (Reflectivity = 99.4%, $\Delta \lambda = 0.08$nm, $\lambda = 1533.4$nm) in conjunction with a circulator 1 (C1). The reflected signal was amplified using another EDFA (EDFA2) to overcome the loss of the acousto-optic modulator (AOM) which served to gate the pulse and filter the ASE generated by the second EDFA from being launched into the sensing fibre. The resultant signal pulse had a peak power of 4.5W, pulse width of 3.5ns and spectral linewidth of <100MHz. The high peak power within the short pulse served to maximise the energy in the backscattered signal. The AOM was synchronised with the EOM and pulses were generated at a repetition rate of 6600Hz. The signal was passed through a 95/5% fibre coupler (FC1). The 5% arm of the coupler functioned as a monitor of the signal pulse profile. This signal was then launched into the sensing fibre though circulator C2 shown in Figure 5-5. The pulse profile from the amplified DFB source is shown inFigure 5-2.

Figure 5-1: Experimental configuration of pulsed source used for distributed strain and temperature measurement
5.2.3 Filtering and Detection

In order for the Brillouin signal to be interrogated it has to be separated from the Rayleigh by means of a filtering technique. Previous experiments relied on the use of bulk Fabry-Perot interferometers [2][11]. In general, they are not commercially viable in terms of cost and size, and their associated loss limits the measurand resolution that can be achieved. A Mach-Zehnder fibre interferometer has recently been developed which offers the advantages of an all-fibre device that is simple, cheap and small in size, with the ability to sufficiently filter the Rayleigh from the Brillouin signals [12]. Similar fibre Mach-Zehnder interferometers were also used in the following experiments. There are two possible configurations using a single fibre Mach-Zehnder, either as a single-pass Mach-Zehnder (SPMZ) configuration or a double-pass Mach-Zehnder (DPMZ) configuration.

A schematic diagram of a single-pass Mach-Zehnder is shown in Figure 5-3. It consists of two 50/50 fibre couplers spliced together, with a path imbalance between the two arms of the device [12]. In the double-pass configured interferometer, an isolator is used to join both arms on one side of the Mach-Zehnder as shown in the dotted lines of Figure 5-3. The Mach-Zehnder is tuned such that the Rayleigh signal is

![Pulse profile of pulsed amplified DFB source with 3.5ns pulse width](image.png)

**Figure 5-2:** Pulse profile of pulsed amplified DFB source with 3.5ns pulse width
blocked by the isolator whilst the Brillouin signal is fed back through the interferometer.

\[ T(\nu) = \left( \frac{1}{2} \left[ 1 + \cos \left( \frac{2\pi \nu}{\text{FSR}} \right) \right] \right)^n \]  

(5-2)

where \( n=1,2 \) for single-pass or double-pass configuration respectively, FSR is the free spectral range of the interferometer dictated by the path imbalance between the two arms of the device. The FSR is related to the path imbalance length by:

\[ \text{FSR} = \frac{c}{n \Delta l} \]  

(5-3)

where FSR is expressed in terms of frequency, \( \Delta l \) is the path imbalance and \( n \) is the refractive index of the fibre core. At a wavelength of 1533nm, a path imbalance of approximately 9.3mm is required to produce a FSR of 22GHz corresponding to the separation between the Stokes/anti-Stokes Brillouin signals. This would then provide maximum transmission for the Brillouin signals whilst rejecting the Rayleigh signal at the minimum of the transfer function.

**Figure 5-3:** Illustration of single-pass and double-pass (incorporating the path in dotted lines) Mach-Zehnder used in the experiment
Figure 5-4: Comparison of transfer function spectral profiles for (a) SPMZ (b) DPMZ for the purpose of optical filters

Figure 5-4 illustrates the transfer function of a SPMZ and a DPMZ with the peak of the transfer function normalised to 1, for a path imbalance equivalent to a free spectral range (FSR) of 22GHz. The interferometric filters are considered to have ideal maximum throughputs. The SPMZ is observed to have a pass bandwidth (FWHM) of 11GHz, and 7.92GHz for the DPMZ. If a source of finite bandwidth (e.g. 3GHz) is used to obtain the backscattered signals, the larger bandwidth of the SPMZ permits a larger contamination of the Rayleigh signal into the pass band of the SPMZ as compared to the DPMZ. The performance of the DPMZ is therefore notably suitable in the application of separating the Rayleigh from the Brillouin signal. In addition, the flatter region at the minimum transmission of the DPMZ has the benefit of allowing a greater tolerance whilst experimentally locking the Rayleigh signal frequency to the transfer function minimum.

With the path imbalance between both arms was set to approximately 9.3mm, the measured rejection ratio of the Rayleigh signal from the Brillouin signal was in excess of 28dB, and the Mach-Zehnder interferometer has an insertion loss of less than 2dB. The high rejection of the Rayleigh signal is required to minimise the effect of coherent Rayleigh noise (CRN) (Section 5.3.3), which has a detrimental effect on the strain and temperature resolution. The amplitude fluctuation in the Rayleigh
backscattered signal may be explained as follows. Rayleigh scattering occurs due to backscattering from scattering elements which are of the order of an optical wavelength. The backscattered signals from this large number of scattering elements at different positions interfere with each other, which influences the resultant backscattered intensity. In optical fibres, the scattering coefficient and spatial distribution of these scattering elements are random, which causes intensity fluctuations in the backscattered signal.

5.2.4 Experiment

The experimental set-up for the DTS systems consisted of the short pulse width source, sensing fibre and the all-fibre double-pass configured Mach-Zehnder interferometer as shown in Figure 5.3. The sensing fibre was 1km in total, consisting of three sections of conventional single-mode silica fibre (NA=0.12, cutoff=1.2µm) spliced together with lengths of 600m, 200m and 200m respectively. The spontaneous Brillouin backscattered signal was detected through an InGaAs photodetector and transimpedance amplifier with a bandwidth of 100MHz and sensitivity of 0.1mV/nW. Signal averaging was performed by a PC and $2^{17}$ averages were obtained.
Figure 5-5: Experimental set-up for high spatial resolution Brillouin distributed temperature sensor
5.2.5 Results

Figure 5-6 shows a plot of the spontaneous Brillouin backscattered signal taken at a distance of 550m down the sensing fibre. The second drum (200m) was heated to a temperature of 67°C, an increase of 44°C from the room temperature of 23°C. It can be seen from the plot that there is a clear rise in the heated section. In addition, the signal at the end of the sensing fibre is well above the noise floor, indicating that measurements may be made for sensing lengths exceeding 1km. Although it is possible to generate higher pump peak powers with the available source, distortion of the backscattered trace due to self-phase modulation and/or stimulated scattering readily observed if the peak pump power exceeds a certain threshold and would lead to erroneous results.

Figure 5-6: Brillouin backscattered signal illustrating the signal rise due to a heated section at 67°C, before the signal was compensated for splice losses
The Brillouin signal obtained cannot be used to measure absolute temperature due to the dependence of the signal on fibre attenuation and localised splice/bend losses. In order to take absolute measurements, the Brillouin signal has to be referenced to the Rayleigh backscattered signal which is independent of temperature fluctuations. To minimise coherent effects, the Rayleigh signal was obtained by using a broadband pulsed source in place of the DFB laser diode. The ratio of the Brillouin and Rayleigh signals is known as the Landau-Placzek ratio and provides a temperature dependent signal which is corrected for splice/bend losses and fibre attenuation, and this ratio is shown in Figure 5-7. The RMS noise on the Landau-Placzek ratio was calculated to provide information on the temperature resolution of the trace, which corresponded to 4.3°C. Figure 5-8 shows an expanded trace of the step in Brillouin backscattered signal for sections at 67°C and 23°C, to illustrate the spatial resolution of 35cm. The seemingly larger fall time in Figure 5-6 as compared to Figure 5-8 is due to the oscilloscope sampling rate falling to accommodate a longer viewed length.

![Figure 5-7: Landau-Placzek ratio which shows the splice loss compensated by dividing Brillouin signal with the Rayleigh signal](image-url)
From Figure 5-8, it is observed that Brillouin scattering still occurs using a pulsed source shorter than the acoustic lifetime, contrary to the comments of previous literature [6]. In this respect, Brillouin scattering occurs by rapidly reflecting from the acoustic wave with the bandwidth of the Brillouin backscattered signal being broadened, and the scattering does not occur for the total duration of the acoustic phonon lifetime. Based on the results to consider distributed sensors with a spatial resolution smaller than the acoustic phonon lifetime, the bandwidth of the Brillouin signal is increased to that of the pump pulsed source. To enable combined distributed temperature and strain measurements with a very high spatial resolution to be made, it is necessary that the Brillouin frequency shift can be resolved accurately with similar spatial resolution.
5.3 Long Range Combined Distributed Strain and Temperature Sensor

5.3.1 Source
The previous section examined the use of an amplified pulsed semiconductor DFB laser diode as a source for a high spatial resolution DTS system. In this section, a similar source is used in a combined distributed strain and temperature sensor. The narrow linewidth of the DFB source (typically tens of MHz) is suitable for the more stringent linewidth requirements for strain sensing, compared to the linewidth requirements of a DTS system (<3GHz).

5.3.2 Filtering and Detection
In addition to separating the Brillouin signal from the Rayleigh signal as in the case for the DTS system described earlier, it is necessary to determine the Brillouin frequency shift caused by variations in strain or temperature along the sensing fibre.

To resolve the Brillouin frequency shift for the following combined distributed strain and temperature measurements, two in-fibre Mach-Zehnder interferometers were linked in series. The light at the output of the DPMZ (used to separate the Rayleigh signal from the Brillouin signal) as in the case for the previous DTS system (Section 5.2.3) was passed through a SPMZ. The SPMZ was designed to provide adequate sensitivity for the Brillouin frequency change with the applied strain/temperature effect. Figure 5-9 illustrates the transfer function of a Mach-Zehnder designed with a FSR of 6.8GHz. When the Rayleigh signal lies at a minimum of the transfer function, the Brillouin signals corresponding to zero strain lay at approximately 70% of the transfer function maximum when the sensing fibre is not heated and not strained. As an increase in temperature or strain is applied to the sensing fibre, the Brillouin shift increases and causes a decrease in signal intensity from the output of the SPMZ as shown in Figure 5-9.
To accurately evaluate the Brillouin frequency shift, it is necessary to determine the source linewidth requirements by which a detrimental effect would occur for an increased source linewidth. We may express the resulting visibility of the Mach-Zehnder interferometer as:

\[
\text{Visibility} = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \quad (5-4)
\]

**Figure 5-9:** *Single-pass Mach-Zehnder transfer function with an FSR = 6.8GHz, illustrating a Brillouin frequency shift of 540MHz on the Stokes and anti-Stokes signals*
As an example, if we consider a source with a Gaussian lineshape of 100MHz, the resulting visibility evaluated by using the convolution of both the normalised Mach-Zehnder transfer function and pulse spectrum is 99.5%, compared to 52.6% visibility for a source linewidth of 4GHz shown in Figure 5-10. Hence, it is predicted that the DFB source is sufficient to produce signals with sufficient visibility through the Mach-Zehnder.

![Graph showing the effect of source linewidths on visibility](image)

**Figure 5-10**: *Plot illustrating the effect of 2 source linewidths (100MHz and 4GHz) on the resulting visibility*

The SPMZ for measurement of the Brillouin frequency was constructed and tested to verify the FSR of the transfer function. The path imbalance between the two arms was designed to be approximately 30mm, corresponding to 6.8GHz. Figure 5-11 illustrates the experimentally obtained transfer function of the SPMZ using a tuneable laser. The frequency of the tuneable laser was swept through the FSR of the Mach-Zehnder transfer function monitored using a scanning Fabry-Perot interferometer. This was achieved by using a digital oscilloscope and storing the relative peaks as the DFB laser was successively swept in frequency with the Fabry-Perot interferometer is set in the scanning mode; the overall envelope trace revealing that the spectrum can be obtained. The first plot illustrates the DFB laser being scanned and detected on the scanning Fabry-Perot interferometer, which demonstrates that the DFB power remains...
more or less constant throughout the scanning range. From the spectrum of the SPMZ, the visibility is calculated to be approximately 97%.

![Figure 5-11: Plot of the DFB laser scanned through (a) directly and (b) through single-pass Mach-Zehnder before passing through the scanning Fabry-Perot interferometer and using the peak detection averaging on the oscilloscope](image)

Both the Mach-Zehnders were insulated from thermal fluctuations and air currents by placing them in an enclosed package. This was to prevent any instability in the path imbalance between the arms of the interferometer, which would cause fluctuations in the output signal within the measurement time.

### 5.3.3 Coherent Rayleigh Noise

One of the major setbacks in obtaining good measurand resolution is due to the phenomenon of coherent Rayleigh noise (CRN). It is a fundamental noise on the Rayleigh backscattered signal which cannot be reduced by continuous averaging using the same signal wavelength of the source. This introduces a percentage noise on the Rayleigh signal, which manifests itself as additional noise in the Landau-Placzek ratio in two ways. First, the CRN contribution could occur from the reference Rayleigh signal used to compensate the Brillouin signal for attenuation/splice losses. Secondly, the large percentage of CRN on the Rayleigh signal creates difficulties in
designing an efficient filter with a sufficiently high rejection ratio of the Rayleigh signal from the Brillouin signal.

CRN or ‘fading’ noise is a well-known problem [14] and consists of noise observed on the Rayleigh backscattered signal when a source with a narrow linewidth is used. Briefly described, this noise is due to the coherent interference of a large number of scatter elements, which generates random intensity fluctuations in the backscattered signal. However, these coherent effects may be reduced either by utilising a broadband width source or by averaging over a number of frequencies with a tuneable narrow source [15]. The backscattered Rayleigh signal generated at a particular frequency decorrelates from that at another frequency due to the backscattered signal being generated from the interference of different groups of scattering centres. As an example, the amplitude fluctuation on the Rayleigh signal was reduced from 0.16dB to 0.08dB when the source wavelength was scanned over 1.25nm [16]. With the latter technique of frequency shift averaging (FSAV), the coherent noise effect is reduced by a relationship proportional to the square root of the number of different frequency averages made [16]. Fading noise is however, not observed in Brillouin backscattered signals as the random phase fluctuations due to the spontaneous propagating density fluctuations result in the noise being averaged over the scatter elements.

In a Brillouin strain and temperature sensor, it is necessary to use a narrow linewidth pulsed source to generate the required Brillouin backscattered signals. To overcome CRN problems, a second source that could consist of either a broadband width or a tuneable narrow linewidth source was used to generate a Rayleigh signal with reduced CRN. In the following experiments, an Erbium-doped Q-switched fibre laser similar to that described in Section 4.2 was used. The reflectivity of the in-fibre Sagnac loop mirror used for this experiment was 19% and the laser had a measured broadband spectrum of 3.5 nm.

Figure 5-12 and Figure 5-13 show the Rayleigh backscattered traces of a length of sensing fibre using both a narrow linewidth laser diode source and the broadband Q-switched laser respectively. It is seen that the percentage noise on the Rayleigh signal is greatly reduced by using a broadband laser and that the splice losses between different drums of fibres become visible.
Figure 5-12: Rayleigh backscattered signal obtained using a narrow linewidth pulsed laser diode

Figure 5-13: (a) Rayleigh backscattered signal obtained using a broadband Q-switched fibre laser, (b) Expanded trace illustrating the splice losses between drums of fibres
5.3.4 Experiment

To perform the simultaneous strain and temperature measurement, the components required in the system are the amplified narrow linewidth pulsed DFB laser source, the two Mach-Zehnder interferometers, a broadband Q-switched laser source used to obtain the Rayleigh signal, sensing fibre and the detection and averaging systems. The amplified pulsed source signal was split through a 95/5 coupler. 5% of the signal was used as a reference signal to control the optical filters.

The system configuration is as shown in Figure 5-14. A circulator (C2) was used to couple 850mW of input light source into the sensing fibre. The sensing fibre consisted of 15km of 125μm conventional telecommunications single-mode silica fibre having a cut-off frequency of 1180-1280nm and fibre attenuation below 0.22dB/km. The first length of sensing fibre was a 8.62km drum (D1), followed by two sections of 0.46km drums (D2 and D3). Splices were made between drums D1, D2, D3 and D4. Fibre drum D2 was placed in an oven and subjected to a temperature of 53°C, an increase in temperature of 30°C from the other drums of fibre from room temperature at 23°C (measured with a thermocouple). Drums D4 and D5 consisted of a continuous length of fibre. Between D4 and D5 there was a 110m section of fibre that was loosely reeled on to 11 pairs of pulleys separated by 5m. The pulleys were selected such that the diameters were large enough to minimise macrobend losses. In addition, the surfaces of the pulleys used in the experiment were polished to reduce such losses. Vertical weights were then added on an overhanging fibre at one end of the 120m length of fibre to provide strain. The change in length of the fibre was measured and the average strain over the 120m calculated. The backscattered signal was then collected through the circulator (C2) and filtered through the two Mach-Zehnder interferometers.
Figure 5-14: Experimental set-up for Brillouin distributed strain and temperature sensor
The optical filtering system used consisted of both the in-fibre Mach-Zehnder interferometers described earlier. The SPMZ was tuned by monitoring the output port of the SPMZ whilst launching the laser signal (its frequency being equal to the Rayleigh signal frequency) from the 5% arm of the 95/5 coupler (FC1 in Figure 5-1) into the remaining input port of the SPMZ. Using this technique it is possible to tune the transmission characteristics of the Mach-Zehnder such that the Rayleigh signal lies at the maximum or minimum of the transfer function. The tuning laser signal is then switched off and the Brillouin backscattered signals for the condition of maximum and minimum throughput at the signal wavelength are summed thus obtaining a measurement of the Brillouin backscattered intensity that is independent of frequency shift. Either individual measurement provides a measure of both changes in Brillouin intensity and frequency shift and as the Brillouin intensity has been measured independently of frequency by summing the two outputs, the Brillouin frequency shift can be calculated.

The backscattered traces were obtained from the output of the single pass Mach-Zehnder using a 300μm InGaAs photo-detector and a preamplifier which has a sensitivity of 10mV/nA, transimpedance gain of 10MΩ and an electrical low-pass filter bandwidth of 3MHz. As a result, the spatial resolution of the system was detector limited to 10m. The backscattered traces were averaged 2^{16} times with an averaging time of 16 minutes. By triggering the oscilloscope on the pulse generator by which the pulsed source is driven and using the time delay function on the scope, it is possible to view a particular section of the backscattered trace on an expanded time scale to capture the trace of the rise/fall time of the backscattered signal.
5.3.5 Results

5.3.5.1 Brillouin Backscattered Signals

Figure 5-15 shows the output of the single-pass Mach-Zehnder when the Mach-Zehnder has been tuned such that the laser signal (same wavelength as the Rayleigh signal) has been tuned to (a) the maximum and (b) the minimum of the transfer function. Figure 5-16 depicts the variation in Brillouin frequency shift due to strain/temperature effects, causing an intensity signal variation at the output of the SPMZ when the laser control signal is at the minimum of the SPMZ transfer function. The dashed line represents the laser control signal frequency (similar to the backscattered Rayleigh signal frequency). Figure 5-17 shows the Brillouin frequency shift variation when the laser control signal is at the maximum of the SPMZ transfer function. Figure 5-15 (c) shows the sum of Figure 5-15 (a) and (b) that represents the intensity changes of the Brillouin signal along the length of fibre and is independent of any frequency shift.

![Brillouin backscattered signals from the output of the SPMZ when the Mach-Zehnder was tuned such that the Rayleigh signal is at (a) minimum and (b) maximum of the transfer function, (c) provides the sum of backscattered traces (a) and (b)](image-url)
**Figure 5-16:** Brillouin frequency shift variation due to applied strain/temperature when the laser control signal is tuned to the minimum of the SPMZ transfer function

**Figure 5-17:** Brillouin frequency shift variation due to applied strain/temperature when the laser control signal is tuned to the maximum of the SPMZ transfer function
The attenuation and splice/bend losses are compensated for by dividing the traces of Figure 5-15 (a) and (c) by the Rayleigh signal obtained separately by using the broadband Q-switched laser (Landau-Placzek ratio), and are shown in Figure 5-18 (a) and (b). The Rayleigh backscattered trace obtained using the Q-switched laser is shown in Figure 5-19.

**Figure 5-18:** Plot of normalised Landau-Placzek ratio indicating measurements for (a) Brillouin intensity change and (b) Brillouin intensity and frequency shift change

**Figure 5-19:** Rayleigh backscattered trace obtained by using a broadband Q-switched fibre laser
By using the trace of Figure 5-18 (a), it is possible to determine the Brillouin intensity dependent profile (Brillouin frequency shift independent) along the sensing fibre. This Landau-Placzek ratio (LPR) is then converted to a percentage change reference to the LPR at the unheated and unstrained region of the sensing fibre, which generates the profile shown in Figure 5-20. The dashed line overlaying the experimental data depicts the theoretical predictions of the calculated percentage change in LPR using the Brillouin and Rayleigh backscattered signal information. Both the traces show very close agreement.

**Figure 5-20:** Percentage change in LPR due to variations in Brillouin backscattered intensity (dashed lines illustrate the theoretical calculations)
To obtain the Brillouin frequency shift at every point along the sensing fibre, Figure 5-18(a) is normalised to (b), resulting in a profile dependent only on the Brillouin frequency shift, shown in Figure 5-21. Similar to the intensity variation predictions, the theoretically evaluated profile for the Brillouin frequency shift shows good agreement with the experimental data.

**Figure 5-21:** Resolved Brillouin frequency shift due to temperature and strain variations (dashed lines illustrate the theoretical calculations)
The spatial resolution was determined by obtaining an expanded time scale plot of the Brillouin backscattered signal. This was obtained by measuring the fall time of the backscattered signal at a splice point in the trace and was measured to limited by 10 metres, as shown in Figure 5-22.

![Figure 5-22: Brillouin backscattered signal illustrating a spatial resolution of 10m](image)

To measure the long term stability of the sensor over a period of time, an experiment was conducted over a period of 12 hours with the same applied temperature of 53°C and applied strain of 6300µε throughout this duration, and the Brillouin backscattered traces obtained are illustrated in Figure 5-23. From the measurements taken after 2 hours, 4 hours, 8 hours and 12 hours, the intensity profile with similar environmental conditions exhibit similar Brillouin backscattered traces.
Figure 5-23: Stability measurement of Brillouin backscattered signals when the laser control signal tuned to (a) the minimum and (b) the maximum of the SPMZ transfer function for (i) 2 hours after commencing measurements (ii) 4 hours (iii) 8 hours (iv) 12 hours.
5.3.5.2 Resolving Temperature and Strain

The coefficients relating the Brillouin frequency shift and intensity are known constants as explained in Chapter 2 and can be used in conjunction with the sets of data obtained (frequency shift and intensity variations) to produce strain and temperature profiles. These are shown in Figure 5-24 and Figure 5-25. The temperature and strain resolutions of the backscattered traces were estimated from the r.m.s noise of the signals to be 4°C and 290µε.

Figure 5-24: Resolved temperature profile along the sensing fibre for a heated section of 30°C
Using Equation (2-11) in Chapter 2, it is possible to evaluate both the measurands of strain and temperature by taking the inverse matrix relating to the Brillouin intensity and frequency shift provided that the determinant has a nonzero value \[18\]:

\[
\begin{bmatrix}
\varepsilon \\
T
\end{bmatrix} = \frac{1}{C_{\nu_T} C_{\nu_T} - C_{p_T} C_{\nu_T}} \begin{bmatrix}
C_{p_T} & -C_{\nu_T} \\
-C_{p_T} & C_{\nu_T}
\end{bmatrix} \begin{bmatrix}
\nu_B \\
P_B
\end{bmatrix}
\]

(5-5)

The errors in strain and temperature measurements are then given by:

\[
\begin{align*}
|\delta \varepsilon| &= \frac{C_{p_T} |\delta \nu_B| + C_{\nu_T} |\delta P_B|}{C_{\nu_T} C_{\nu_T} - C_{p_T} C_{\nu_T}} \\
|\delta T| &= \frac{C_{p_T} |\delta \nu_B| + C_{\nu_T} |\delta P_B|}{C_{\nu_T} C_{\nu_T} - C_{p_T} C_{\nu_T}}
\end{align*}
\]

(5-6) (5-7)

A further experiment was then performed using 3 different values of weights applied to the system of pulleys providing 3 different extensions in the sensing fibre.
respectively. The experiment was carried out by initially applying the heaviest weight causing the longest extension in fibre, and subsequently decreasing the extension in fibre. Figure 5-26 shows a plot of the backscattered signals for the 3 different fibre strains respectively. The slope in the backscattered signal at the strained region is caused by the strain distribution over the length of strained region. As the fibre extension was reduced by removing part of the weights attached on one end of the sensing fibre, it can be seen that the slope on the backscattered has reversed. This is due to the slight friction on the pulleys causing a hysteresis-like behaviour on the system of pulleys.

Figure 5-26: Brillouin backscattered plots using 3 different weights
The corresponding Landau-Placzek ratio for the three plots of the Brillouin backscattered signals showing both intensity and frequency changes are shown in Figure 5-27. It is observed that under different strain conditions, the resultant Landau-Placzek ratio evaluated at the heated section remains the same, whilst the profiles at the strained section are varying under different strains.

**Figure 5-27: Landau-Placzek ratio illustrating the intensity and frequency change dependence for 3 different extension lengths**
5.4 Conclusions

In conclusion, spontaneous Brillouin-based distributed sensors were demonstrated utilising a semiconductor DFB laser diode that was pulsed and amplified. By using very short pulses, a high spatial resolution distributed temperature sensor with 35cm spatial resolution was demonstrated over a 1km length of sensing fibre. A long-range combined distributed temperature and strain sensor was then demonstrated. This sensor utilised the signals extracted from two cascaded in-fibre Mach-Zehnder interferometers to independently resolve both strain and temperature measurements, by measuring both the intensity and frequency variations in the Brillouin backscattered signal. The intensity dependence of the Brillouin signal due to variations in strain and temperature was measured by summing the two outputs from the single-pass Mach-Zehnder; the Brillouin frequency shift dependence was measured by obtaining the output from one arm of the single-pass Mach-Zehnder and compensating for Brillouin intensity changes. Using this filtering system and the Landau-Placzek ratio to compensate for splice and bend losses, variations in strain and temperature was independently identified. The low insertion loss is crucial to achieve adequate signal to noise ratio, and has resulted in a major advance in measurement accuracy over previously reported results \[2\]. The sensor has been demonstrated for a length of 15km, and a temperature resolution of 4°C, strain resolution of 290µε and a spatial resolution of 10m has been achieved. In practical applications, this sensor has the potential to offer long-range monitoring over tens of kilometres, and is particularly useful in applications which permit access to just one end of the sensing fibre.
5.5 References


CHAPTER SIX

ULTRA NARROW LINEWIDTH SOURCES FOR DISTRIBUTED STRAIN AND TEMPERATURE SENSING

6.1 Introduction

In the previous chapter, a semiconductor DFB laser was used to provide a narrow linewidth source for simultaneous strain and temperature sensors. A typical DFB laser has a time averaged laser linewidth in the region of tens of MHz to hundreds of MHz (e.g. Nortel LC155GC-20A). It is beneficial to investigate the possibility of incorporating a narrow linewidth fibre-based source in place of the semiconductor DFB source. The fibre-based source is attractive in that it is capable of generating a time averaged output of at least equivalent or less than that of a semiconductor DFB laser with high output powers. Potentially, these fibre-based lasers may also be cost-effective.

This chapter describes various design and experimental results of these fibre-based lasers. Finally, experimental strain results are shown using one such fibre laser as the source; its relative advantages and disadvantages over conventional laser diodes are discussed.
6.2 Introduction to narrow linewidth lasers

Multi-mode operation in lasers is identified as the fundamental reason for a broad frequency spectrum. To enable the development of narrow linewidth lasers, it is important to understand the reasons leading to multi-mode operation and various methods of suppressing these modes to achieve single-mode operation. The concept of spatial hole burning is known as the primary cause for multi-mode operation and linewidth broadening in lasers including fibre lasers.

The concept of spatial hole burning was first observed and described by Tang et al in 1963 [1]. For an ideal homogeneously broadened laser transition which we assume is the case for the Erbium profile [2], the lineshape for the stimulated emission cross section versus frequency/wavelength is fixed and identical for all atoms in the laser medium [3]. The magnitude of the gain at any frequency will increase or decrease depending only on the population inversion, with the spectral profile of the laser gain maintaining a constant lineshape.

When the gain of an ideal homogeneous laser system is increased, the longitudinal mode closest to the peak of the lineshape will lase provided the cavity losses are wavelength independent. In the case where the losses of the cavity are wavelength dependent, the laser would still operate at a single longitudinal mode, although this mode may not be the one with the largest stimulated emission cross section. During steady-state laser operation, the gain of the lasing mode equals the cavity losses (resonator and output coupling losses), whilst all other modes experience the same loss but have a net gain lower than unity.

The most significant factor that leads to multi-mode operation in a practical homogeneously broadened laser is spatial inhomogeneity in the gain, due to ‘spatial hole burning’ caused by the standing-wave nature of the Fabry-Perot laser. In a linear resonator, the forward and backward propagating waves of a lasing mode will interfere to form a standing-wave which will then in turn deplete the gain at the peaks of the standing-wave rather than at the nodes as shown in Figure 6-1. As such, the population inversion increases towards the nodes of the standing wave as compared to
the peaks, resulting in spatial inhomogeneity of the gain. As a result, adjacent modes may experience an overall gain large enough to initiate lasing.

Figure 6-1: Field distributions for two adjacent modes and population inversion for the initial oscillation mode

6.3 Methods of Achieving Narrow Linewidth Operation

There are two fundamental techniques to achieve narrow linewidths in lasers. In mode-selection methods, the laser cavity is constructed in such a manner that the modes adjacent to the first lasing mode to reach threshold have a larger difference in net gain than the extra gain that follows as a result of spatial hole burning. Another method to avoid spatial hole burning is to prevent standing-waves from forming in the laser cavity. Both these approaches may also be combined to provide a more effective suppression of multi-mode lasing.

6.3.1 Mode Suppression

To effectively suppress all other modes in a laser except the preferred lasing mode, one can introduce extra cavity losses or a frequency selective element. In this situation, the non-lasing modes will experience a loss larger than the net gain that would be achieved as a result of spatial hole burning. The usual method is to incorporate an interferometric loss within the cavity in the form of an intracavity etalon. However, this technique requires that the preferred lasing mode is located at the minimum of the loss curve of the etalon, which often requires some form of active
locking technique. Also, the introduction of an additional etalon will increase cavity losses, degrading the performance of the laser.

One can also suppress all but one lasing mode by increasing the spacing between adjacent modes such that other modes lie outside the width of the laser gain curve. This is usually achieved by designing very short cavity lengths. This was successfully performed in microchip lasers, which consist of a flat piece of laser crystal with reflective coatings on both sides [4]. In fibre lasers, this can be achieved by designing a very short (few centimetres long) standing-wave cavity combined with one or two narrow band Bragg gratings that select a single longitudinal mode [5]. One disadvantage of this approach is that it limits the design to short cavities, often limiting the pump efficiency such that devices cannot be easily scaled to high output powers.

6.3.2 Suppression of standing-wave formation

As an alternative to the mode suppression techniques previously discussed, lasers may be designed to avoid formation of standing waves, and hence spatial hole burning. The two currently most common methods employed are the unidirectional ring cavity and the twisted-mode laser, initially demonstrated in 1963 [1] and 1965 [6] respectively.

In twisted-mode lasers, the gain medium is configured between two quarter-wave plates, which transform the light into circular polarised light before entering the gain medium. The two circular polarised states travelling in opposite directions do not interfere with each other if they contain similar polarisations (either right or left circular polarised) and therefore the gain is depleted uniformly as no standing waves are formed.

In a unidirectional ring laser or travelling wave laser, lasing is forced to operate in one direction only, thus enabling uniform depletion of the gain medium and avoiding the formation of standing waves. This technique requires an ‘optical diode’ to prevent light from travelling in the opposite direction. Two examples of components that can be used for this purpose are acousto-optic modulators and optical isolators.
Experiments conducted with fibre lasers often employ the use of fibre pigtailed optical isolators due to their fibre compatibility, compactness and reliable extinction ratio (~35dB).

6.3.3 Stability of Narrow Linewidth Fibre Lasers

Although there is intense research in fibre lasers to generate narrow linewidth sources, stabilising the frequency of the laser has proven to be more difficult. Morkel et al reported the first unidirectional operation of a single-frequency fibre ring laser with a measured linewidth of less than 60kHz [7]. However, such ring cavities would usually include a polarisation-controller to govern the polarisation state within the ring. With proper adjustment of the polarisation-controller, only a single peak separated within the free spectral range (FSR) of a scanning Fabry-Perot interferometer would be observed, as compared to multiple peaks in absence of birefringence optimisation. Even with optimisation, stability of a ring cavity is poor and is sensitive to environmental perturbations, and changes would occur over a time scale of 1-2 seconds. An alternative experimental configuration was demonstrated which allows the selection of the laser wavelength [8]. In this case, a fibre Bragg grating was used to select the wavelength region of operation. Even with optimisation of the polarisation controller, mode-hopping of the laser was still frequent.

To suppress mode-hopping in ring lasers, bandpass filters using Fabry-Perot filters [9][10][11] and active stabilisation [12] have been utilised. By using Fabry-Perot filters in a tandem configuration, it was also possible to achieve tuneable wavelength and single-mode operation [9][10]. Alternatively, the use of polarisation maintaining fibres and couplers in the ring cavity would also ensure single-frequency operation [13]. The first demonstration of utilising the twisted-mode technique in a fibre laser to eliminate spatial hole burning and enforce single-frequency operation was demonstrated in 1996 [14]. The linewidth was measured to be 10kHz with a CW output power of 0.6mW. However, a simple method of reducing mode-hopping has been demonstrated in a ring cavity configuration [15] without the need for many optical components. This was achieved by incorporating a section of unpumped erbium-doped fibre in the ring.
cavity as a standing-wave configuration. The frequency stabilisation property of the Erbium-doped fibre was initially demonstrated using two sections of Erbium-doped fibres, one length being the amplifying section and the other being an absorbing section \([16]\). The underlying principle for this mechanism is that the mode that initially lases within the cavity would partially saturate the absorbing Erbium-doped section, and would thus suffer a lower loss than the other adjacent competing modes. This technique was adopted to stabilise the frequency of Q-switched ring laser in CW operation and is described in section 6.4. A low-doped Erbium fibre was used as a saturable absorber which forms a self-induced grating whilst the gain medium comprised of a length of high-doped erbium fibre.

Short, grating-based fibre lasers also offer the ability to provide single-frequency lasing. These lasers may consist of fibre Bragg grating lasers (FBGL) or fibre distributed feedback lasers (DFB). The narrow linewidth feedback gratings and short cavity provide good stability and reduces the tendency for mode-hopping. However, the more general difficulty associated with these lasers is the ability to maintain good lasing stability. Apart from the consideration of longitudinal modes, there is the possibility of two polarisation modes simultaneously lasing within the cavity. If the fibre is isotropic there is no preference for a certain polarisation and in general both polarisation modes will begin to lase \([17]\). The difference in optical frequencies between these two modes is expressed by:

\[
\Delta \nu_{\text{pol}} = \frac{B \nu}{n} \quad (6-1)
\]

Where \(B\) is the fibre birefringence, \(\nu\) is the optical frequency and \(n\) is the refractive index. With the intrinsic birefringence of a standard single-mode optical fibre of approximately \(10^{-6}\), the two polarisation modes will be spaced by typically a few hundred MHz. Polarisation single-mode lasers can be generated by increasing the fibre birefringence with UV-light. This is achieved as a result of inducing high intensity light pulses illuminating the fibre from one side and can resulting in an anisotropic index change along the fibre radius. By inducing a birefringent phaseshift
in a grating, the situation that the phase is shifted by $\pi/2$ is only fulfilled for one polarisation at a time. The other polarisation suffers from a higher lasing threshold and lasing of this polarisation state is therefore suppressed. The $\pi/2$ phaseshift within the grating is needed as a single grating is written over the entire gain region of the laser. With this technique, a construction of a fibre laser operating in a single polarisation mode has been demonstrated [18].

6.4 Narrow linewidth Erbium-doped Q-switched fibre ring laser

One possible approach to achieve a narrow linewidth pulsed source for sensing applications is to use a Q-switched laser configuration. Unlike previous Q-switched lasers mentioned in earlier chapters, there is a need for better frequency selection and control to generate the required narrow linewidth. One major advantage of a Q-switched configuration is the simplicity of components, requiring just one pump laser for providing the population inversion in the amplifying gain medium.

For typical Q-switching, the pulse builds from spontaneous emission and the stored energy is emitted in a short pulse. Assuming that there is one photon in each longitudinal mode at the time when the Q-switch is opened [19], the oscillation builds up from a ‘quantum noise source’ [20] as the spontaneous emission is a random process. The pulse then builds up from spontaneous emission noise, this results in the pulse containing a mixture of longitudinal modes, which varies randomly from pulse to pulse, even in the absence of spatial hole burning.

6.4.1 Q-switching with a narrow frequency spectrum

By introducing a significantly higher gain for just one of the longitudinal modes in a laser, narrow linewidth Q-switched pulses are generated. Q-switched microchip lasers have been designed as such, where just one mode lies within the main laser gain curve [21][22]. However, these devices are usually restricted to materials with a narrow gain curve, typically with a bandwidth less than 0.3nm.
Narrow linewidth Q-switched lasers can also be achieved if one of the modes initially has a higher intensity than the other modes. Two methods have been demonstrated to achieve this: either an external single-frequency signal is fed into the laser cavity which is also known as injection-seeding, or alternatively the laser cavity is allowed to lase CW prior to completely opening the Q-switch, and the Q-switch pulse builds up from this initial laser oscillation.

6.4.1.1 Injection-seeding in Q-switched Lasers

In injection seeding a Q-switched laser, the single-frequency output from a continuous-wave (CW) ‘master’ laser is coupled into the cavity of a ‘slave’ laser, in which the Q-switching operation takes place. Although prior to opening the Q-switch, the losses of the ‘slave’ cavity exceed the gain, the injected signal resonates as a mode in the ‘slave’ cavity, in a manner similar to a signal resonating in a passive Fabry-Perot interferometer. As the Q-switch of the ‘slave’ cavity is suddenly opened, the intensity of the signal is many orders of magnitude greater than the peak intensity of the spontaneous emission. This results in a pulse building up from the narrow linewidth injection-seeded signal. Although this technique is theoretically attractive, some form of active stabilisation of the cavity length is required in practical lasers to match the resonant conditions for both master and slave lasers. To avoid these complexities, designs consisting of just a single laser cavity were investigated.

6.4.1.2 Narrow linewidth operation of passive Q-switched lasers

It has been observed that narrow linewidth operation of Q-switched lasers can occur if a suitable saturable absorber is introduced into the cavity \[23\]. The saturable absorber introduces a significant loss, but is not sufficient to prevent the laser from lasing CW. Once the laser exceeds the threshold and begins to bleach the absorber, narrow linewidth Q-switched pulses are generated, provided the initial CW lasing was single-frequency \[24\].

However, there are several disadvantages of passively Q-switched lasers. Although saturable absorber materials are well established for lasers in the 1\(\mu\)m wavelength region (such as \(\text{Cr}^{4+}:\text{YAG}\)), there is still considerable research involved to locate suitable saturable absorbers in the 1.5\(\mu\)m wavelength region. Furthermore, the pulse
timing and repetition rate is not easily controlled as it depends on parameters such as the pump intensity and the losses of the cavity. This is not desirable in the case of distributed sensing where accurate control of the pulse timing is essential. The timing control is much more accurately governed by some form of active switching. The following section describes an active Q-switched laser incorporating a form of frequency-selective mechanism.

6.4.1.3 Active Narrow Linewidth Q-switched Lasers by the Prelase Method

To achieve narrow linewidth pulses, it is necessary to introduce some form of narrow linewidth initial lasing prior to opening the active Q-switch, similar to the development of passive Q-switched pulses. This was first demonstrated using an electro-optic modulator (EOM) which was opened in two stages and is now known as the prelase technique [25][26]. The first stage allowed a slight opening of the Q-switch to allow weak single-mode CW operation to be established, and the second stage completely opened the Q-switch to achieve maximum pulse power build-up.

It has been mentioned in Sections 6.3.1 and 6.3.2 that single-frequency CW fibre lasers can be achieved using either a short Fabry-Perot type lasers incorporating an in-fibre grating or a unidirectional travelling-wave fibre ring laser. However, since the Q-switching element must lie within the laser cavity, short Fabry-Perot Q-switch lasers cannot easily be achieved. Unfortunately, ring cavity type lasers generally consist of long cavities that as a result, make them susceptible to mode-hopping due to environmental perturbations and the close proximity between adjacent modes. One solution is to combine a ring laser with some form of mode stabilisation technique.

In the following experiment, a narrow linewidth prelase signal was achieved using an unpumped section of Erbium-doped fibre as a saturable absorber as described in Section 6.3.3. This method allowed the suppression of mode-hopping due to the standing-wave saturation effects of the unpumped erbium section, acting as a narrowband filter.
6.4.2 Experiment

Figure 6-2 shows a schematic diagram of the experimental set-up employed to produce the narrow linewidth Q-switched fibre laser. The gain medium consists of a 1.9m length of Erbium doped fibre (ND899). The saturable absorber was a second length of Erbium-doped fibre (ND810) which was unpumped. The specifications for these two lengths of Erbium-doped fibres are listed in Table 6-1.

Table 6-1: Specifications of ND0899 and ND0810 Erbium-doped fibres

<table>
<thead>
<tr>
<th>Fibre Number</th>
<th>ND0899</th>
<th>ND0810</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical Aperture</td>
<td>0.17</td>
<td>0.125</td>
</tr>
<tr>
<td>Cut-off wavelength</td>
<td>940nm</td>
<td>910nm</td>
</tr>
<tr>
<td>Erbium concentration</td>
<td>800ppm</td>
<td>80ppm</td>
</tr>
</tbody>
</table>

The amplifying fibre was pumped with a MOPA laser diode (SDL-5672) at a wavelength of 980nm. A wavelength division multiplexer (WDM) was used to couple the pump light into the amplifying fibre. A circulator was incorporated in the set-up to
ensure unidirectional operation for the fibre ring laser and to couple the laser field into
the saturable absorber.

An in-fibre Bragg reflector (reflectivity 99%, centre wavelength 1530.2nm, linewidth
0.05nm) was used to provide feedback to the cavity and reflected the cavity field to
form a standing-wave pattern between the circulator and grating. The Bragg reflector
was not sufficient to discriminate other adjacent longitudinal modes within the
bandwidth of the grating. However, it was needed as part of the cavity to ensure that
the lasing wavelength fell within the Erbium absorption band for the self-induced
grating to form. If a broadband mirror were used instead, there would be a tendency to
shift to other lasing wavelengths where reabsorption is weak. The output was
extracted from the cavity using a 50/50 fibre coupler. An optical isolator at the output
was used to prevent any feedback into the laser cavity that could cause instabilities.

Q-switching operation was achieved using an electro-optic modulator (EOM). The
EOM (Quantum Technology, LN-9) consisted of a lithium niobate crystal within a
sealed unit with anti-reflection coated windows to minimise transmission losses. It
had a rise/fall time of approximately 4ns, and a maximum extinction ratio of 95%. To
eliminate spurious reflections, all components were fusion spliced. The nonspliced
ends of fibres were angle polished at 17° to minimise Fresnel end reflections back into
the cavity. Efficient operation of the EOM relies on linearly polarised light, and two
dichroic sheet polarisers were inserted into the cavity. To stabilise the laser, care was
taken to thermally insulate the laser cavity.

6.4.3 Results

6.4.3.1 CW operation of single-frequency laser

Under CW conditions with the EOM removed, the lasing spectrum was initially
observed on an optical spectrum analyser with 0.1nm resolution and a sweep width of
5nm. Only a single peak that was stable at the wavelength of 1530nm was observed
and is shown in Figure 6-3. The linewidth measured was resolution-limited by the
spectrum analyser.
To confirm single-frequency operation of the CW output, a scanning Fabry-Perot interferometer (SFP) with a free spectral range (FSR) of 1GHz and a finesse of 70 and a 3MHz bandwidth photodetector were used. By identifying the laser cavity length, the cavity mode spacing between the longitudinal modes was estimated to be approximately 25MHz. A single peak was observed which was resolution-limited by the SFP as shown in Figure 6-4. No mode-hopping was observed over several minutes. In contrast, when the unpumped Erbium doped fibre was replaced by an equivalent length (2m) of undoped conventional single mode telecommunications fibre, stability was poor and frequent mode-hopping was observed between adjacent cavity modes every few seconds.

Figure 6-3: Frequency spectrum from the optical spectrum analyser
Further investigation of the spectral behaviour in the fibre laser output was achieved using a delayed self-heterodyne interferometer [27]. In such an interferometer, the optical field is divided into two paths and a relative path delay, \( t_d \) is introduced in one arm using an extra length of optical fibre before the two paths are recombined again. Assuming that the main fluctuations of the laser signal are due to phase fluctuations, the resultant field at the detector is:

\[
E_{\text{total}} = \frac{1}{4} E_0 e^{i\theta(t)} + \frac{1}{4} E_0 e^{i\omega t_0 + \theta(1+\tau_c)}
\]  

(6-2)

In order to measure the laser linewidth accurately, \( t_d \) has to be longer than the phase coherence time \( \tau_c \) of the laser. To obtain the resulting spectrum of the detector current, the Fourier transform of the autocorrelation function of the detector current is evaluated. If \( t_d \) is much longer than the phase coherence time \( \tau_c \), the spectrum of the laser field would exhibit a Lorentzian lineshape spectrum which has a FWHM twice that of the original source linewidth [27].

The interferometer provided a resolution of 4kHz with a 50km fibre delay line and the RF spectrum analyser (Marconi 2382) had a resolution of 1kHz. Figure 6-4 shows the

![Graph showing frequency spectrum of the CW fibre ring laser](image)

**Figure 6-4 :** Frequency spectrum of the CW fibre ring laser
set-up for obtaining the spectral waveform of the laser with an all-fibre interferometer. The resulting beat signal waveform from the RF spectrum analyser is shown in Figure 6-5. The spectrum shows that the resulting linewidth had a Lorentzian lineshape, which indicates that the delay line was significantly longer than the laser coherence length. The RF linewidth was measured to be approximately 10kHz FWHM. This indicated an optical linewidth of 5kHz for the CW laser.

**Figure 6-5:** Experimental set-up for the delayed self-heterodyne linewidth measurement

**Figure 6-6:** Beat frequency spectrum obtained from the RF spectrum analyser with the spectrum fitted to a Lorentzian profile
6.4.3.2  Q-switched operation of the fibre ring laser

To achieve Q-switched operation, the EOM was inserted into the cavity. If two linear polarisers aligned perpendicular to each other are inserted in the cavity with the EOM in between the polarisers, no prelase signal would be allowed to develop. By gradually rotating one polariser with respect to the other and observing the lasing spectrum whilst the laser cavity is in the high-Q state, a prelase signal sufficient to ensure narrow linewidth lasing is obtained. The measured prelase signal had a small CW power of approximately 0.1mW. In the short high-Q state duration of operation, an applied voltage on the electro-optic modulator of 4.5kV was found to allow high transmission of light through the polarisers. Typical pulses from the output of the laser with peak powers of 400mW were obtained with the EOM operating at a repetition rate below 1kHz and duty cycle of 10% (EOM in high-loss state for 90% of the period), and pump power of 165mW. The pulse output was measured using a 3ns rise time calibrated InGaAs pin photodetector and a 200MHz digitising oscilloscope.

Figure 6-7 shows the development of the prelase signal followed by the emission of the large peak power of the Q-switched pulse. The fluctuations after the emission of the Q-switched pulse is due to the relaxation oscillation which eventually decays to a steady CW prelase signal. This effect occurs when the laser inversion is depleted after the Q-switch pulse and the inversion builds again and reaches threshold [28]. The oscillation occurs in lasers when the fluorescence lifetime (of the order of ms) is longer the photon lifetime (of the order of ns). It exhibits a response with an oscillation decay rate and relaxation-oscillation frequency which is approximately 25kHz for this laser. Figure 6-8 shows an expanded time scale profile of the Q-switched pulse, at a repetition rate of 961Hz.
Figure 6-7: Plot of Q-switched behaviour and prelase signal

Figure 6-8: Q-switched pulse profile
The variation of peak power and pulsewidth of the Q-switched pulses as functions of the modulation frequency of the EOM are shown in Figure 6-9. Beyond 1kHz, there is a fall-off in the peak power and broadening of pulsewidth from 390 – 580ns with increasing repetition rates. The decrease in peak power with increasing repetition rate is due to the finite recovery time of the population inversion in the pumped Erbium doped fibre when the laser is in the low-Q state.

![Graph showing variation of peak power and pulsewidth with repetition rate](image)

**Figure 6-9 : Variation of peak power and pulsewidth with repetition rate**

Due to the pulsed nature of the Q-switched operation, it is more difficult to measure the spectrum of the Q-switched laser. Using the Fabry-Perot interferometer, two methods of measuring the spectrum were investigated.

1) By using a digital oscilloscope and storing the relative peaks as the scope is successively scanned whilst the Fabry-Perot interferometer is set in the scanning mode, an overall trace of the spectrum can be accumulated over several minutes, and the time averaged linewidth may be obtained from the trace.

2) By switching off the scanning mode of the Fabry-Perot interferometer and manually tuning the applied voltage on the PZT of the interferometer, a profile of intensity versus applied voltage may also provide the spectral information of the laser linewidth.
The results from both these measurements were observed to be in good agreement and the time averaged spectrum of the Q-switched operation using the prelase technique is shown in Figure 6-10 at a repetition rate of 961Hz. The linewidth formed was measured to be less than 60MHz. This linewidth measurement differs from that of Figure 6-6 in that it is a pulsed spectral measurement made by scanning the Fabry-Perot interferometer due to the inability to use the delayed self-heterodyne technique. The larger linewidth observed with the pulsed measurement as opposed to the transform-limited value may be attributed to several factors. The finesse of the Fabry-Perot achieved for the chosen free spectral range may not be high enough to allow a fine resolution for more detailed measurements. In addition, any frequency jitter due to vibrations would contribute in the broadening of the stored and averaged trace. Another possible explanation is due to the laser itself. As there are no frequency-selective elements in the laser cavity other than the prelase signal, the laser oscillates on the longitudinal mode closest to the gain peak. During Q-switched operation, there is less time available for the prelase signal to allow a strong frequency selection. As a result, if the gain peak is close to two adjacent modes, there is a possibility to oscillate on either of these two modes. For adequate frequency selection, it may therefore be beneficial to introduce some form of active stabilisation or additional frequency selection in the form of an etalon.

In contrast, a measurement was also made with the two linear polarisers being exactly cross-polarised to each other at 90° to eliminate any prelase signal. Without the single-frequency self-seeding from the prelase, frequent mode-hopping of the Q-switched pulses was observed smearing the overall spectrum over the scanning Fabry-Perot FSR of 4GHz, even though the unpumped Erbium-doped fibre was still included in the cavity.
6.4.4 Summary

In summary, a Q-switched laser was designed to produce narrow linewidth pulses. Although a linewidth of less than 60MHz was achieved, the minimum Q-switched pulse width achievable was 400ns. To optimise the source for distributed sensing based on spontaneous Brillouin scattering, there is still a need for further reduction of the pulse width of the Q-switched laser, as typical sensors may require spatial resolutions of approximately 10m, corresponding to a 100ns pulse width. Although it is still possible to reduce the cavity length by shortening the fibre pigtailed ends of the various components, it may still prove difficult to construct a sufficiently short cavity for the emission of short Q-switch pulses. Furthermore, there is a substantial loss within the cavity including the loss of the saturable absorber, which may possibly result in a longer build-up time for the Q-switch pulse. It is therefore beneficial to compare the performance of fibre ring lasers to short cavity, grating-based fibre lasers.
6.5 Short Cavity Fibre Lasers Incorporating Bragg Gratings

6.5.1 Narrow linewidth build-up utilising Fibre Bragg Gratings

Fibre lasers incorporating UV-written fibre Bragg gratings offer an alternative range of useful, potentially inexpensive and high performance single-frequency devices. High performance grating-based single-frequency fibre lasers have been the subjects of intense research recently [29][30]. This is due to its simplicity in the grating fabrication and laser construction. Although unable to provide Q-switched operation within the very short cavity length, these lasers may be externally modulated and amplified to provide sufficient peak pulse power within the signal to successfully implement a distributed strain sensing and temperature system with good signal-to-noise ratio without considerable signal averaging.

To ensure single-frequency operation of a grating-based laser, a short laser cavity length (typically few centimetres) and a narrow wavelength selective filter are required. This is to ensure that only a few axial modes fall within the grating bandwidth so as to avoid mode hopping. There are two possibilities for constructing these fibre Bragg grating lasers; 1) using Erbium-doped germanosilicate fibres and 2) using Erbium/Ytterbium-doped phosphosilicate fibres. Both Erbium and Erbium/Ytterbium fibre Bragg grating lasers can provide fibre compatible sources with narrow linewidth, high output powers and low threshold pump powers.

With Erbium-doped fibres, large amounts of germanium can be incorporated into the core and this increases the photosensitivity which aids the writing of strong Bragg gratings. However, in the case of Erbium-doped fibre lasers, a few cm-long fibre does not allow sufficient pump absorption as a consequence of the low pump absorption per unit length. As a result, these lasers result in relatively low CW output powers and low lasing efficiency [31][32]. Increasing the Erbium concentration in conventional Erbium-doped germanosilicate fibres to increase the output powers is not possible as ion clustering occurs, leading to a degradation in laser efficiency and instabilities in performance [33][34]. The use of Erbium/Ytterbium-doped fibres allows a much larger pump absorption at the wavelength of 980nm due to absorption by Yb$^{3+}$ ions, followed by an energy transfer to the erbium level. Typically, a single-frequency
Erbium/Ytterbium laser would have a cavity length of a few cm spliced to a grating with a reflection bandwidth of \( \sim 0.2 \text{nm} \). However, with a substantially smaller reflection bandwidth of 0.09nm (11.3GHz), a laser operating in single-frequency with a cavity length of up to 10cm has been demonstrated\(^3\). Although operating with improved performances over Erbium-doped grating-based lasers, these Erbium/Ytterbium-doped lasers still require the gratings to be written external to the doped fibres. This is because in the case of Erbium/Ytterbium-doped fibres, a phosphosilicate glass host is needed to ensure efficient energy transfer between the Erbium and Ytterbium ions. With phosphorus doping, the fibre photosensitivity is reduced even in the presence of added germanium, creating difficulties in grating fabrication.

The lack of photosensitivity in conventional Erbium/Ytterbium-doped fibres was overcome by utilising an Erbium/Ytterbium-doped fibre core surrounded by a B/Ge/Si photosensitive annular region \(^3\). The Boron compensates for the increase in refractive index from Germanium doping. The fibre developed by Dong \textit{et al.} previously at the University of Southampton provided the possibility to fabricate Erbium/Ytterbium-doped fibre Bragg grating lasers (FBGL) used in this experiment. The structure of the fibre is shown in Figure 6-11. The resulting fibre had a numerical aperture (NA) of \( \sim 0.2 \), cut-off wavelength of 1270nm, small-signal absorption of \( \sim 230 \text{dB/m} \) and 25dB/m at the wavelengths of 980nm and 1535nm and Erbium to Ytterbium concentration ratio of 20:1. The experimental results for the Erbium/Ytterbium-doped FBGLs are obtained with such a configuration, and the optimisation of FBGL performance with different amplifier lengths is also analysed.
6.5.2 Performance of fibre Bragg grating laser (FBGL)

6.5.2.1 Experiment

The FBGL that was used in the experiment operated in the wavelength region of 1550nm and was produced by the author using the phase-mask technique to generate the gratings. The photosensitivity of the Erbium/Ytterbium-doped fibre was enhanced using the hydrogen loading technique [37]. Lasers operating in the wavelength region of 1550nm would experience a lower gain per unit length, resulting in lower output powers. One possible method to increase the power output is by using the Master Oscillator Power Amplifier (MOPA) configuration, where the residual co-propagating pump power from a short FBGL is used to pump a length of amplifier fibre, and was previously demonstrated for Erbium-doped FBGLs [36].

Figure 6-12 shows this configuration of the Erbium/Ytterbium-doped FBGL for achieving single-frequency laser output at 1550nm. The pump power was coupled directly to one end of the laser cavity that consisted of a high reflecting grating (reflectivity >99% at 1545.9nm). An output coupler grating (reflectivity ~90%) was written approximately 1.5 cm away. The bandwidth of the high reflectivity grating was larger than the output coupler grating, ensuring laser operation even with a slight peak wavelength mismatch between the gratings during fabrication. The gratings were
written with the phase-mask technique using a pulsed KrF excimer laser, and their reflectivities were determined by observing the transmission spectrum of the gratings. Figure 6-13 shows the experimentally obtained transmission spectrum of the output mirror grating for the FBGL. The slope on the curve is due to the nonuniformity in optical transmission for the LED source used to obtain the spectrum.

![Figure 6-12: Experimental configuration for the Erbium/Ytterbium Fibre Bragg Grating Laser (FBGL) design](image)

In the FBGL, the total length of Erbium/Ytterbium fibre used in addition to the fibre within the cavity affects the output power. Ideally, there should be as little Erbium/Ytterbium fibre at the pump input end prior to the first grating, as this results in unnecessary pump absorption. However, a short length of Erbium/Ytterbium fibre at the laser output end provides signal amplification using the residual pump power. This provides a simple configuration and avoids splice losses between the laser and amplifier section. The amplifier section of the Erbium/Ytterbium-doped fibre was spliced to a pigtailed 1550nm optical isolator to prevent feedback into the laser. The operation characteristics of FBGLs with different amplifier lengths from 0 to 3.2 cms for a fixed pump power were observed. Using Bragg gratings as the laser cavity reflectors rather than butt-coupled end reflectors provided a simple construction coupled with stable and robust operation of the lasers.
6.5.2.2 Results

The optical spectrum of the FBGL was observed to contain a single peak at the operational wavelength of 1545.8nm, using a spectrum analyser with a 0.1nm spectral resolution. At the wavelength region of 980nm with an amplifier length of 3.2 cm, there were no observable peaks, showing that the pump was completely absorbed. The performance characteristics of FBGLs with different amplifier lengths are shown in Figure 6-14, with Erbium/Ytterbium-doped amplifier lengths of (a) 3.2 cm (b) 2.8 cm (c) 2 cm (d) 1 cm (e) no amplifier length. The results show that for a pump power of 100mW, the maximum CW output power is obtained for an amplifier length of 2.8 cm. A maximum output power of 8.5mW was obtained for a pump power of 100mW, and included the isolator and splice losses.
To confirm single-frequency and single-polarisation state operation of the CW output, a scanning Fabry-Perot interferometer (SFP) with a free spectral range (FSR) of 10GHz and a finesse of 70, and a 3MHz photodetector were used. A single peak was observed as shown in Figure 6-15, and the measurement of the linewidth was resolution-limited by the SFP to be less than 150MHz. The single-frequency peaks observed on the SFP were stable typically for several minutes without any mode-hopping.
Figure 6-15: Single-frequency operation of the FBGL

The operating wavelength of the laser was seen to increase gradually as the pump power was increased gradually. This has been previously reported in other FBGLs [30], and is attributed to the associated temperature rise in the fibre laser. As the pump power was increased from 90mW to 100mW, a wavelength increase of 1.2GHz was observed. In addition, a different mode was observed to lase as the pump power was increased, and the mode change occurred at a pump power of approximately 73mW. Figure 6-16 shows the appearance of the second mode using a scanning Fabry-Perot interferometer with a FSR of 10GHz. The frequency spacing of the peaks was approximately 4.9GHz, corresponding to the length of the laser cavity.
Figure 6-16: Frequency spectrum displaying the mode change of FBGL using a SFP of (a) the initial mode as the dominant mode (b) the second mode as the dominant mode

6.5.2.3 Summary

Although achieving a single-frequency operation without mode-hopping over a several minutes, the FBGL laser still operated with amplitude instabilities due to the occasional evolution of a second polarisation mode, which causes an oscillatory-like power transfer between the two polarisation modes. In the next section, attempts were made to improve the lasing quality of fibre lasers incorporating Bragg gratings, by introducing preferential single-mode selection. To what extent this polarisation
instability can be avoided in distributed feedback fibre lasers is investigated in the following section.

### 6.5.3 Distributed feedback (DFB) fibre laser

To achieve a more stable lasing frequency whilst providing single-frequency operation, attempts were made to design DFB fibre laser structures. The expression for a grating reflectivity may be expressed as [38]:

\[
R(\lambda, \Lambda_g, L_g) = \left| \frac{\Omega}{S(\lambda, \Lambda_g)} \cdot \sinh(S(\lambda, \Lambda_g) \cdot L_g) \right|^2
\]

where \( \Omega \) is the coupling coefficient, \( L_g \) is the grating length, \( \lambda \) is the wavelength and \( \Lambda_g \) is the grating period, \( S(\lambda, \Lambda_g) \) is the dephasing parameter and \( \Delta \beta(\lambda, \Lambda_g) \) is the detuning parameter of the propagation constant. In a distributed Bragg reflector (DBR) structure, the coupling between two gratings in series may be evaluated by a reflection equation similar to that used to describe a simple Fabry-Perot cavity. However, to achieve a distributed feedback (DFB structure), a \( \pi/2 \) phase shift section has to be introduced in the middle of the structure to provide good coupling within the whole laser. In the case of index coupling for the distributed feedback system, there is no resonance at the Bragg wavelength. Adjacent modes lie symmetrically with respect to the Bragg wavelength and are spaced at equal intervals. At the Bragg wavelength, the round trip condition is not fulfilled and after one round trip, the wave propagating through the grating has been shifted by \( \pi \). Adding the additional phase shift will then enable the laser to operate at the Bragg wavelength.

Figure 6-17 shows the reflection spectrum of three structures with different grating lengths and spacing between the gratings. The total length of the gratings and cavity considered for all three cases is 48mm with modulation index of 0.6x10⁻⁴. The three cases are for DBR structures with grating lengths of 4mm, 12mm and a DFB structure.
respectively. With a DFB structure, the resulting spectrum yields a ‘filter’ which has a high transmission for a very narrow-band width whilst reflecting other frequencies, thereby providing robust frequency selection.

![Graphs showing reflectivity vs. wavelength for DBR and DFB structures](image)

**Figure 6-17**: Reflection spectrum of grating-based fibre device from a DBR structure to a DFB structure. The total length considered is 48mm, with a constant modulation index depth of 0.6x10^-4. (a) is a DBR structure of two 4mm long uniform Bragg gratings with a spacing of 40mm between the gratings. (b) is a DBR structure of two 12mm long uniform Bragg gratings with a spacing of 24mm between the gratings. (c) is a DFB structure designed with a 4mm long distributed \(\pi/2\) phasishift in the middle section.
6.5.3.1 Experiment

To produce the DFB laser, a Bragg grating was induced in a length of Erbium/Ytterbium-doped fibre. To ensure robust single polarisation operation, the experimental grating fabrication set-up configured by researchers at the University of Southampton was utilised. The process consists of writing the gratings with CW UV light at 244nm, polarised perpendicular to the propagation axis of the fibre [39]. The gratings of the DFB laser were made with a coupling coefficient of 200m⁻¹ and the laser had an overall length of 5cm. To test the laser, the DFB was pumped using a pigtailed 980nm laser diode through a wavelength division multiplexer (WDM) and the light at 1.5μm was extracted from the opposite arm of the WDM as shown in Figure 6-18. The lasing performance was then monitored on a scanning Fabry-Perot (SFP) interferometer.

![Figure 6-18: Experimental configuration for pumping the DFB fibre laser](image)
6.5.3.2 Results

The laser spectrum from the SFP interferometer output is shown in Figure 6-19. The free spectral range of the interferometer was set to be 5GHz. A single peak on the SFP interferometer trace confirmed the single-mode operation of the laser. Furthermore, no second polarisation mode was observed from the interferometer over duration of tens of minutes, confirming its robust single-mode operation.

![Frequency spectrum of DFB fibre laser output using a scanning Fabry-Perot interferometer](image)

Figure 6-19: Frequency spectrum of DFB fibre laser output using a scanning Fabry-Perot interferometer

6.5.3.3 Summary

Grating-based fibre laser structures consisting of both DBR and DFB configurations were developed and tested. Being CW sources, these lasers have to be externally modulated and then further amplified to provide satisfactory sources for distributed sensing applications. Unlike the DBR laser which exhibits a fluctuation in the output polarisation state, the DFB laser with gratings written with a polarised UV-beam was found to provide increased stability in terms of both amplitude and frequency.
6.6 Brillouin Measurements Using a Modulated DFB Fibre Laser Source

An experiment was conducted utilising the DFB fibre grating laser developed in the last section in conjunction with a similar distributed strain and temperature sensing set-up described in Chapter 5. By pumping the DFB fibre laser with 80mW at 980nm, CW powers of 8mW at 1550nm was generated. The signal was pulsed and amplified before being launched down the sensing fibre. The fibre section D2 was placed in an oven and heated to 53°C and all other fibre sections were at room temperature of 23°C. The fibre section under the system of pulleys was strained to approximately 4000µε. Figure 6-20 shows the final schematic design of the experiment used to demonstrate the combined distributed strain and temperature sensor.
Figure 6-20: Spontaneous Brillouin-based distributed strain and temperature sensor using a DFB fibre grating laser source
The results of the spontaneous Brillouin backscattered signals from the output of the SPMZ are shown in Figure 6-21 when the laser control signal was tuned to (a) the minimum of the Mach-Zehnder transfer function and (b) maximum of the Mach-Zehnder transfer function. A separate source with a broad band width must be used to obtain reference Rayleigh signal to normalise the Brillouin signals. Similar to the procedure used in Chapter 5, the normalised Brillouin traces provide information on the Brillouin intensity variation and frequency shift, subsequently providing both the temperature and strain profiles along the sensing fibre.

![Figure 6-21: Brillouin backscattered signals using a DFB Bragg grating fibre laser as a source, when the Rayleigh signal has been tuned to the (a) minimum (b) maximum of Mach-Zehnder transfer function](image)

Due to the extremely narrow linewidth characteristics of a typical DFB fibre grating laser (with a linewidth of approximately 100kHz), there is a high phase correlation between the backscattered Rayleigh signal generated by the narrow frequency pump laser, resulting in substantial CRN noise caused by spatial fluctuations in the fibre refractive index [40]. The effect of CRN is more serious than that using a semiconductor DFB laser diode (linewidth typically few tens of MHz) as observed particularly from Figure 6-21 (b). This causes a more serious effect of Rayleigh contamination on the Brillouin signals and will ultimately limit the measurand
resolution of the sensor. The additional introduction of CRN decreases both the strain and temperature resolution from the relations in Equations (5-6) and (5-7) in Chapter 5. However, with careful design of the Mach-Zehnder interferometer with better visibility, it is expected that a sufficiently high rejection ratio of the Rayleigh signal from the Brillouin signal may be achieved. Alternatively, other forms of techniques may be employed to achieve better rejection of Rayleigh signal. This may include using an extremely high reflection filter such as an in-fibre Bragg grating, or using a using heterodyne detection to separate the Brillouin signals from the Rayleigh signal by means of electrical filtering.

6.7 Conclusions

This chapter has described the design and construction of fibre lasers comprising both narrow linewidth unidirectional ring lasers and short cavity fibre grating-based lasers. By combining the prelase technique and use of saturable absorber, an elegant mechanism for narrow linewidth Q-switching was achieved. Narrow linewidth CW grating-based fibre lasers which were amplified and gated offer a simple alternative to Q-switched lasers as sources suitable for combined distributed strain and temperature sensing. Ultimately, the improvement in amplitude and frequency stability of DFB fibre lasers as compared to FBGLs has enabled Brillouin backscattered signals to be obtained and averaged throughout the measurement duration. Parallel to the Brillouin backscattered results obtained using a semiconductor DFB source, these results demonstrate the capability of using DFB fibre lasers for distributed strain and temperature measurements, with the possibility of achieving better Brillouin frequency shift resolution due to the narrow laser linewidth.
6.8 References


CHAPTER SEVEN

CONCLUSIONS

7.1 Summary and Conclusions

This thesis has investigated and discussed issues relating to the use of pulsed fibre laser sources for distributed optical fibre sensing based on Rayleigh, Raman and Brillouin scattering. The sensing systems that were described utilised the technique of Optical Time Domain Reflectometry (OTDR) coupled with the use of Landau-Placzek ratio, which offer a unique way of locating measurand variations over very long distances with high accuracy determined by the source pulse width. The successful development of Erbium-doped Q-switched fibre lasers provides compact and elegant sources which will have a significant influence on practical distributed fibre sensing systems. However, care must be taken to ensure efficient coupling from the output of the large mode area Q-switched Erbium-doped laser as opposed to the output coupling from fibre-based Q-switched lasers utilising conventional Erbium-doped fibres. In terms of operating wavelength, a successful OTDR system operating in the $1.65\mu m$ wavelength region has been demonstrated, and a sensing range of 100km with a spatial resolution of 10m has been achieved through the technique of delayed Raman amplification. The outcome results in the possibility of using this technique either for a $1.4/1.5\mu m$ or $1.5/1.65\mu m$ system and extending the use OTDR systems for very long sensing ranges, which is useful for monitoring active communication links. However, there exist several issues to be resolved before such systems become commercially exploited, such as nonlinearity threshold limits generated by the pump, probe or data bit rate pulses. Furthermore, suitable narrowband selective filters may need to be incorporated to ensure sufficient rejection of undesired signals. Several sources have been developed for the purpose of temperature measurement and simultaneous measurement of strain and temperature using spontaneous Brillouin scattering. By gating an amplified semiconductor diode laser, a high spatial resolution (35cm) Brillouin-based temperature sensor was demonstrated over a longer range (>1km) than
previously reported measurements. This system may prove useful for distributed 
temperature measurements in short to medium range structures such as vessels or 
reactors, provided that the averaging time for the Brillouin measurements may be 
reduced. Should this high spatial resolution measurement be extended to include 
strain measurements, the Brillouin centre frequency has to be resolved with sufficient 
accuracy to account for the Brillouin linewidth broadening. For simultaneous 
Brillouin sensors intended to operate over a longer sensing range and lower spatial 
resolution, several possible fibre-based sources have been developed; an amplified 
gated semiconductor laser diode source, a narrow linewidth Q-switched Erbium-
doped laser, a fibre-based distributed Bragg reflector (DBR) laser, and a fibre-based 
distributed feedback (DFB) laser. Simultaneous strain and temperature measurements 
were successfully demonstrated using both the amplified gated laser diode source and 
the amplified gated fibre DFB laser for a sensing range of 11km and spatial resolution 
of 10m. The high frequency stability and flexibility of controlling the pulse widths (by 
varying the gating time of the EOM) in both these gated lasers provides potentially 
useful sources for practical simultaneous strain and temperature sensors. The narrow 
linewidth (approximately 100kHz) of the DFB laser may provide additional benefit 
over the semiconductor laser diode source in providing a higher frequency shift 
sensitivity resulting in a higher strain/temperature resolution. However, the narrow 
linewidth fibre DFB laser generates a higher percentage contamination of coherent 
Rayleigh noise (CRN) on the backscattered Brillouin signal, which in practical 
systems require a high rejection ratio optical filter to minimise the contribution of 
CRN. If an even lower spatial resolution (>40m) is allowed, the Q-switched laser also 
provides a stable and compact source suitable for these simultaneous measurements. 
Finally, the investigation into fibre DBR lasers established that these lasers are not as 
robust and suitable compared the previously mentioned lasers in terms of frequency 
and amplitude stability due to dual polarisation mode operation. The results obtained 
from the overall study are now summarised.

Pulsed sources operating in the low attenuation 1550nm third telecommunications 
window allow the Rayleigh and Brillouin backscattered signals to have similar and 
minimal attenuation. However, the maximum power that may be launched down the 
sensing fibre is governed by the onset of stimulated Raman scattering, stimulated
Brillouin scattering or self-phase modulation effects. The initial development of the pulsed sources was based on optimising the performance of Q-switched Erbium-doped fibre lasers. A computer model was generated to evaluate the evolution of Q-switched pulses as the wave undergoes multiple round trips within the laser cavity by rate equations for the Erbium-silica system. The ability to generate very high peak power Q-switched sources was demonstrated using a large mode area Erbium-doped fibre, which has higher energy storage within the fibre. This has allowed pulses of 4kW with a pulse width of 11ns (corresponding to approximately 50\(\mu\)J) to be generated and represented the highest energy extracted from a Q-switched Erbium-doped fibre laser at that time. Further optimisation of the core radius and dopant concentration has allowed pulses with energy as high as 0.5mJ to be generated [1]. An experiment also demonstrated that for a given length of Erbium-doped fibre and cavity parameters (fibre dopant concentration, feedback mirror reflectivity and cavity losses), an optimum pulse with the highest peak power may be obtained through varying the output mirror reflectivity, and this trend was confirmed by the computer model.

With the ability to produce high peak power and short pulses using these Q-switched Erbium-doped lasers, a source at the wavelength of 1.65\(\mu\)m source was developed. This was performed through the process of stimulated Raman scattering whereby the output pulses of the Q-switched laser at 1.5\(\mu\)m were passed through a length of conventional silica fibre. With a generation fibre of 390m, pulses at 1.65\(\mu\)m with peak power of 1.4W and pulse width of 45ns were produced. Two applications of distributed sensing using this 1.65\(\mu\)m source were then demonstrated. The first was to develop an ultra long OTDR system for fault detection on live transmission lines of C-band transmission systems and also for the monitoring of cable installation of L-band transmission systems. The technique utilised delayed Raman amplification of the 1.65\(\mu\)m signal pulse by a co-propagating 1.53\(\mu\)m pump pulse. As both the pulses overlap and crosses each other, amplification occurs through a process of energy transfer. The position of this overlap is determined by the initial delay that is set between both these pulses. An increase in dynamic range of 17.5dB was achieved and the 1.65\(\mu\)m system was capable of performing measurements exceeding 100km.
Using an amplified narrow-linewidth semiconductor DFB laser source, two spontaneous Brillouin-based distributed sensors were demonstrated. The first sensor was a distributed temperature sensor with a high spatial resolution and the second was a combined distributed strain and temperature sensor. The 35cm spatial resolution distributed temperature sensor was achieved by generating short pulses of 3.5ns with high peak powers to maximise the backscattered energy, combined with the low loss filtering and detection system. The demonstration of such a sensor unwraps the possibilities of a variety of distributed sensors capable of monitoring structures with a high spatial precision. To achieve good strain resolution, a relatively narrow linewidth pulsed source is needed compared to that of the Q-switched fibre lasers used in previous intensity-based distributed Brillouin and Raman temperature sensors. A simultaneous strain and temperature measurement was first performed by gating and amplifying the semiconductor DFB laser diode, and using two in-fibre Mach-Zehnder interferometers to resolve both the Brillouin intensity and frequency shift variations. By using these two sets of measurements and the two coupled equations relating these parameters to the strain and temperature coefficients, both strain and temperature measurements were resolved independently. The use of fibre Mach-Zehnders have enabled good signal-noise ratio to be achieved as compared to previous measurements using bulk Fabry-Perot interferometers.

Further development of the fibre sources investigated various possibilities of achieving a narrow linewidth fibre-based laser source for combined distributed strain and temperature measurements. These lasers are potentially capable of generating ultra narrow linewidths for providing sufficient Brillouin frequency shift resolution whilst providing high output powers. In a Q-switched Erbium-doped fibre loop laser, a simple and elegant technique of achieving narrow linewidth operation through using a prelase signal in conjunction with a fibre saturable absorber was performed. This allowed reliable narrow linewidth Q-switched operation of the laser with peak powers of 400mW with a linewidth less than 60MHz at a fixed repetition rate. The pulse width of 390ns was relatively long which sets a constraint on the sensor spatial resolution. Short cavity fibre Bragg grating lasers were also fabricated and investigated as an alternative method to provide a CW single-frequency signal, which could then be pulsed and amplified for distributed fibre sensing. Although both
Erbium-doped fibre loop lasers and short cavity fibre Bragg grating lasers enabled single-frequency operation, it was by using a short distributed feedback Erbium/Ytterbium fibre laser which demonstrated a robust operation in terms of amplitude and frequency jitter. Stable operation was ensured by polarising the UV-beam that was used to write the grating, providing a strong preference to lase on a single polarisation mode. With this DFB laser, a simultaneous strain and temperature measurement was performed, thus confirming the ability and stability of such a laser.

7.2 Future work

There are several possibilities in which the future work on Q-switched Erbium-doped fibre lasers may be extended. For example, analysis of the pulse development of these lasers in both the time and frequency domain such as pulse chirp will provide better insight into the properties of such lasers. Another important area would be to investigate other types of doped fibre Q-switch lasers operating at other wavelengths.

Following the success of performing simultaneous distributed strain and temperature sensing with a narrow linewidth pulsed source, there is now a need to fully characterise and explore the long term performance of such a sensor. By measuring the spontaneous Brillouin signal variation under a set of applied temperatures, the sensing fibre can be subjected to various applied strains for each set of applied temperatures. Similarly, such trends can be made when the sensing fibre is subjected to a set of applied strain values, under different temperature conditions.

The work on the simultaneous Brillouin strain and temperature sensors may be further optimised to achieve better strain and temperature resolution, and spatial resolution. For example, the use of an optical preamplifier such as an Erbium-doped fibre amplifier may enhance the signal that is detected. This would allow better measurand resolution and requiring less averaging times. Issues such as incorporating the use of narrowband filters to prevent ASE saturation of the detector and the noise effects of these amplifiers should be considered. There are also other possible techniques for separating the Rayleigh signal from the Brillouin signal that should be considered. One method may be to use in-fibre Bragg grating optical filters, which has
the advantages of being fibre compatible, compact and low loss. Recent advances
have now made this feasible due to the possibility of high rejection of the Rayleigh
signal from the Brillouin signal (>30dB), and this aspect is now currently under
investigation. Other techniques involve using coherent detection, which by using a
narrow linewidth optical source for both the CW reference signal and probe pulse,
provides excellent separation of the backscattered traces through electrical filtering.
7.3 References


APPENDIX A

THEORETICAL DESCRIPTION OF Q-SWITCHING BEHAVIOUR IN FIBRE LASERS

In order to investigate the Q-switched lasing behaviour, it is necessary to first evaluate the time evolution of the photons within the laser cavity. When the switch is first opened, the number of photons will encounter both gain and loss in one round trip, which will be result in the number of photons becoming:

\[
\begin{align*}
\left( R_1 R_2 e^{2 L \alpha_{\text{me}} (\gamma - a_{\text{me}})} - a_{\text{se}} \right) N_p
\end{align*}
\]  

(A-1)

The rate of change after one round trip in the number of photons which is the total number of photons after one round trip minus the number from the initial condition for the round trip period will then be:

\[
\frac{dN_p}{dt} = \left( \frac{R_1 R_2 e^{2 L \alpha_{\text{me}} (\gamma - a_{\text{me}})} - 1}{\tau_{RT}} \right) N_p
\]  

(A-2)

The threshold gain occurs when the gain equals the cavity losses, and the relation is expressed as:

\[
R_1 R_2 e^{-(2a_{\text{se}} + 2a_{se})} = e^{-2\gamma L_{\text{thres}}}
\]  

(A-3)

To express Equation (A-4) in terms of the total inversion over its threshold value, we note that the cavity round-trip time \(\tau_{RT}\) can be related to the photon lifetime by the fraction of photons surviving a cavity round trip through the expression:

\[172\]
\[
\tau_p = \frac{\tau_{RT}}{1 - R_1R_2e^{-(2\alpha_{tue} + 2\alpha_{ax})}} \quad (A-4)
\]

By substituting Equations (A-3) and (A-4) into Equation (A-2), the rate of change in photons may now be expressed as:

\[
\frac{dN_p}{dt} = \frac{N_p}{\tau_p} \left( n - n_{\text{th}} \right) \quad (A-5)
\]

It is also possible to simplify Equation (A-5) using a small-signal Taylor series expansion of \( e^y = 1 + y \), and the expression can then be expressed as:

\[
\frac{dN_p}{dt} = \frac{N_p}{\tau_p} \left( n - n_{\text{th}} \right) \quad (A-6)
\]

We can omit the time-related term by normalising Equation (3-11) with respect to the photon lifetime \( T = t/\tau_p \) hence arriving at the first fundamental equation for Q-switching behaviour:

\[
\frac{dN_p}{dT} = N_p \left( n - n_{\text{th}} \right) \quad (A-7)
\]

By evaluating the rate equations between the upper and lower lasing levels, the following expressions are obtained:

\[
\frac{dN_1}{dt} = \frac{P_p\sigma}{Ah\nu} (N_2 - N_1) \quad (A-8)
\]

\[
\frac{dN_2}{dt} = -\frac{P_p\sigma}{Ah\nu} (N_2 - N_1) \quad (A-9)
\]
where $A$ is the transverse cross-section area of the fibre and $\sigma$ is the stimulated emission cross-section. By multiplying both sides of equations (A-8) and (A-9) with the volume of the gain medium and subtracting Equation (A-8) from Equation (A-9), the following expression is obtained:

$$\frac{d(N_2 - N_1)AL_{\text{fibre}}}{dt} = -\frac{2P_t\sigma}{Ah\nu}(N_2 - N_1)AL_{\text{fibre}} \quad (A-10)$$

With the knowledge that $g(t) = (N_2 - N_1)\sigma L_g$, $\tau_{\text{RT}} = 2g_{\text{th}}\tau_p$ and the relation for gain coefficient to population inversion $g(t)/g_{\text{th}} = n/n_{\text{th}}$, the terms in Equation (A-10) can be simplified and expressed as the rate of change of population inversion:

$$\frac{dn}{dt} = -2\frac{N_p}{\tau_p} \frac{n}{n_{\text{th}}} \quad (A-11)$$

where $N_p$ is the number of photons inside the cavity. By normalising Equation (A-11) with respect to the photon lifetime $T = t/\tau_p$, it becomes:

$$\frac{dn}{dT} = -2N_p \frac{n}{n_{\text{th}}} \quad (A-12)$$

This is the second fundamental equation that describes the Q-switched behaviour. The factor of two implies that if the number of photons in the cavity is increased by one, then the population inversion correspondingly decreases by two. To obtain both the peak power and pulse width, we have to divide Equation (A-7) by Equation (A-12) to remove the time dependence whilst integrating to provide:

$$N_p(\text{final}) - N_p(\text{initial}) = \frac{1}{2} n_{\text{th}} \ln \left( \frac{n_f}{n_i} \right) - (n_f - n_i) \quad (A-13)$$
As there is negligible photon density present before the lasing action commences, it is possible to assume that \( N_p(\text{initial}) = 0 \). Equation (3-14) then becomes:

\[
N_p(\text{final}) = \frac{1}{2} n_{th} \ln \left( \frac{n_f}{n_i} \right) - (n_f - n_i)
\]  

(A-14)

In addition, the photon density \( N_p(\text{final}) \) also becomes 0 after the depletion of the Q-switched pulse. The final inversion \( n_f \) is given by the relation:

\[
n_{th} \ln \left( \frac{n_f}{n_i} \right) - (n_f - n_i) = 0
\]  

(A-15)

\[
\frac{n_f}{n_i} = \exp \left[ - \left( \frac{n_i - n_f}{n_{th}} \right) \right]
\]  

(A-16)

The value of \( (n_i - n_f)/n_i \) provides information regarding the fraction of the initial inversion that is converted to laser energy:

\[
\left( \frac{n_i - n_f}{n_i} \right) = 1 - \exp \left[ - \left( \frac{n_i - n_f}{n_{th}} \right) \right]
\]  

(A-17)

The peak power available from the laser output is equal to the stored energy within the cavity multiplied by the fraction lost by output coupling per round trip divided by the time taken to undergo a round trip:

\[
P_0(\text{max}) = \frac{\hbar u N_p(\text{max})(1 - R_1)}{\tau_{RT}}
\]  

(A-18)

The remaining parameter for the Q-switch pulse is the pulse width. Although an exact solution can be obtained by locating the full width half maximum (FWHM) of the
pulse profile, a reasonable estimate can be obtained by the total output pulse energy divided by the maximum output peak power:

\[ \Delta t = \frac{W_0}{P_0 \text{ (max)}} \]  

(A-19)
APPENDIX B

OPERATING PRINCIPLE OF FIBRE SAGNAC LOOP REFLECTORS

Light is coupled across and through a fibre coupler with the cross coupling through the relation:

\[
\begin{pmatrix}
E_{3n} \\
E_{4n}
\end{pmatrix}
= \sqrt{1 - \gamma} \begin{pmatrix}
\sqrt{1 - K_n} & i\sqrt{K_n} \\
i\sqrt{K_n} & \sqrt{1 - K_n}
\end{pmatrix}
\begin{pmatrix}
E_{1n} \\
E_{2n}
\end{pmatrix}
\]  
(B-1)

where \(n=\text{x, y}\) for both \(x\) and \(y\) polarisations, and \(E_{1n}, E_{2n}, E_{3n}\) and \(E_{4n}\) describes the fields for ports 1, 2, 3, 4 respectively, \(K_n\) is the coupling coefficient and \(\gamma\) is the coupler loss. Both the fields \(E_{3n}\) and \(E_{4n}\) then travel around the Sagnac loop in opposite directions while experiencing the birefringence properties of the loop described by Jones matrices \(J_C\) and \(J_A\), representing clockwise and anti-clockwise directions of the fields.

\[
\begin{pmatrix}
E'_{3x} \\
E'_{3y}
\end{pmatrix}
= J_C \begin{pmatrix}
-E_{3x} \\
E_{3y}
\end{pmatrix} e^{-aL} = \begin{pmatrix}
J_{xx} & J_{xy} \\
J_{yx} & J_{yy}
\end{pmatrix}
\begin{pmatrix}
-E_{3x} \\
E_{3y}
\end{pmatrix} e^{-aL}
\]  
(B-2)

\[
\begin{pmatrix}
-E'_{4x} \\
E'_{4y}
\end{pmatrix}
= J_A \begin{pmatrix}
-E_{4x} \\
E_{4y}
\end{pmatrix} e^{-aL} = \begin{pmatrix}
J_{xx} & J_{yx} \\
J_{xy} & J_{yy}
\end{pmatrix}
\begin{pmatrix}
-E_{4x} \\
E_{4y}
\end{pmatrix} e^{-aL}
\]  
(B-3)

where the prime denotes the fields travelling in the opposite directions from its original directions. The signal waves then propagate back into the coupler by recombining through ports 3 and 4. The fields emanating from the coupler generate fields at ports 1 and 2 once again and are given by:
\[
\begin{pmatrix}
E'_{in} \\
E'_{2n}
\end{pmatrix} = \sqrt{1-\gamma} \begin{pmatrix}
\sqrt{1-K_n} & i\sqrt{K_n} \\
i\sqrt{K_n} & \sqrt{1-K_n}
\end{pmatrix} \begin{pmatrix}
E'_{3n} \\
E'_{4n}
\end{pmatrix}
\] (B-4)

Equation (B-4) may be expanded to provide the full description of the matrices in terms of both x and y polarisations and the input ports:

\[
\begin{pmatrix}
E'_{ix} \\
E'_{iy} \\
E'_{2x} \\
E'_{2y}
\end{pmatrix} = e^{-al} (1-\gamma) \begin{pmatrix}
a & e & c & h \\
e & b & g & d \\
c & g & a & f \\
h & d & f & b
\end{pmatrix} \begin{pmatrix}
E_{ix} \\
E_{iy} \\
E_{2x} \\
E_{2y}
\end{pmatrix}
\] (B-5)

\begin{align*}
a &= -2i\sqrt{1-K_x} \sqrt{K_x} J_{xx} \\
b &= 2i\sqrt{1-K_y} \sqrt{K_y} J_{yy} \\
c &= 2(K_x - 1)J_{xx} \\
d &= (1 - 2K_y)J_{yy} \\
e &= i\sqrt{1-K_y} \sqrt{K_x} J_{xy} - \sqrt{1-K_x} \sqrt{K_y} J_{yx} \\
f &= i\sqrt{1-K_x} \sqrt{K_y} J_{xy} - \sqrt{1-K_y} \sqrt{K_x} J_{yx} \\
g &= \sqrt{1-K_x} \sqrt{1-K_y} J_{xy} + \sqrt{K_x} \sqrt{K_y} J_{yx} \\
h &= -[\sqrt{1-K_x} \sqrt{1-K_y} J_{xy} + \sqrt{K_x} \sqrt{K_y} J_{yx}]
\end{align*}

By assigning the power reflectivity as \( R_{11} \) for input port 1 and, it is possible to represent the reflectivity by:

\[
R_{11} = (1-\gamma)^2 e^{-2al} \left( J_{11} E_1 \right) \left( J_{11} E_1 \right)
\] (B-6)

If we now consider that for the coupling ratio and attenuation for both x and y polarisations are equal (\( K_x = K_y = K \)), the reflectivity may then be evaluated by using Equation (B-6) and performing algebra manipulation:
\[ R_{11} = (1 - \gamma)^2 e^{-2\alpha l} \bar{E}_1^* (\bar{J}_{11}^* J_{11}) E_1 \]  \hfill (B-7)

\[ \bar{E}_1 (\bar{J}_{11}^* J_{11}) E_1 = |E_{1k}|^2 (aa^* + ee^*) + |E_{1j}|^2 (bb^* + ee^*) \]

where

\[ aa^* = [-2i\sqrt{1 - K \sqrt{KJ_{xx}}}][2i\sqrt{1 - K \sqrt{KJ_{xx}}}] \]
\[ = 4(1 - K)K|J_{xx}|^2 \]  \hfill (B-8)

\[ bb^* = [2i\sqrt{1 - K \sqrt{KJ_{yy}}}][-2i\sqrt{1 - K \sqrt{KJ_{yy}}}] \]
\[ = 4(1 - K)K|J_{yy}|^2 \]  \hfill (B-9)

\[ ee^* = [i(\sqrt{K} \sqrt{1 - K(J_{xy} - J_{yx}))}][-i(\sqrt{K} \sqrt{1 - K(J_{xy} - J_{yx}))}] \]
\[ = K(1 - K)[2(1 - |J_{xx}|^2) - (J_{xy}^* J_{xy} + J_{yx}^* J_{yx})] \]  \hfill (B-10)

By substituting Equations (B-8), (B-9) and (B-10) into Equation (B-7), the reflectivity then becomes:

\[ R_{11} = (1 - \gamma)^2 e^{-2\alpha l} K(1 - K)\Gamma \]  \hfill (B-11)

where \( \Gamma = 2\left(|J_{xx}|^2 + 1\right) - (J_{xy}^* J_{xy} + J_{yx}^* J_{yx}) \)

With the matrix being symmetric, \( J_{xy} = J_{yx} \), and the expression for \( \Gamma \) reduces to \( 4|J_{xx}|^2 \).
APPENDIX C

ERROR IN FREQUENCY MEASUREMENT FOR
BRILLOUIN SPECTRUM

The Brillouin spectral profile is characterised by a Lorentzian lineshape given by:

\[
g(v) = \frac{\left(\frac{\Delta v}{2}\right)^2}{(v - \nu_B)^2 + \left(\frac{\Delta v}{2}\right)^2} \cdot g_0 \quad \text{(C-1)}
\]

where \(g_0\) is the Brillouin central frequency and \(\Delta \nu_B\) is the FWHM linewidth. If the assumption that the frequency measurement is made at the centre of the spectral profile with an error equals to \(\delta \nu_B\) in the presence of a rms noise value of \(N\), then:

\[
g(\nu_B) - N = \frac{\left(\frac{\Delta v}{2}\right)^2}{(\delta \nu_B)^2 + \left(\frac{\Delta v}{2}\right)^2} \cdot g_0 \quad \text{(C-2)}
\]

The maximum intensity of the spectral profile at \(\nu = \nu_B\) is the considered signal \(S=g(\nu_B)=g_0\). The signal-to-noise ratio is given by:

\[
\text{SNR} = \frac{\langle i_s^2 \rangle}{\langle i_n^2 \rangle} = \frac{S^2}{N^2} \quad \text{(C-3)}
\]

Substituting Equation (C-3) into Equation (C-2), the relation then becomes:

\[
\left( g(\nu_B) - \frac{S}{\sqrt{\text{SNR}}} \left(\delta \nu_B\right)^2 + \left(\frac{\Delta \nu_B^2}{2}\right)^2 \right) = \left(\frac{\Delta \nu_B^2}{2}\right) g_0 \quad \text{(C-4)}
\]
\[ \delta v_B = \frac{\Delta v_B}{2\left(\sqrt{\text{SNR}} - 1\right)^{1/2}} = \frac{\Delta v_B}{2\text{SNR}^{1/4}} \]  
(C-5)

assuming that SNR \gg 1. The factor of 2 is derived for determining the line centre frequency. If the evaluation is considered around and at the centre frequency, the expression is smaller than Equation (C-5) by a fraction of \( \sqrt{2} \).
List of Publications

Sally M. Maughan, Huai Hoo Kee and Trevor P. Newson
‘Novel distributed fibre sensor using microwave heterodyne detection of spontaneous Brillouin backscatter’

Huai Hoo Kee and Trevor P. Newson
‘1.5µm Brillouin-based fibre optic distributed temperature sensor with high spatial resolution of 20cm’

Huai Hoo Kee, Gareth P. Lees and Trevor P. Newson
‘Technique for measuring distributed temperature with 35cm spatial resolution utilizing the Landau-Placzek ratio’

Huai Hoo Kee, Gareth P. Lees and Trevor P. Newson
‘An all-fibre system for simultaneous interrogation of distributed strain and temperature sensing using spontaneous Brillouin scattering’

Huai Hoo Kee, Gareth P. Lees and Trevor P. Newson
‘Simultaneous independent distributed strain and temperature measurements over 15 km using spontaneous Brillouin scattering’

Huai Hoo Kee, Gareth P. Lees and Trevor P. Newson
‘Spontaneous Brillouin-based distributed temperature fibre sensor with 35cm spatial resolution’

Huai Hoo Kee, Gareth P. Lees and Trevor P. Newson
‘Distributed optical fibre sensing at 1.65µm using a Q-switched fibre laser’

Huai Hoo Kee, Gareth P. Lees and Trevor P. Newson
‘1.65µm long range distributed testing of optical fibres using a compact Q-switched fibre laser’
Huai Hoo Kee, Gareth P. Lees and Trevor P. Newson
‘Low loss, low cost spontaneous Brillouin-based system for simultaneous distributed strain and temperature sensing’

Huai Hoo Kee, Gareth P. Lees and Trevor P. Newson
‘A novel 1.65µm Raman based Distributed Temperature Sensor’

Huai Hoo Kee, Gareth P. Lees and Trevor P. Newson
‘A stable narrow linewidth Q-switched Er-doped fibre laser’

Huai Hoo Kee, Gareth P. Lees and Trevor P. Newson
‘Narrow linewidth CW and Q-switched Erbium doped fibre loop laser’

Huai Hoo Kee, Gareth P. Lees and Trevor P. Newson
‘An extended range OTDR system at 1.65µm based on delayed Raman amplification’

Huai Hoo Kee, Gareth P. Lees and Trevor P. Newson
‘A method of increasing the range of 1.65µm long range OTDR system based on Raman amplification’
International Optical Fibre Sensors (OFS’ 97), Williamsburg, USA, Paper No. OThC32 (1997)

Gareth P. Lees, Huai Hoo Kee and Trevor P. Newson
‘A novel OTDR system using Raman amplification of a 1.64µm probe pulse’

Huai Hoo Kee, Gareth P. Lees and Trevor P. Newson
‘A high power Q-switched Erbium doped fibre laser producing 50µJ pulses’
Quantum Electronics-13, Cardiff, UK (1996)

Huai Hoo Kee, Gareth P. Lees and Trevor Newson
‘A novel method of increasing the range of 1.65µm OTDR using a Q-switched Erbium Fibre Laser’
Quantum Electronics-13, Cardiff, UK (1996)