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Nonlinear Techniques for Optical Wavelength Conversion

Richard Provo

November 25, 2010
Abstract

This thesis describes the studies performed for the implementation and characterisation of various nonlinear optical wavelength conversion techniques. The experimental work presented within this thesis is accompanied by discussion of the practical considerations necessary for the successful implementation of the nonlinear wavelength conversion techniques described.

The primary focus of this thesis and the largest body of experimental research is on the experimental characterisation of the four wave mixing effect of Bragg Scattering in optical fibers. Experimental and numerical characterisations of this process have been performed. The studies have enabled the phase matching condition, conversion efficiencies and bandwidth to be measured for this effect in a highly nonlinear fiber. The phase matching curve has been measured for two fibers with opposite sign $\beta_4$ dispersion coefficients and an experimental implementation of a transparent high-speed optical switch based on this effect has also been demonstrated for the first time. The interfering effects of competing nonlinear processes have been investigated and the impact of zero dispersion wavelength fluctuations have been studied. Additionally this process has been used to recover the dispersion parameters for two highly nonlinear fibers and the error free transmission of a 10Gb/s data signal over 33nm has demonstrated.

The four wave mixing effect of Bragg Scattering has also been investigated in the active medium of nonlinear semiconductor optical amplifiers. Several experimental procedures are outlined for the use of this effect for wavelength conversion applications. A direct experimental comparison has been performed between Bragg
Scattering and Modulation Instability for wavelength conversion of data signals in these devices with Bragg Scattering demonstrating an improved performance over the single pump process. Bragg Scattering has been used to effect the wavelength conversion of both multiple data channels and high speed data signals. Two 10Gb/s data channels spaced at both 50 and 100GHz were successfully converted and single channel conversion was demonstrated at speeds as high as 80Gb/s.

The third topic investigated concerns wavelength conversion in nonlinear crystals. The construction of two 10Gb/s sources has been demonstrated for the characterisation of novel micro-structured plastic fibers. Sum frequency and second harmonic generation were both used for the generation of a 10Gb/s source in the visible. This source was used to demonstrate the first successful transmission of a 10Gb/s data signal through a micro-structured polymer optical fiber.
Acknowledgments

I would like to thank my supervisor John Harvey for providing me with the opportunity and the resources necessary to perform this study. John, whilst oftentimes difficult to locate has proven a most valuable asset to my studies, his knowledge of optics has provided me with a greater practical understanding of the many effects I have studied that no amount of book work and mathematics could instill.

I would like to express my gratitude to David Méchin, whose guidance, both inside the lab and out has been invaluable. David has been a great help and was always willing to listen to, and discuss ideas and approaches to solve the many issues I encountered throughout this study.

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I would like to thank the team of highly skilled individuals who reside in the Mechanical Workshop, particularly Steve Warrington and Matt Hogg for the skills and advice they have provided for the fabrication of the various necessary parts and equipment I have needed. I would also like to thank Brian Davis and the Electronic Workshop for all the assistance that they have provided.

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<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Ratio</td>
</tr>
<tr>
<td>CH</td>
<td>Carrier Heating</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>DCF</td>
<td>Dispersion Compensating Fiber</td>
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<tr>
<td>DFB</td>
<td>Distributed Feedback Laser</td>
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<td>DFG</td>
<td>Difference Frequency Generation</td>
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<tr>
<td>DSF</td>
<td>Dispersion Shifted Fiber</td>
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<tr>
<td>DWDM</td>
<td>Dense Wavelength Division Multiplexing</td>
</tr>
<tr>
<td>ECL</td>
<td>External Cavity Laser</td>
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<tr>
<td>EDFA</td>
<td>Erbium Doped Fiber Amplifier</td>
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<tr>
<td>FROG</td>
<td>Frequency Resolved Optical Gating</td>
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<td>FWM</td>
<td>Four Wave Mixing</td>
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<td>GVD</td>
<td>Group Velocity Dispersion</td>
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<td>HNLF</td>
<td>Highly Nonlinear Fiber</td>
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<tr>
<td>MI</td>
<td>Modulation Instability</td>
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<tr>
<td>Abbreviation</td>
<td>Definition</td>
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<tr>
<td>MPOF</td>
<td>Micro-structured Polymer Optical Fiber</td>
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<tr>
<td>NLSE</td>
<td>Nonlinear Schrödinger Equation</td>
</tr>
<tr>
<td>OSA</td>
<td>Optical Spectrum Analyser</td>
</tr>
<tr>
<td>OTDR</td>
<td>Optical Time Domain Reflectometry</td>
</tr>
<tr>
<td>PC</td>
<td>Phase Conjugation</td>
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<tr>
<td>PCF</td>
<td>Photonic Crystal Fiber</td>
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<tr>
<td>PMD</td>
<td>Polarisation Modal Dispersion</td>
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<tr>
<td>PMMA</td>
<td>Polymethyl Methacrylate</td>
</tr>
<tr>
<td>POF</td>
<td>Polymer Optical Fiber</td>
</tr>
<tr>
<td>PPLN</td>
<td>Periodically Poled Lithium Niobate</td>
</tr>
<tr>
<td>PRBS</td>
<td>Pseudo Random Bit Sequence</td>
</tr>
<tr>
<td>SBS</td>
<td>Stimulated Brillouin Scattering</td>
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<tr>
<td>SFG</td>
<td>Sum Frequency Generation</td>
</tr>
<tr>
<td>SHB</td>
<td>Spectral Hole Burning</td>
</tr>
<tr>
<td>SHG</td>
<td>Second Harmonic Generation</td>
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<tr>
<td>SOA</td>
<td>Semiconductor Optical Amplifier</td>
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<td>SPM</td>
<td>Self Phase Modulation</td>
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<td>SRS</td>
<td>Stimulated Raman Scattering</td>
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<td>RZ</td>
<td>Return to Zero</td>
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<tr>
<td>TBPF</td>
<td>Tunable Band Pass Filter</td>
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<td>VCSEL</td>
<td>Vertical Cavity Surface Emitting Laser</td>
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ABBREVIATIONS

VOA Variable Optical Attenuator

WDM Wavelength Division Multiplexing

XGM Cross Gain Modulation

XPM Cross Phase Modulation

YDFA Ytterbium Doped Fiber Amplifier

ZDF Zero Dispersion Frequency

ZDW Zero Dispersion Wavelength
Chapter 1

Introduction

1.1 Background

Nonlinear optical wavelength conversion is the generation of photons at new optical frequencies through the nonlinear interactions of an electromagnetic wave with the media in which it is propagating. Nonlinear optical wavelength conversion is an important and useful technique as it allows both the creation of coherent signals at optical frequencies that lasers cannot easily be made, and allows the transfer of information from one optical carrier to another almost instantaneously.

Nonlinear optical wavelength conversion dates back to 1961, when the generation of a new optical frequency via a nonlinear optical interaction within a quartz crystal was demonstrated for the first time [1]. Since then, nonlinear wavelength conversion in a number of different media has received vast and varied attention. The different nonlinear processes have been employed for a myriad of purposes within both research and industry, ranging from optical sampling (second harmonic generation frequency resolved optical gating and parametric four wave mixing based sampling scopes)[2, 3], generation of new sources (eg green laser pointers), laser cutting and welding (second and third harmonic generation)[4], amplification (parametric amplification and stimulated Raman scattering)[5, 6], spectroscopy [7, 8], and wavelength conversion in data systems [9].

Recently, due to the rapid growth of fiber optic networks, nonlinear optical wave-
length conversion has attracted increasing attention as a candidate for all optical routing of optical data signals. The use of all optical techniques for network functions and signal processing is appealing, as by their nature, the optical nonlinearities employed can be both ultra-fast and phase sensitive. The current generation of optical network systems use wavelength division multiplexed (WDM) systems, where signals are distributed and routed in the wavelength domain. In future dense wavelength division multiplexed (DWDM) networks where bit-rates are increased and larger bandwidths are utilised more efficiently by new modulation schemes, wavelength converters and switches will need to offer broadband tunability, transparent interoperability and scalability [10, 9].

The predominant area of research into all-optical wavelength conversion solutions has been focused around the conversion and routing of wavelengths near the loss minimum of modern single mode silica fiber ($\sim 1.5\mu m$). As such, the second order effects in nonlinear crystals where sum frequency, difference frequency and second harmonic generation generate harmonics with greatly different wavelengths to their parent signals are of limited use for wavelength conversion within the communications band. Various techniques involving cascaded second order processes within the various crystalline media have been proposed and demonstrated to counter some of these issues, such as in [11]. However, as the mixing is performed within periodically poled crystal waveguides the coupling losses, poor wavelength tuning and the difficulty of integration of these systems with current fiber optical networks suggest that these effects are more suited to end-point sampling and that the probability of widespread application in network switching is low.

Another area of nonlinear optical mixing where significant research has been performed is four wave mixing (FWM). FWM is a third order nonlinear effect and since the early demonstrations in the 1970’s of FWM in fibers [12, 13] several promising features of FWM processes have been identified. FWM effects are phase sensitive processes, thus offer transparency to phase modulation formats and FWM processes utilising the ultra-fast Kerr effect in fibers offer unparalleled bandwidths [14].
1.1. BACKGROUND

In the late 1980’s FWM effects were also investigated and demonstrated within the active medium of semiconductor optical amplifiers (SOA) [15, 16]. Early work using SOAs demonstrated that strong nonlinear mixing was possible and wavelength conversion was achievable across most of the gain window of these devices. However, reduced efficiencies with signal detunings and polarization gain sensitivities due to asymmetrical waveguide structures within these early devices limited their practical use. Modern nonlinear SOAs with optimized waveguide structures and high gains offer improved performance over those early devices that were based on anti-reflection coated laser diodes. FWM wavelength conversion and switching in SOAs have been performed over wide wavelength ranges [17] and for high bit-rates [18]. This indicates that despite the associated amplified spontaneous emission generated within SOAs during FWM processes they could be a promising candidate for nonlinear switching and wavelength applications in future DWDM networks.

Contrary to the strong nonlinear mixing seen in both crystals and SOAs, the nonlinear coefficient of silica fibers is much lower, thus FWM in fibers typically requires high pump powers and long interaction lengths. As such initial FWM demonstrations involved the use of pulsed laser sources or high powered gas lasers, which were of limited practical use for wavelength conversion of data signals in the region of 1.5μm. However since the advent of high power continuous wave (CW) lasers and erbium doped fiber amplifiers in the wavelength region of 1.5μm, FWM research in fibers has received a growing amount of attention for uses in modern day fiber optic networks and promising results have been demonstrated for wavelength routing and switching using FWM processes.

The majority of the focus around FWM for wavelength conversion applications has been on effects such as Modulation Instability (MI) and Phase Conjugation (PC) [19], these effects are capable of converting signals to phase conjugated idlers over wide ranges [20], and providing high gain at the chosen wavelengths [21, 22]. The production of phase conjugated idlers provides the added benefit of the possibility for use in dispersion compensation schemes [23, 24]. However, despite these benefits,
the presence of parametric gain during the process also leads to the addition of noise in the converted signals. Another, less widely studied FWM effect, offers the possibility of wideband wavelength conversion without gain and the potential for noise free signal translation. Early studies of this effect demonstrated that arbitrary tunability was available through the selection of suitable pump wavelengths and that the converted signal was a direct copy (no spectral inversion or phase conjugation) of the input signal [25, 26]. In 2002, the work outlined in [27, 28] demonstrated that the complete exchange between two signals at different wavelengths could be achieved by this effect and that promising network functions may be derived from it. Since then, this effect has been described by a number of terms such as asymmetrical FWM, wavelength exchange and Bragg Scattering. The latter term, Bragg Scattering, was coined by Colin McKinstrie [29] due to the spatial analogue of this process. Since 2004 many new studies of this effect have been performed and theoretical derivations of the noise properties indicate that complete and noise free translation of quantum states should be possible [30]. This FWM process therefore offers promising suitability for both data conversion and for wavelength conversion of few photon signals.

1.2 Objective of Thesis

The objective of this thesis is to provide an overview of the experimental use of nonlinear techniques for the applications of wavelength conversion. This overview will focus primarily on the more recent developments around the FWM process of Bragg Scattering, as the majority of the work performed in this study has involved characterising and developing an optimised Bragg Scattering wavelength conversion experimental set-up. Experimental studies involving the use of this process in both fibers and SOAs are described and relevant outcomes discussed. The aim is to provide detailed analysis and characterisation of this process within fibers and also to discuss the experimental use of this FWM effect in active media such as SOAs. We also study the second order nonlinear effects in crystals, focusing on experimental
work performed to generate a 10Gb/s data source in the visible wavelength band to characterise prototype plastic optical fibers. The earlier sections cover the background of the nonlinear mixing processes utilised and the developments of these techniques for the purposes of wavelength conversion.

1.3 Outline

This thesis contains three distinct experimental chapters that involve the use of nonlinear effects in different media for optical wavelength conversion. Each of these chapters includes a theoretical background on the material specific nonlinearities exploited for wavelength conversion. These theory sections will introduce the relevant nonlinear properties and discuss the theoretical expectations.

Chapter 2 provides an outline of the requisite theory to develop the discussions in the later experimental sections. The general treatment of this chapter is necessitated by the diversity of the experimental work performed throughout this study. An overview of the propagation of light in dielectric media is provided and the concepts of dispersion, loss and polarisation are discussed. The propagation of light in optical fibers is also handled within this chapter with fiber specific parameters such as modal dispersion included. The nonlinear response of a medium is then discussed and using Maxwell’s equations we derive the wave equation for a nonlinear medium. Briefly introduced in this final section of Chapter 2 is the concept of phase matching in nonlinear processes.

Chapter 3 covers more thoroughly the nonlinear effects seen predominantly in glass optical fibers, with a particular focus on the FWM effect of Bragg Scattering. Minimisation of the competing and interfering nonlinear effects during a Bragg Scattering experiment are discussed. Derivation of a general solution for Bragg Scattering from the FWM coupled amplitude equations is covered and key findings and characteristics of the process are presented. The experimental sections of this chapter involve the measurement and comparison of the phase matching condition of the Bragg Scattering process to that of the derived theory. The results are presented and
discussions raised about impairments to the process. The recovered phase matching curves are used to determine the dispersion parameters of the fibers used in these experiments, and simulations are performed to quantify some of the effects affecting this process. We investigate and discuss the use of Bragg Scattering for the conversion of a 10Gb/s data signal. Quantitative analysis of the Bragg Scattering response is discussed in relation to fiber imperfections and further experimental procedures are performed for comparison to theory.

Chapter 4 discusses Bragg Scattering in SOAs with a more practical viewpoint taken towards the implementation of this process for several wavelength conversion experiments. The nonlinear dynamics of SOAs are presented and typical nonlinear wavelength conversion systems are discussed. Requirements for implementation of FWM experiments within SOAs are covered. The FWM effect of Bragg Scattering is compared to MI within the SOA and deductions from the observations presented. Wavelength conversion experiments of multiple data channels using Bragg Scattering were also studied and the results are analysed. High bit-rate wavelength conversion was also performed on a 80Gb/s return-to-zero (RZ) bit sequence. The performance of the Bragg Scattering set-up for these applications using nonlinear mixing in SOAs is discussed.

Chapter 5 presents the work undertaken in the attempts to characterise novel micro-structured polymer optical fibers (MPOF). This work involved the construction of a high power 10Gb/s test source at ~ 650nm. This was achieved using sum frequency generation (SFG) and second harmonic generation (SHG) in nonlinear crystals. The background of second order nonlinear processes is presented and the use of quasi phase matching architectures are discussed. The development and performance of two experimental set-ups are presented and discussed.

Chapter 6 presents a brief summary of the work done and provides suggestions for future experiments in this area of study.
Chapter 2

Propagation of Light in Dielectric Media

2.1 Introduction

In order to effectively study the nonlinear effects responsible for the generation of new optical frequencies through interactions of the electromagnetic wave with the media in which it is propagating, one must have knowledge of how electromagnetic waves propagate and interact within a dielectric medium. This chapter deals with the broad topic of how light propagates through the various media of interest used within this thesis. The broadness of this section is necessitated by the different, although related, studies described in this thesis. The types of propagation include propagation in waveguides (fibers and semiconductor optical amplifiers) and propagation in free space and in bulk media (nonlinear crystals).

Aside from the three different types of nonlinear phenomena studied, the main focus of this section concerns the propagation of light within a fiber as the optical networks where nonlinear wavelength conversion finds its applications primarily operate within optical fibers. The results from this section can be applied to bulk media if the effects of the waveguide are disregarded.
2.2 Polarisation of Electromagnetic Waves

The polarisation of an electromagnetic wave refers to the direction in which the electric field is aligned. In a transverse wave (as most optical waves are) the Electric and Magnetic fields are orthogonal to both each other and the direction of propagation. By convention the direction of propagation of a transverse electro-magnetic wave is in the $z$ direction, so the polarisation of the waves may lie anywhere on the $x - y$ plane. If the electromagnetic field were to consist of a single polarisation, that with the electric field aligned with the $x$-axis, for example, this would correspond to a linearly polarised wave. If the wave consists however of two components, one aligned with the $x$ and one with $y$-axis, where the two components were out of phase with one another, this would cause the relative polarisation of the wave to rotate in a circular or elliptical fashion. Orthogonal and parallel are descriptions that are not restricted to linear states of polarisation, but refer to the relative states between any two or more optical waves. For example, orthogonal waves could describe perpendicular linear states or counter rotating circularly polarised states. Within this thesis, the discussions are restricted to linearly polarised beams as this simplifies both the analysis and the experimental work required. The state of polarisation of the waves within this study were controlled through the use of fiber polarisation controllers and half wave plates. In most cases careful control of the relative polarisations of the waves is necessary for the efficient nonlinear mixing processes studied in later chapters. Additional information on polarisation of an electromagnetic waves can be found in texts such as [31].

In practice the polarisation states of waves co-propagating with one another may not necessarily stay linear (or constant), as, due to random birefringence within different media these polarisation states can change. However, if the waves are not too different in optical frequency the relative polarisations of the waves with respect to one another will be preserved. Thus, if we inject two waves orthogonally polarised into an optical fiber such that after a length $L$, the received waves are circularly polarised, the orthogonality of the waves will be preserved, whereas the
2.3 Losses in Optical Networks

Loss is a universal measure in optical systems and it depends not only on the primary optical medium but also on the optical components of the systems. It is the removal of energy from a signal to destinations unwanted or unintended. Loss can be attributed to many different causes such as (for example), material properties; scattering or absorption, or to component/coupling effects; imperfect reflection or transmission through optical elements. Whatever the cause, loss is typically viewed as something that needs to be minimised within an optical system. As such great lengths are taken to ensure anti-reflection coatings are applied to optics, impurities are removed from optical materials and the signal transmission through various elements of an optical system is optimised. With modern advances in thin-film coatings on lenses, mirrors and other optical components, reflection and transmission losses through, into and out-of these components can be as low as 0.5% over a range of wavelengths determined by the specific coating. The losses associated with modern silica fibers are likewise very low and are discussed further in the following sections of this chapter.

2.4 Chromatic Dispersion

As an electromagnetic wave propagates through a medium, its interaction with the bound electrons of the medium generally depends on the frequency of the wave. Due to this, the refractive index of an optical medium is dependent on the wavelength of the light propagating through it. This results in waves of different wavelengths propagating at different velocities within dispersive media.
Far from the medium resonances, the refractive index can be approximated by the Sellmeier equation [33]

\[ n^2(\omega) = 1 + \sum_{j=1}^{m} \frac{B_j\omega_j^2}{\omega_j^2 - \omega^2}, \]  

(2.1)

where \( \omega_j \) is the resonance frequency and \( B_j \) is the strength of the \( j \)th resonance. For example, in optical fibers, the parameters \( B_j \) and \( \omega_j \), depend on the core constituents and are experimentally found by fitting the measured dispersion curves to Eq.(2.1) with \( m = 3 \). For bulk fused silica these parameters, from [34], are given in Table 2.1 and the variation of both the refractive and group indices are shown in Figure 2.1.

Table 2.1: Parameters used in Eq.(2.1) for modeling the wavelength dependence of the refractive index for bulk fused silica.

<table>
<thead>
<tr>
<th>j</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_j )</td>
<td>0.6961663</td>
<td>0.4079426</td>
<td>0.8974794</td>
</tr>
<tr>
<td>( \lambda_j(\mu m) )</td>
<td>0.0684043</td>
<td>0.1162414</td>
<td>9.896161</td>
</tr>
</tbody>
</table>

Figure 2.1: Variation of refractive index, \( n \) and group index, \( n_g \), with wavelength for fused silica.
2.4. CHROMATIC DISPERSION

Dispersion plays an important part in the propagation of short optical pulses, as a short pulse in the time domain has a broad spectrum in the frequency domain, and the different parts of the optical spectrum all travel at different speeds. In the absence of nonlinear effects, this will cause the pulse to broaden and can be detrimental in most applications where short pulses are used. The effect of fiber dispersion can be more clearly seen by expanding the mode-propagation constant $\beta$ in a Taylor series about the center frequency $\omega_0$

$$\beta(\omega) = \frac{n(\omega) \omega}{c} = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2} \beta_2(\omega - \omega_0)^2 + \cdots,$$

(2.2)

where

$$\beta_m = \left(\frac{d^m \beta}{d\omega^m}\right)_{\omega=\omega_0} \quad (m = 0, 1, 2, \ldots).$$

(2.3)

The parameters $\beta_1$ and $\beta_2$ are related to the refractive index $n$ and its derivatives through the following

$$\beta_1 = \frac{1}{v_g} = \frac{n_g}{c} = \frac{1}{c} \left( n + \omega \frac{dn}{d\omega} \right),$$

(2.4)

$$\beta_2 = \frac{1}{c} \left( 2 \frac{dn}{d\omega} + \omega \frac{d^2 n}{d\omega^2} \right),$$

(2.5)

where $v_g$ is the group velocity and $n_g$ is the group index. Physically, the envelope of an optical pulse travels at the group velocity. $\beta_2$ is called the group velocity dispersion (GVD) parameter - it quantifies the variation of the group velocity. A non-zero GVD parameter leads to the different spectral components in an optical pulse traveling at slightly different velocities and is responsible for the pulse broadening.

Figure 2.2 shows the dependence of the GVD parameter on wavelength. Of note is the point $\sim 1.3 \mu m$ where $\beta_2 = 0$. This is called the zero dispersion wavelength (ZDW). Optical pulses centered at wavelengths below this point propagate in
the normal dispersion regime, that is, longer wavelengths travel faster than shorter wavelengths. In contrast to this, optical pulses centered at wavelengths above the ZDW propagate in the anomalous dispersion regime where the opposite occurs.

![Figure 2.2: Wavelength dependence of $\beta_2$ in fused silica.](image)

### 2.5 Birefringence

In some optical media the refractive index experienced by an optical wave can depend on the polarisation of the wave relative to the material. This effect is called birefringence or double refraction and occurs only in anisotropic materials. For these materials the birefringence magnitude is defined as

\[
\Delta n = n_e - n_o,
\]

where $n_e$ and $n_o$ are the refractive indices of the polarisations parallel (extraordinary) and perpendicular (ordinary) to the axis of anisotropy respectively.

Birefringence occurs naturally in many materials (crystals in particular) but it can also be induced in (usually) isotropic materials by directional stresses/strains or
applied electric fields. Birefringence in waveguides made from isotropic materials is related to the dimensions of the waveguides. For cylindrical waveguides (fibers) made from silica, any deviation from the cylindrical symmetry can induce birefringence.

2.6 Optical Fibers

Optical fibers are of fundamental importance to all fiber optic systems. As such the transmission characteristics of these fibers are key to determining the performance of these systems. These transmission characteristics are governed by the structural composition of the fiber. The structural properties of a fiber determine how an optical field evolves as it travels through the fiber. These optical fields can be described as guided electromagnetic waves and are called the modes of the fiber. There are only a discrete number of spatial modes that can propagate through an optical fiber. The number of modes supported by a fiber is related directly to the structural characteristics of the fiber.

In this section we present the basic concepts for the propagation of optical signals in optical fibers, paying particular attention to the step index single mode optical fibers, as these are the type of fibers used throughout this thesis for the study of nonlinear effects.

2.6.1 Fiber Characteristics

In its most basic form an optical fiber consists of a glass core with a refractive index of $n_1$, surrounded by a cladding layer that has a slightly lower refractive index of $n_2$. These types of fibers are referred to as step-index fibers as the difference between the core and cladding refractive indices is abrupt in contrast to the slowly changing refractive index seen within graded index fibers. Figure 2.3 shows a typical cross section of the two types of fibers.
Two parameters that characterise a step index fiber are the relative core-cladding index difference, given as

\[ \Delta = \frac{n_1 - n_2}{n_1} \],

(2.7)

and the \( V \) parameter, which is defined as

\[ V = k_0 a \sqrt{n_1^2 - n_2^2} \],

(2.8)

where \( k_0 = \frac{2\pi}{\lambda} \), \( a \) is the core radius and \( \lambda \) is the wavelength of the light.

The \( V \) parameter determines the number of modes supported by the fiber. In a single mode fiber the \( V \) parameter is typically \(< 2.405 \) [35], whereas fibers with a \( V \) parameter above this support multiple propagation modes. To improve the nonlinear effects seen within an optical fiber, some specialty fibers are made that exhibit higher than normal nonlinear coefficients. These fibers may be doped with rare earth elements and/or have particularly small core areas to improve the nonlinear response. As the intensity of the optical signal is inversely proportional to the core area, the use of single mode fibers (with a very small core) is prevalent in the field of nonlinear optics, as this confines the traveling wave to a single core mode.


2.6. OPTICAL FIBERS

2.6.2 Fiber Losses

Another important fiber characteristic is the loss of power an optical signal experiences as it travels through a fiber. If $P_{in}$ is the power initially launched into a fiber of length $L$, then the transmitted power $P_T$ is given by

$$P_T = P_{in} \exp (-\alpha L),$$  \hspace{1cm} (2.9)

where the $\alpha$ (the attenuation constant) is a measure of total fiber losses from all sources. It is usual to express $\alpha$ in units of dB/km using the relation

$$\alpha_{dB} = \frac{10}{L} \log \left( \frac{P_T}{P_{in}} \right) = 4.343\alpha.$$  \hspace{1cm} (2.10)

The low loss of modern optical fibers is a key reason for their use in long-haul communications networks. As might be expected, the loss within a fiber is greatly dependent on the wavelength of the light. The loss spectrum for a typical single mode fiber is shown in Figure 2.4 [31], along with the estimated contributions from various factors. With a loss minimum at $\sim 1.5 \mu m$, it is unsurprising most long-haul
networks operate about this region. The dominant contributions to a silica fiber’s loss are due to Rayleigh scattering and the material absorption. Any impurities in the silica also contribute greatly to the above mentioned spectrum. Due to this, great measures are taken to ensure the purity of the silica used in optical fibers, as even small impurities can have a large negative impact on the transmission characteristics. The most important impurity is the OH$^-$ ion which is responsible for the dominant peak at 1.4\mu m. Special precautions are taken during the manufacture of fibers to ensure that the OH$^-$ ion level is kept as low as possible.

2.6.3 Fiber Dispersion

The dispersion parameter $D$ is commonly used in place of $\beta_2$, to describe the total dispersion in a single mode fiber. It is related to $\beta_2$ by

$$D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2} \beta_2. \quad (2.11)$$

The dispersion parameter (or $\beta_2$) depends on both the material the waveguide is constructed from, and the physical characteristics of the waveguide itself, such that

$$D = D_M + D_W, \quad (2.12)$$

where, $D_M$ is the material dispersion and $D_W$ the waveguide dispersion. This contribution from the waveguide parameters enable fiber manufacturers to tailor the dispersion by careful design of the fiber’s physical dimensions. This enables the ZDW of specialty fibers to be shifted closer to the loss minimum of 1.5\mu m allowing one to take advantage of the low loss and dispersion. These fibers are commonly referred to as dispersion shifted fibers (DSF) and often are designed with specific purposes in mind, for example DSFs that have their ZDW shifted to wavelengths above 1.6\mu m exhibit a very large positive value of $\beta_2$ in the region of 1.5\mu m. These are useful for dispersion compensation and are often referred to as dispersion com-
Figure 2.5: Material; $D_M$ and waveguide; $D_W$ contributions to total dispersion $D$ for a typical step index silica fiber with $\Delta = 0.003$ and $a = 4 \mu m$.

2.6.3.1 Modal Dispersion

Aside from the material and waveguide dispersion previously discussed, multimode fibers with $V$ parameters higher than 2.405 also exhibit modal dispersion. This is due to the difference in transit times between the fastest and slowest supported modes. If one considers a straight section of step index multimode fiber where the rays (or modes) are guided via total internal reflection, it is obvious that a ray injected at normal incidence will take less time to travel the length of the fiber than one injected at an angle of incidence of $20^\circ$. This very simple approach, whilst not wholly accurate, is sufficiently appropriate for cases when the number of modes supported within a fiber is high (ie: the core is large) and thus useful for understanding the origin of modal dispersion. The propagation of rays within different fibers is shown in Figure 2.6.
In efforts to lower the modal dispersion seen within multimode fibers, different core profiles can be used. A graded index core profile such as that in Figure 2.3 can reduce the modal dispersion by allowing the rays injected at steeper angles to propagate for significant amounts of time in areas of the core where there is a lower refractive index. This increases the speed of the higher order modes in relation to the fundamental mode and reduces the effects of modal dispersion somewhat.

2.6.3.2 Polarisation Modal Dispersion

Even single mode optical fibers are in reality capable of supporting two degenerate polarisation modes that are polarised orthogonally to each other. This leads to slightly different propagation constants for the two orthogonal polarisations and is termed polarisation modal dispersion (PMD). For perfectly cylindrical fibers, these two modes propagate at the same velocity, however perfect symmetry is unachievable in practice and even the slightest variation or stress within a fiber can cause this birefringence. In fibers designed to be symmetric (standard single mode fibers), the axis of this slight birefringence varies randomly throughout the length of the fiber, causing the polarisation of light launched into the fiber to evolve in a random
fashion. This is typically harmless for continuous waves, but will cause short pulses to broaden, as one polarisation component will travel faster than the other [37].

2.7 Nonlinearities

Nonlinear optical effects generally are not seen in the natural world due to the requisite high intensities needed. These nonlinear optical effects refer to a response of a medium that is not related in a linear fashion to the optical field. The above mentioned effects such as loss and dispersion are examples of linear effects. A thorough derivation of the origin of these nonlinear effects is not performed here, but can be found for example in [38].

We instead consider the fact that the response of any dielectric to light becomes nonlinear for intense electromagnetic fields. These nonlinearities arise from the anharmonic motion of bound electrons under the influence of an applied field. As a result, the total polarisation $P$ induced by the electric dipoles is not linear with respect to the electric field, but can be represented by the more general relation,

$$P = \epsilon_0 \left( \chi^{(1)} \cdot E + \chi^{(2)} : EE + \chi^{(3)} : EEE + \ldots \right), \quad (2.13)$$

where $\epsilon_0$ is the vacuum permittivity and $\chi^{(j)}$ is the $j$th order susceptibility where $j = (1, 2, \ldots)$. In general $\chi^{(j)}$ is a tensor of rank $j + 1$. The linear susceptibility $\chi^{(1)}$ represents the dominant contribution to the induced polarisation and its effects are included through the attenuation coefficient $\alpha$ and refractive index $n$.

The second order susceptibility $\chi^{(2)}$ is responsible for effects such as second harmonic and sum frequency generation. These effects are in practice seen only in materials that lack an inversion symmetry on the molecular level.

The third order susceptibility $\chi^{(3)}$ is responsible for the lowest order nonlinear effects seen in materials which exhibit an inversion symmetry, such as silica fibers. Effects such as third harmonic generation, four wave mixing and nonlinear refraction are manifestations of the third order nonlinearity.
2.7.1 Wave Propagation in Nonlinear Media

In this section we derive equations governing the propagation of electromagnetic waves in nonlinear media. The starting point is Maxwell’s equations,

\begin{align}
\nabla \times \mathbf{E} & = -\frac{\partial \mathbf{B}}{\partial t}, \\
\nabla \times \mathbf{H} & = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}, \\
\nabla \cdot \mathbf{D} & = \rho_f, \\
\nabla \cdot \mathbf{B} & = 0,
\end{align}

where \( \mathbf{E} \) and \( \mathbf{H} \) are the electric and magnetic field vectors respectively, and \( \mathbf{D} \) and \( \mathbf{B} \) are the electric and magnetic flux densities. The current density vector \( \mathbf{J} \) and the charge density \( \rho_f \) represent the sources for the electromagnetic field.

The flux densities \( \mathbf{D} \) and \( \mathbf{B} \) arise in response to the electric and magnetic fields \( \mathbf{E} \) and \( \mathbf{H} \) propagating inside the medium and are related to them through

\begin{align}
\mathbf{D} & = \varepsilon_0 \mathbf{E} + \mathbf{P}, \\
\mathbf{B} & = \mu_0 \mathbf{H} + \mathbf{M},
\end{align}

where \( \varepsilon_0 \) is the vacuum permittivity, \( \mu_0 \) is the vacuum permeability and \( \mathbf{P} \) and \( \mathbf{M} \) are the induced electric and magnetic polarisations. In non magnetic media, such as those investigated throughout this thesis, \( \mathbf{M} = 0 \).

To obtain the Wave Equation, we take the curl of Eq.(2.14) and using Eq.(2.15) we obtain

\[
\nabla \times \nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{J}}{\partial t} - \mu_0 \frac{\partial^2 \mathbf{D}}{\partial t^2}.
\]

Utilising the identity, \( \nabla \times \nabla \times \mathbf{E} = \nabla \nabla \cdot \mathbf{E} - \nabla^2 \mathbf{E} \), and taking \( \nabla \nabla \cdot \mathbf{E} = 0 \), along with the expression for \( \mathbf{D} \) above, we obtain,
\[ \nabla^2 E = \mu_0 \frac{\partial J}{\partial t} + \mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2} + \mu_0 \frac{\partial^2 P}{\partial t^2}. \] (2.21)

If we separate the total polarisation \( P \) into its linear and nonlinear parts, according to

\[ P = P_L + P_{NL}, \] (2.22)

where \( P_{NL} \) represents the lowest order nonlinearity induced in the medium the Wave Equation becomes thus

\[ \nabla^2 E = \mu_0 \frac{\partial J}{\partial t} + \mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2} + \mu_0 \frac{\partial^2 P_L}{\partial t^2} + \mu_0 \frac{\partial^2 P_{NL}}{\partial t^2}. \] (2.23)

For a charge free medium (like most encountered) \( J = 0 \), and if we assume that at all times \( P_{NL} \) is parallel to \( E \), then the Wave Equation may be written in its scalar form for a charge free medium as

\[ \nabla^2 E = \mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2} + \mu_0 \frac{\partial^2 P_L}{\partial t^2} + \mu_0 \frac{\partial^2 P_{NL}}{\partial t^2}. \] (2.24)

The above equation describes the evolution of an optical wave through a nonlinear medium. We will see later that by utilising this solution for Maxwell’s equations we can derive coupled amplitude equations for multiple waves propagating simultaneously through a nonlinear medium. The \( P_{NL} \) term is responsible for the nonlinear interaction and generation of waves at new frequencies. This is particularly important for wavelength conversion situations.

### 2.7.2 Phase Matching

Phase matching is a commonly referred to requirement in nonlinear optics and is one of the main considerations needed to be taken into account when designing a nonlinear wavelength converter.

As mentioned in Section 2.6.3 optical waves propagating through a dispersive
medium will experience different refractive indices dependent on the frequency at which they oscillate. This results in waves of different wavelengths or frequencies propagating at different velocities.

During a nonlinear mixing process energy from an optical wave(s) can be transferred to another wave(s) at frequency multiples (or harmonics) of the fundamental wave(s) as they propagate through a nonlinear medium. For simplicity let us consider a fundamental and its harmonic. At the start of this nonlinear interaction these waves will have a relative phase of zero. Thus they can be considered to be in phase. As they travel through the nonlinear medium the relative phase between them begins to change as one wave travels faster than the other. The nonlinear interaction occurs at every point within the medium so initially the power flows from the fundamental to the harmonic and a gradual build up in the harmonic field’s intensity will occur. After some distance of propagation however, the relative phase between them will change such that they will have a relative phase of $\pi$. Once this point is reached, the harmonic wave that is being continuously generated is now out of phase with the harmonic wave generated at an earlier position in the medium. These waves begin to destructively interfere, thus power no longer flows from the fundamental wave to its harmonic, but rather back from the harmonic to the fundamental; power flow is reversed and the gradual reduction of intensity in the harmonic occurs. The distance over which this reversal in power occurs is referred to as the coherence length for the process. Generally the length of the medium must be shorter than the coherence length for significant mixing to occur.

In order to achieve significant power transfer from the fundamental wave(s) to the generated mixing terms or harmonics, phase matching must be satisfied and the effects of dispersion countered. In practice there are a number of different techniques used to achieve this - such as birefringent, dispersive and quasi phase matching. These techniques will be discussed in later chapters where they are utilised for the efficient generation of new wavelengths in various nonlinear media.
Chapter 3

Nonlinear Wavelength Conversion in Highly Nonlinear Fibers

In this chapter we will discuss the use of single mode optical fibers for the study of nonlinear effects. Close attention will be paid to the four wave mixing (FWM) effect of Bragg Scattering as that is the primary area of study for wavelength conversion throughout the course of this thesis. Numerical and experimental characterisations of this process have been performed and practical limitations of this effect are discussed.

We begin with the presentation of fiber specific nonlinear effects, followed by discussion and implementation of the experimental minimisation of some of these interfering effects and their implications on the Bragg Scattering process. Four coupled equations are derived that govern the evolution of the participant waves in a Bragg Scattering process. This result is used for theoretical predictions of the response of the Bragg Scattering process.

The development of a successful Bragg Scattering wavelength conversion scheme is outlined and measurements of experimental phase matching curves and Bragg Scattering conversion response are detailed. Numerical simulations based on the coupled amplitude equations are described where applicable and the deviations from the predicted theory are discussed.
Using the measured Bragg Scattering phase matching curves we recover the dispersion parameters of the HNLFs used within this chapter. We analyse various characteristics of the phase matching curves and the Bragg Scattering conversion response. The effects of uneven pump powers on the phase matching curves are discussed, along with the interference from competing effects and fiber imperfections during the Bragg Scattering process.

The artifacts in the recovered Bragg Scattering response and phase matching curves arising from fiber imperfections lead to a discussion of ZDW fluctuations. Methods are described for the measurement of the relative size and profile of these fluctuations and a numerical model is used to simulate their implications on the Bragg Scattering response.

The effect of stimulated Raman scattering (SRS) on the Bragg Scattering process is discussed in detail and some practical suggestions for the minimisation of this effect are presented. The Bragg Scattering response to pump power is theoretically analysed and experimentally measured. Using numerical simulations and theoretical predictions based on the response of the Bragg Scattering effect to pump power, a high speed nonlinear switch based on this effect is numerically modeled and experimentally implemented.

We use Bragg Scattering for the error free conversion of a 10Gb/s data signal over a 33nm wavelength shift. We discuss and investigate the performance of the Bragg Scattering process for data conversion with various conversion efficiencies.

Experimental characterisation of the bandwidth of the Bragg Scattering response has been undertaken, and the practical tunable range, bandwidth and efficiency of Bragg Scattering in optical fibers is discussed.

3.1 Introduction

Glass optical fibers have been used extensively for the study of nonlinear effects since the development of low loss optical fibers in the 1970's [39]. Glass is an amorphous solid, therefore it possess an inversion symmetry and does not display
any second order nonlinear response (unless special preparations are undertaken such as in [40]). As such, the nonlinearities studied in this chapter all arise from the third order susceptibility $\chi^{(3)}$. The fibers used within this section are highly nonlinear dispersion shifted fibers, but we simply refer to them as highly nonlinear fibers (HNLF). These fibers have been manufactured to exhibit high nonlinearities ($\sim 10$ times higher than standard single mode fiber; achieved through small core diameters) and possess zero dispersion wavelengths (ZDW) located within the C-band.

### 3.2 Fiber Nonlinearities

Silica fibers, compared to other commonly used nonlinear media, do not possess large nonlinear coefficients. Nonlinear effects, however, can occur with high efficiencies due to the low loss and long interaction lengths offered by fibers. For low intensity optical signals, the induced polarization $P$ is proportional to the electric field $E$. When the optical signal intensity increases, the response of bound electrons to the electromagnetic field becomes nonlinear and the induced polarization is no longer directly proportional to the electric field and Eq. (2.13) can be expressed as

$$ P = \epsilon_0 \left( \chi^{(1)} \cdot E + \chi^{(3)} : EEE \right), \quad (3.1)$$

where we limit our considerations to only the lowest order nonlinear effect for silica fibers, which arises from the third order susceptibility, $\chi^{(3)}$.

### 3.3 Nonlinear Refraction

As mentioned above, the main nonlinear effects seen in optical fibers result from the third order susceptibility $\chi^{(3)}$, which is responsible for phenomena such as third harmonic generation, four-wave mixing and nonlinear refraction. The effects which involve the generation of new waves at different optical frequencies, such as third
harmonic generation and four-wave mixing only occur efficiently when special efforts are made to achieve phase matching. Due to this the majority of the nonlinear effects commonly seen in optical fibers result from nonlinear refraction. Nonlinear refraction refers to the intensity dependence of the refractive index which can be written as

\[
\tilde{n}(\omega, |E|^2) = n(\omega) + \hat{n}_2|E|^2, \tag{3.2}
\]

where \(|E|^2\) is the intensity within the fiber, \(n(\omega)\) is the linear part of the refractive index, given by Eq.(2.1) and \(\hat{n}_2\) is the nonlinear index coefficient that is related to \(\chi^{(3)}\) by

\[
\hat{n}_2 = \frac{3}{8\pi} \text{Re} \left( \chi^{(3)}_{xxxx} \right), \tag{3.3}
\]

where Re stands for the real part and the optical field is assumed to be linearly polarised so that only one component \(\chi^{(3)}_{xxxx}\) contributes to the nonlinear refractive index. This intensity dependent refractive index leads to effects such as self phase and cross phase modulation (SPM and XPM respectively). SPM is responsible for the broadening of ultra short optical pulses due to the nonlinear refractive index inducing index differences between the high power peak of the pulse and the low power leading and trailing edges. XPM refers to the nonlinear phase shift of an optical field induced by another field. The two fields involved in XPM can have different wavelengths, directions of propagation and states of polarisation.

### 3.4 Stimulated Inelastic Scattering

The parametric nonlinear effects involving the third order susceptibility \(\chi^{(3)}\) are elastic in the sense that no energy is exchanged between the electromagnetic field and the dielectric medium. There is another class of nonlinear effects that results from stimulated inelastic scattering, which does involve the transfer of energy between the optical field and the medium it is traveling through. Two important nonlinear
3.4. STIMULATED INELASTIC SCATTERING

Effects fall into this category; both of them are related to the vibrational excitation modes of silica. These phenomena, known as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS), were among the first nonlinear effects studied in optical fibers [41, 42].

3.4.1 Stimulated Brillouin Scattering

Stimulated Brillouin scattering is a high gain, nonlinear effect that can be detrimental to the study of other nonlinear effects in optical fibers. SBS is caused by inelastic scattering of the electromagnetic field from acoustic phonons within the fiber. The incident and reflected (scattered) waves form an interference pattern which serves, through the process of electrostriction, to promote the continued growth of the acoustic wave. This stimulated acoustic wave forms a traveling grating within the fiber which causes more of the incident wave to be reflected, until a steady state situation is reached. In a fiber, the scattered wave propagates in the opposite direction to the incident and acoustic waves. This reflected wave is down-shifted in frequency (typically \(\sim 10\text{GHz}\) for single mode fiber) because of the Doppler shift associated with a grating moving at the acoustic velocity \(v_A\), which is determined by the properties of the nonlinear media. If left unchecked, SBS can reflect virtually all of the incident wave, severely limiting the power which can be transmitted down the fiber.

The power threshold \(P_{th}\) at which the transmitted power is limited to a constant level and the balance is reflected can be as low as 1mW for CW light in single mode fibers [43]. Fortunately, the gain bandwidth of the SBS process is very narrow \((\Delta v_B \approx 50\text{MHz})\) as it is related to the damping time of the acoustic waves. If any frequency components of an input optical wave fall outside this bandwidth, they will not generate any SBS gain. Consequently, the Brillouin gain is decreased and the threshold power is increased. This can be expressed as

\[
g_B' = \frac{g_B}{1 + (\Delta v_B/\Delta v)^2},
\]  

(3.4)
where \( g'_B \) (\( g_B \)) is the Brillouin gain with (without) line broadening and \( \Delta v \) is the linewidth of the input optical wave. Thus, if one uses an input optical wave with \( \Delta v \gg \Delta v_B \) then the SBS threshold, \( P_{th} \), increases significantly.

### 3.4.2 Stimulated Raman Scattering

Stimulated Raman scattering is a related nonlinear process that also involves the inelastic scattering of the electromagnetic field from phonons within the fiber. SRS however, involves the scattering from optical phonons rather than acoustic phonons as seen with SBS. This process can be described as a photon, from an input optical wave, scattering from one of the molecules to a lower energy photon, whilst the molecule makes a transition to a higher energy vibrational state. Likewise, a photon can be scattered to a higher energy photon, if the molecule transitions to a lower energy state. Due to this, the vibrational levels of the molecules within the fiber determine the frequency shift and profile of the Raman gain curve. This has several important consequences, namely, the bandwidth for the Raman gain is much larger than that of the SBS and the scattered wave can propagate in both the backward and forward directions. Like SBS, SRS can be detrimental to the study of other nonlinear effects seen in optical fibers. SRS can severely limit the performance of multichannel light wave systems by transferring power from one optical wavelength to another via Raman induced gain and loss. The Raman gain coefficient for silica is shown in Figure 3.1 for frequency detunings when pump and signal are co-polarised [44]. This Raman gain decreases by an order of magnitude when the signals are polarised orthogonally [45].

### 3.5 The Suppression of Stimulated Brillouin Scattering

As discussed previously, stimulated Brillouin scattering is a nonlinear process that can occur in optical fibers at relatively low input powers (for spectrally narrow
signals) that can effectively limit the maximum power able to be transmitted down an optical fiber. As such, this effect is particularly noticeable and troublesome when FWM experiments are performed with CW pumps. By broadening the spectrum of these pumps sufficiently the SBS threshold can be increased to powers above that of the pumps, thus allowing maximum pump transmission through the HNLF. This allows a stronger FWM effect to be seen. An experiment was carried out to determine the best scheme for reducing the effect of SBS via phase modulating the pump waves before amplification.

### 3.5.1 Experimental Set-up

The experimental set-up used to measure the effect of the different modulation schemes is shown in Figure 3.2, where CW laser light was modulated via a Lithium Niobate phase modulator with two different modulation schemes. This was then amplified, passed through the HNLF and the transmitted power was measured. The polarisation controller is necessary as the phase modulator only modulates one axis of polarisation, so the input light must be aligned with this axis of modulation. The
alignment to this axis is achieved by varying the polarisation controller to maximise the transmitted power through the fiber.

### 3.5.2 Experimental Results

The results in Figure 3.3 show that for optimum suppression a modulation format using a pseudo random bit sequence (PRBS) is the best modulation scheme. The PRBS scheme is superior to that of a sine wave as it possess a more continuous spectrum, thus broadening the signal more effectively than a sinusoidal modulation. The residual difference in input and output powers (approximately 2dB) is due to the loss experienced through the HNLF and its connectors.

![Figure 3.3: Power transmission for the various SBS suppression schemes.](image)
3.6. **FOUR WAVE MIXING**

### 3.5.3 Summary

This experiment showed that to effectively suppress the SBS on high power continuous wave pumps a modulation format using a PRBS offers the best results. The experiments throughout this thesis that use a HNLF incorporate a similar suppression scheme for each high power pump wave used.

This phase modulation experiment examined the SBS suppression on a single pump. In the FWM experiments studying the Bragg Scattering effect, we utilised a co-modulation Scheme (where both pumps were modulated with the same phase modulation signal) as this causes the phase modulation from each pump to cancel with the other (for the Bragg Scattering case), thus not transferring the phase modulation onto the Bragg Scattering idler/signal [46].

### 3.6 Four Wave Mixing

Parametric processes are nonlinear phenomena that rely on the modulation of a medium parameter, such as refractive index, to provide the interaction between several optical waves. Of primary interest in this section are the parametric processes called four wave mixing. FWM effects are defined as third-order parametric processes. FWM, in general, involves the nonlinear interaction between four optical waves. FWM in fibers has been extensively studied as it can be very efficient at generating new frequencies. Its main features can be understood by considering the third order polarisation term in Eq.(3.1) given as:

\[
P_{NL} = \epsilon_0 \chi^{(3)} : \mathbf{EEE},
\]

where \( P_{NL} \) is the induced nonlinear polarisation, \( \epsilon_0 \) is the vacuum permittivity and \( \mathbf{E} \) is the electric field.

Consider four optical waves that are oscillating at frequencies of \( \omega_1, \omega_2, \omega_3, \omega_4 \) and are linearly polarized along the \( x \)-axis. The total electric field can be written as:
\[ E = \frac{1}{2} \hat{x} \sum_{j=1}^{4} E_j \exp \left[ i \left( \frac{n_j \omega_j z}{c} - \omega_j t \right) \right] + c.c, \quad (3.6) \]

where all four waves are assumed to be propagating in the same direction (z-direction) and the \( n_j \) is the refractive index. If we substitute Eq. (3.7) in Eq. (3.5) and express \( P_{NL} \) in the same form as \( E \) using

\[ P_{NL} = \frac{1}{2} \hat{x} \sum_{j=1}^{4} P_j \exp \left[ i \left( \frac{n_j \omega_j z}{c} - \omega_j t \right) \right] + c.c, \quad (3.7) \]

we find that \( P_j \) \((j = 1 \text{ to } 4)\) consists of a large number of terms involving the products of three electric fields. For example, \( P_4 \) can be expressed as

\[ P_4 = \frac{3 \epsilon_0}{4} \chi^{(3)}_{xxxx} \left[ |E_4|^2 E_4 + 2 \left( |E_1|^2 + |E_2|^2 + |E_3|^2 \right) E_4 \right. \]
\[ + 2E_1 E_2 E_3 \exp (i\theta_+) + 2E_1 E_2 E_3^* \exp (i\theta_-) + \cdots, \quad (3.8) \]

where \( \theta_+ \) and \( \theta_- \) are defined as

\[ \theta_+ = (k_1 + k_2 + k_3 - k_4) z - (\omega_1 + \omega_2 + \omega_3 - \omega_4) t, \quad (3.10) \]
\[ \theta_- = (k_1 + k_2 - k_3 - k_4) z - (\omega_1 + \omega_2 - \omega_3 - \omega_4) t. \quad (3.11) \]

The first four terms containing \( E_4 \) in Eq. (3.8) are responsible for the self phase modulation and cross phase modulation effects. The remaining terms are the result of FWM. The parametric coupling of these terms depends on the phase mis-match between \( P_4 \) and \( E_4 \) governed by \( \theta_+ \), \( \theta_- \) or a similar quantity. If this phase mismatch is very small, significant FWM can occur. This requires matching not only the frequencies but the wave vectors as well, as, due to the relatively low nonlinear response of silica optical fibers, the waves must remain in phase for extended interaction lengths for these nonlinear effects to be significant. In quantum mechanical terms, FWM will only occur when both the net energy and momentum
3.6. FOUR WAVE MIXING

are conserved. There are two types of FWM terms in Eq.(3.8). The term we are interested in contains $\theta_-$ (the $\theta_+$ term corresponds to effects such as third harmonic generation). This term corresponds to the case where two photons at frequencies of $\omega_1$ and $\omega_2$ are destroyed, and simultaneously, photons at frequencies of $\omega_3$ and $\omega_4$ are created such that

$$\omega_1 + \omega_2 = \omega_3 + \omega_4. \quad (3.12)$$

The phase-matching requirement for this process is

$$\Delta k = (n_3 \omega_3 + n_4 \omega_4 - n_1 \omega_1 - n_2 \omega_2) / c = 0. \quad (3.13)$$

This is relatively easy to satisfy if $\omega_1 = \omega_2$. This is the partially degenerate case most often seen in optical fibers and given the term Modulation Instability (MI). It occurs when a strong pump wave is injected into a fiber and if phase matched, two sidebands spontaneously grow from noise, symmetrically spaced about the pump frequency. The frequency shift of the sidebands is

$$\Omega_s = \omega_1 - \omega_3 = \omega_4 - \omega_1. \quad (3.14)$$

This effect can also be seeded where, if a weak signal is injected at $\omega_3$, not only will this signal experience amplification (this effect is called the parametric gain), but a new wave at $\omega_4$ is also generated. These sidebands are often referred to as the Stokes and anti-Stokes waves or sometimes called the signal and idler waves. Specifying a pump wave generally indicates it is a strong (high intensity and undepleted) wave with respect to the sidebands.

The non-degenerate case, where $\omega_1 \neq \omega_2$, if phase matched, can also result in spontaneous growth of sidebands spaced symmetrically about the average pump frequencies. This process is termed Phase Conjugation (PC) and as with the case of MI, results in a phase conjugated idler if a weak signal is injected at the appropriate frequency such that the phase matching condition is satisfied.
The effects of MI and PC have been extensively studied and are commonly utilised for both amplification and signal processing applications [21, 22, 5, 24]. With the broadband tunability and high gains possible these effects are well suited as optical parametric amplifiers. However, with the high gain and large bandwidths also comes the generation of noise.

In this study, we are interested in a particular case of non-degenerate FWM where the phase matched frequencies are not spaced symmetrically about the average pump frequencies. This non-degenerate case exhibits no parametric gain at the phase-matched frequencies and as such, the sidebands will not spontaneously grow from noise but instead will only occur by seeding with a weak signal. This process is called Bragg Scattering and is discussed in detail in the following section.

The wavelength distributions for the three main FWM effects can be seen in Figure 3.4, where a weak signal interacts with two strong pumps (in the case of MI, two photons from the one pump wavelength, commonly referred to as a single pump process).

![Figure 3.4: Wavelength spacings of the four coupled side bands through the three different FWM processes](image-url)
3.7 Bragg Scattering

Bragg Scattering, sometimes referred to as wavelength exchange and non-degenerate asymmetrical FWM, has recently attracted attention as a useful FWM effect for wavelength conversion applications [25, 26]. In this thesis we will call it by the name Bragg Scattering - the term Bragg Scattering was coined for this particular effect due to the spatial analogue drawn between this effect and that of reflection from a Bragg grating [29].

Bragg Scattering is the case where the FWM pumps are spaced asymmetrically about the average frequency as seen in Figure 3.4. This leads to a situation where generation of an idler at $\omega_4$ occurs only when a signal is present at $\omega_2$. In contrast to a MI or PC process, where vacuum fluctuations can cause spontaneous growth at the phase matched frequencies of $\omega_{MI}$ and $\omega_{PC}$, power flow into the Bragg Scattering idler is driven by the presence of photons at the signal wavelength and is characterised by the relationship $\omega_1 + \omega_4 = \omega_2 + \omega_3$.

Previous studies have demonstrated that tunable and arbitrary wavelength conversion is possible using Bragg Scattering [47], and recent work in large effective area fibers (LEAF) has identified the Bragg Scattering effect as a possible candidate for distant wavelength conversion applications [48]. Other studies have focused around the wavelength exchange effect where two signals are exchanged during the mixing process [28, 27]. Several theoretical reviews have indicated that Bragg Scattering effect exhibits the possibility to be free from noise usually associated with FWM effects [30]. These previous works all demonstrate and discuss the use of Bragg Scattering for various wavelength conversion and exchange purposes. The work presented in the following section aims at building a base of knowledge necessary to successfully implement these types of wavelength conversion experiments and further characterise the response of this process to various impairments and free parameters, such as pump powers, wavelength distributions and dispersion profiles.

In the following sections we derive a set of four coupled equations that govern the evolution of the participant waves for a Bragg Scattering process in a HNLF.
We solve these equations and discuss the implications of the theoretical response and noise properties of this process. We detail the experimental implementation and characterisation of the Bragg Scattering effect in two different HNLFs. The relative merits of the different Bragg Scattering implementations regarding wavelength distributions and the relative states of polarisations are discussed and we experimentally measure the phase matching curve for two HNLFs with opposite signs of the $\beta_4$ term in the Taylor expansion of the dispersion of the fiber as expressed in Eq.(2.2). Using the coupled amplitude equations with the effects of SRS included, the Bragg Scattering process has also been numerically modeled in these fibers. We experimentally characterise the response of the Bragg Scattering effect and implement several wavelength conversion experiments and a nonlinear switch based on the Bragg Scattering process. We investigate the effect of fiber imperfections and competing/interfering nonlinear effects and discuss the limitations these cause.

3.7.1 Coupled Amplitude Equations

The derivation of a set of coupled equations that describes the evolution of the four participant waves in a Bragg scattering process is very similar to that traditionally followed for the case of MI and PC as found in [43, 49]. The main difference lies in the allocation of the strong pump and weak signal wavelengths. Contrary to Eq.(3.12), the condition for conservation of energy for Bragg Scattering is given as

$$\omega_1 + \omega_4 = \omega_2 + \omega_3,$$  \hspace{1cm} (3.15)

where $\omega_1 < \omega_2 < \omega_3 < \omega_4$. This corresponds to the case where two strong pumps are injected into a highly nonlinear fiber at frequencies $\omega_1$ and $\omega_3$. The presence of weak signal at the phase-matched frequency of $\omega_2$ will result in the generation of an idler at $\omega_4$.

The starting point is the Wave Equation, described in Eq.(2.24) for the total electric field with the third order nonlinear polarisation. If we substitute Eq.(3.6) and Eq.(3.7) together with an expression for the linear part of the polarisation and
3.7. BRAGG SCATTERING

neglect the time dependence (assuming quasi CW conditions), we can arrive at a set of coupled amplitude equations

\[
\begin{align*}
\frac{dA_1}{dz} &= i\gamma (|A_1|^2 + \epsilon|A_2|^2 + 2|A_3|^2 + \epsilon|A_4|^2) A_1 + i\gamma \epsilon A_2 A_3 A_4^* e^{i\Delta k z}, \\
\frac{dA_2}{dz} &= i\gamma (\epsilon|A_1|^2 + |A_2|^2 + \epsilon|A_3|^2 + 2|A_4|^2) A_2 + i\gamma \epsilon A_1 A_3 A_4 e^{-i\Delta k z}, \\
\frac{dA_3}{dz} &= i\gamma (2|A_1|^2 + \epsilon|A_2|^2 + |A_3|^2 + \epsilon|A_4|^2) A_3 + i\gamma \epsilon A_1 A_2 A_4 e^{-i\Delta k z}, \\
\frac{dA_4}{dz} &= i\gamma (\epsilon|A_1|^2 + 2|A_2|^2 + \epsilon|A_3|^2 + |A_4|^2) A_4 + i\gamma \epsilon A_1^* A_2 A_3 e^{i\Delta k z},
\end{align*}
\]

where the wave-vector mis-match \(\Delta k\) is given by (see Eq.(3.13))

\[
\Delta k = \left( n_1 \omega_1 + n_4 \omega_4 - n_2 \omega_2 - n_3 \omega_3 \right) / c,
\]

and the nonlinear parameter \(\gamma\) is given by

\[
\gamma = \frac{n_2 \omega_0}{c A_{eff}},
\]

where \(\omega_0\) is the average frequency of the four waves and \(A_{eff}\) is the effective core area [43].

The parameter \(\epsilon\) is determined by the state of polarisations of the four waves; \(\epsilon = 2\) for \(BS_{||}\), and \(\epsilon = 1\) for \(BS_{\perp}\), as seen in Figure 3.5 [50]. \(BS_{||}\) refers to the case when all four waves are co-polarised with one an other, whereas \(BS_{\perp}\) indicates that adjacent waves are perpendicular. This second case minimises spurious FWM effects between the adjacent waves [51]. More generalised equations for other variations of the polarisation states for the waves can be constructed in a similar fashion with the inclusion of further polarisation coupling terms [50].

If we treat waves 1 and 3 (Eq.(3.16) and (3.18)) as the pumps and assume they are strong with respect to the other waves and remain undepleted throughout the fiber, then these two coupled mode equations are easily solved to give
\[ A_1(z) = \sqrt{P_1} \exp \left[ i \gamma (P_1 + 2P_3) z \right], \] (3.22)
\[ A_3(z) = \sqrt{P_3} \exp \left[ i \gamma (2P_1 + P_3) z \right], \] (3.23)

where \( P_1 \) and \( P_3 \) are the incident pump powers at \( z = 0 \). This solution shows that the pumps only acquire a phase shift as a result of SPM and XPM in the undepleted pump approximation. By substituting this solution for the pumps into the equations for the signal and idler Eqs.(3.17) and (3.19), after some derivation (performed in detail in Appendix A) one is able to arrive at the general solutions of:

\[ B_2 = \left[ \cos (\kappa z) + i \frac{\delta}{\kappa} \sin (\kappa z) \right] B_2(0) + i \gamma \sin (\kappa z) B_4(0), \] (3.24)
\[ B_4 = i \frac{\gamma}{\kappa} \sin (\kappa z) B_2(0) + \left[ \cos (\kappa z) - i \frac{\delta}{\kappa} \sin (\kappa z) \right] B_4(0), \] (3.25)

where \( B_2 \) is the signal wave and \( B_4 \) is the idler wave, and

\[ \kappa = \sqrt{|\gamma|^2 + \delta^2}, \] (3.26)

where \( \gamma \) is the nonlinear coupling coefficient

\[ \gamma = \epsilon \gamma \sqrt{P_1 P_3}, \] (3.27)
and $\delta$ is the phase mis-match for the Bragg scattering process

$$\delta = \frac{\Delta k}{2} + \frac{\gamma \Delta P}{2},$$

(3.28)

where $\Delta P = P_1 - P_3$.

This set of equations describes the propagation and evolution of the weak signal and idler wave. These are generalised solutions for the assumptions made and they describe to good effect the Bragg Scattering response when both signal and idler waves are initially present, which corresponds to the effect called wavelength exchange [28, 27]. Assuming phase matching is satisfied ($\delta = 0$), this results in the complete exchange in power between the signal and idler waves after a sufficient propagation length such that $2\kappa z = \pi$. Wavelength exchange has been studied in several texts and has potential uses as a novel network function for switching data signals between existing channels. An important result of the above derivation is to note that the total power in the signal and idler sidebands is constant, thus power is only transferred between the signal and idler waves and no gain is experienced.

This general solution can be simplified somewhat if the initial power of idler wave is zero (this is often the case in wavelength conversion applications and accordingly is the situation we focus on in the following sections), to yield

$$B_2 = \left[ \cos (\kappa z) + i \frac{\delta}{\kappa} \sin (\kappa z) \right] B_2 (0),$$

(3.29)

$$B_4 = i \frac{\gamma}{\kappa} \sin (\kappa z) B_2 (0).$$

(3.30)

If the process is phase matched ($\delta = 0$), efficient conversion from the signal to the idler occurs and power flows in a sinusoidal fashion between the signal and idler waves.

Similarly to MI and PC, Bragg Scattering is strictly dependent on the phase matching condition being satisfied and significant Bragg Scattering can only be seen very close to the phase matched frequencies. To simplify the analysis of the
dependence of Bragg Scattering on its phase matching condition the pump powers can be chosen such that they are equal in intensity ($\Delta P = 0$), reducing the phase matching condition to a purely linear wave vector dependence of

$$
\delta = \frac{\Delta k}{2} = \frac{1}{2} \left[ \beta (\omega_1) + \beta (\omega_4) - \beta (\omega_2) - \beta (\omega_3) \right] = 0. \quad (3.31)
$$

By expanding the propagation constants in a Taylor series about the average frequency $\omega_a$, we obtain

$$
\delta = \frac{(\omega_b^2 - \omega_c^2)}{2} \left[ \beta_2 + \frac{\beta_4 (\omega_b^2 + \omega_c^2)}{12} \right], \quad (3.32)
$$

where, $\omega_a = (\omega_2 + \omega_3)/2$, $\omega_b = (\omega_3 - \omega_2)/2$ and $\omega_c = (\omega_4 - \omega_1)/2$ (as seen in Figure 3.4). This shows that $\beta_4$ is crucial for the occurrence of Bragg Scattering, so in practice, as $\beta_4$ is generally much smaller than $\beta_2$, the average frequency must be close to the ZDF of the fiber if Bragg Scattering is to be demonstrated.

### 3.7.2 Noise Properties

Bragg Scattering is unique among FWM effects in that it doesn’t exhibit any gain and the total sideband power remains constant. This implies that under the correct conditions it is possible to have a pure Bragg Scattering process that is free from any generated noise commonly associated with the other FWM effects in fibers that exhibit parametric gain [52, 53]. This sets it apart from MI and PC and makes it a promising candidate for low noise, few photon wavelength conversion applications, with the potential ability to translate one photon to another photon at a different wavelength. The noise properties of the Bragg scattering process have been investigated [30], indicating that Bragg Scattering can perfectly transfer information (or quantum states) from one wavelength to another. Several studies have been performed to examine the noise properties of Bragg Scattering in optical fibers [54, 55] and these have shown that it does indeed possess improved noise properties compared to MI and PC. Although further experimental demonstrations of these noise
properties are beyond the scope of this thesis, the implications of the various experimental set-ups, wavelength distributions and polarisation states are discussed with considerations given to practical limitations of experimental wavelength converter applications.

In the above derivations of the coupled amplitude equations that govern the Bragg Scattering process, it is assumed that the polarisations of the participant waves remains constant with respect to each other throughout the interaction. This is a good assumption so long as the length of the fiber is not too long and the relative wavelengths of the waves not too dissimilar [32]. Bragg Scattering can occur for several polarisation schemes. Figure 3.6 shows a few of the possibilities considered within the course of this thesis and it should be noted that for all cases except that of (d), Bragg Scattering occurs within fibers [50] (in case (d) there is no coupling between the idler and signal waves).

The different states of polarisation of the waves in a Bragg Scattering process have significant impact on the response of the Bragg Scattering process. Disregarding all other effects, they differ only by their nonlinear coupling coefficients. However, due to the occurrence of other nonlinear effects, not all states of polarisation
are equal in terms of the suitability for low noise applications. As the SRS gain (or loss) practically vanishes for orthogonal waves, orthogonal polarisation schemes can offer some benefits over the co-polarised scheme. Whilst the co-polarised case of (a) gives stronger coupling between the waves, requiring less pump powers, each wave is susceptible to the SRS from the three other waves and other unwanted nonlinear mixing from the effects of MI and PC will occur more strongly between adjacent waves. In the case of (b), the close spacing between the pumps will produce strong nonlinear mixing of these two waves and SRS will cause power transfer between pumps. However, the low power signals polarised orthogonally to these two waves will have minimised interaction via SRS and other FWM processes with the pumps. With the case of (c), the nonlinear mixing of adjacent waves is minimised as they are orthogonal to one another. However the increased pump separation leads to stronger SRS power transfer between the pumps. If the Bragg Scattering spacings were to be such that the waves were outside the SRS gain bandwidth then the effects of SRS between waves could be neglected, but with such widely spaced waves the assumption that the relative polarisations of the waves stay constant throughout the length of the fiber would no longer be appropriate and, as discussed in later sections, the impact of any zero dispersion fluctuations along the length of the fiber will be increased.

For each different state of polarisation there are different pros and cons that need to be considered when designing a Bragg Scattering wavelength converter. Even though the Bragg Scattering process is theoretically free from noise, the effects of SRS on the signal and idler waves (determined by both the states of polarisation and wavelength spacing between the waves) cannot necessarily be neglected and will place limits on a practical process. The use of the different states of polarisations are discussed where relevant in the following experimental sections where various Bragg Scattering processes are implemented.
3.7.3 Simulations

The numerical simulations performed within this study focus primarily on the solution of the coupled mode equations, described above, via numerical integration. This method yields greater insight into the evolution of the individual coupled waves throughout the fiber and allows for the effects of pump depletion. Methods such as solving the nonlinear Schrödinger equation (NLSE) via the split-step Fourier method are more applicable where the number of signal carriers becomes large, i.e., in the case of modeling a WDM system when this would lead to the number of coupled FWM waves to increase to a complex set of a large number of equations. The other case where the NLSE is more suitable is when the pump waves are modulated at a very high rate or are very short pulses. In this situation, the CW/quasi CW approach to the pump wave solutions is no longer a good approximation and one needs to incorporate the high bandwidth of the pumps. More information on these situations can be found in [56].

To further the accuracy of the numerical simulations, the coupled mode equations with the effects for SRS were solved. These equations are given in a previous analysis [57], and provide a full account of the effect of both the Stokes and anti-Stokes Raman scattering.

This method of modeling is expected to offer accurate results as long as most of the injected power remains in the four waves participating in the Bragg Scattering process. If a significant amount of power is instead converted via other FWM and nonlinear effects into waves not accounted for in the previous four coupled amplitude equations, then these equations will no longer be a good representation of what is occurring. This usually occurs when the frequency spacings between the waves becomes small and/or the power in the pumps becomes large enough to incite the spontaneous growth of the MI and/or PC sidebands.
3.8 Bragg Scattering Phase Matching

In this section we investigate the phase matching condition for Bragg Scattering and discuss its features with both the theoretical analysis and experimental results presented. Previous measurements of the phase matching curves for Bragg Scattering have been performed in LEAF [48], this section is a continuation and extension of the characterisation of these curves for two different HNLFs. These measured curves are then used to recover the dispersion profiles of these HNLFs.

As discussed earlier, Bragg Scattering in optical fibers is highly dependent on the phase matching of the four waves. This phase matching describes how one must balance the dispersion seen by each wave to ensure they remain in phase to allow efficient energy transfer. This is accomplished by suitable wavelength selection for the pumps and signal waves such that the second and fourth order dispersion coefficients act to keep them all in phase with one another. In practice these four waves must be spaced about the zero dispersion wavelength and as the contribution from 4th order dispersion $\beta_4$ is typically small, the average frequency of the four waves needs to be near to the zero dispersion frequency so that the contribution from $\beta_2$ is likewise small and thus balanced by the 4th order term.

As seen in Eq.(3.32), a dispersion independent minimum of the phase mis-match is found when $\omega_b = \omega_c$. This is not a particularly useful solution as this is the case where the wavelengths of the pumps and the signals lie on top of one another. The more useful case, where $\omega_b$ and $\omega_c$ are distinct, corresponding to four different wavelengths and is the case that would normally be utilised for applications such as wavelength conversion or exchange.

3.8.1 Theoretical Curves

In practice, there are an infinite number of different wavelength combinations available to provide a phase mis-match of zero. However, to simplify the whole process, it is usual, at least throughout this study, to have one constant wavelength of the four and vary the remaining three waves to find the phase matched point. Aside from
3.8. BRAGG SCATTERING PHASE MATCHING

Figure 3.7: Important features of Bragg Scattering phase matching curves, here the ZDW = 1555.25 nm and the four participant waves are indicated by the four different colours. The dashed curves show the change from the solids with varying $\omega_b$, dots show the change/dependence on the of the ratio of $\beta_2 : \beta_4$; the dotted curves have a $\beta_4$ half as large as solid and dashed curves. Values $\Delta \omega_{a+}$, $\Delta \omega_{a0}$ and $\Delta \omega_{a-}$ are given in Eqs: (3.34), (3.35) and (3.36), respectively.

By solving this for the above mentioned case (one fixed wavelength, three tuned) with the fiber dispersion parameters typical of our HNLFs, one can find the points where maximum conversion of the Bragg Scattering idler will be found.

This results in distinctive phase matching curves for the wavenumber mis-match, which, for the ideal case are shown in Figure 3.7. The four waves participating in Bragg Scattering should be placed on these curves to achieve maximum (complete) conversion from the signal wave to the idler. As such, these curves are of great use
for deciding where to place the pump wavelengths in order to shift a signal at one arbitrary wavelength to another. Simply by tuning the two pump wavelengths, one is able to choose which wavelength the corresponding idler shall be generated at. The four waves (be they high-power pumps or low-power signals) indicated by these curves are completely interchangeable so long as the distribution of the high power pumps remains asymmetrical with respect to the average frequency.

The resultant phase matching curves for the Bragg Scattering process manifest themselves as sideways horseshoe shaped curves when the wavelengths of the four participant waves are plotted against $2\pi c/\omega_a$. The broadness/tightness of this curve with respect to average frequency is directly affected by the magnitude of the $\beta_2 : \beta_4$ ratio in the fiber, as seen in Figure 3.7, where the theoretical curves plotted with dots have the same parameters as the solid curves except that $\beta_4$ is half as large. This broadens and slightly shifts the resultant phase matching curve, providing a larger tuning in $\omega_c$ for small shifts in average frequency. The position of the phase matching curve along the x-axis ($\omega_a$), is determined primarily by the zero dispersion frequency (ZDF) and to a lesser extent the spacing between waves 2 and 3 ($\omega_b$). Changing the ZDF shifts the curves to the left or right, whereas changing the ratio of $\beta_2 : \beta_4$ opens or closes the curve. If the sign of $\beta_4$ changes, then the phase matching curve exists for average frequencies in the opposite dispersion regime (anomalous) with a mirrored orientation about the ZDF to that of the previous example.

An expression for the lateral shift in average frequency, $\Delta \omega_{a+}$, for the phase matching curves performed with different $\omega_b$ values (solid and dashed lines in Figure 3.7) is due to the 3rd and 4th order dispersion coefficients of the fiber. At the apex of the phase matching curves, where $\omega_c = \delta = 0$ then, as $\beta_2(\omega_a) \approx \beta_3(\omega_0)\omega_a$ and $\beta_4(\omega_a) \approx \beta_4(\omega_0)$, the change in average frequency for different $\omega_b$ values is

$$\Delta \omega_{a+} = -\frac{\beta_4 \omega_b}{6\beta_3} \Delta \omega_b,$$

(3.34)

where we assume the change in $\omega_b$ ($\Delta \omega_b$), is small compared to $\omega_b$. 
The lateral offset of these curves from the ZDF is given to good approximation by

$$\Delta \omega_{a0} = -\frac{\beta_4 \omega_b^2}{12 \beta_3},$$  \hspace{1cm} (3.35)

and the shift induced by changing the ratio of $\beta_2 : \beta_4$ to $\alpha \beta_2 : \beta_4$ just adds the scaling factor $\alpha$, to the above expression

$$\Delta \omega_{a-} = -\frac{\beta_4 \omega_b^2}{12 \alpha \beta_3}. \hspace{1cm} (3.36)$$

### 3.8.2 Experimental Set-up

To experimentally verify these phase matching curves a number of different set-ups were implemented. These experiments have evolved over the course of these studies as new equipment was acquired and our methodology improved. Accordingly the experimental set-ups we describe below are the most recent and successful ones that we have employed.

We have tested a number of fibers for the use of Bragg Scattering. Our main focus has been with using the HNLF supplied to us from Sumitomo Electric Industries as its higher nonlinear coefficient has allowed better conversion efficiency than the previously studied LEAF. Two Sumitomo fibers were studied (both commercially available) one with a negative $\beta_4$ coefficient and another with a positive $\beta_4$.

The phase matching experiments were performed to gain a better understanding of the Bragg Scattering process and also to judge how suitable the fibers were for our nonlinear studies. The experiments were based on tuning two of the input wave’s wavelengths, that of the signal and the L-band pump. Thus, as the signal and L-band are tuned, the average frequency ($\omega_a$), $\omega_b$ and $\omega_c$ also varied. This is different in circumstance to the measurement of the phase matching curves for processes such as MI where the sidebands exhibit gain and can spontaneously grow from vacuum fluctuations. For Bragg Scattering one cannot simply pump strongly and examine the spontaneous growth of the sidebands to measure the phase matching point,
one must inject not only the strong pump waves but also a signal near the phase
matched wavelength in order to generate an idler. This signal then needs to be tuned
to discover the point of maximum conversion into the idler. This complicates things
somewhat as it requires control over the three input wave’s wavelengths, powers and
polarisation states to accurately measure the phase matching condition.

These experiments can be carried out by manually tuning each wavelength and
observing the transmitted power in the idler wave but it is much quicker and less
user intensive if one operates the lasers via a computer and captures the spectra of
the output. We chose to scan the signal wavelength finely about the phase matched
point for a number of different L-band pump wavelengths. This method was selected
over the method of a constant signal with a tuned pump, as it allows us to filter
the L-band pump to remove the amplified spontaneous emission (ASE) and it also
removes any effects of the wavelength dependent gain from our amplifier skewing
the phase matching plots.

Figure 3.8: Bragg Scattering phase matching experimental set-up

Figure 3.8 shows the experimental set-up used for the phase matching exper-
iments. The three input waves are generated via external cavity lasers (ECL),
ECL1&2 are the pumps and ECL3 is the signal wave. The polarisations of these
waves are adjusted manually with the polarisation controllers; first for alignment
of the pumps with the phase modulator to remove the SBS via adjustment of PC1
and PC2 (by maximising the transmitted power for each pump in turn), then for
alignment with one another and the signal (using PC3, PC4 and PC5) as they are
combined through the filter wavelength division multiplexers\(^1\) (WDMs). The pump waves were passed through 2nm bandpass filters (BPF) prior to combination with the signal to remove any ASE generated in the high power amplifiers. The polarisations for the waves was chosen for maximum interaction (co-linear; state (a) in Figure 3.6) as this enabled the use of sufficiently low enough pump powers such that the effects of SRS and other FWM effects were negligible.

The experiments were performed by stepping one or two of the ECLs and using an optical spectrum analyser (OSA) to record the spectra for each signal and pump step. The 99/1 splitters allowed measurements of both the input and output spectra and relative powers of the participating waves to be easily taken. This enabled precise control over the input powers to the HNLF and by inclusion of a polariser also allowed accurate alignment of the polarisation of the input waves.

![Figure 3.9](image-url)  
**Figure 3.9:** Measured colour scan for two pumps at 1551 and 1584nm; the signal is scanned through 1560 to 1576nm generating an idler ranging from 1525 to 1540nm. For each point of the signal wavelength a spectrum is taken via the OSA and these spectra are plotted along the \(x\)-axis. The other coupled FWM artifacts can be seen criss-crossing the graph and are labeled with the effects that generate them. Relative intensity’s are displayed via colour in dB.

\(^{1}\)These devices are commercially available and based on thin film filter technology, they can be used to combine and separate light at different wavelengths over wide wavelength ranges.
A computer program was written in LABVIEW to step the wavelengths of choice and record the observed spectra in the region of the idler (or that specified by the user). Using an OSA to record the generated spectra rather than a power meter to measure the power in the region of the idler gives us the ability to discriminate between the generated Bragg Scattering idler and any interference signals produced from non phase matched FWM processes. Inspection of each of the recorded spectra is advisable and was performed before processing.

By finely tuning the signal wavelength across the phase matching point for several L-band pump wavelengths the program produces an array of spectra for each L-band point. These spectra are plotted against the signal wavelength to produce 2D colour images. An example of a full spectral scan for the HNLF with a positive $\beta_4$ is shown in Figure 3.9, this is for the L-band and C-band pump wavelengths of 1584 and 1551nm respectively. The recorded spectra are plotted along the horizontal axis, with the relative strengths of the signals represented by colour intensity. The area of interest in this scan is that occupied by the Bragg Scattering idler. Running this program with a spectral span confined to where the Bragg Scattering idler is generated provides higher resolution imaging of the generated idler’s spectrum. Then, by utilising a peak finding algorithm the point of maximum conversion can be found for each L-band wavelength. This yields our phase matched wavelengths for one point on the average frequency curve. These plots also display the tuning bandwidth available at these detunings with one constant wave. A higher resolution scan of just the generated Bragg Scattering idler is shown in Figure 3.10 along with the recovered idler response. The Bragg Scattering idler crosses with the MI generated idler in the center of the plot, but as the point of maximum conversion doesn’t coincide with this point and the MI idler is sufficiently weak with respect to the Bragg Scattering idler, this is not a problem.

By running this software over an even smaller range about the peak phase matching point one can use a very fine scan on the signal and rapidly take the relevant data. This saves time by enabling the processing of previous spectra to be manually
Figure 3.10: High resolution colour scan about the phase matching point with relative intensity in dB (above) and recovered Bragg Scattering idler response (below).
performed as the program acquires more data for additional points on the phase matching curve.

3.8.3 Experimental Results

Experimental measurements have been made for two HNLFs, one with a positive 4th order dispersion coefficient and the other with a negative 4th order dispersion coefficient.

Fibers with a negative $\beta_4$ show a phase matching response that resembles a horseshoe shape that lies below the ZDW when plotted against $2\pi c/\omega_a$. This is due to the phase matching relying on the 2nd and 4th order dispersion coefficients to have opposite signs to balance the phase mismatch between the participant waves. The phase matching curve measured for the fiber with negative $\beta_4$ can be seen in Figure 3.11. This phase matching curve, while agreeing with the features that we expect from the previously mentioned theory, displays some outliers about the curve that warrant a closer examination. In fact, the scans across the phase matching point for this fiber are quite unusual; as one expects a sinc-like response.
in the idler power as the signal is tuned across the point of minimum phase mismatch. The scans shown in Figure 3.12 show the irregular and asymmetrical phase matching response exhibited by this fiber. This can be attributed to longitudinal zero dispersion fluctuations along the fiber and the effects of these are discussed further in Section 3.9. As such it is unsurprising that the phase matching curve possesses irregular outliers around the expected curve.

![Figure 3.12: Idler responses for similar wavelength shifts for both positive and negative $\beta_4$ HNLFs.](image)

In comparison, the positive $\beta_4$ fiber possessed a much cleaner and more symmetrical phase matching response as the signal was tuned across the phase matching point. The comparison between these two fibers was performed for similar sized wavelength shifts and frequency spacings ($\omega_b$ and $\omega_c$) - the difference in generated idler wavelength is due to the difference in the two fibers zero dispersion wavelengths.

The phase matching curves for the positive $\beta_4$ fiber are shown in Figure 3.13. Of particular note concerning the positive $\beta_4$ phase matching curve is the reversed orientation it possesses with respect to that for the negative $\beta_4$ fiber. As one expects, in order to balance the 2nd and 4th order dispersions, one must now operate with an average frequency in the anomalous regime.
The two phase matching curves for the positive $\beta_4$ were measured on consecutive days. Correspondingly, a small drift in the ZDW (attributed to temperature fluctuation) was observed in the results. Both runs returned the same dispersion profile, but had ZDW that differed by $0.01\text{nm}$. This can be explained when one considers the effect of temperature on the ZDW. Even a small change in temperature can change the ZDW noticeably (up to $0.06\text{nm}/^\circ\text{C}$) [58]. As these curves are highly sensitive to this ZDW fluctuation, the $0.01\text{nm}$ difference between the two fitted curve’s ZDW is well within expected tolerances for our lab environment.

Perhaps not immediately apparent is the practical benefits to be gained by using a fiber with a positive $\beta_4$ for Bragg Scattering experiments. As these fibers exhibit 2nd and 4th order dispersions with like signs in the normal regime, effects such as MI (and PC) which are phase matched via the equation $\beta_2 \Omega^2 + \beta_4 \Omega^4 + 2\gamma P_{\text{Total}}$, where $P_{\text{Total}}$ is the combined power in both pumps and $\Omega$ is the frequency detunings of the waves as described in [49], cannot efficiently occur for average frequency values that are above the ZDF. Accordingly, by designing a Bragg Scattering experiment with both pumps in the normal regime, one can avoid to a large extent the interference
from these effects and achieve a much more pure form of Bragg Scattering wavelength exchange/frequency conversion. This will undoubtedly be the most sensible choice in fibers for experiments designed to measure or take advantage of this effect’s unique noise free properties.

3.8.3.1 Recovery of Fiber Dispersion Parameters

Accurate measurement of the dispersion profiles of optical fibers is an area of research that will be important for future fiber wavelength converters or dispersion compensators. In this subsection we measure the ratio of the second and fourth order dispersion coefficients and from this measurement we recover the dispersion parameters of our HNLFs. Previous studies have demonstrated similar measurements to these but instead utilising the single pump process of MI [59, 20].

By utilising a least squares fit to the above measured phase matching curves, the fibers dispersion parameters can be recovered. By starting with the given manufacturers dispersion parameters in a polynomial expansion, a fit to the measured data was performed. As the phase matching condition for Bragg Scattering depends only on the wave number mis-match for situations of equal pump power, this yields measurement of the ratio between $\beta_2$ and $\beta_4$ for the average frequencies covered by the phase matching curves. To fully recover the dispersion parameters, one must then scale the recovered $\beta$ parameters by a suitable amount, which is achieved by using the given value for $\beta_2$ by the manufacturer at a specific wavelength (typically 1550nm) and scaling the $\beta$ values accordingly. This yields a measurement that agrees well with independent measurements for the average frequencies measured for the negative $\beta_4$ fiber. The measurements of $\beta_2$ for the negative $\beta_4$ fiber are shown in Figure 3.14. The independent characterisations of the negative $\beta_4$ fiber were performed using scalar MI, as described in [60] and the modulation phase-shift method as described in [61]. The parameters for the positive $\beta_4$ fiber were also recovered and these were used in the simulations in the following sections. The parameters for both the positive and negative $\beta_4$ Sumitomo fibers can be found in Table 3.1.
Figure 3.14: Measurement of $\beta_2$ for the negative $\beta_4$ Sumitomo fiber.

Table 3.1: Fiber parameters for the two Sumitomo highly nonlinear fibers.

<table>
<thead>
<tr>
<th>Sumitomo fiber 1</th>
<th>L (m)</th>
<th>$\lambda_0$ (nm)</th>
<th>$\frac{dD(\lambda_0)}{d\lambda}$ (ps/nm$^2$/km)</th>
<th>$\gamma$ (W⋅km)$^{-1}$</th>
<th>$\beta_4(\lambda_0)$ s/m$^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specified</td>
<td>1000</td>
<td>1555</td>
<td>0.035</td>
<td>20</td>
<td>$-1 \cdot 10^{-55}$</td>
</tr>
<tr>
<td>Measured</td>
<td>-</td>
<td>1555.25</td>
<td>0.0352</td>
<td>-</td>
<td>$-2.9 \cdot 10^{-55}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sumitomo fiber 2</th>
<th>L (m)</th>
<th>$\lambda_0$ (nm)</th>
<th>$\frac{dD(\lambda_0)}{d\lambda}$ (ps/nm$^2$/km)</th>
<th>$\gamma$ (W⋅km)$^{-1}$</th>
<th>$\beta_4(\lambda_0)$ s/m$^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specified</td>
<td>750</td>
<td>1559.2</td>
<td>0.02</td>
<td>30</td>
<td>$0.5 \cdot 10^{-55}$</td>
</tr>
<tr>
<td>Measured</td>
<td>-</td>
<td>1559.02</td>
<td>0.0227</td>
<td>-</td>
<td>$0.9 \cdot 10^{-56}$</td>
</tr>
</tbody>
</table>

3.8.3.2 Effect of Pump Power on the Phase Matching Curve

For the preceding cases of the phase matching for the Bragg Scattering process, it has been assumed that the pump powers are equal at all times throughout the fiber. This is generally the case if we are careful with our launch conditions and for low input pump powers. However if the pumps are strong enough that SRS between them becomes a problem or if one pump is injected into the fiber sufficiently stronger than the other pump, a power dependent term appears in the phase matching condition
3.8. BRAGG SCATTERING PHASE MATCHING

Figure 3.15: Simulated addition of the $\gamma \Delta P$ term in Eq.(3.28) on the Bragg Scattering phase matching curve for a negative $\beta_4$ fiber.

as seen in Eq.(3.28). If sufficiently large, the addition of this power dependent term, $\gamma \Delta P$, can change the experimentally measured phase matching curve. This effect would be particularly noticeable where the frequency detunings of the waves are small (relative to the ZDF), as the corresponding dispersion terms in the phase matching condition would likewise be small in this case. The phase matching curves now instead of depending only on the wave vector mis-match also depend on the pump difference power. This changes the shape of the curves and shifts the point of zero phase mis-match slightly. The curves for cases where the two pumps are unequal can look very similar to the phase matching curves for a PC process. An example of the effect of the additional power dependent term on the phase matching curve is shown in Figure 3.15. The phase matching curve is seen to now deviate noticeably for small frequency detunings and also the possibility exists for phase matched Bragg Scattering to now occur in the dispersion regime where typically it would not.
3.8.4 Competing and Interfering Effects

Unfortunately, in practice the process of FWM is seldom ideal, and so the maximum conversion to a Bragg Scattering idler may not necessarily lie exactly on the theoretical curve, but slightly away from it. These effects can work to slightly skew the curve of maximum conversion from the ideal by providing gain preferentially to higher or lower wavelengths and also work to draw energy away from the intended idler wave, thus reducing the overall efficiency of the process. For small detunings of the signal from the pump waves, four coupled sidebands are generated through the three FWM effects of Bragg Scattering, MI and PC. Each of these four sidebands are coupled directly to each other via the three different FWM effects. Growth of these coupled sidebands causes them to exchange power with one another and severely distort the ideal Bragg Scattering curve, especially when the target wavelength for the Bragg Scattered idler or signal coincides with a phase matched or nearly phase matched wavelength for the other FWM process.

Clean pumps are also necessary for a clean Bragg Scattering process as any noise on the pumps due to ASE or other effects will be transferred onto the idler within
3.8. BRAGG SCATTERING PHASE MATCHING

the Bragg Scattering bandwidth. An example spectrum of such a case is shown in Figure 3.16 where the pumps used for an early Bragg Scattering experiment are unfiltered. This leads to a high level of ASE about the signal and the L-band pump. This ASE seeds the MI process on the L-band pump and the conversion of the L-band pump’s MI bands onto the idler occurs.

The effect of SRS can also work negatively to distort these phase matching curves when the frequency shifts between the pumps and the signals approach those for efficient SRS. The FWM effects, however, cause only minor changes to the phase matching when the spacing between the pumps and the signals are large. Typically, unless special measures are taken, the effects of MI and PC are poorly phase matched for large detunings. These effects are more of an issue when shorter shifts are attempted with all the waves close together about the ZDW. In order to obtain efficient Bragg Scattering it is necessary to find the best compromise between the SRS and competing FWM effects as more often than not minimising one leads to enhancing the other. For a better model of the theoretical phase matching curve as the waves near each other and the ZDW these effects must be taken into account.

Fiber imperfections unavoidably created during the manufacture of HNLF can manifest themselves as longitudinal ZDW fluctuations. These ZDW fluctuations can also cause deviations in the Bragg scattering response, most notably the asymmetries seen in the conversion response of the idler with signal tunings. For a perfect case the idler response should be sinc-like with respect to the phase mis-match. However, due to ZDW fluctuations, asymmetries arise. The problems these ZDW fluctuations cause are not limited to the Bragg scattering process, but are detrimental to other processes that rely on the dispersion of the fiber. ZDW fluctuations and their effect on the Bragg Scattering process is discussed in more detail in the following section, along with the use of the Bragg Scattering response to quantify/map these fluctuations.
3.8.5 Summary

In this section, the phase matching curves of the Bragg Scattering effect have been studied and experimentally verified. We have demonstrated Bragg Scattering in two fibers with different signs of $\beta_4$ and the phase matching curves for these two fibers have been measured. Knowledge of these phase matching curves enables one to choose suitable pump wavelengths to shift a signal at an arbitrary wavelength to an idler at any other desired wavelength. By fitting these measured phase matching curves to a polynomial expansion, the dispersion parameters for these two fibers have been measured. Good agreement between independent measurements of the dispersion for the negative $\beta_4$ fiber are shown. The effects of an additional power dependent term in the phase matching condition have also been discussed and the expected outcomes of such a power term are presented. The effects of ZDW fluctuations have been observed in the Bragg Scattering conversion response during these experiments and discussions are raised about the use the Bragg Scattering conversion response for the dispersion fluctuation profiling of fibers.

3.9 The Impact of Zero Dispersion Wavelength Fluctuations on Bragg Scattering

The preceding discussion about the phase matching points and Bragg Scattering response assumes that the ZDW of the fiber is a constant value, both along the length of the fiber and during the time of the experiment. In practice, imperfections in the drawing of these fibers can lead to ZDW fluctuations of the order of several nanometers for kilometer lengths of fiber [62]. These ZDW fluctuations are severely detrimental to FWM effects as the phase matching conditions that govern these effects depend strongly on the ZDW [63, 64]. This can limit the efficiency of the Bragg Scattering process and induce asymmetries in the measured Bragg Scattering tuning response. Measurement of these longitudinal ZDW fluctuations can be performed both destructively, which requires cutting the fiber into pieces and measuring the
3.9. THE IMPACT OF ZDWF ON BRAGG SCATTERING

Figure 3.17: Modeled ZDW fluctuations ($\Delta \lambda_0$) plotted against position for the 750m long positive $\beta_4$ fiber.

dispersion of each piece of fiber in turn, and nondestructively. Nondestructive techniques are obviously preferable (if continued use of the fiber is required) and previous techniques have employed a range of methods, including optical time domain reflectometry (OTDR) and measurements of the FWM response from overlapping ultra short pulses and parametric amplification [65, 66, 67]. In this section utilise our measured Bragg Scattering response to recover the longitudinal ZDW fluctuation profile of our positive $\beta_4$ HNLF (Sumitomo 2 in Subsection 3.8.3.1).

By considering that a length of fiber can be described by several adjoining sections each with a slightly varying ZDW from the next one, it is possible to model the idler response curve for a Bragg Scattering process within this fiber. We have modeled a multi-section fiber by using the coupled amplitude equations solved piece-wise for each fiber section, with the input of each fiber section the output of the previous. Good results have been obtained using this method to fit a ZDW fluctuation over a 750m long ten section fiber and the resultant best fit of the ZDW fluctuations for the ten section fiber are shown in Figure 3.17. The fit was performed for the measured Bragg Scattering response with the L-band wavelength of 1589nm using a nonlinear minimisation algorithm based on the Nelder-Mead simplex method.
Using this model the observed response from our positive $\beta_4$ fiber was simulated for different signal/pump detunings and these results are shown in Figure 3.18. This leads to a non-ideal, asymmetric conversion response in the idler. For the fibers tested within this thesis, these asymmetries are clear to see, especially for the earlier negative $\beta_4$ fiber from Sumitomo. These asymmetries are directly related to the magnitude of the ZDW fluctuations and as such give a qualitative measurement of the relative uniformity and suitability of a fiber for the ZDW sensitive FWM processes. Even the nearly ideal response of the positive $\beta_4$ fiber displays these asymmetries and deviates from the theoretically ideal case when the frequency detunings are large enough.

A ZDW that varies over time is not one commonly considered, as in practice it is not seen on a time scale short enough to have any significance on a running wavelength conversion set-up. However, if during the course of a wavelength conversion run the temperature of the fiber used for nonlinear effects changes, the ZDW will fluctuate accordingly (up to $\sim$ 0.06nm/°c) [58]. This small difference may be dismis-
3.9. THE IMPACT OF ZDW ON BRAGG SCATTERING

sible in temperature controlled labs, but in the absence of temperature control, even a change as small as 0.01nm in ZDW can shift the phase matching curve noticeably, particularly for fibers with a low $\beta_4$. However, for a practical wavelength conversion situation where 100% conversion is just as acceptable as 95% conversion of a signal to the idler, such small ZDW fluctuations will not be noticed so long as these fluctuations remain small with respect to the tuning bandwidth of the Bragg Scattering idler. However, situations where these effects are significant are those such as in the Bragg Scattering implemented switch (discussed in Section 3.12). Compared with a wavelength conversion situation, where a slightly lower signal power may not be such an issue, a 5% reduction in efficiency in the switch arrangement leads to a large reduction in the extinction ratio between the two ports in the switch. Thus in situations such as these, temperature control will be necessary for stable operation over prolonged periods.

3.9.1 Zero Dispersion Wavelength Mapping

As the Bragg Scattering response depends strongly on the dispersion profile of the fiber, any fluctuations throughout the length of the fiber will impair this response. If the ZDW fluctuations are of the order of the bandwidth of the Bragg Scattering conversion response then these fluctuations lead to clearly observable asymmetries in the measured conversion response of the Bragg Scattering idler. If they are sufficiently small compared to the bandwidth of the response, the idler will still exhibit asymmetries/deviations from theory but the features of these asymmetries will be smoothed out by the bandwidth of the Bragg Scattering response. As seen in the above examples of idler tuning response (Figure 3.18), for the situation of a small $\omega_c$, the Bragg Scattering bandwidth is large enough that the features of the asymmetries are very small. These fluctuations in ZDW lead to a broadening of the Bragg Scattering bandwidth and also to degradation of the extinction ratio between the peaks of the oscillations in the response. The efficiency of the Bragg Scattering effect is also lowered by the ZDW fluctuations and this necessitates the
use of higher pump powers to achieve complete (or near complete) conversion to the Bragg Scattering idler as $\omega_c$ is increased.

As mentioned previously, the relative size of the ZDW fluctuations can be inferred from the idler response. For larger $\omega_c$ values, a relatively narrow phase matching response for the idler is observed. If the magnitude of the ZDW fluctuations approaches, or are greater than this bandwidth, then the observed idler response will differ significantly from the predicted theoretical response. Due to this, accurate ZDW mapping is possible with Bragg Scattering experiments for large wavelength shifts such that the asymmetries are clearly resolved in the idler’s response.

Figure 3.19 shows the measured idler response for the positive $\beta_4$ fiber with a larger frequency detuning (L-band pump at 1600nm). The previously recovered ZDW profile was also used to simulate this response. By comparison with the response shown in Figure 3.18 the features of these asymmetries clearly become more pronounced as the size of the detunings increase.

This also demonstrates that whilst the ten segment fiber model (recovered from a shorter wavelength shift response) fails to provide a good fit to the response for larger
3.10. THE EFFECT OF SRS ON BRAGG SCATTERING

Detunings, it does predict the main features of the response. This indicates that improving the resolution of our ZDW profile by decreasing the segment size in our model is necessary to account for the fluctuations observed for the larger detunings. Unfortunately, the computing time required for the numerical model employed for the recovery of this profile increases dramatically as the fiber section size is decreased. Future work involving more elegant solutions to recover the dispersion profile from the measured Bragg Scattering response might employ methods similar to those outlined in [67, 68] and speed the computing up time significantly. The resolution of this method for recovery of the ZDW profile is limited by the frequency detunings of the Bragg Scattering process. Thus, control over the accuracy of these profiles is possible by employing larger or shorter wavelength shifts.

3.10 The Effect of Stimulated Raman Scattering on Bragg Scattering

Stimulated Raman scattering affects both the conversion efficiency and response of the Bragg Scattering process by shifting the peak of maximum conversion from that for the ideal theoretical case. The magnitude and direction of the shift depends on the pump/signal spacings and distributions. For the staggered pump/signal/pump/idler set-up, similar to that shown in Figure 3.5, the SRS shift experienced by the signal from the L-band pump is equal to and thus reinforced by the SRS shift induced on the idler by the C-band pump. In most cases, the signal and C-band pump spacings do not exceed 13THz (- peak of the Raman gain) and this is certainly true for all the experiments in this study. Therefore, the gain seen by the signal due to the C-band pump furthers the shift seen by the L-band pump when spacings between the signal and L-band pump are also less than 13THz. Once either of these spacings is exceeded, the SRS shifts the spectrum of the converted idler in the opposite direction due to the change in sign of the slope of the SRS gain curve. In this case the SRS experienced on the idler from the L-band pump and the gain on the signal
from the C-band pump are different for the different spacings.

Aside from shifting the point of maximum conversion efficiency on the phase matching curves, the SRS also has an effect on the efficiency of the Bragg Scattering process. As such, the conversion efficiency into the idler wave may appear greater (or less) than the theoretical maximum of 100% due to the SRS gain (or loss) experienced by the signals during the process. The nett effect of the SRS gain is always to induce a change on the Bragg Scattering process, but by careful considerations of the spacings and distributions of the waves, this change can be managed/minimised for an optimum case.

Aside from the direct gain or loss experienced by the signal or idler, the SRS also transfers power between the strong pumps. This has the undesirable effect of unbalancing the relative pump powers throughout the fiber. This also leads to a change in the Bragg Scattering response, as it inadvertently causes a mis-match in power and thus the phase matching condition as mentioned in Section 3.8.3.2, possesses a length dependent $\gamma \Delta P$ term. This power transfer between pumps due to SRS can dominate the shift induced in the phase matching point, as depending on the pump spacings, the power transfer between pumps can be significant, especially for high pump powers with large wavelength spacings. These effects, whilst complicated to analyse, can be accounted for via simulation and the addition of the Raman gain into the coupled mode equations. This complicates the matter somewhat and does not lead to an easy analytical solution.

Several practical steps can be taken to minimise the effect of SRS on the Bragg Scattering process for a wavelength conversion system. Choosing pump spacings so that for a staggered pump/signal/pump/idler set-up the difference in frequency between the L-band pump and the signal is equal to or less that the frequency spacing between the signal and the C-band pump can help balance these effects out (gain from the C-band, countering loss from the L-band) - this system provides better signal and idler transmittance’s at the end of the fiber.

Also, a sensible choice of state of polarisations of the waves can mitigate some
3.11. BRAGG SCATTERING RESPONSE TO PUMP POWER

of the effects of SRS. By placing the signals orthogonal to the pumps, the SRS gain and loss in these signals virtually disappears. However, placing the signal and idler waves orthogonal to the pumps requires that the pump powers be greater (due to the lower nonlinear coupling of orthogonal waves) and that the pump waves are parallel to each other. Because of this the SRS power transfer between pumps will still occur [30].

Although the efficiency of the Bragg Scattering process with respect to the wavelength detunings has not yet been measured, we expect to see manifestations of the real part of the Raman susceptibility as measured in [69]. However the effect of this is on the two pump process of Bragg Scattering is not easily estimated as the combined effects of the two pumps complicate the analysis somewhat.

3.11 Bragg Scattering Response to Pump Power

As mentioned in the above section, if the phase mis-match is zero and the initial idler wave is also zero, the equations governing evolution of the signal and the idler waves simplify to

\[ B_2 = \cos \left( \epsilon \gamma \sqrt{P_1 P_3} z \right) B_2 (0), \quad (3.37) \]
\[ B_4 = i \sin \left( \epsilon \gamma \sqrt{P_1 P_3} z \right) B_2 (0), \quad (3.38) \]

where \( B_2 \) is the signal, \( B_4 \) is the idler. This implies that the power flow from the signal to the idler should exhibit a sinusoidal response with respect to the nonlinear length, \( \gamma P L \).

This is an interesting proposition, as if one doubles the length or the power once 100% conversion from signal to idler occurs, then 100% of the idler should be converted back to the signal. In doing so the signal wave is restored, but with an induced \( \pi \)-phase change. This can be exploited to build a high-speed nonlinear switch and is discussed further in Section 3.12.
3.11.1 Experimental Set-up

The following experiment was designed to test the hypothesis that full back conversion to the signal wavelength is possible. By utilising the HNLF with a positive $\beta_4$ and placing the pumps below the ZDW, the MI and PC sidebands are suppressed allowing higher pump power to be injected into the fiber before the four wave assumption in our simulations breaks down.

The experimental set-up shown in Figure 3.20, is similar to the phase matching measurement experiment, except that the pump powers are now controlled via a variable optical attenuator (VOA) prior to combination with the signal. Only a single EDFA is required as both pumps are now at constant wavelengths and within the bandwidth of a single amplifier. These pumps were again filtered via fiber coupled 2nm BPFs. The first BPF passes one of the pumps and rejects the remaining ASE and other pump. This rejected signal is then passed through the second BPF which removes the remaining pump from the ASE background. The pump wavelengths chosen for this experiment were 1542 and 1551 nm. As the positive $\beta_4$ fiber has a ZDW of 1559 nm, this ensures both pumps are below the ZDW and in normal dispersion regime to minimise the effects of the MI and PC. The signal was tuned to locate the phase matching point, which was at $\sim$ 1567 nm.

![Figure 3.20: Power conversion experimental set-up.](image)

By utilising the orthogonal pump scheme as in case (b) in Figure 3.6 (where the pumps are orthogonal to the signals), and placing the pumps in the normal dispersion regime we can obtain a response relatively free from the competing effects of MI and
PC. However the effects of SRS are unavoidable and as we will discuss, cause some difficulty in obtaining an ideal Bragg Scattering response.

3.11.2 Experimental Results

The experiments studying the response to pump power were performed under several different conditions to obtain an optimised case for conversion response. To obtain an ideal response, one would prefer a pure Bragg Scattering process. Keeping the frequency spacings between waves small, the efficiency of the Bragg Scattering process approaches the theoretical 100% case. However these spacings also encourage competing nonlinear mixing between waves. Enlarging these spacings reduces the Bragg scattering efficiency somewhat and also strengthens the SRS effects. Consequently there will always be a trade off in generating Bragg Scattering. The experimental results for both pumps located below the ZDW (in the normal regime), polarised orthogonally to each other are shown in Figure 3.21, where the normalised signal and idler powers\(^2\) are plotted against the input pump power. The coupled amplitude and SRS simulations match this case quite well as this wavelength and polarisation arrangement minimises the spurious FWM and beating effects. However, the reduction in signal extinction ratio seen when the pump powers are at 400mW is due to the SRS transferring the power between the pumps, effectively creating a phase mis-match that increases as the pump powers increase. The gain seen in this process is also due to the SRS from the pumps affecting the signals.

The case where the pump’s and signal’s polarisations are aligned parallel to each other generates many FWM effects and as such, the coupled amplitude simulation is unsuccessful in predicting what occurs for sufficiently high pump powers. The results shown in Figure 3.22 illustrate a sinusoidal response for low powers and an exponential growth in the signal and idler as the power of the pumps increases. This is due to the SRS amplifying both the signal and the idler waves simultaneously, leading to a degradation of the extinction ratio between the two. Even though

\(^2\)Normalised powers are plotted for the signal and idler as the absolute powers are unimportant and unrelated to the response as long they remain small compared to the pump powers.
the MI and PC processes are poorly phase matched during this exercise, the beating between the pumps increases to the point where significant power is present in them. As such the exact evolution of the signal and Bragg Scattering idler waves through the fiber during this process is uncertain and unreliably modeled by the coupled amplitude equations.

As theory would suggest, the period of the idler response for the case with co-linear pumps should be twice that of the orthogonal case due to the difference in the nonlinear coupling factor. This holds true for low injected pump powers as seen in Figure 3.22. However, as the pump powers increase, the continued transfer of power between the pumps and the generation of beat signals and other spurious mixing products causes the measured period of the Bragg Scattering response to increase. This is much more pronounced when the pumps are situated in a regime where MI and PC can be phase matched, as spontaneous growth of these sidebands rapidly steals power from the pumps and interferes with the Bragg Scattering process. Even having one pump in a regime where spontaneous growth of these sidebands occurs rapidly degrades the Bragg Scattering response as due to XPM the sidebands can
be transferred between the pumps and signals.

3.11.3 Discussion

As suggested from the theory, the conversion response of the Bragg Scattering effect is sinusoidal with respect to pump power. However interfering effects such as SRS and unwanted FWM products lead to deviation from a true sinusoid. Power flows from the signal to the idler in a nearly sinusoidal fashion. By placing the pumps in the normal/anomalous regime (positive or negative $\beta_4$ fiber) one can reduce the effect of SRS and competing FWM effects by sensible choice of the state of polarisation of the waves. Full conversion to the idler is achievable with pump powers as low as 200mW (for the co-linear case) for this particular fiber. By doubling the pump powers, back conversion to the signal wavelength is achieved. The back converted signal should possess a $\pi$-phase shift with respect to the injected signal.
3.12 Bragg Scattering High Speed Nonlinear Switch

In this section we outline the use of Bragg Scattering for nonlinear switching. We demonstrate that due to Bragg Scattering’s sinusoidal response to the nonlinear length it is possible to construct a switch that exploits the $\pi-$phase change induced in the back-converted signal (similar in principle to the work discussed in [70]).

As mentioned in the power response section, if the pump powers are large enough, the power in the idler will be converted back into the signal and this back-converted signal should possess a $\pi-$phase shift with respect to the non-converted signal, such that,

$$B_2(z) = e^{i\pi}B_2(0).$$ (3.39)

By exploiting this induced $\pi-$phase shift in an interferometer/loop arrangement (as shown in Figure 3.25), high-speed optical switching can be performed between Ports 1 and 2. The efficiency of this switch is determined by the extinction ratio between the switched ports on and off states. This is largely determined by the efficiency of the Bragg Scattering process and, to a lesser extent, the uneven splitting ratio in the 50/50 coupler. Assuming a perfect 50/50 coupler, the amount of light sent down Port 2 is determined by whether or not the light propagating in one direction sees an additional $\pi-$phase shift over the light propagating in the other direction. In a Bragg Scattering process, once the signal is converted to the idler and begins to be converted back to the signal wavelength, it acquires an additional $\pi-$phase change. Once sufficient power is converted back from the idler to the signal wavelength efficient switching to Port 2 should be possible.

To model this switching the above discussed coupled amplitude equations were again used. As the effects of SRS and XPM are equal in both directions for CW cases, the amount of phase accumulated by both counter and co-propagating signals due to these effects should be the same. The simulations shown in Figure 3.23 show that both the counter and co-propagating signals experience a relatively linear increase
in phase due to XPM as the pump powers are increased. Once the pump powers exceed $\sim 400\,\text{mW}$ (where the signal is fully converted into the idler wavelength) the back-converted co-propagating signal gains an additional $\pi-$phase shift. As Bragg Scattering does not occur bi-directionally, the counter propagating signal only acquires phase due to XPM. This simulation clearly shows the manifestation of the $\pi-$phase change upon back conversion and demonstrates that with sufficient pump power a high speed nonlinear switch can be constructed.

Simulations performed with an imperfect fiber, modeled with the addition of a varying ZDW to the coupled amplitude equations show that even though the signal conversion efficiency may be reduced, the signal phase still exhibits a $\pi-$phase shift with respect to the counter propagating signal after a sufficient increase in power. The results for the simulation of a fiber with a varying ZDW are shown in Figure 3.24. By a sensible selection of the states of polarisation of the waves and reasonable conversion efficiency, a nonlinear switch based on this effect should be realisable in a real fiber.
3.12.1 Experimental Set-up

The switch experimental set-up shown in Figure 3.25 consists of a similar implementation to that for measuring the power response in the previous section, although now the HNLF sits within a loop mirror arrangement. This allows half of the signal to propagate with the pumps, participating in the Bragg Scattering process, whilst the counter propagating portion of the signal is unaffected by FWM. The pumps are coupled into and out of the loop via WDM couplers. When the pumps are running such that the signal is converted fully into the idler wavelength then back converted into the signal wavelength, the recombination of the two counter propagating signals should result in the light exiting via Port 2 instead of Port 1, which is the case with no pumps running.

The pump wavelengths were chosen to be 1541.58 and 1551.94nm - similar to the power response measurement. This allowed the use of the same filters to remove the ASE from the pumps and the phase matched signal was located at 1565.2nm. Optimisation of the loop was achieved by alignment of the polarisation controller.
3.12. BRAGG SCATTERING HIGH SPEED NONLINEAR SWITCH

Figure 3.25: Bragg Scattering switch experimental set-up.

PC6 to produce maximum reflection out Port 1 with no pumps running. The input pump power to the HNLF was adjusted with the VOA to first maximise the back conversion into the signal wavelength then, with the loop connected, the isolation between the Ports 1 and 2.

3.12.2 Experimental Results

The results seen in Figure 3.26 show the output spectrum for Port 1 and Port 2, with and without the pumps running. The observed switching showed an isolation of over 22dB between the on and off states for both ports. The injected pump powers were $\sim 800\text{mW}$ in the 'on' state and $0\text{mW}$ in the 'off' state. To ensure this switching is a result of the Bragg Scattering induced $\pi$-phase shift, the signal was shifted to the non-phase matched wavelength of 1590nm and the experiment repeated. The only observed difference in the signal between the on and off pump states was the gain observed in both ports (due to SRS). No switching occurred at the non-phase matched signal wavelength. Thus it can be deduced that the switching is the result of Bragg Scattering and not any other underlying asymmetrical nonlinear effects.

3.12.3 Discussion

In summary, we have demonstrated the operation of a transparent optical switch based on the Bragg Scattering effect in an optical fiber. This process has the poten-
Figure 3.26: Measured Bragg Scattering switch response between Ports 1 and 2.

tial to provide an ultra-fast all-optical data switch for high-speed communications systems, the speed of the switch being only limited by the rise and fall times of the applied pumps. To our knowledge this experiment also demonstrated for the first time the \( \pi \)-phase shift generated by the FWM process of Bragg Scattering.

3.13 Bragg Scattering Data Conversion

This section details the conversion of a 10Gb/s data signal via the Bragg Scattering effect in our positive \( \beta_4 \) fiber (discussed previously within this section). We demonstrate a 33nm wavelength shift with no observable power penalty in the bit error ratio (BER) tests performed for near 100% conversion efficiency. We also experimentally investigate the power penalty induced by a lower conversion efficiency, caused by both non-optimal polarisation states and pump powers.

A bit error ratio test involves the transmission of a data signal (usually a PRBS) through the system under test. A comparison is performed between the received signal and the transmitted signal, and any errors between these two bit sequences determine the error ratio. The lower this ratio, the better the system is performing and typically any error ratio below \( 10^{-9} \) is considered 'error free'. This error ratio
naturally depends on the power in the received signal (as lower power signals are more sensitive to noise) and as such BER curves are plotted against received power. A useful characterisation of a system’s performance is one based on a power penalty. This is simply the amount of power one must increase the received signal by to achieve error free detection. When BER curves for the transmitted and received signals are plotted together this is simply the difference in power (usually given in dB) between two BER curves (before and after the system under test) at the point of error free detection. More information on BER tests can be found in texts that cover test and measurement in communications systems such as [61].

3.13.1 Experimental Set-up

The experimental set-up can be seen in Figure 3.27. It is similar in form to the previous experiments for phase matching, except that this time the signal wave is modulated by a Mach Zhender Lithium Niobate amplitude modulator with a data signal (\(2^{23} - 1\) PRBS) at 10Gb/s. The signal is then combined with the pumps in a 70/30 coupler and passed through the fiber. The polarisation states of the waves are aligned for maximum conversion (co-linear). We have chosen the pump wavelengths to be 1551 and 1585nm with a signal at 1566nm, this produces an idler 33nm away at 1533nm. After the fiber, the pumps and other mixing terms were removed via filter.
WDMs and the generated idler was passed through a variable optical attenuator and onto the photodiode. The photocurrent in the photodiode was used as the measure of optical received power and BER tests were performed.

3.13.2 Results

The pump wavelengths were chosen such that the pump’s beat signal was generated sufficiently distant from the Bragg Scattering idler to enable efficient removal via WDM whilst keeping the Bragg Scattering wavelength shift sufficiently small such that close to 100% conversion was achievable. The output spectrum is shown in Figure 3.28, this shows that excellent conversion efficiency has been achieved and that the mixing terms generated by the competing effects of MI and PC are minimal.

![Output spectrum (solid blue) of the Bragg Scattering process with the input signal (dotted red).](image)

The BER tests were performed several times to ensure that the runs were consistent and the initial BER tests were performed for the maximum conversion efficiency (approaching 100%). As seen from Figure 3.29 the two BER curves for the idler and signal lie virtually atop each other and the received eye diagrams are virtually indistinguishable.
3.13. BRAGG SCATTERING DATA CONVERSION

![Figure 3.29: BER test for a 33nm wavelength shift at 10Gb/s (eye diagrams inset).](image)

Of note is that the back-to-back BER curve of the signal drops marginally below that of the idler’s curve when the error ratio drops below approximately $10^{-8}$. This can be explained by inspection of the idler spectrum after filtering through the WDM filters. As seen in Figure 3.30 the spectrum after filtering still contains components of the other mixing terms from the pumps, which while small in comparison to the idler wave still induce a noise floor on the system which becomes noticeable for very low error ratios.

The BER tests showed excellent converted signal quality for $\sim 100\%$ conversion, but in a practical system $100\%$ conversion efficiency might not necessarily be achievable. BER tests were therefore also performed for several conversion efficiencies to study the impacts of lower conversion efficiency on system performance. The conversion efficiency was varied in two different manners, by reduction of the pump powers and control of the states of polarisation. The BER tests for both methods of conversion reduction are shown in Figure 3.31 for $\sim 100\%$, $\sim 80\%$ and $\sim 63\%$ conversion efficiency (reductions of 0, 1 and 2dBm in the converted idler).

These BER tests show that although small, a power penalty is indeed incurred for non-optimal conversion efficiency. This is most easily understood if one again
considers the output idler spectrum; as the conversion efficiency is reduced, the idler’s signal to noise ratio is also reduced, thus the mixing terms and the noise floor (ASE band) about the idler wave will have a greater impact on the BER.

3.13.3 Discussion

The BER tests performed on a 10Gb/s data signal have shown that the Bragg Scattering process can produce excellent quality converted signals. The noise in the converted signal could be further improved by better filtering, ie the use of a band pass filter at the idler wavelength. The BER tests performed for various conversion efficiencies also show that even for a significant reduction in efficiency the power penalty induced in the Bragg Scattering idler is small (less than 1dBm).
Figure 3.31: BER tests on various conversion efficiencies, achieved through pump power reduction (top) and signal polarisation mis-alignment (bottom).
CHAPTER 3. NONLINEAR WAVELENGTH CONVERSION IN HNLFS

3.14 Bragg Scattering Wavelength Conversion

This section summarises the efforts in this study to experimentally achieve optimal Bragg Scattering wavelength conversion. We discuss observed efficiencies and conversion range in the implemented experiments and provide measurements of the tuning bandwidth for the Bragg Scattering idler in the positive $\beta_4$ fiber.

3.14.1 Conversion Efficiency

The efficiency achievable with the Bragg Scattering effect depends primarily on the uniformity of the fiber. As mentioned in earlier sections, the FWM efficiency can be degraded by a fiber with sufficient ZDW fluctuations. If the Bragg Scattering wavelength shift is small enough such that the bandwidth of the response is not overly affected by the ZDW fluctuations then 100% conversion to the idler is attainable. Indeed, results obtained as part of the data conversion experiments in the previous section demonstrated near 100% conversion, as seen in Figure 3.28. The effect of SRS amplification (and attenuation for that matter) will alter both the phase matching condition and the observed efficiency. Again by using shorter wavelength shifts the effects of SRS can be minimised and by sensible selection of pump wavelengths and polarisations a near ideal Bragg Scattering response can be implemented. Unfortunately this restricts the possible usable wavelength configurations when designing a low noise experiment.

We have implemented a range of experiments with varying degrees of efficiency achieved. Efficiencies as high as 95% have been demonstrated within the negative $\beta_4$ fiber, whereas in the positive $\beta_4$ fiber efficiencies of greater than 99.8% have been obtained.

3.14.2 Conversion Range

The theoretical wavelength range of conversion for a Bragg Scattering process is large, restricted only by the wavelengths of the available pumps. However, with
larger wavelength shifts, interference from SRS and other effects become more of a problem. Some of these effects can be minimised somewhat by correct choice of the states of polarisation of the waves and sensible wavelength distributions.

Bragg Scattering shifts of up to 180nm have been previously demonstrated in LEAF fibers, but these experiments have produced low efficiencies [48]. This low efficiency of the larger wavelength shifts can be attributed to several factors. As the spacings between the pumps and signals increases towards 13THz the SRS increases, which leads to increased power transfer between waves, not only between signal and pump, but from one pump to another leading to the Bragg Scattering phase matching condition changing as the uneven power term develops down the length of the fiber. This leads to a position dependent phase mis-match through the fiber, which leads to lower conversion efficiency. Other unresolvable issues with the long wavelength shifts arise as, due to the necessity of widely spaced pumps (which in turn generate widely spaced signals), the polarisation evolution of the different waves are no longer constant with respect to each other. Another issue with large wavelength shifts is the effect of ZDW fluctuations, as the frequency detunings increase, so too do the observed effects of these fluctuations.

Throughout this study we have focused mainly on conversion within the L, C and S-bands, due mainly to the availability of high powered pumps in these regions. The restrictions on a practical set-up for long range Bragg Scattering wavelength converters would be PMD and the effects of ZDW fluctuations in the fiber. With the continued development of HNLF and other novel fibers (PCF for example) larger wavelength shifts and more efficient Bragg Scattering processes should be achievable.

3.14.3 Conversion Bandwidth

The tunability of the Bragg Scattering process is an important parameter for wavelength conversion applications as the bandwidth of the response would limit the maximum data rates able to be converted. We have measured the idler tunability with both pump wavelengths fixed at several different values. The results show that
the bandwidth of the conversion depends mostly on $\omega_c$ and to a lesser extent $\omega_b$.

Figure 3.32: Idler tuning bandwidth for fixed C-band pump wavelengths at 1546nm (above) and 1551nm (below), the arrows in each plot indicate the idler response for the relevant L-band wavelengths.

The results are shown in Figure 3.32, with the measured tuning response shown by the crosses and with the solid lines the fit (in some cases extrapolated) to a sinc-function response. These results were taken for the positive $\beta_4$ fiber and show that tuning bandwidths range from $\sim 1.5$ to $\sim 4$nm for a wavelength shifts of $\sim 30$ to
~ 45nm for the various pump conditions. Larger shifts are achievable with different pump positions.

The extrapolated tuning range for the case with the two pump wavelengths at 1546 and 1578nm does not accurately give a representation of the tuning bandwidth available in this region as due to the ZDW of this fiber being at 1559nm, the phase matched signal wavelength lies in the ~ 1572nm region. This position is sufficiently close to the L-band pump wavelength that the peak idler response is not well described by a sinc-function. As the reader may recall, the phase matching condition is also satisfied for the case where $\omega_b = \omega_c$ (mentioned previously in Section 3.8). This leads to an increased conversion efficiency into the idler when the signal is tuned close to the L-band pump (this likewise tunes the idler close to the C-band pump wavelength).

Figure 3.33: Measured, extrapolated and simulated bandwidths for signal/idler tuning with a fixed C-band pump at 1546nm and L-band pump wavelengths of 1578nm (upper plot) and 1582nm (lower plot).

The simulated response is shown in Figure 3.33, this clearly shows the increased efficiency as the signal/idler are tuned close to the pump wavelengths. For comparison, the simulated response when the L-band pump is located at 1582nm is
also included, showing that the sinc-fit performed for the bandwidth extrapolations is suitable for positions of the signal detuning sufficiently distant from the pumps (to the half-power point). For the situation where the C-band pump is situated at 1551 nm this effect is not as noticeable until the L-band pump approaches 1575 nm.

3.15 Summary

This chapter has been devoted to the study of the nonlinear effects in optical fibers for wavelength conversion applications, primarily focusing on the characterisation of the FWM effect of Bragg Scattering. We have presented analytical and numerical models for this effect in optical fibers and have discussed the limitations of these models. We have used these derived models to predict the response of the Bragg Scattering phase matching curves for various input pump conditions and we have experimentally verified the theoretically predicted characteristics of the phase matching curves for a Bragg Scattering process in two HNLFs with opposite sign $\beta_4$ dispersion coefficients. Using these measured phase matching curves we have successfully recovered the fiber dispersion parameters for the two different HNLFs with good agreement to independent measurements.

The results gained during the phase matching experiments identified asymmetries in the Bragg Scattering conversion response due to longitudinal ZDW fluctuations. We have investigated the impact of these fluctuations on the Bragg Scattering conversion response and a numerical simulation has been performed to fit the ZDW profile our fiber. Comparisons with the simulated Bragg Scattering conversion response in our numerically modeled fiber agree well with the experimentally measured response. These results are promising as they indicate that the Bragg Scattering response can be used for recovery of the ZDW fluctuations within a HNLF.

The effect of SRS on the Bragg Scattering response has also been observed and numerical models that incorporate this are used to fit the Bragg Scattering response to pump power. These simulated and experimental results were then used to construct a high speed nonlinear optical switch based on the $\pi$-phase shift experienced
in the back converted Bragg Scattering signal. This switch has been implemented and a high extinction ratio between the switching ports and the on and off states has been demonstrated. To our knowledge this is the first time that the $\pi$-phase shift generated by the Bragg Scattering process has been experimentally demonstrated.

We have successfully used Bragg Scattering for the error free conversion of a 10Gb/s data signal over a 33nm wavelength shift. We have investigated the performance of Bragg Scattering for data conversion with various conversion efficiencies and have observed small induced power penalties (less than 1dB) for conversion efficiencies as low as 63%. We have also measured the Bragg Scattering conversion bandwidth for a variety of pump and signal detunings and discussed the practical limitations on the efficiency and range of a wavelength conversion experiment based on the Bragg Scattering effect.
Chapter 4

Nonlinear Wavelength Conversion in Semiconductor Optical Amplifiers

In this chapter we experimentally investigate the use of FWM within the active medium of a semiconductor optical amplifier (SOA). This is a natural extension to the work performed in fiber using the Bragg Scattering process. Bragg Scattering is a promising candidate for optical wavelength conversion applications, not just due to its improved noise qualities, but also where the preservation of the relative phase is important (non-conjugated idler and un-inverted spectrum) such as in situations where multiple channels might be shifted simultaneously.

The use of a nonlinear SOA is appealing due to the ease of integration and the relatively weak phase matching conditions within them. This leads to a broad bandwidth over which Bragg Scattering occurs, providing the possibility of wide band, multiple channel wavelength conversion whilst preserving the inter-channel ordering and phase.

The experimental work presented within this chapter was carried out in Dublin City University in conjunction with the Research Institute for Networks and Communications Engineering (RINCE).

In this chapter we investigate the FWM effect of Bragg Scattering in a traveling wave SOA. The SOA used for these experiments is from CIP Technologies, product
number: CIPSOA-XN. This high confinement factor device is specifically designed for nonlinear applications, with a fast gain recovery of 10ps, large small signal gain of 25dB and a polarisation dependent gain of only 1dB. Using this device several Bragg Scattering processes were experimentally implemented. We discuss the merits of utilising SOAs for FWM effects. We also compare experimentally simultaneous FWM effects within the SOA for wavelength conversion of telecoms data signals.

4.1 Introduction

SOAs have emerged as a promising component of optical systems for switching and signal processing applications. The strong nonlinear carrier dynamic response, which initially led to them falling out of favor as a gain block in preference to the almost ideally linear EDFAs, has found practical uses for nonlinear applications. The small package and ease of integration have led to many developments in the field of nonlinear specific SOA structures. Now with the ability to purchase commercially available nonlinear SOAs the popularity of SOAs for signal processing applications continues to grow and many studies have been performed for all optical wavelength conversion using SOAs [71].

4.2 Characteristics of Traveling Wave Semiconductor Optical Amplifiers

Of main interest in this thesis are traveling wave SOAs (single pass SOAs) made with InP/InGaAsP materials. These devices, ranging from a few hundred microns to a couple of millimeters long, can produce high gains (> 35dB) in the wavelength bands utilised by modern fiber optic systems (1530 to 1575nm). A schematic diagram of a typical traveling wave SOA is shown in Figure 4.1. It consists of a forward biased p-n hetero-junction through which electrical current flows, and an optical waveguide to confine the light to the active region of the device. Anti-reflection coatings are
applied to the input and output ends in conjunction with the use of angled cavities to reduce optical feedback in order to avoid lasing.

By supplying a current to the device, a large carrier concentration build-up within the active layer results in a population inversion and optical gain via stimulated emission occurs. Aside from the gain experienced within the active layer, an optical signal can also interact with the carriers in the active region of the SOA in a nonlinear fashion. The nonlinear effects seen within an SOA can be comparative to those typically seen within fibers, obviously with a few fundamental differences. Whilst fibers play a passive role in the generation of nonlinear effects, the carriers of the SOA are responsible for the nonlinear phenomenon seen in SOAs. As such, the nonlinear response of an SOA can be altered by changing the current flowing through the device or the temperature of the device. Even though the interaction lengths are many orders of magnitude shorter than that of fibers, SOAs with large small-signal gains and high confinement factors exhibit a strong nonlinear response. Early SOAs based on semiconductor laser diodes exhibited large polarisation dependent gains due to the asymmetrical waveguide structures of these devices. With the advances in manufacturing and design of SOAs, this polarisation sensitivity has been greatly reduced, with modern polarisation insensitive SOAs exhibiting a polarisation dependent gain as low as 0.5\,dB [72].
4.3 Nonlinear Response

Perhaps the simplest form of nonlinear response seen within an SOA is caused through the phenomenon of carrier depletion. As an optical signal passes through an SOA the carrier concentration in the active region is depleted as the signal is amplified through stimulated emission. As the carriers are depleted, the gain the signal experiences is reduced. This modulation in the gain can be used to convert data from one wavelength to another as the gain that the optical signals experience is dependent on the total optical power within the SOA. Thus, by injecting a weak continuous wave idler with a strong (modulated) signal at a different wavelength, the data on the strong signal will be transposed onto the weak idler - this effect is called cross gain modulation (XGM). A schematic diagram of a typical SOA wavelength converter based on XGM is shown in Figure 4.2. XGM can be implemented in either counter or co-propagating schemes and results in an inverted converted signal.

![XGM wavelength conversion schematic.](image)

Along with the modulation of the gain, the refractive index in the active region is also modified as the carrier concentration is depleted. This results in cross phase modulation (XPM) when two or more optical wavelengths are present in an SOA. Wavelength converters utilising XPM in SOAs usually involve one or more SOAs placed in an interferometric configuration. Wavelength converters based on XPM are superior to those using XGM as they offer better power efficiency and lower chirp in the converted signal due to the reduced gain modulation needed for efficient switching [73]. A typical XPM wavelength conversion scheme is shown in Figure 4.3. The converted signal can be either an inverted or non-inverted replica depending on
the operating bias chosen for the interferometer. The bias for these interferometers can be adjusted by the currents flowing in each SOA or the addition of a separate phase control in one arm of the interferometer. In the set-up shown, the pump wave is passed through only one of the SOAs which causes XPM with the counter propagating signal, the SOA in the other arm provides gain and control over the bias point of the interferometer. The modulation of the refractive index is also responsible for pulse distortion and chirping as the leading edge of a pulse experiences a different refractive index than the trailing edge. The characteristic time of these interband effects is the stimulated lifetime of the carriers which is in the order of hundreds of picoseconds. These interband effects are the dominant mechanism for nonlinear effects with small frequency detunings.

Two other phenomena responsible for gain and index modulations within the active region of SOAs are carrier heating (CH) and spectral hole burning (SHB) [74]. Unlike XGM and XPM, CH and SHB are intraband effects and are the result of changes in the energy distribution of the carriers, rather than the density. As such, they exhibit much shorter characteristic times (hundreds of femtoseconds) and are the main mechanism for nonlinear effects with large frequency detunings. CH is the result of stimulated emission subtracting carriers with lower than average energies and free carrier absorption moving carriers to higher energies. The nett increase in energy (temperature) results in a reduction of the gain. SHB arises when an injected optical signal creates a hole in the intraband carrier distribution. This
modulates the occupation probability of the carriers within a band and leads to fast gain modulation.

4.4 Four Wave Mixing in Semiconductor Optical Amplifiers

FWM within SOAs for wavelength conversion has been studied extensively for a variety of purposes including wavelength conversion and optical switching applications [75, 76]. However the majority of studies performed have focused on the degenerate single pump process of MI and (to a lesser extent) the two pump process of PC. In contrast the asymmetrical two pump process of Bragg Scattering has received very sparse attention. The following section presents work detailing the implementation of several FWM based wavelength conversion experiments utilising the Bragg Scattering effect and identifies that Bragg Scattering can possess inherent benefits that may be taken advantage for such applications.

The mechanism for FWM in SOAs differs from that of FWM in fiber as the SOA carrier dynamics are the primary source of the nonlinear response. As such, modeling for FWM in the SOA must take into account the gain and carrier dynamics. Several approaches have been used for this purpose - from the simplified lumped model considerations of separate gain, nonlinear and ASE blocks [77] through to thorough derivation of the coupled amplitude equations within SOAs [15]. Detailed modeling of the FWM process within our SOA is beyond the scope off this thesis, but the interested reader is encouraged to read the referenced texts for further details on how one goes about this task.

The analytical theory presented in [78] demonstrates that perhaps the single most important measure of an SOA’s suitability for FWM applications is the small signal gain. SOAs with large small signal gains exhibit higher FWM efficiencies than those with low small signal gains. The high small signal gain and carrier dynamics of SOAs lead to a lower dependence on the wavenumber mis-match than
is usually required for nonlinear mixing processes. As such, typical phase matching conditions for nonlinear effects like FWM, such as those discussed in Chapter 3, are not present as strongly in SOAs [79]. This results in the prolific nonlinear mixing of optical signals with relatively weak input powers throughout the gain region of the amplifier.

4.4.1 Experimental Comparison of Four Wave Mixing Effects in Semiconductor Optical Amplifiers

In this section an experimental comparison between Bragg Scattering and modulation instability (MI) is carried out in an SOA. Many FWM schemes in SOAs utilise single pump, degenerate FWM (MI) for wavelength conversion applications [80, 81]. Wavelength converters that utilise MI offer simplified experimental set-ups over the double pump cases as they require only one pump laser. However, they also suffer from reduced conversion efficiency with further pump detunings compared to the double pump processes of Bragg Scattering and PC [82, 17]. We demonstrate that using the Bragg Scattering process can offer noise improvements over that of a single pump MI process. It is expected that the additional noise generated in the single pump process of MI will also be present for the double pump process of PC.

As mentioned previously, one benefit of FWM in an SOA is that the phase matching condition that needs to be satisfied for efficient power transfer between waves in fibers has a much reduced impact on the FWM efficiency. This, coupled with the strong gain experienced by signals within the SOA, leads to multiple idlers from several different effects growing in power simultaneously. As it is no longer necessary to carefully select the wavelengths of the four waves to satisfy phase matching and to achieve efficiency, one can instead look to utilise/compare these idlers produced from the different processes. As such, new and interesting experiments can be implemented.

We look at a comparison between the MI and the Bragg Scattering produced idlers, given a wavelength schematic such as Figure 4.4. This situation allows the
generation of idlers from both the MI and Bragg Scattering effects that are spectrally very close to one another. This enables a direct comparison between the two effects to be experimentally performed.

Figure 4.4: Wavelength distribution for FWM comparison experiment where two idlers are simultaneously generated from the same signal via the effects of Bragg Scattering (BS) and Modulation Instability (MI).

4.4.1.1 Experimental Set-up

The experimental set-up as shown in Figure 4.5 consists of two continuous pump waves provided by external cavity lasers (ECL1 and 2), which are coupled together via a WDM and combined with the 10Gb/s modulated signal through a 50/50 coupler. These waves are then passed through the SOA, with the states of polarisations aligned for maximum mixing within the SOA.

Figure 4.5: FWM comparison in SOA experimental set-up.

Pump 1 was injected at 1573.5nm with a power of 1.16dBm while pump 2 was 1583nm and -0.13dBm. The signal was at 1578nm with a power of -10.8dBm and
this produced the two idlers of interest, one at 1569nm via the one pump interaction of MI (with the 1573.5nm pump), and the other at 1568.6nm from the two pump interaction of Bragg Scattering. These generated idlers were separated by the use of tunable band-pass filters (TBPF) and then directed to our photodiode. The pump powers were chosen to be $> 10\text{dB}$ above the signal to saturate the gain of the SOA. The spacing of these idlers are determined from the placement of the pumps and the signal and was chosen to be kept small to ensure both idlers experienced the same gain and frequency shift.

The initial experimentation was performed using a different receiver than that shown in Figure 4.5 and this resulted in comparatively poor receiver sensitivities and unrealistically bad back-to-back measurements in the bit error ratio (BER) tests.

By switching to a different photodiode in conjunction with a trans-impedance amplifier (TIA) the receiver sensitivity was improved, but as the transmitted signal was far from the EDFAs gain peaks, the back-to-back BER measurements were still unacceptably poor. This necessitated the measurement of the back-to-back (transmitted signal) to be performed in the wavelength region of the converted idlers, this was achieved by tuning the signal ECL to $\sim 1570\text{nm}$.

### 4.4.1.2 Results

By careful choice of the pump and signal wavelengths (such that the signal wave is injected slightly off center between the two pumps), idlers converted from the MI and Bragg Scattering processes are generated spectrally close to one another, as seen from the spectrum at the output of the SOA in Figure 4.6.

BER tests were performed on the MI and Bragg Scattering idlers respectively by tuning the filters in the receiver. These BER curves, shown in Figure 4.7, demonstrate that the Bragg Scattering idler exhibited a consistently smaller power penalty than the MI idler, possibly due to the improved noise properties of the Bragg Scattering process as discussed in Chapter 3. Of course, due to the gain and prolific four wave mixing within nonlinear SOAs, a theoretical noise free Bragg Scattering idler
Figure 4.6: Output spectrum for the FWM comparison with the simultaneous generation of both a Modulation Instability (MI) and Bragg Scattering (BS) idler.

is even further from practical possibility than the case within a fiber. However, with improvements in the efficiency of nonlinear SOAs, the noise improvements possible from this process might well become significant in future wavelength conversion applications utilising SOAs.

This experimental set-up was modified slightly to allow simultaneous transmission of short (~2ps) RZ pulses, such as those used in the following experiments for the high speed data conversion study. These short pulses were used to highlight the phase differences between MI and Bragg Scattering processes. As the pulses have a significant bandwidth and exhibit significant spectral phase variation, the phase reversal (conjugation) can be measured via FROG [3] techniques. As seen in Figure 4.8 the MI generated idler exhibits a flipped spectral phase with respect to that of the Bragg Scattering idler and transmitted signal.

4.4.1.3 Discussion

Even though the power penalties between the MI and Bragg Scattering idlers were measured as small, they were consistently there throughout the course of this inves-
Figure 4.7: BER curves for the FWM comparison experiments. Results for the improved experimental set-up with optimised receiver (above), results for initial experiments performed with non-optimised receiver (below) - the back-to-back measurements in the bottom figure are not included as they are unrealistically poor due to the receiver sensitivity.
tigation. This implies that the Bragg Scattering process can offer somewhat lower noise wavelength conversion over the single pump process of MI. A further investigation and comparison with an idler produced from the two pump PC process would further improve these results, however implementation of a set-up where the Bragg Scattering and PC idlers are produced spectrally close to one another poses a problem and efforts would be needed to ensure effects from the different gain and frequency detunings were taken into account when performing this experiment.

These findings show that it is possible to improve the noise of a wavelength conversion system by using the double pump Bragg Scattering effect over that of the single pump MI process (or PC). This work also highlights the fact that the strong nonlinear response of the SOA allows simultaneous generation of multiple FWM products which could be of use for future signal processing applications, such as the one discussed in [83]. The use of an SOA in this situation would allow greater flexibility in the choice of pump wavelengths as the relatively constant efficiency of FWM in SOA produces multiple FWM products with similar powers.

![FROG measurements of the two FWM processes](image)

Figure 4.8: FROG measurements of the two FWM processes
4.4.2 Four Wave Mixing in Semiconductor Optical Amplifiers for Multiple Channel Data Conversion

Due to the high nonlinear response of the SOA used and the relatively constant conversion efficiency (broad tunability) of the Bragg Scattering process implemented in SOAs, multiple channel wavelength conversion is a promising application. In the following experiment this broad tunability was exploited to perform multi-channel wavelength conversion of 10Gb/s PRBS data signals with channel spacings of 50 and 100GHz using Bragg Scattering. The use of Bragg Scattering offers the ability to transfer blocks of multiple channels, keeping the relative frequency order and phase of the converted signals unchanged. This is unique among FWM processes as with MI and PC processes the relative channel order is reversed and the phase of the signals is conjugated. Previous experiments have been performed with multiple channel wavelength conversion using both single and double pump schemes [84, 85] to convert multiple channels at various data rates in SOAs. We demonstrate with a 10nm shift that Bragg Scattering in an SOA is suitable for multiple wavelength conversion of two data channels at both 50 and 100GHz spacings with data rates of 10Gb/s.

4.4.2.1 Experimental Set-up

The experimental set-up for the dual channel wavelength conversion system is shown in Figure 4.9. It consists of four external cavity lasers (two pumps and two signals). Again, the two pumps are kept strong compared to the signals to ensure they saturated the gain of the SOA. The two signals are independently modulated with the data and the then combined and attenuated before being combined with the pumps and passed through the SOA. The polarisations of the waves were aligned for maximum mixing (co-linear). TBPFs were used to separated the signals at the output of the SOA and BER tests were performed on each signal. This was carried out with channel spacings of 100 and 50GHz.

The receiver consisted of cascaded EDFAs and TBPFs followed by a photodiode
and trans-impedance amplifier. This receiver showed excellent sensitivities in the wavelength region of the signals, as seen in the BER graphs.

4.4.2.2 Results

The output spectrum for the 50GHz channel spacings is shown in Figure 4.10. These show that the pumps remain sufficiently high (over 20x the signals) throughout the process, effectively saturating the gain. As seen in the output spectrum, significant nonlinear mixing is occurring within the SOA. For the 50GHz spacings the two input wavelengths were 1549.72 and 1550.2nm for channel 1 and 2 respectively and the generated idler output wavelengths were 1560.26 and 1560.68nm respectively. To increase the channel spacing for the 100GHz measurement, channel 2 was unchanged and channel 1 was moved to 1549.36nm which generated an idler at 1559.86nm.

The BER tests were performed at 10Gb/s on both channels, and as a comparison one channel was switched off and a BER test was performed for a single channel wavelength conversion system. As seen in Figure 4.11 the BERs show minimal power penalty between the 50 and 100GHz channels, and less than 1dB power penalty over the single converted signal. This bodes very well for multiple channel wavelength conversion schemes utilising SOAs in this manner as the cross talk between two channels is low (and because cross talk has diminishing effects as the number of channels are increased). The overall power penalty for wavelength conversion in this SOA is $\sim 4$dB and is mostly due to the fact that the input signals are closer to
the gain peak of the receiver amplifiers, thus improving the receiver sensitivity for the back-to-back measurements significantly.

Of particular note is the power penalty incurred for the dual channel conversion over that of a single converted channel. The difference in power penalties between the converted double channel and the single channel case is only slightly larger than that for the back-to-back measurements, promising very low signal cross talk. This cross talk penalty is kept low by ensuring that the CW pumps saturate the gain of the SOA, keeping the XGM between the weak signals to a minimum.

4.4.2.3 Discussion

The use of Bragg Scattering within a highly nonlinear SOA for signal processing and wavelength conversion applications is appealing due to the broad bandwidth offered by the SOAs conversion response. The simultaneous conversion of multiple data channels is demonstrated with a low observed power penalty due to crosstalk for two channels spaced at both 50 and 100GHz. We have demonstrated a 10nm shift and, as with most wavelength conversion schemes in an SOA, the size of this wavelength shift is limited by the gain bandwidth of the SOA. The use of Bragg
Scattering provides the possibility to shift a block of signals whilst retaining the channels relative phase and frequency ordering within the block, as opposed to multiple channel conversion offered via MI or PC where the frequency ordering is reversed and the phase of the signals are conjugated. This offers unique possibilities for network functions using SOAs as the nonlinear medium. It is expected that the additional power penalty for increased numbers of channels will be similarly low.

4.4.3 80Gb/s Data Conversion Using Four Wave Mixing in Semiconductor Optical Amplifiers

The following experiment displays the use of Bragg Scattering in SOAs for high speed data conversion. Nonlinear effects within SOAs utilising XGM and XPM have been demonstrated up to 320Gb/s [86], but these conversion schemes are phase insensitive and are not transparent to the modulation format. With the progression of high speed optical networks a phase sensitive high speed wavelength conversion scheme will be necessary for the conversion of signals incorporating phase modulation. As seen previously, the conversion of multiple data channels is also possible.

Figure 4.11: Dual channel wavelength conversion BER curves.
with FWM set-ups, whereas XGM and XPM are limited to single channel applications. Accordingly, demonstration of the capability of FWM within SOA for high speed wavelength conversion is necessary. This is particularly important when utilising the Bragg Scattering process as this offers several possible advantages, discussed in previous sections, over the symmetrical processes of MI and PC. This section investigates the use of Bragg Scattering within a SOA for high speed wavelength conversion of data signals. We convert a signal at 80Gb/s over 11nm and discuss the quality of the signal based on the recovered eye diagrams of the RZ signal.

4.4.3.1 Experimental Set-up

The experimental set-up is shown in Figure 4.12. This consists of an actively modelocked laser (a U²T TMLL1550), producing ∼ 2ps pulses at a repetition rate of 10GHz. These pulses are modulated via a Mach-Zhender modulator, amplified and filtered prior to time division multiplexing up to 80Gb/s. The filtering removes the ASE from the EDFA and broadens the pulses to ∼ 5ps, effectively narrowing the bandwidth and ensuring that the converted Bragg Scattering idler is spectrally distinct from the MI idler. This 80Gb/s RZ pulse stream is then combined with the pumps and passed through the SOA.

Figure 4.12: 80Gb/s data conversion experimental set-up.
4.4.3.2 Results

The output spectrum for the 80Gb/s wavelength conversion experiment can be seen in Figure 4.13. As mentioned above, the spectral spacing between the Bragg Scattering idler and the MI idler necessitated the 2nm filtering of the RZ pulses.

![Figure 4.13: 80Gb/s conversion output spectrum](image)

Although BER tests were not performed on the converted 80Gb/s data due to time constraints with the required equipment, qualitatively the converted signal looked to be of a high quality. The measured eye diagrams for the received signal are shown in Figure 4.14 and are good replicas of the transmitted eyes. Whilst this does not necessarily imply error free transmission, the quality of the eye definitely indicates it is a possibility.

4.4.3.3 Discussion

We have successfully demonstrated the conversion of an 80Gb/s RZ data stream through Bragg Scattering in an SOA. Recovered eyes promised excellent signal conversion, whilst BERs were unable to be performed due to time constraints with the equipment. This still indicates that Bragg Scattering within an SOA is a promising
candidate for high speed data conversion. By increasing the pump spacings, larger bandwidth signals (shorter) pulses and thus higher bit rates would be able to be converted.

4.5 Summary

Whilst the nonlinear techniques involving XGM and XPM in SOAs offer simplified set-ups over those utilising FWM, they are not phase sensitive and are not transparent to the modulation format and are limited to single channel wavelength conversion applications. XGM and XPM are also limited by the response time of the carrier density which is inherently slower than the response of the dynamics that are responsible for FWM effects at distant wavelength shifts.

Within this chapter we have discussed the mechanisms for nonlinear mixing within SOAs focusing on the experimental use of these devices for wavelength conversion applications. We have experimentally verified the suitability of the FWM effect of Bragg Scattering in SOAs for multiple wavelength and high speed data conversion applications. We performed an experimental comparison of the Bragg Scattering effect with the other FWM effect of MI and found slightly better perfor-
mance with the Bragg Scattering process. These improvements are derived from the process itself and the limiting factors for the noise in Bragg Scattering process are due to the medium that it is employed in. These improvements along with the possibilities to convert multiple wavelengths and signals whilst preserving the relative phase of the signals indicate that Bragg Scattering employed within SOA is likely to find use in future high speed transparent WDM networks. As improvements in SOA design are made and the noise figures for nonlinear SOAs are reduced, then the improvement in signal quality offered by using the Bragg Scattering process for wavelength conversion applications could prove significant.
Chapter 5

Nonlinear Crystals

This chapter presents the work undertaken in developing a high power 10Gb/s optical source in the visible. Since no high speed fiber coupled modulators are available which operate in the visible region with high enough power handling capabilities, a novel approach was required. This modulated source was produced via wavelength conversion using the second order response within a nonlinear crystal. The motivation for this work was the need to characterise newly developed micro-structured polymer optical fibers (MPOF). The MPOFs that are studied within this chapter were designed based on modeling work [87] at the Optical Fiber Technology Center which is part of the University of Sydney [88]. These prototype fibers are a likely candidate for optical sensing and short distance data-link applications. In the following sections we cover the use of nonlinear crystals for wavelength conversion, primarily focusing on the construction of a 10Gb/s telecommunications source at a wavelength of 640nm which lies in the loss minimum of the PMMA used to manufacture the fibers. We will cover the relevant theory for the use of crystals for nonlinear mixing and discuss the phase matching principles and conditions required. We discuss two experimental set-ups implemented for the testing of these fibers and present for the first time the successful demonstration of 10Gb/s data transmission through MPOF fibers.
5.1 Introduction

The very first experiment in nonlinear optics consisted of the generation of a second harmonic signal from a ruby laser beam focused into a quartz crystal. The efficiency of this experiment was very poor, but it identified the nonlinear response of crystals as a useful way in which to perform optical wavelength conversion. As such, nonlinear mixing within various crystals is now widely used to generate new optical frequencies for a variety of purposes.

There are four different types of second order processes that occur within nonlinear media; optical rectification, second harmonic generation (SHG), sum frequency generation (SFG) and difference frequency generation (DFG). The most important and useful effects are arguably the SHG and SFG processes. For further reading on optical rectification and DFG the reader is directed to [38, 31]. SHG and SFG are commonly used for many purposes ranging from the inexpensive efficient generation of visible radiation (laser pointers) to optical sampling of ultra short pulses (FROG) [3]. These are the two effects exploited for the use of wavelength conversion in this chapter and they are generated by the strong second order response of Lithium Niobate crystals. These crystals are commercially available and commonly have nonlinear coefficients that are many orders of magnitude higher than that of glasses and polymers. This allows strong nonlinear interactions in relatively short crystal lengths.

5.2 Second Harmonic and Sum Frequency Generation

Second harmonic generation and sum frequency generation are both second order nonlinear processes. They have been studied extensively, with a myriad of practical uses. They result from the mixing of three optical waves where, due to conservation of energy, their frequencies are given by
\[ \omega_1 + \omega_2 = \omega_3, \quad (5.1) \]

where in the case of SHG, \( \omega_1 = \omega_2 = \omega \) and \( \omega_3 = 2\omega \).

As an example of a SHG process, consider an electric field incident on a nonlinear medium with a 2nd order response, where the incident field is of the form

\[ E(t) = E e^{-i\omega t} + \text{c.c}, \quad (5.2) \]

where c.c represents the complex conjugate.

By considering Eq. (2.13) and limiting our analysis to the first order nonlinear response \( \chi^{(2)} \) (which is proportional to the electric field squared) we find the nonlinear polarisation term is given by

\[ P_{NL}(t) = 2\epsilon_0 \chi^{(2)} EE^* + \epsilon_0 \chi^{(2)} (E^2 e^{-2i\omega t} + \text{c.c}). \quad (5.3) \]

We see that the second order polarisation term contains two components, the first at zero frequency and the second at \( 2\omega \). The first term, called optical rectification, is responsible for the generation of a DC potential across the nonlinear medium. The second term is responsible for the generation of radiation at twice the fundamental frequency (the second harmonic frequency).

By use of the wave equation and the slowly varying envelope assumption, and assuming that the fundamental wave remains undepleted, it can be shown that the growth of this second harmonic field can be described by

\[ E(z, t)^{(2\omega)} = -\frac{i\omega \chi^{(2)}}{2n_2\epsilon} P_0^{(\omega)} \text{sinc}(\Delta kz/2) e^{i\Delta kz/2}, \quad (5.4) \]

where the wavenumber mis-match is \( \Delta k = k^{(2\omega)} - 2k^{(\omega)} \) and \( P_0^{(\omega)} \) is the incident (and undepleted) power of the fundamental wave. For a phase matched process (\( \Delta k = 0 \)) the power of the second harmonic increases linearly with the propagation distance and incident pump power. If the process is not phase matched, the driving
polarisation at $2\omega$ drifts in and out of phase with the generated wave and power flows sinusoidally to and from the second harmonic signal as it propagates through the medium, with a period of $\pi/\Delta k$, which is commonly referred to as the coherence length, $L_c$.

The derivation for SFG is similar to the above for SHG, except that the input electric field consists of two different wavelengths leading to the generation of a wave at the sum frequency of the two incident waves. More information for this and the SHG derivations can be found in a number of texts such as [38].

5.2.1 Quasi Phase Matching

To achieve phase matching and an efficient SHG process, it is necessary that $n(\omega) = n(2\omega)$. This is difficult to achieve in practice, as due to chromatic dispersion the different wavelengths will experience different refractive indices. Commonly employed techniques for phase matching of SHG processes utilise the birefringence of some materials such that the fundamental is polarised so it propagates aligned to the ordinary axis and the generated wave is produced aligned along the extraordinary axis. By suitably cutting and rotating a birefringent crystal it is possible to match the two refractive indices for the orthogonal waves. This method is common for phase matching in birefringent nonlinear crystals [89] and the phase matching bandwidth can be quite large for some crystals.

There are however situations where phase matching via birefringence is not possible, as some materials with high nonlinear responses may not be birefringent, or possess insufficient birefringence to compensate for the dispersion of the linear refractive indices at the wavelengths of interest. In these cases a technique called quasi phase matching can be utilised. Quasi phase matching involves the periodic modulation of the crystal’s nonlinear properties [90]. This leads to a periodic variation of the nonlinear susceptibility, resulting in a need to replace $\chi^{(2)}$ with spatially periodic $\chi^{(2)}(z)$ when deriving an expression for the growth of the second harmonic. As this technique does not rely on the birefringence, it offers the benefit of allowing
all the waves to be co-polarised, enabling the alignment of the polarisation of the waves with the highest nonlinear axis of the crystal [91].

The effect of quasi phase matching is easiest to understand if one considers the simplest form of a spatially periodic $\chi^{(2)}(z)$ where $\chi^{(2)}(z)$ switches from $\chi^{(2)}$ to $-\chi^{(2)}$ every period $T$. If one were to match this periodicity with that of the coherence length for the un-phase matched second harmonic signal as in the previous section, such that

$$T = L_c = \frac{\pi}{\Delta k}, \quad (5.5)$$

then this corresponds to a reversal in $\chi^{(2)}$ at every point in the medium when the power flow to the second harmonic is likewise reversed. Thus power can be kept flowing into the second harmonic leading to a cumulative build up of the power throughout the medium as seen in Figure 5.1.

This periodic variation in the nonlinear coefficient of the crystal can be achieved by several means, some of which include the application of a spatially reversing static electric field through placement of electrodes in close proximity to the material.
(this is called poling) or by diffusion of various impurities through a spatial mask. All of these methods work to reverse the direction of one of the crystal’s primary axis, which causes a reversal in the permanent electric polarisation within the crystals.

The crystals used for the experimental work within this chapter are periodically-poled Lithium Niobate (PPLN), where the periodic poling is based upon the use of a strong, spatially varying electric field applied to the material to permanently change the crystal’s electric polarisation vectors in an alternating fashion. The size of these segments of reversed $\chi^{(2)}$ can be varied to support different phase mis-matches, thus enabling multiple poling channels to be written along side one another to allow some tunability by switching channels within the crystal. Further fine tuning of these gratings can be achieved through a thermally controlled oven to increase/decrease poling pitch slightly. This allows, with the use of a single crystal with five channels, a tunability for phase matching of over 30nm. The phase matching curve for our SHG crystal is shown in Figure 5.2, with the five different channels and their temperature phase matching curves.

![Figure 5.2: Quasi phase matched SHG crystal phase matching curves, with the poling periods for each channel displayed at the top.](image-url)
5.3. DEVELOPMENT OF A 10GB/S MODULATED SOURCE AT 650NM

The SFG crystal has a phase matching arrangement similar to that for the SHG crystal but had three channels instead of five. The two crystal’s specifications are shown in Table 5.1.

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Material</th>
<th>Poling Period (µm)</th>
<th>Temperature (°c)</th>
<th>Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHG</td>
<td>PPLN</td>
<td>18.2 : 0.2 : 19</td>
<td>160-200</td>
<td>10x10x0.5</td>
</tr>
<tr>
<td>SFG</td>
<td>MgO PPLN</td>
<td>11.6 : 0.3 : 12.2</td>
<td>135</td>
<td>10.19x4.7x0.5</td>
</tr>
</tbody>
</table>

Both crystals were anti-reflection coated for both the fundamental wave(s) and the generated second(sum) harmonic wavelengths. The crystals were in temperature controlled ovens and on theta/phi rotation and translation stages for alignment purposes. The poling channels for the SHG crystal were 500µm wide, with 200µm blanks between them while the SFG crystal had 200µm channels with 1mm blanks. Both crystals were PPLN, but the SFG crystal was doped with Magnesium Oxide. This provides a higher photorefractive damage threshold [94] and allows operation of the crystal at lower temperatures.

5.3 Development of a 10Gb/s Modulated Source at 650nm

The work presented in the following section was motivated through a need for a 10Gb/s source in the visible for the continuation of the testing of several MPOF fibers. The aim for these fibers is to establish them as an inexpensive alternative to glass fibers for use in short distance optical links. The current issue with testing these prototype fibers is the loss they exhibit, which has been measured as ~ 0.3dB/m at the loss minimum of ~ 650nm and is much higher at other wavelengths. Previous experiments involving pulse broadening measurements with a modelocked Krypton laser have been performed [95] and bandwidths of up to 10GHz over 30m lengths were indicated. The issues with testing these fibers arise from the relatively high loss.
that they exhibit. Figure 5.3 shows the attenuation curve for a standard step-index PMMA POF as measured in [96].

To determine the bandwidth unambiguously however, an actual data source near the loss minimum needs to be constructed with enough power to enable transmission through a significant length of the fiber. Unfortunately no suitable sources or low noise optical amplifiers are available at the target wavelengths and commonly used VCSEL sources do not output enough power and cannot be directly modulated at 10Gb/s, while recently developed electro-optic modulators for wavelengths in the 650nm range suffer from a poor extinction ratio and low damage thresholds (\(\sim 1\text{mW}\)). The solution adopted was to approach the problem through nonlinear mixing of a data signal in the communication bands down to the visible region of interest by exploiting the ultra fast response of the \(\chi^{(2)}\) nonlinearity. Preliminary work to develop the source was performed in 2008 [97] but insufficient power at 650nm was obtained. This called for a redesign and a new implementation of the experiment which is detailed in the following sections.

The two fibers tested within this section had been tested previously in the pulse broadening experiments. Both fibers are from the University of Sydney and their core profiles can be seen in Figure 5.4. The fiber on the left is referred to as the 400\(\mu\text{m}\) fiber and the one on the right as the 600\(\mu\text{m}\) fiber (outer diameters).
5.3. DEVELOPMENT OF A 10GB/S MODULATED SOURCE AT 650NM

Figure 5.4: MPOF core profiles for the two fibers tested with outer diameters of 400µm and 600µm (left and right).

5.3.1 Experimental Aims

As no 10Gb/s sources exist in the wavelength region of interest with sufficient power to characterise these fibers, two sources were created, both similar in principle, just slightly different in their mechanism. Nonlinear mixing through a bulk crystal was used to achieve a generated wavelength of 640nm. This wavelength was desired as these fibers exhibit a loss minimum in this region [98]. The source created would need to generate significant power and would have to exhibit good stability and noise characteristics for repeat measurements of BERs.

In the following experiments two differently pitched PPLN crystal were used, each manufactured with five channels for the specific purpose of SHG or SFG. The pump wave(s) were combined in a fiber WDM coupler and focused through a single lens system out of the fiber into the crystal. This set-up was the easiest to implement and manipulate, as by varying the distance of the fiber from the lens the focusing of the beam could be tightened or relaxed (along with a translation in distance of the beam waist). This reduces the degrees of freedom compared to a multiple lens system (fiber-collimator-focuser-crystal), thus simplifying the set-up requiring the use of only two translation stages (one for the crystal and one for the fiber).

To obtain the best conversion in the second order processes, a confocal arrangement was utilised, where by calculating the beam waist using the standard Gaussian
beam translation matrices, the focusing within the crystal was such that the beam
waist in the center of the crystal was $1/\sqrt{2}$ of that of the beam waist on either face of
the crystal. This enables the highest conversion in a free space focusing arrangement
[99].

5.3.2 Sum Frequency Generation Source

As the loss minimum of the fibers under test lies near 650nm, this was the obvious
target wavelength for the nonlinear mixing process. As such, an experimental test
source was designed around the sum frequency mixing of two pump lasers, one
of which would be modulated via a Mach-Zhender amplitude modulator with the
desired 10Gb/s signal. This initial set-up, shown in Figure 5.5 utilised a CW Nd-
YAG laser running at 2W as the 1064nm pump. This was coupled with a 1600nm
pump provided from an EDFA running at 2W, seeded with a PRBS modulated
signal. These two pump wavelengths would generate a signal at 639nm, sufficiently
close to the loss minimum for our purposes. Generation of a signal closer to the loss
minimum is limited by the availability of pumps at the correct wavelengths. The
two pumps were combined via a fiber WDM coupler and focused through the crystal
via a 4mm focal length lens.

The polarisation of the pumps were kept co-linear and aligned with the nonlinear
axis of the crystal via a fiber polarisation controller (1600nm pump) and free-space
half-wave plate (1064nm pump). Alignment of the beam within crystal was aided
by the fact that 639nm is visible to the naked eye, so scattering from within the
crystal allowed easy positioning within the correct channel of the PPLN. The crystal
was kept at a constant temperature in a thermally controlled oven and the average power generated at 639nm was 60mW when optimally aligned.

Hot mirrors (thin film bandpass filters) were initially used to separate the pumps from the generated 639nm signal before injecting the 639nm signal into the fiber. However, as focusing through the crystal was optimised and the pump powers increased, non optimal reflection of the 1600nm pump caused localised heating and thus cracking of the hot mirrors. This issue was resolved via implementation of a prism to separate the different wavelengths, with the high power pump waves being directed into a beam block of significant thermal mass. Once the pumps were discarded, the signal was directed to the fiber coupling stage where it was focused into the fibers under test. After propagation through the fibers, the signal was coupled into a short graded index silica multimode fiber patch cord attached to the photodiode (a Newport D-15-FC). This signal was amplified via two cascaded 30Gb/s RF amplifiers to enable the sometimes very weak optical signal to be recovered. BER tests were performed before and after the fibers under test for various lengths (limited by the transmission power).

5.3.2.1 Results

The results gained from this implementation of the visible source are displayed in Figures 5.6 and 5.7. Data rates were necessarily limited via low-pass filtering of the detected RF signal as significant noise was present at frequencies around 10GHz. As seen from the variation in the receiver sensitivities from the successive BERs, the source was not stable between measurements, making these results somewhat unreliable. However on occasion the source would stabilise for a time long enough to do two successive BERs and preliminary characterisations of the fibers were performed.

5.3.2.2 Discussion

Unfortunately, the Nd-YAG laser available was not as stable as we had hoped, causing significant noise to be present on the generated signal. This noise ranged from
power fluctuations over the second timebase to noise at over 10GHz. Longitudinal mode mixing and hopping from the Nd-YAG laser was deemed the most likely source of this noise. With perseverance, reduced data rates and filtering the received electrical signal with 6GHz low pass filters some preliminary measurements were able to be performed on the MPOFs. The noise limited the effective data rates we could run to 5Gb/s, and experiments were performed as best as they could within these limitations. Clearly this implementation of a visible source is unable to reliably operate at the data rates required for effective measurements to be performed. Further improvements to this source will require the use of a more stable 1µm pump source to eliminate the RF noise generated by our current laser.
Figure 5.7: 5Gb/s BER curves for transmission through 20m (top) and 37m (bottom) of 600μm MPOF (eye diagrams inset).
5.3.3 Second Harmonic Generation Source

In an effort to gain results whilst waiting for a more stable 1µm source, the crystal was exchanged for a differently pitched PPLN, one optimised for SHG, to create a system generating 774nm via SHG from a single strong pump. This experiment was devised not only to try to get some early results but also to confirm that the issues we were having originated with the 1µm source.

By using a single pump at 1548.2nm modulated at 10Gb/s and then amplified to an average power of 5W, 150mW of generated 774nm signal was created. This generated signal exhibited excellent quality and stability enabling several BER tests to be performed on the various MPOFs even though the signal was not located at the loss minimum for these fibers. The experimental set-up for the 10Gb/s visible source went through an iterative assembly as the technique for efficient mixing was perfected. Shown in Figure 5.8 is the final/most recent set-up with which the best results have been taken.

![Figure 5.8: Experimental set-up for the SHG source.](image)

This SHG experimental set-up was similar in many ways to the previously described SFG source. However, it was simplified somewhat by the use of a single pump source rendering the WDM coupler unnecessary. A tunable laser running at 1548nm was again modulated via a Mach-Zhender amplitude modulator with the chosen data signal. This was then amplified to 5W through a C-band EDFA. This was focused again with a 4mm focal length lens into the nonlinear crystal. The pump was again separated via a prism and discarded, whilst the signal was directed to the fiber coupling stage. Utilising the same receiver set up described previously, BER tests were performed before and after the fibers under test. This source exhib-
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...ited a much cleaner generated signal and enabled successful repeat measurements to be performed. A characterisation of this source was also performed.

5.3.3.1 Experimental Results at 774nm

![BER test of SHG conversion at 10Gb/s (eye diagrams inset).](image)

The use of a single modulated pump wave enabled higher peak powers to be achieved within the crystal. This higher peak power still did not fully compensate for the increased loss seen at 774nm, and thus the lengths of fiber able to be tested were reduced. This test signal was of a high quality and a characterisation of this source was performed through a BER comparison of the pump and the generated SHG signal as seen in Figure 5.9. This comparison showed excellent results, with the SHG BER performing slightly better than the pump. This no doubt was due to the effective filtering of the SHG signal from the phase matching bandwidth of the crystal (which is of the order of ~1nm at these wavelengths) which removes the residual ASE generated within the EDFA. The BER curves were performed multiple times and a polynomial fit was performed over the four consecutive runs. The photo diode response at 774nm and 1548nm was taken into account when calculating the received powers. As there are no optical amplifiers available at the wavelength of...
774nm, all amplification of the signal was performed in the electrical domain and thus the receiver sensitivities are limited to modest values.

Figure 5.10: 10Gb/s BER tests performed on 20m of 400µm (top) and 600µm (bottom) MPOFs (eye diagrams inset).
The 774nm source exhibited excellent stability, noise properties and significantly more power than that of the SFG experiment which enabled repeatable BER tests to be performed. The results for these are shown in Figure 5.10. These results show that the 400µm fiber is still not bandwidth limited, whereas the 600µm fiber is beginning to show a modal dispersion induced power penalty. The effects of modal dispersion can also be seen in the measured eye diagrams for the 600µm fiber, (inset of the BER curves). This manifests itself as a rounding off of the corners and closing of the eyes, which can be seen clearly in contrast to the 400µm eyes where no modal dispersion is observable.

![Figure 5.11: BER test of 150m of CHROMIS fiber at 10Gb/s (eye diagrams inset).](image)

Figure 5.11: BER test of 150m of CHROMIS fiber at 10Gb/s (eye diagrams inset).

As a further investigation based on the use of this source we tested the transmission of a 10Gb/s data stream through 150m of commercially available perfluorinated graded index POF made by CHROMIS (with a core diameter of 62µm). This fiber has been demonstrated to support high bandwidths over 100m lengths with wavelengths ranging from 800 to 1300nm. Ideally this test would be performed with as short a wavelength as possible, and our experiment was performed at 774nm. This yielded excellent results as seen in the Figure 5.11 where a modest power penalty, due to the modal dispersion, was induced in the BERs. The recovered eye diagrams...
also showed the onset of modal dispersion, characterised by the rounding off of the edges. To the best of our knowledge this fiber has never been characterised at this short a wavelength.

5.3.3.2 Discussion

The SHG source generated a clean and powerful signal at a wavelength of 774nm. This allowed for the first time successful characterisation and transmission at 10Gb/s through MPOFs at near visible wavelengths. The single pump set-up allowed higher peak powers to be obtained within the nonlinear crystal and accordingly higher average powers were produced in the second harmonic signal. The improved performance of this source enabled effective characterisation of the bandwidths of the two MPOFs.

Of interest was the power penalty measured for the 600µm fiber. Even though BER tests were beginning to show the onset of modal dispersion, the power penalty shown by this fiber is surprisingly small. By examining its core profile, seen in Figure 5.4, the micro-structured holes are large enough that one could expect it to behave much as a naked PMMA rod surrounded by air, effectively making it a step-index multimode fiber. For this case, the length bandwidth product of such a step-index multimode fiber would be expected to be very much lower than that measured here. This implies that there are effects occurring which improve the performance of the MPOF that must be taken into consideration. The most likely candidate for this improvement in bandwidth could be the combined effects of preferential mode attenuation and strong mode mixing. Preferential mode attenuation can lead to the higher order modes (or rays with steeper propagation angles) being attenuated more than the lower order modes (or a group of modes with similar modal velocities to be selected by a differential loss mechanism). This can occur due to the increased interactions of the higher order modes with both the material and the core/cladding boundary. As it is difficult with large molecule polymers to achieve a perfect core/cladding boundary, it is entirely possible that the majority of
this higher order mode attenuation results from the scattering of these modes from
imperfections at the core/cladding boundary. With the case of micro-structured
fibers where the core/cladding boundary is more complex than a standard step in-
dex fiber, this effect is exacerbated. This attenuation of the higher order modes
leads to both increased loss and bandwidths by attenuating the higher order modes.
The strong mode mixing increases the bandwidth by ensuring the power within the
fiber is constantly shifting between the modes. This strong mode mixing is also
responsible in part for the high losses within these fibers by coupling power into
these higher order modes which are then attenuated. The combination of these two
effects could explain why these fibers exhibit large losses and increased bandwidths.
These arguments are supported by the reduction in the measured far-field numer-
icial aperture after transmission through these fibers. Further and more detailed
explanations of these effects can be found in [96, 100, 101].

Whilst the results produced with the use of this source provided a good start,
transmission through longer lengths of fiber were still limited by the high loss of the
MPOFs and will have to await the delivery of a low noise, high power 1µm source.

5.3.4 Summary

The work presented in this chapter has provided a basis for the testing of novel
MPOF fibers bandwidth characteristics. As no commercially available high power
sources exist at 10Gb/s in the wavelength range from 630 to 800nm the development
of this source was particularly noteworthy. Average powers for the 10Gb/s signal
were in excess of 60mW for the 638nm signal and 150mW for the 774nm signal.
The difference in powers can be attributed to the different processes employed to
generate the given signals. The 774nm signal was produced through SHG from a
strong (5W) pump at 1548nm, whereas the 639nm signal was generated through
SFG from two pumps, one of which was modulated at 10Gb/s. As this process is
peak power dependent, the SHG case enabled the peak power to double whilst under
a modulation scheme with a mark-space ratio of 1/2, whereas with the SFG source,
the 1\textmu m pump laser was not modulated, so the peak power was limited to that of the average power. Focusing and divergence issues with the two pump sources were also contributing to lower efficiency within the crystal, as the 1\textmu m pump had a significantly different beam profile from that of the 1600nm pump. Further work on the SFG source would benefit from the use of a doublet lens to focus the pumps into the crystal.

The experimental results for the SFG source were hampered by the noise issues originating from the 1\textmu m pump. Preliminary characterisation of the MPOF fibers were able to be carried out for data rates up to 5Gb/s, but as the source was not stable over any significant time period, these results were not repeatable and operation at the desired 10Gb/s data rate was unachievable. The SFG source generated 60mW average power at the wavelength of 639nm. This enabled transmission through \sim 40m of MPOF fiber and efforts were made to resolve the noise issues in the 1\textmu m source by replacement with a YDFA and a DFB operating at 1064nm. This source is scheduled for future delivery.

Despite the above mentioned issues with the initial source, we successfully tested several fibers using the SHG source, as seen in the previous section. The quality of the 10Gb/s converted signal proved to be excellent and more than adequate for these testing purposes. The lower BER seen in the 774nm signal is testament to the excellent conversion achieved. The most significant source of noise in this set-up would have to be that from the pump itself (ASE) the effective filtering through the crystal’s narrow phase matching bandwidth helps remove any ASE generated noise from the converted signal.

The work performed within this section has allowed the first successful transmission of a 10Gb/s signal in the visible through MPOF fibers. The measurements of the BER curves for two differently structured fibers has shown that micro-structuring can improve the bandwidth of MPOFs significantly.
Chapter 6

Conclusion

Within this study we have performed a comprehensive review of the experimental characteristics of the Bragg Scattering effect within optical fibers. We have measured the phase matching curves for this effect in two highly nonlinear fibers which exhibit opposite sign $\beta_4$ dispersion coefficients and have used the Bragg Scattering response to determine the dispersion parameters for both of these fibers. Using the observed asymmetries in the Bragg Scattering conversion response we predict both the size and profile of the zero dispersion wavelength fluctuations for one of the highly nonlinear fibers. We compared our measured conversion response to a numerically simulated response using these predictions and found good agreement. We have measured and discussed the Bragg Scattering tuning range, efficiency and bandwidth for several pump and idler wavelength detunings and have studied the Bragg Scattering response to input pump power. We have investigated via simulation the effects of uneven pump powers on the observed phase matching curves and we discussed the impact of stimulated Raman scattering on the Bragg Scattering process. We have constructed a high speed all optical switch based upon the Bragg Scattering process and have demonstrated good switching extinction ratios between ports. This work demonstrated for the first time the $\pi$-phase shift associated with the back converted signal in the Bragg Scattering process. We have also utilised Bragg Scattering in fibers for the error free conversion of a 10Gb/s data signal over a 33nm wavelength shift, additionally we have demonstrated the power penalties
induced by non-optimal Bragg Scattering conversion efficiencies. Throughout these studies we have presented practical suggestions and limitations regarding the implementation of a Bragg Scattering experiment for wavelength conversion applications. We have discussed the minimisation of competing and interfering effects through the sensible selection of the states of polarisation and wavelength distributions of the waves, and the implications that these have on the Bragg Scattering process.

We have also demonstrated Bragg Scattering in semiconductor optical amplifiers for wavelength conversion applications. We have discussed the benefits of using Bragg Scattering over other nonlinear effects in semiconductor optical amplifiers and compared the performance of the two four wave mixing effects of Modulation Instability and Bragg Scattering in a wavelength conversion experiment. We have used Bragg Scattering for the wavelength conversion of multiple data channels with both 50 and 100GHz channel spacings and observed low power penalties due to crosstalk. We have also investigated Bragg Scattering in semiconductor optical amplifiers for high bit rate wavelength conversion applications and have successfully converted an 80Gb/s data channel.

Aside from the investigations of the four wave mixing effect of Bragg Scattering we have also presented the work on wavelength conversion in nonlinear crystals for the generation of a 10Gb/s modulated source at visible wavelengths for the characterisation of prototype micro-structured polymer optical fibers. We have used both sum frequency and second harmonic generation to convert a modulated signal at $\sim 1550\text{nm}$ down to the visible waveband. Using these generated signals in the visible we have taken steps towards successfully characterising the bandwidth performance of these micro-structured polymer optical fibers. We have presented for the first time the transmission of a 10Gb/s data signal through 20m of two differently structured micro-structured polymer optical fibers.

Future applications of the Bragg Scattering process will depend mostly on the progress and improvements of the fibers in which it is implemented. The Bragg Scattering process is very sensitive to zero dispersion wavelength fluctuations, especially
for larger wavelength shifts. As such the uniformity of the highly nonlinear fiber is crucial for experiments designed to exploit this process’s unique attributes. With the future development and improvements in the manufacturing of highly nonlinear fibers, Bragg Scattering will become an important feature in low noise wavelength conversion applications.
Appendix A

Coupled Mode Equations

\[
\frac{dA_1}{dz} = i\gamma (|A_1|^2 + \epsilon |A_2|^2 + 2|A_3|^2 + \epsilon |A_4|^2) A_1 + i\gamma \epsilon A_2 A_3 A_4^* e^{i\Delta k z}, \quad (A.1)
\]

\[
\frac{dA_2}{dz} = i\gamma (|A_1|^2 + |A_2|^2 + \epsilon |A_3|^2 + 2|A_4|^2) A_2 + i\gamma \epsilon A_1 A_3 A_4 e^{-i\Delta k z}, \quad (A.2)
\]

\[
\frac{dA_3}{dz} = i\gamma (2|A_1|^2 + \epsilon |A_2|^2 + |A_3|^2 + \epsilon |A_4|^2) A_3 + i\gamma \epsilon A_1 A_2 A_4 e^{-i\Delta k z}, \quad (A.3)
\]

\[
\frac{dA_4}{dz} = i\gamma (|A_1|^2 + 2|A_2|^2 + \epsilon |A_3|^2 + |A_4|^2) A_4 + i\gamma \epsilon A_1^* A_2 A_3 e^{i\Delta k z}, \quad (A.4)
\]

where the wave-vector mis-match \( \Delta k \) is given by,

\[
\Delta k = \frac{(n_1 \omega_1 + n_4 \omega_4 - n_2 \omega_2 - n_3 \omega_3)}{c}, \quad (A.5)
\]

and \( \epsilon \) is determined by the state of polarisations of the four waves: \( \epsilon = 2 \) for \( BS_{||} \), and \( \epsilon = 1 \) for \( BS_{\perp} \). In this example, the state of polarisation of the waves are such that adjacent waves are perpendicular to each other.

If we treat waves 1 and 3 (Eq.(A.1) and (A.3)) as the pumps and assume they are strong with respect to the other waves and remain undepleted throughout the fiber, then they are easily solved to give

\[
A_1(z) = \sqrt{P_1} \exp \left[ i\gamma (P_1 + 2P_3) z \right], \quad (A.6)
\]

\[
A_3(z) = \sqrt{P_3} \exp \left[ i\gamma (2P_1 + P_3) z \right], \quad (A.7)
\]
where $P_1$ and $P_3$ are the incident pump powers at $z = 0$. This solution shows that the pumps only acquire a phase shift as a result of SPM and XPM in the undepleted pump approximation.

Simplifying Eq.(A.2) and (A.4) gives

$$\frac{dA_2}{dz} = i\gamma \epsilon (P_1 + P_3) A_2 + i\gamma \epsilon A_1 A_3^* A_4 e^{-i\Delta k z}, \quad (A.8)$$

$$\frac{dA_4}{dz} = i\gamma \epsilon (P_1 + P_3) A_4 + i\gamma \epsilon A_1^* A_2 A_3 e^{i\Delta k z}. \quad (A.9)$$

Substituting the solution for the pump waves (Eqs.(A.6) and (A.7)) into (A.8) and (A.9) we have

$$\frac{dA_2}{dz} = i\gamma \epsilon \left[ (P_1 + P_3) A_2 + \sqrt{P_1 P_3} A_4 e^{-i\Theta z} \right], \quad (A.10)$$

$$\frac{dA_4}{dz} = i\gamma \epsilon \left[ (P_1 + P_3) A_4 + \sqrt{P_1 P_3} A_2 e^{i\Theta z} \right], \quad (A.11)$$

where

$$\Theta = \gamma (P_1 - P_3) + \Delta k. \quad (A.12)$$

To solve these we introduce

$$B_2 = A_2 \exp [i\sigma_2 z], \quad (A.13)$$

$$B_4 = A_4 \exp [i\sigma_4 z], \quad (A.14)$$

where

$$\sigma_2 = \frac{1}{2} (\Delta k - \gamma (2\epsilon - 1) P_1 - \gamma (2\epsilon + 1) P_3), \quad (A.15)$$
\[ \sigma_4 = -\frac{1}{2} (\Delta k + \gamma (2\epsilon + 1)P_1 + \gamma (2\epsilon - 1)P_3). \tag{A.16} \]

Differentiating and rearranging Eqs. (A.13) and (A.14) yields another expression for \(dA_j/dz\) such that

\[
\frac{dA_2}{dz} = \frac{dB_2}{dz} \exp \left[-i\sigma_2 z\right] - A_2 i\sigma_2, \tag{A.17}
\]

\[
\frac{dA_4}{dz} = \frac{dB_4}{dz} \exp \left[-i\sigma_4 z\right] - A_4 i\sigma_4. \tag{A.18}
\]

Substituting (A.17) and (A.18) into both (A.8) and (A.9) respectively, we now find

\[
\frac{dB_2}{dz} = i(\sigma_2 + \gamma \epsilon (P_1 + P_3)) B_2 + i\gamma \epsilon \sqrt{P_1 P_3} B_4 e^{i(\sigma_2 - \sigma_4 - \Theta)z}, \tag{A.19}
\]

\[
\frac{dB_4}{dz} = i(\sigma_4 + \gamma \epsilon (P_1 + P_3)) B_4 + i\gamma \epsilon \sqrt{P_1 P_3} B_2 e^{i(\sigma_4 - \sigma_2 + \Theta)z}, \tag{A.20}
\]

which simplify to

\[
\frac{dB_2}{dz} = i\delta B_2 + i\tilde{\gamma} B_4, \tag{A.21}
\]

\[
\frac{dB_4}{dz} = -i\delta B_4 + i\tilde{\gamma} B_2, \tag{A.22}
\]

where \(\tilde{\gamma}\) is the nonlinear coupling coefficient

\[
\tilde{\gamma} = \epsilon \gamma \sqrt{P_1 P_3}, \tag{A.23}
\]

and \(\delta\) is the phase mis-match for the Bragg Scattering process

\[
\delta = \frac{\Delta k}{2} + \frac{\gamma (P_1 - P_3)}{2}. \tag{A.24}
\]
These have a general solution of

\[ B_2 = \left[ \cos (\kappa z) + i \frac{\delta}{\kappa} \sin (\kappa z) \right] B_2 (0) + i \gamma \sin (\kappa z) B_4 (0), \]  
\[ B_4 = i \gamma \sin (\kappa z) B_2 (0) + \left[ \cos (\kappa z) - i \frac{\delta}{\kappa} \sin (\kappa z) \right] B_4 (0), \]  

where

\[ \kappa = \sqrt{\gamma^2 + \delta^2}. \]
Appendix B

List of Publications


6. R. Provo, S. Murdoch, JD Harvey and D. Méchin. Experimental Demonstra-
tion of the Phase Matching Curve for Bragg Scattering in a Positive $\beta_4$ Fiber.

Bibliography


[57] F. Vanholsbeeck, S. Coen, P. Emplit, M. Haelterman, and T. Sylvestre. Coupled-mode analysis of stimulated Raman scattering and four-wave mixing


