STIMULATED BRILLOUIN SCATTERING (SBS) CHARACTERIZATION IN MODERN FIBRES AND A TECHNIQUE OF SLOW LIGHT GENERATION

BY

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DECLARATION

DECLARATION BY THE STUDENT

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DEDICATION

I dedicate this work to Maturi’s family and Giasaiga clan for their support and inspiration.

ABSTRACT

Stimulated Brillouin scattering (SBS) is one of the recent technology that is being developed to generate slow light in optical fibres. It is one of the simplest and most applicable methods of slow light production. Slow light is the reduction of group velocity for optical pulses propagating through a dispersive material. SBS in silica based optical fibres is a fundamental nonlinear phenomenon considered as interaction of light and pressure wave in a material. The same scattering process can be viewed quantum mechanically as if annihilation of a pump photon creates a Stokes photon and an acoustic phonon simultaneously. SBS process in optical fibres occurs at a frequency shift of approximately 11GHz. In this work a high power laser pump was used to obtain the Brillouin gain of a low power signal of -10 dBm. Four single mode modern fibres namely, standard fibre (STD), large area fibre (LA), reach fibre (R) and reduced slope fibre (RS)of different optical characteristics were used in the study. Brillouin threshold for STD, LA, R and RS was compared and the effect of length on Brillouin threshold was determined. Variation of signal delay with pump power, fibre length and temperature in SBS slow light was studied. The effect of pump linewidth on Stokes power was also investigated. It was found that both the R and RS fibres had the highest Brillouin activity. Brillouin threshold of each of the four fibres decreased with increase in length of fibre. However, Stokes power was observed to increase with fibre length. Signal delay was realized for pump power between 27 dBm and 30dBm for STD, LA and RS fibre. A maximum delay of 7.6 ps was observed for STD fibre. However, signal speed up of 4.2 ps was realized for R fibre. It was also noted that signal delay increased with increase in fibre length. An increase in temperature resulted to a corresponding increase in Stokes power and signal delay of 1.6ps for RS. Moreover, increase in pump linewidth caused a decrease in Stokes power. This study is of great significance since it immensely contributes to practical applications in optical telecommunication, operation of SBS based optical sensors and information systems such as optical buffers, optical synchronizers and optical equalizers.

TABLE OF CONTENTS

CONTENT PAGE

DECLARATION ii

DEDICATION iii

ABSTRACT iv

TABLE OF CONTENTS v

LIST OF FIGURES vii

LIST OF ABBREVIATIONS AND SYMBOLS ix

ACKNOWLEDGEMENT xii

INTRODUCTION 1

1.1 Background 1

1.2 Problem Statement 4

1.3 Justification 5

1.4 Objectives 6

LITERATURE REVIEW 7

2.1 Introduction 7

2.2 Fibre Nonlinearity 7

2.3 Nonlinear Birefringence 8

2.5 Slow Light 14

2.5.1 Waveguide Dispersion 15

2.5.2 Waveguide-Loops 15

2.5.3 Coupled- Resonator Structures 16

2.5.4 Coherent Population Oscillation (CPO) 17

2.6 Stimulated Brillouin Scattering 18

2.6.1 Light Scattering 18

2.6.2 Brillouin Gain Spectrum 22

2.6.3 Coupled Intensity Equations 23

2.6.4Brillouin Threshold 23

2.6.5 Gain Saturation 25

2.6.6 Brillouin Slow Light in Optical Fibres 25

METHODOLOGY 29
3.1 Research Design.. 29
3.2 Simulation Setup 29
3.2.1. SBS Generation.. 29
3.2.2. Slow Light Processing and Measurement 30
CHAPTER FOUR 32
RESULTS AND DISCUSSIONS.. 32
4.1. Effect of Input Power on Stokes Power in Different Fibres at Different Linewidth. 32
4.2Stokes Power and Pump Power in Different Types of Fibre at Given Lengths.......... 33
4.3. The variation of Stokes Power with Fibre Length for Different Types of Fibres 35
4.4. Total Power and Temperature. 36
4.5 Effect of Pump Power on Signal Delay 37
4.6 Effect of Length on Signal Delay 41
4.7 Temperature and Slow Light... 42
CHAPTER FIVE 44
CONCLUSIONS AND RECCOMMENDATIONS 44
5.1 Conclusions... 44
Appendix 1.. 52
Conference Presentation and Publications 52

LIST OF FIGURES

Figure 2. 1: Lorentzian gain peak and the dispersion profile of the refractive index *n* and group index n_g associated with the gain spectrum by the Kramers-Kronig relations. 11

Figure 2. 2: Shows orientation of the wave vectors involved in Stimulated Brillouin scattering in an optical fibre. 20

Figure 2. 3: Concept of tunable delay introduced by slow light. 27

Figure 3. 1: Simulation setup for generating SBS based slow light. The PC: polarization controller, PM: power meter, ISO: Isolator, OSA: optical spectrum analyzer. SL: slow light 31

Figure 4. 1: (a) Effect of pump line width on Stokes power for LA RS and R. (b) Optimization of Stokes gain with linewidth for STD fibre. 32

Figure 4. 2: (a) Brillouin Stokes power as a function of Brillouin pump power for different single mode fibres at probe signal power of -10 dBm. (b) Brillouin threshold power as a function of fibre length for SMF_ reduced slope (RS), large area (LA), standard (STD) and reach (R). 33

Figure 4. 3: Stokes power variation with fibre length for STD, LA, R and RS fibre. . 35

Figure 4. 4: Effect of temperature on Stokes power for (a) 0.005km and (b) 0.01km SMF_Reach fibre, Large Area fibre, Standard fibre and Reduced Slope fibre. 36

Figure 4. 5: Variation of total power with time for different pump power for 1km SMF (a)Large Area (b) Standard fibre (c) Reach and (d)Reduced Slope. 37

Figure 4. 6: Variation of total power with time for different input power for 1.5km SMF (a) Large Area (b) Standard fibre (c) Reach and (d)Reduced Slope. 38

Figure 4. 7: Variation of power with time for different input power for 2km SMF(a)Large Area signal delay 4.1 ps (b) Standard fibre signal delay of 7.6 ps (c)

Reach signal delay 1.7 ps and (d)Reduced Slope signal delay 0.02 ps. 39

Figure 4. 8: Relationship between time delay with pump power for STD, LA, R and RS at 1km, 1.5km and 2km...40

Figure 4. 9: Variation of signal delay with length for LA, STD, R and RS fibres. 41

Figure 4. 10: Variation of power with time for different temperature for 0.6km SMF_Reduced Slope. The time delay is 1.6ps. 42

Figure 4. 11: Variation of power with time for different temperature for 1.5km SMF_Reduced Slope. 43

LIST OF ABBREVIATIONS AND SYMBOLS

CPO- Coherent Population Oscillation

CROW-coupled-resonator optical waveguide

CW- Continuous Wave

DGD- Differential Group delay

EDF- Erbium Doped Fibre

FWM- Four-wave mixing

GVD-Group Velocity Dispersion

ICT- Information Communication Technology

I_P- Pump Intensity

I_S-Stokes Intensity

KKR- Kramer-Kronig Relation

LA- Large Area

MZM- Mach-Zehnder Modulator

OSA-Optical Spectrum Analyzer

PC-Polarization Controller

PM-Power Meter

PMD-Polarization Mode Dispersion

R- Reach

RS- Reduced Slope

SBS- Stimulated Brillouin Scattering

SMF-Single Mode Fibre

SPM-Self Phase Modulation

SRS-Stimulated Raman Scattering

STD- Standard

VPI- Virtual Photonics Include

WDM-Wavelength Division Multiplexing

XPM-Cross Phase Modulation

A_{eff} -Effective core Area

c -Speed of Light

L_{eff} -Effective Length

$\vec{E}$ -Electric Field

n -Refractive Index

θ -Angle between Pump and Stokes field

ε_0 -Vacuum Permittivity

χ -Magnetic Susceptibility

α -Attenuation Constant

g_B -Brillouin Gain Coefficient

Ω -Frequency Shift

β_m -Modal Birefringence

V_g -Group Velocity

λ -Wavelength

$\Delta\tau$ -Differential Group Delay

L_B -Beat Length

k_a -Wave vector of Acoustic wave

γ -Nonlinear Effect

v_B -Brillouin shift

K -Bulk Modulus

ρ - Material density

δ - Temperature dependent parameter

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CHAPTER ONE

INTRODUCTION

1.1 Background

It remains evident that optical fibre is steadily replacing copper wire as means of communication and data transmission. This is because of their excellent performance in regard to speed and capacity. Optical fibres are used in both long haul optical communication and Metro networks to transmit information using light as a carrier. An optical fibre has two regions of varying refractive index, known as the core and cladding [1]. The guidance of light signal within the fibre is as a result of total internal reflection of the light within the core and cladding interface.

Fibre optic cable advantages over copper include:

i) Speed: Fibre optic networks operate at high speeds - up to the gigabit.

ii) Bandwidth: has large carrying capacity.

iii) Distance: Signals can be transmitted further without needing to be strengthened.

iv) Resistance: Greater resistance to electromagnetic noise such as radios, motors or other nearby cables.

v) Maintenance: Fibre optic cables costs much less to maintain.

There are two major types of optical fibres namely: multimode and single mode fibres (SMF). Multimode fibre is designed to carry more than one signal at a time and can be categorized as step-index or graded-index fibre. Step- index multimode fibre has large core, up to 100 microns in diameter [2]. As a result, some of light rays that make up the digital pulse may travel a direct route, whereas others zigzag as they bounce off the cladding. These alternative pathways cause the different grouping of light rays, referred to as modes, to arrive separately at a receiving point. While graded-index multimode fibre contains a core which the refractive index diminishes gradually from the centre axis out towards the cladding. The higher the refractive index at the centre makes the light rays moving down the axis advance more slowly than those near the cladding. On the other hand, single mode fibres (SMF) are optical fibres designed to carry a single signal at a time [3]. It is used mainly for long distance signal transmission. SMF has a narrow core, and the index of refraction between the core and the cladding changes less than it does for multimode fibres. SMF allows for higher capacity to transmit information because it can retain the fidelity of each light pulse over longer distances, and it exhibits no dispersion caused by multiple modes. SMF also enjoys lower fibre attenuation and reduced delay spread than multimode fibre [4].The availability of low loss silica fibres has led not only to a revolution in the field of optical fibre communications but also to the advent of the new field of nonlinear fibre optics. Stimulated Brillouin scattering (SBS) and Stimulated Raman scattering (SRS) processes were studied as early as 1972 [1]. This work stimulated the study of other nonlinear phenomena such as parametric four-wave mixing and self-phase modulation [1, 5]. These effects negatively impact on the signal transmission e.g. crosstalk and power scattering. SBS is a nonlinear effect with low threshold and it is the result of interaction between an incident light wave and the optical fibre where most incident power is backscattered. Hence, this effect generally disturbs the signal transmission in optical communication systems. Therefore, it is normally attempted to suppress SBS in optical components and networks. However, there are many applications which exploit and benefit from the properties of SBS. The use of a single mode optical fibre as a medium for SBS offers additional advantages such as a low pump-power requirement owing to long interaction lengths and small areas, compatibility of the device with existing telecommunication systems and room temperature operation. Besides, slow-and fast light, Brillouin scattering was used to implement fibre lasers, fibre amplifiers [1]and optical fibre sensors [6]. SBS is an important effect used to produce slow light.

So far, slow light has been realized in wide variety of materials with different physical phenomena. This include; ultra-cold or-hot atomic gases [7-10], crystalline solids [11, 12], semiconductors [13, 14], optical fibres [15-17], and photonic structures [18, 19]. Slow light propagation in ultra-cold atomic gases was used to obtain a Bose-Einstein condensate [20]. The speed was reduced to 17m/s in a vicinity of a narrowband electromagnetically induced transparency (EIT). The environmental conditions were, however, a scientific challenge to be solved by photonic community. A significant step towards real applications was achieved in 2005 when slow light was experimentally and efficiently realized in an optical fibre using stimulated Brillouin scattering (SBS) [21]. To date, Brillouin slow light systems have proved to be an unmatched and unprecedented flexible timing as a result of their unique spectral tailoring capability [22, 23]. This makes Brillouin slow light attractive delay line in high flexibility of SBS, essentially the possibility to be achieved in any type of optical fibre and at any wavelength. Slow light techniques aim to increase group index by increasing dispersion ($dn/d\omega$). In the region of normal dispersion where $dn/d\omega > 0$ and $v_g < c$, light pulse propagates slower than light in vacuum this is called "slow light". In the region of anomalous dispersion where $dn/d\omega < 1$, then the case of "fast light", $v_g > c$ is realized. Such propagation is called "superluminal," owing to the fact that the group velocity is greater than the speed of light in a vacuum.

The SBS has several advantages compared to other methods of producing slow light [24].

1. For the time delay only small pump powers of a few milliwatts are required. Since the time delay depends directly on applied pump power, it can be continuously tuned over a wide range.
2. The SBS works at room temperatures and in all fibre types within their whole transparency range. It operates at all wavelengths, especially at those which are used in optical communications. Thereby, the input and output wavelengths of the signal pulses are maintained.
3. For the SBS-based slow light setups reliable off-the-shelf telecommunications components can be used.

The main limitations of SBS slow light include;

i. Narrow Brillouin bandwidth of around 35 MHz limits the maximum delayable distortion-free data rates to a few tens of Mbit/s which are not contemporary for today's data transmissions.
ii. The time delay of the pulses is accompanied by a strong broadening of the pulse width which reduces the effective time delay.
iii. The maximum achievable time delay saturates at high pump powers and hence, is limited by the pump depletion.

To resolve these drawbacks to improve SBS slow light performance broadband SBS, time delay enhancement and distortion reduction has been employed[25, 26].The ubiquitous role occupied by optical fibres in modern communication systems has stimulated research to realize slow light and SBS slow light has so far outperformed all the existing methods.

1.2 Problem Statement

Increased demand on higher bandwidth for internet services requires development of all optical networks with ultrahigh speed photonic switching and routing. Designing routers to temporary store or buffer packet of information is a challenge and one possibility is to buffer optical signal by reducing the speed of light. Therefore the best technology for slowing down light is required. Electromagnetically induced transparency (EIT) and coherent population oscillation (CPO) were the first methods used to slow down light. But these methods need expensive instruments and can be realized only in some special gas or crystal for certain wavelength which make it difficult in practice. For this reasons alternative methods that do not suffer from this drawbacks and work at wavelengths used in optical communications are necessary. Slow light via SBS has proved to be the most promising technique. Since, SMF can transmit signals over long distance with low distortion, therefore generation of slow light using optical fibre can be an alternative. Furthermore, different SMF have different optical properties which can influence the nature of SBS. It is therefore significant to determine the fibre which has low signal distortion while giving maximum delay.

1.3 Justification

Stimulated Brillouin Scattering in optical fibre can be one of the effective method of producing slow light at room temperature. Its advantage over other technologies include the fact that it is simple to implement and can be obtained at any wavelength within transparent window of optical fibre. In addition, SBS only requires moderate pump powers of about 3dBm and can use off the shelf fibre optics components, providing easy integration in optical buffering, optical switching and routing. Hence, SBS slow light provides a platform for the development of wide range of applications in optical signal processing and optical communication. Since, SBS slow light can be controlled via pump, it can therefore be tailored to minimize distortion and optimize bandwidth. Thus, this study is of great significance because of its contribution to practical applications in optical telecommunication and information systems.

1.4 Objectives

i) To characterize optical fibres on the basis of stimulated Brillouin scattering.

ii) To determine the parameters that influence SBS in optical fibre.

iii) To generate slow light using Stimulated Brillouin Scattering method.

iv) To study the factors that affect SBS based slow light.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Stimulated Brillouin scattering is one of the nonlinear effect that can occur in optical fibre during signal transmission. Introduction of high signal power into the fibre is known to be the cause of spontaneous Brillouin scattering. This chapter gives an introduction to fibre nonlinearity and fundamentals of slow light systems. Different techniques of generating slow light has been highlighted. The fundamental of SBS such as its generation, properties like Brillouin gain spectrum, Brillouin threshold and gain saturation are discussed.

2.2 Fibre Nonlinearity

The response of any dielectric medium to light becomes nonlinear; for intense electromagnetic fields and optical fibres are not an exception. On a fundamental level, the origin of nonlinear response is related to a harmonic motion of bound electrons under influence of an applied field. As a result, the total polarization $\vec{P}$ induced by electric dipoles is not linear in the field *E*, but satisfies the more general relation [1],

$$\vec{P} = \varepsilon_0 \left(\chi \vec{E} + \chi^2 \vec{E}^2 + \chi^{(3)} \vec{E}^3 \right) \tag{2.1}$$

where ε_0 is the vacuum permittivity and χ is susceptibility. The linear susceptibility χ represents the dominant contribution to $\vec{P}$ and its effects are included through the refractive index n and the attenuation coefficient α. The second order susceptibility $\chi^{(2)}$ is responsible for such nonlinear effects as second harmonic generation and sum frequency generation. However, it is a non-zero only for media that lack inversion symmetry at the molecular level. As SiO_2 is symmetric molecule, $\chi^{(2)}$ vanishes for silica glasses. As a result, optical fibres do not normally exhibit second order nonlinear effects. The lowest order nonlinearity effects in optical fibres originate from the third order susceptibility $\chi^{(3)}$ which is responsible for phenomena such as third harmonic generation, four wave mixing (FWM) and nonlinear refraction. Most of nonlinear effects in optical fibres originate from nonlinear refraction, a phenomenon referring to the intensity dependent on the refractive index.

The nonlinear effects governed by the third order susceptibility $\chi^{(3)}$ are elastic in the sense that no energy is exchanged between the electromagnetic field and the dielectric medium. A second class of nonlinear effects results from stimulated inelastic scattering in which the optical field transfers part of its energy to the nonlinear medium. Two important nonlinear effects in optical fibres fall in this category; both of them are related to 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 fibres. The main differences between the two are; optical phonons participate in SRS while acoustic phonons participate in SBS [1], and SBS in SMF occurs only in the backward direction whereas SRS can occur in both directions.

2.3 Nonlinear Birefringence

Birefringence in optical fibre is the difference in refractive index between particular pair of orthogonal polarized modes. In polarization-maintaining fibres, the built-in birefringence is made much larger than random changes occurring due to stress and core-shape variations. As a result, such fibres exhibit nearly constant birefringence along their entire length. This kind of birefringence is called linear birefringence [1]. Nonlinear effects in optical fibres can be observed at relatively high power levels. Since the discovery of intensity-dependent change in the refractive index of medium [27], it has been well known that the self-induced nonlinear birefringence in an optical Kerr medium (medium whose refractive index changes when an electric field is applied) leads to ellipse rotation, i.e. intensity-dependent rotation of elliptically polarized light. In its simplest form, the refractive index *n* can be written as [28]

$$n' = n_0 + \underbrace{n_2 \frac{P}{A_{eff}}}_{\substack{\text{nonlinear} \\ \text{contribution}}} \tag{2.2}$$

where n_0 is the linear refractive index, n_2 is the nonlinear-index coefficient, A_{eff} is the effective core area of the medium and P is the optical power inside the fibre. The intensity dependence of the refractive index leads to a large number of interesting nonlinear effects; the most widely studied due to their negative effect to the signal in a WDM system are self-phase modulation (SPM), cross-phase modulation (XPM) and four wave mixing (FWM) [1]. Nonlinear fibre optics plays an increasingly important role in the design of high-capacity light wave systems. When the nonlinear effects in optical fibres become important, a sufficiently intense optical field can induce nonlinear birefringence whose magnitude is intensity dependent.

The change of velocities of light is bound to oscillations of material particles. This process is represented by the refractive index n which depends on the material itself. The influence of the material is expressed by the relative permittivity ε_r and the relative magnetic permeability μ_r. Then the refractive index can be written as:

$$n(\omega) = \sqrt{\varepsilon_r(\omega)\mu_r(\omega)} \text{ with } \varepsilon_r(\omega) = 1 + \chi(\omega) \tag{2.3}$$

Where $\chi(\omega)$ denotes the frequency-dependent electric susceptibility. The electric susceptibility is a material property which describes the ability of polarization of the medium inside an electrical field. In dispersive dielectric media $\mu_r(\omega) \approx 1$ and the refractive index, the permittivity and the susceptibility are complex. Therefore, the complex relative permittivity becomes:

$$\hat{\varepsilon}_r(\omega) \approx \hat{n}(\omega)^2 = (n'(\omega) + jn''(\omega))^2 = n'^2(\omega) - n''^2(\omega) + 2jn'(\omega)n''(\omega) \tag{2.4}$$

where the real part leads directly to the refractive index n and the imaginary part leads to an absorption α. Both the refractive index n and the absorption coefficient α are frequency-dependent which is known as dispersion. Additionally, both quantities are directly related to each other. In 1928, Kramer and Kronig showed that there are integral connections between the real and the imaginary parts of the complex linear susceptibility, $\chi'(\omega)$ and $\chi''(\omega)$, which henceforth was called Kramers-Kronig Relation (KKR).

The most common expression of the KKR is

$$\chi'(\omega) = \frac{2}{\pi}\int_0^\infty \frac{\omega'\chi''(\omega')}{\omega'^2 - \omega^2} d\omega' \tag{2.5}$$

$$\chi''(\omega) = -\frac{2}{\pi}\int_0^\infty \frac{\omega'\chi''(\omega')}{\omega'^2 - \omega^2} d\omega' \tag{2.6}$$

In practice, modified versions of equation 2.5 and 2.6 which directly relate the refractive index $n(\omega)$ and the absorption coefficient $\alpha(\omega)$ is used [29] as indicated in equation 2.7 and 2.8.

$$n(\omega) = 1 + \frac{c}{\pi}\int_0^\infty \frac{\alpha(\omega')}{\omega'^2 - \omega^2} d\omega' \tag{2.7}$$

$$\alpha(\omega) = -\frac{4\omega^2}{\pi c}\int_0^\infty \frac{n(\omega') - 1}{\omega'^2 - \omega^2} d\omega' \tag{2.8}$$

Within the full width at half maximum (FWHM) bandwidth the absorption spectrum leads to a strong anomalous dispersion where the refractive index has a negative slope. Hence, according to group velocity expression [24], the group index will be decreased and the group velocity will be increased. In contrast to this, a peak or gain spectrum would lead to a strong normal dispersion where the group index is increased and group velocity is decreased. Thus, the KKR show that a strong material resonance, which results in amplification or absorption processes, produces a large dispersion which is necessary for slow or fast light. Such a feature is the basis of many methods for group velocity alteration.

Figure 2.1 below indicates that there is large and positive group index in the region of strong linear dispersion in *n*.

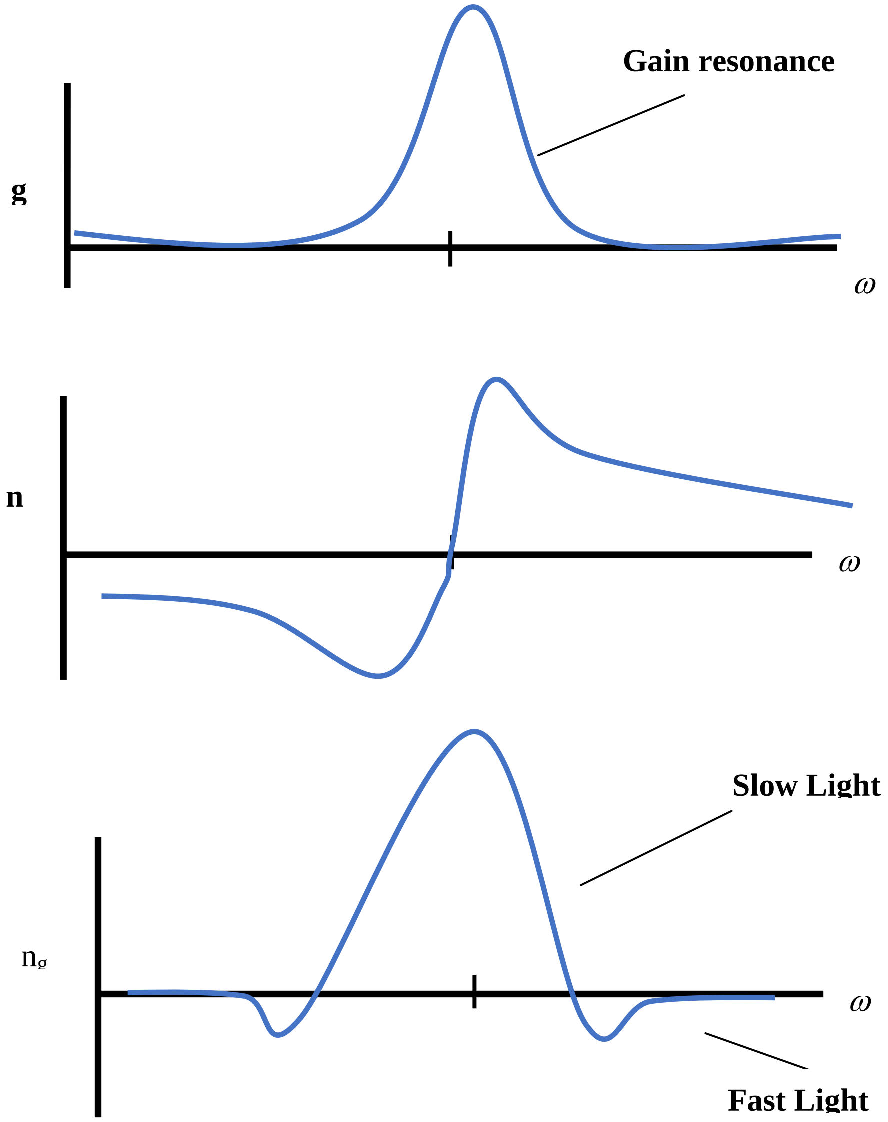

Figure 2. 1: Lorentzian gain peak and the dispersion profile of the refractive index n and group index n_g associated with the gain spectrum by the Kramers-Kronig relations.

This region of slow-light propagation is accompanied by fast-light regions due to strong normal dispersion in the wings of the refractive index dispersion profile.

2.4 Polarization Mode Dispersion

A fibre with constant modal birefringence has two principal axes along which the fibre is capable of maintaining the state of linear polarization of the incident light. These axes are called slow and fast axes based on the speed at which light polarized along them travels inside the fibre. When low power, continuous-wave (CW) light is launched with its polarization direction oriented at an angle with respect to the slow (or fast) axis, the polarization state of the CW light changes along the fibre from linear to elliptic, elliptic to circular, and then back to linear in a periodic manner over a distance known as the beat length [21]. The input polarization is oriented either to the fast or slow axis, only one polarization state and one pulse is present at the output, this defines eigenstate of the system. The output polarization is also same as input polarization, and an output pulse is delayed with respect to fast axis. The difference in phase velocity results in fast component walking through the slow component, slipping on full optical wave over birefringent beat length.

A single mode fibre is not truly single mode because it supports two degenerate modes that are polarized in two orthogonal directions. Under ideal conditions (perfectly cylindrical symmetry and stress free fibre), a mode excited with its polarization in the x-direction would not couple to the mode with the orthogonal y-polarization state. In real fibres, small departures from cylindrical symmetry because of random variations in core shape and stress-induced anisotropy result in a mixing of two polarization states by breaking the mode degeneracy. Mathematically, the mode propagation constant β becomes slightly different for the modes polarized in the x and y directions. This property is referred to as modal birefringence [1]. The strength of modal birefringence is defined as

$$\beta_m = \frac{\left|\beta_x - \beta_y\right|}{k_0} = \left|n_x - n_y\right| \qquad (2.9)$$

Where n_x and n_y are the modal refractive indices for orthogonally polarized states and k_0 is the wave vector. For a given value of β_m, the two modes exchange their powers in a periodic fashion as they propagate inside the fibre with a periodic length given by;

$$L_B = \frac{2\pi}{\left|\beta_x - \beta_y\right|} = \frac{\lambda}{B_m}. \qquad (2.10)$$

The length L_B is called the beat length. The axis along which the mode index is smaller is called the fast axis because the group velocity is larger for light propagating in that direction. For the same reason, the axis with large modal index is called the slow axis. In standard optical fibres, β_m is not constant along the fibre but changes randomly because of fluctuations in the core shape and anisotropic stress. As a result, light launched into the fibre with fixed state of polarization changes its polarization in a random fashion. This change in polarization is typically harmless for continuous wave (CW) light because most photo-detectors do not respond to polarization changes of the incident light. It becomes an issue for optical communication systems where short pulses are transmitted over long lengths. If an input pulse excites both polarization components, the two components travel along the fibre at different speeds because of their different group velocities. The pulse becomes broader at the output end because group velocities change in response to random changes in fibre birefringence. This phenomenon is referred to as polarization mode dispersion (PMD). Because the imperfections are random, the pulse spreading effects correspond to a random walk, and thus have a mean polarization-dependent time-differential $\Delta\tau$ (also called the differential group delay, or DGD) proportional to the square root of propagation distance *L*:

$$\Delta\tau = D_{PMD}\sqrt{L} \tag{2.11}$$

D_{PMD} is the PMD parameter of the fibre, typically measured in ps/√km, a measure of the strength and frequency of the imperfections. The extent of pulse broadening can be estimated from time delay ΔT occurring between the two polarization components during propagation of an optical pulse. For fibre of length L and constant birefringence B_m, ΔT is given by

$$\Delta T = \left| \frac{L}{v_{gx}} - \frac{L}{v_{gy}} \right| = L\left|\beta_{1x} - \beta_{1y}\right| = L\delta\beta_1 . \tag{2.12}$$

2.5 Slow Light

Slow light refers to the reduction of group velocity for optical pulses propagating through a dispersive material. Although slow light was initially motivated by scientific curiosity, this technique has been rapidly developed for many potential applications. Successful experiments on slow light propagation has been demonstrated with astonishing control of the group velocity, namely the velocity at which a signal travels in a material from nearly stopping it to exceeding the vacuum velocity, *c* or even reaching negative velocities [7]. Some of the techniques used to generate slow light include; waveguide dispersion, waveguide loops, Coupled Resonator Structures and Coherent Population Oscillation.

2.5.1 Waveguide Dispersion

In an optical fibre, a fraction of the energy in a guided electromagnetic mode propagates in the core, and the remainder propagates in the cladding. The effective refractive index of the mode depends on this fraction. For different wavelengths, the fraction changes, producing an index variation frequency. This dispersion is known as waveguide dispersion or intra-modal dispersion. Additionally, each mode of a multi-mode waveguide has its own group velocity; if a pulse coupled into a multi-mode waveguide propagates in several modes with different group velocities, intermodal dispersion results. Typically optical fibres do not have enough dispersion to be interesting for slow light purposes. However, novel waveguides such as coupled-resonator structures can provide greatly enhanced waveguide dispersion [30].

2.5.2 Waveguide-Loops

The easiest way to realize an optical pulse delay is to send the signal into a delay line with a fixed length, e.g. an optical waveguide or fibre [31]. Inside the fibre segment the pulse propagates with the group velocity which depends on the group index of the transmitting medium. The time delay is then caused by the fibre length and is equal to the group delay $t_g = L/v_g$. If higher delays are needed the delay line can also be passed through several times. The pulse propagates as long in the loop as it will be switched onto another path. Hence, the signal can be stored a certain time or arbitrarily long if the waveguide attenuation is neglected. However, the achievable time delay or storage time depends directly on the constructional defined length of the waveguide. Another problem is the attenuation of the waveguides which strongly reduces the signal power if L is very large. Additionally, very long waveguides also induces a high signal distortion.

2.5.3 Coupled- Resonator Structures

Slow-light effects have also been explored in coupled-resonator structures, alternately called coupled-resonator optical waveguides (CROWs). Low group velocities are observed in the propagation of light across the CROW, as a result of weak coupling and feedback between the resonators [32]. Light couples evanescently into the first resonator. As the light resonates there, it couples evanescently into the second resonator, where it also resonates. It then couples evanescently into the third resonator, and so forth, until it has 'leaked' across the entire waveguide. Photonic crystals are formed by introducing periodic refractive index changes in a dielectric medium. Because of the periodic index modulation, light within certain wavelength bands is unable to propagate in the photonic crystal. In analogy to semiconductor crystals, these bands are called forbidden bands or photonic band gaps. Often, photonic crystals are made by drilling rectangular spaced air holes into a dielectric, with the index contrast between air and the dielectric providing the periodic index modulation. One-, two- and three dimensional photonic crystals can be formed in such a way. By convention, however, the term "photonic crystal" is typically reserved for two- and three-dimensional structures with high index contrast. A small defect introduced in the photonic crystal lattice will allow light to propagate in the vicinity of the defect, creating a resonator. If a periodic series of defects is introduced in the photonic crystal, the resonators can couple evanescently, forming a photonic crystal defect waveguide, another form of CROW. In CROW devices, the electric field is enhanced within the resonators, leading to an enhancement of optical nonlinearity [32]. Nonlinear effects typically depend on the strength of the incident electric field raised to some power. Coupled-resonator optical waveguides typically see a nonlinearity enhancement that scales as a square of the slowing factor [33]. Slow light has also been explored in certain optical filters including fibre Bragg gratings [34]. This is thought of conceptually as a series of coupled resonators. The dispersion and slow light effects in optical filters are similar to those of coupled- resonator structures.

2.5.4 Coherent Population Oscillation (CPO)

Coherent population oscillation (CPO) is a quantum effect that can generate a spectrally narrow hole in the center of an absorption profile due to a wave-mixing interaction. Recently, this narrow spectral feature has been exploited for slow light propagation at room temperature in semiconductor structures [35] such as quantum structure optical amplifiers, in solid crystals [36] and optical fibres [15]. When a strong pump wave illuminates a saturable medium, the population of the ground state is excited to the first absorption band. Then the population returns to the ground state in a few milliseconds (T_1). A weak probe wave is then launched to the medium and interferes with the pump. The induced beating signal makes the population of electron oscillate between the ground state and the excited state. Due to the long decay time T_1, the population oscillations are only appreciable under condition that the product of δ and T_1 is approximately equal to 1, where δ is a beating frequency between the pump and probe waves. When this condition is satisfied, the pump wave can efficiently scatter off the ground state population into probe wave. As a result, a spectral hole appears at the center of the probe frequency and the spectral width of the hole is inversely proportional to the relaxation time T_2. In practical point of view, erbium doped fibres (EDF) gives rise to longer interaction lengths and stronger effects for coherent population oscillations. In addition, since EDF amplifier plays the role of both an absorber and an amplifier depending on the pump power, this system opened the possibilities to realize slow light and experimentally demonstrated the superluminal propagation with negative group velocity [37].

2.6 Stimulated Brillouin Scattering

SBS process has proved to be the best technology to generate slow light at any wavelength. Hence, the generation of the slow light based on SBS is described in this section. The fundamental of SBS itself is explained first. These include the creation and properties of SBS, such as the threshold and the gain spectrum.

2.6.1 Light Scattering

Light scattering is known as a general physical process in an optical medium. When one or more localized non-uniformities are present in the medium, light intends to be forced to deviate from a straight trajectory while being transmitted through the medium. In other words, light scattering occurs as a consequence of fluctuations in the optical properties of the medium. Nevertheless, light can be scattered under conditions such that the optical properties of the medium are not modified by the incident light. This scattering is referred to as spontaneous or linear scattering. In optical fibres, the type of spontaneous scattering is identified in terms of spectral components of the scattered light. It is separated in two main categories: elastic scattering or inelastic scattering. However, the universal principles of energy and momentum conservations are preserved in all cases [1]. In elastic scattering, the induced light from a scattering process has an identical spectral profile to the incident light. In inelastic scattering, energy exchange occurs between light and the dielectric medium, which leads to a frequency shift between incident and scattered lights. By definition, the down-shifted frequency components are referred to as Stokes components while the up-shifted components are called anti-Stokes waves. Different spectral characteristics of the scattered light are observed for different scattering processes since distinct types of interaction between the radiation and the media are respectively involved. The three major scattering phenomena include: Brillouin scattering, Rayleigh scattering and Raman scattering.SBS was first observed in 1964 and is a nonlinear three wave interaction between a forward going pump beam, a forward going acoustic wave, and a backward travelling Stokes beam. The pump field generates the acoustic wave through the process of electrostriction. Electrostriction describes the deformation of the material or change of the density of the medium in the presence of an applied electric field. That is, the electric field of the pump wave exerts oppositely directed forces on the ions in the silica, inducing a strain which generates the sound wave (acoustic wave). In turn, that acoustic field modulates the refractive index of the medium, resulting in a Bragg grating that scatters the pump into Stokes beam. The Stokes scattered light is downshifted in frequency by the Doppler shift, because the grating is moving forward at the acoustic (sound) speed. The process continues and more and more optical power of the pump wave is backscattered and transferable to the Stokes wave. The Brillouin scattering effect becomes stimulated that is, backscattered power exceeds transmitted power if the reason for density modulation is the pump wave itself and the pump power exceeds a certain threshold. The same scattering can be viewed quantum mechanically as if annihilation of a pump photon creates a Stokes photon and an acoustic phonon simultaneously. Since both the energy and the momentum must be conserved during each scattering event the frequencies and the wave vectors are related by;

$$\omega_B = \omega_p - \omega_s \tag{2.13}$$

where ω_p, ω_s are frequencies of pump and Stokes waves respectively and $\omega_B = \omega_a$.

$$k_a = k_p - k_s \tag{2.14}$$

where k_p and k_s are wave vectors of pump and Stokes waves respectively

The frequency ω_B and the wave vector k_a of the acoustic wave satisfy the standard dispersion relation;

$$\omega_B = v_A |k_a| \approx 2 v_A |k_p| \sin(\theta/2) \tag{2.15}$$

where θ is the angle between the pump and the Stokes field. From Equation (2.15) it is evident that frequency shift of the Stokes wave depends on the scattering angle. In particular, ω_B is maximum in the backward direction ($\theta = \pi$) and vanishes in the forward direction $\theta = 0$. In single mode fibres, the only relevant directions are the forward and backward directions. Ideally, since there is no frequency shift in the forward direction, the entire Stokes energy must get backscattered. For this reason, SBS occurs only in the backward direction with the Brillouin shift given by;

$$\nu_B = \frac{\omega_a}{2\pi} = \frac{2n v_a}{\lambda_p} \tag{2.16}$$

However, spontaneous or thermal Brillouin scattering may occur in forward direction in optical fibres but is quite small compared to backscattering.

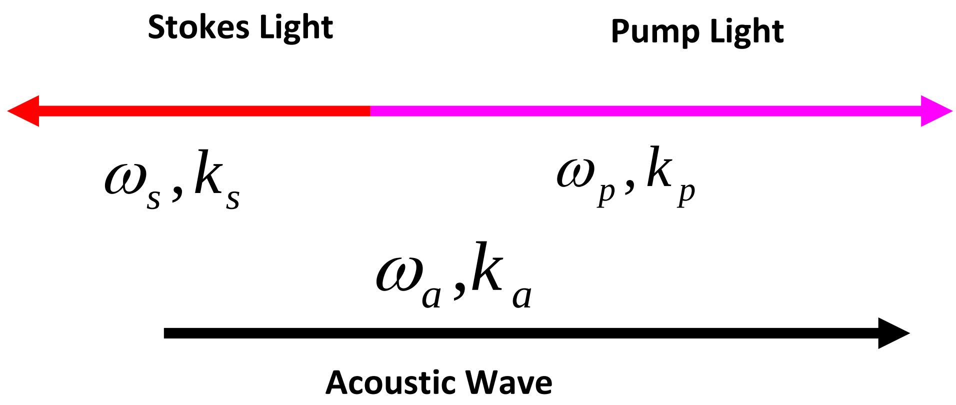

Figure 2. 2: Shows orientation of the wave vectors involved in Stimulated Brillouin scattering in an optical fibre.

As the incident power in a fibre is increased, the increase in Stokes power is slow in the initial stage due to spontaneous scattering. As the pump is increased further, it may lead to an exponential growth of the Stokes power. The input power at which the backscattered power begins to increase and pump wave begins to deplete is known as the threshold. After threshold power is exceeded, the pump power reaching the output end of the fibre is no longer a linear function of input power. Thus at a certain extent of increase in input power, SBS limits the maximum power that can be launched into the fibre for optimum transmission. The process of SBS is classically described as a nonlinear interaction between a pump wave at frequency ω_p and a Stokes wave at frequency ω_s. The two waves are coupled by nonlinear polarizations. It must be pointed out that the higher order polarization associated to SBS is not caused by the nonlinear susceptibilities induced by a parametric process, but by a sound wave induced by mean of electrostriction. Therefore, the description of SBS starts from the propagation of the three interacting waves using the following [38]:

$$\Delta^2 E_p - \frac{n^2}{c^2}\frac{\partial^2 E_s{}^2}{\partial t^2} = \mu_0 \frac{\partial^2 P_p{}^{NL}}{\partial t^2} \qquad 2.17\ (a)$$

$$\Delta^2 E_s - \frac{n^2}{c^2}\frac{\partial^2 E_s{}^2}{\partial t^2} = \mu_0 \frac{\partial^2 P_s{}^{NL}}{\partial t^2} \qquad 2.17\ (b)$$

$$\frac{\partial^2 \Delta\rho}{\partial t^2} + \Gamma\nabla^2 \frac{\partial \Delta\rho}{\partial t} - v_a \nabla^2 \rho = -\nabla. f \qquad 2.17\ (c)$$

where E_p and E_s are the amplitudes of the electric fields of the pump and Stokes waves, respectively. Notice that, here $\Delta\rho$ denotes the density variation rather than the pressure variation to describe the acoustic wave. These equations can in turn be coupled through the electrostrictive force using the material constitutive relations [38]:

$$P^{NL}(r,t) = \Delta\varepsilon E(r,t) = \frac{\gamma_e}{\rho_0}\Delta\rho E(r,t) \qquad (2.18)$$

$$\Delta f(r,t) = \frac{1}{2}\gamma_e \nabla^2 \left(\left| E_p(r,t) + E_s(r,t) \right|^2 \right) \qquad (2.19)$$

To simplify the coupled equations involved in SBS, one can assume that, the state of polarization (SOP) of the pump wave is parallel to the SOP of the Stokes wave, designated by the unit polarization vector. The fibre attenuation is considered negligible while the acoustic damping coefficient is maintained in the expressions. The system is in steady-state conditions, where the life time of acoustic wave is so short that it can be neglected when compared to that of the pump wave.

2.6.2 Brillouin Gain Spectrum

The SBS process provides a way of amplifying a weak signal whose frequency is within the Brillouin gain bandwidth. The growth of the Stokes wave is characterized by the Brillouin gain spectrum $g_B(\Omega)$ peaking at $\Omega = \Omega_B$. The spectral width of the gain spectrum is small because it is related to damping time of acoustic waves or phonon lifetime. Exponential decay of acoustic waves results in gain presenting a Lorentzian spectral profile. That is, acoustic waves are assumed to decay as $\exp(-\Gamma_B t)$, the Brillouin gain has a Lorentzian spectrum of the form [39],

$$g_B(\Omega) = g_B \frac{\left(\Gamma_B/2\right)^2}{(\Omega-\Omega_B)^2 + \left(\Gamma_B/2\right)^2} \tag{2.20}$$

where the peak value of the Brillouin-gain occurring at $\Omega = \Omega_B$ is given by

$$g_p = g_B(\Omega) = g_B \frac{2\pi^2 n^7 p^2{}_{12}}{c\lambda_p^2 \rho_o v_A \Gamma_B}, \tag{2.21}$$

where p_{12} is the longitudinal elasto-optic coefficient and ρ_o is the material density. From equation (2.16) it is noted that v_B varies with λ_p, Δv_B is expected to obey a λ_p^{-2} dependence on the pump wavelength. This narrowing of the Brillouin gain profile with an increase in λ_p cancels the decrease in gain apparent from Equation 2.21. As a result, the peak value g_p is nearly independent of the pump wavelength. For a CW pump, the Brillouin gain is reduced considerably if the spectral width Δv_p of the pump exceeds Δv_B. this can happen when a multimode laser is used for pumping. It also happens for a single-mode pump laser whose phase varies rapidly on a time scale shorter than the phonon lifetime T_B. The SBS process scatters photons off the pump wave so as to create the amplification at the Stokes wave.

2.6.3 Coupled Intensity Equations

The interaction between two counter-propagating waves, pump and Stokes, fulfills the following equations [39]:

$$\frac{dI_p}{dz} = -g_B I_p I_s - \alpha I_p \qquad 2.22\ (a)$$

$$\frac{dI_s}{dz} = -g_B I_p I_s + \alpha I_s \qquad 2.22\ (b)$$

One can readily verify that in the absence of fibre losses $\alpha = 0$,

$$\frac{d}{dz}\left(I_p - I_s\right) = 0 \qquad (2.23)$$

And $\left(I_p - I_s\right)$ remains constant along the fibre.

Equations 2.22(a) and 2.22 (b) assume implicitly that the counter-propagating pump and Stokes waves are linearly polarized along the same direction and maintain their polarization along the fibre. This is the case when the two waves are polarized along a principal axis of a polarization-maintaining fibre. The relative polarization angle between the pump and Stokes waves varies randomly in the conventional optical fibres.

2.6.4Brillouin Threshold

The Brillouin threshold is defined as the input pump power at which the backscattered Stokes power is equal to the pump power at the fibre output [39]. For the purpose of estimating the Brillouin threshold, pump depletion can be neglected. Using $I_p(z) = I_p(0)e^{\alpha z}$

in equation 2.22 (a) and integrate it over the fibre length *L*, the Stokes intensity is found to grow exponentially in the backward direction as

$$I_p(0) = I_s(L)\exp\left(g_B P_0 L_{eff} \Big/ A_{eff} - \alpha L \right) \tag{2.24}$$

where $P_o = I_p(0)A_{eff}$ is the input pump power, A_{eff} is the effective core area, and the effective interaction length is given by

$$L_{eff} = [1 - \exp(-\alpha L)] \Big/ \alpha \tag{2.25}$$

Equation 2.24 show how a Stokes signal incident at z=L grows in the backward direction because of Brillouin Amplification occurring as a result of SBS. In practice, unless the fibre is used as a Brillouin amplifier where a signal is fed, the Stokes wave grows from the noise provided by the spontaneous Brillouin scattering. The noise power can be viewed as injection of a factious photon power mode at a distance where the gain exactly compensates the fibre loss [39]. Brillouin threshold is found to occur at a critical pump power P_{cr} obtained from the equation [40-42]:

$$g_B P_{cr} L_{eff} \Big/ A_{eff} \approx 21 \tag{2.26}$$

where $g_{\mathbf{B}}$ is the peak value of the Brillouin gain.

Low Brillouin threshold makes SBS a dominant nonlinear process in optical fibres [43, 44]. Variation in the doping level along the radial direction leads to slight changes in the acoustic velocity in that direction. As a result, the SBS threshold depends, to some extent, on various dopants used to make the fibre. Similarly, longitudinal variations in the Brillouin shift v_B along the fibre length can reduce the effective Brillouin gain and increases the SBS threshold.

2.6.5 Gain Saturation

Once Brillouin threshold is reached, a large part of the pump power is transferred to the Stokes wave. To account for pump depletion, it is necessary to solve equations 2.22 (a) and 2.22 (b). Their general solution is complicated. However, fibre losses are neglected by setting $\alpha = 0$ we can make use of equation (2.23) and set $I_p = C + I_s$, where C is a constant. The resulting equation can be integrated along the length to yield

$$\frac{I_s(z)}{I_s(0)} = \left(\frac{C + I_s(z)}{C + I_s(0)}\right)\exp(g_{\mathbf{B}} Cz) \qquad 2.27$$

Using $C = I_p(0) - I_s(0)$, the Stokes intensity $I_s(z)$ is given by [10].

$$I_s(z) = \frac{b_0(1 - b_0)}{G(z) - b_0} I_p(0) \qquad 2.28$$

Where $G(z) = \exp[(1 - b_0) g_o z]$, with

$$b_0 = I_s(0) \big/ I_p(0), \text{ and } \qquad g_o = g_B I_P(0) \qquad 2.29$$

The parameters b_0 is a measure of the SBS efficiency as it shows what fraction of the input pump power is converted to Stokes power. The quantity g_0 is the small signal gain associated with the SBS process. Equation (2.28) shows how the Stokes intensity varies along the length in a Brillouin amplifier when input signal is launched at $z = L$ and the pump is incident at $z = 0$.

2.6.6 Brillouin Slow Light in Optical Fibres

In SBS the optical signal enters the optical fibre from one end while a control pump power enters from the opposite end. When frequency difference between the optical signal and the control pump is equal to Brillouin frequency shift, the two beams interfere to create sound waves with this frequency. When the control beam scatters off these sound waves, its frequency is therefore lowered such that it is equal to the carrier frequency of optical pulses. This scattering process only occurs over a narrow range of frequencies, which means that the control beam creates a resonant region in which the response of the fibre to light is maximum. Thus, slow light scheme exploit abrupt phase index variation near narrowband spectral resonance of optical media that induces large group index change based on the Kramer's- Kronig relation. For an optical signal propagating in the direction along an optical fibre provides a narrowband (Δv_B=30-50MHz) Brillouin gain to counter-propagating signal of specific optical frequency (Stokes) by SBS process. The Lorentzian-shaped Brillouin gain induces sudden change of phase index, Δn and group index Δn_g. The induced time delay is expressed in the form

$$\Delta T = \frac{g_B L}{2\Pi} . \frac{I_p}{\Delta v_B} = \frac{G}{2\Pi . \Delta v_B} \qquad 2.33$$

where L is the length of the fibre and G is the exponent of the Brillouin gain. From the equation time delay linearly dependent on the pump power. Since Δn_g only depends on the pump power one can achieve large variation of group velocity if a short length of the fibre is used.

The time it takes for the signal to pass through the optical medium is known as the group delay t_g. Group index and group velocity are the main basis for time delay [24]. Thus the group delay is given by;

$$t_g = \frac{L}{v_g} = \frac{L n_g}{c} \qquad 2.34$$

Consider an optical signal passing through an optical medium with length *L*, as shown in Fig. 2.3 and a delayed signal when it counter-propagates with pump power.

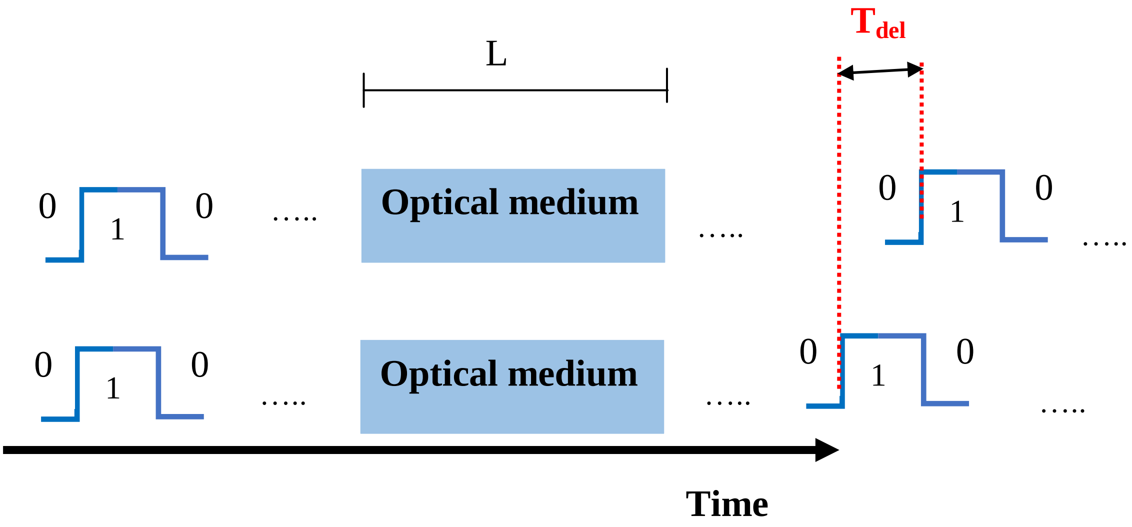

Figure 2. 3: Concept of tunable delay introduced by slow light.

In order to maximize the tunable delay, one may consider to have the optical medium as long as possible. But in practical situation, the length cannot be enlarged infinitely since the absorption losses and the dispersion-induced distortion limit the effective length of the optical medium. Thus the enhancement of tunable delay relies mainly on the increase of the group index, which requires a sharp variation of the refractive index that occurs within a narrow spectral resonance. The key feature of the slow light technique is to introduce a sharp change of refractive index within a narrowband spectral resonance. By making the dispersion of the optical medium sufficiently strong in the vicinity of the resonance, the sharp velocity can be significantly reduced, leading to a large controllable delay. When frequency of the signal beam is tuned to Stokes line, that is, down-shifted by the Brillouin frequency Ω_B from frequency of the pump beam, the opto-acoustic coupling becomes strong. Consequently, light from the pump beam is efficiently scattered into the signal beam, inducing a gain resonance and giving rise to a variation in the refractive index in a narrow frequency range around the resonance frequency, which results in small v_g for the signal beam. To achieve optically controlled slow-light, the fibre is pumped by a continuous wave laser beam (frequency ω_p) that counter-propagates through the fibre with respect to delayed pulse (carrier frequency ω). The pulse delay is largest when ω is set to the peak of the Brillouin resonance ($\omega=\omega_p-\Omega_B$), where Ω_B is the Brillouin frequency shift, and can be varied quickly and in a linear fashion by adjusting the intensity, I_p of pump laser beam. The SBS process leads to strong coupling between pump and Stokes fields via an acoustic wave, which results in amplification of a Stokes field. Unlike the experimental conditions and the operational characteristics of the former slow and fast light systems [45-47], Brillouin slow light was readily realized in standard optical fibres with a simple bench top configuration [23]. Moreover, its room-temperature operation at any wavelength has received tremendous interest from the optical communication society for fascinating potential applications such as all-optical delay lines, optical buffers and signal synchronizations. However, Brillouin slow light is not widely exploited in a continuous data stream for communication applications due to some inherent features of this system: narrow signal bandwidth, strong change of signal amplitude and significant signal distortion. So far, these limitations have been extensively investigated to improve the Brillouin slow light system, as optimizing the gain spectral profile and the induced dispersion in the material.

CHAPTER THREE

METHODOLOGY

3.1 Research Design

In this work simulation were carried out using two simulation packages (Optisystem and VPI). Optisystem is an optical communication Design software used by researchers and engineers to simulate optical links of optical networks. While VPI is a photonic software used in photonic modelling. This chapter present SBS generation, slow light processing and measurement technique.

3.2 Simulation Setup

Figure 3.1 shows the setup used to obtain SBS based slow light. The setuprequires simple and standard telecommunication components. The simulation setup consisted of three major parts: a system for optical pulse generation, a pump system to produce SBS slow light and a measurement system to measure delayed pulses. These systems were connected to the SBS generator (fibre) and slow light medium (fibre) where the signal was delayed. The CW laser at 1552.088nm was used to generate Stokes (probe) signal while SBS pump and slow light (SL) pumps at wavelength of 1552nm were used as pump sources. The wavelength difference is the frequency shift between pump and probe which is a phase matching for maximum effect. The optical pulses were generated by external modulation of wave via a Mach-Zehnder Modulator (MZM).

3.2.1. SBS Generation

To generate SBS, an optical pulse generated by the modulator was launched into SBS standard single mode fibre where it counter-propagated with SBS pump power from the other end of the fibre to produces Stokes signal. The pump power was varied from 0 dBm to 30 dBm to generate backscattered Stokes wave and Stokes power measured for different fibre lengths using analyzer 1 while the SL pump was turned off. The simulation was repeated using LA fibre, R fibre and RS fibre. For maximum power output, the polarization of the pump at the input was adjusted by the polarization controller (PC). For measurement fibre length used here was between 2 km and 10km. To protect SBS pump from backscattered power which propagate towards it, an Isolator was connected to the SBS fibre. Lastly, the pump linewidth was varied and Stoke power was measured.

3.2.2. Slow Light Processing and Measurement

To generate slow light, the output (Stokes) signal from 3km (optimized length) SBS fibre was directed to the slow light medium (fibre) where it was delayed by the counter-propagating slow light pump. The slow light pump was varied and the output signal displayed by the optical spectrum analyzer (OSA) for STD, LA, R and RS fibres with the SBS pump kept constant at 25 dBm. The power meter (PM) was used to measure transmitted SL pump power. Temperature of SL fibre was varied and the signal monitored by OSA for all fibres. The pump power inside the slow light medium creates a Brillouin gain which leads to amplification and delay of the signal pulses. The length used for SBS medium was 3km while that for slow light medium was 1km, 1.5 km and 2km.The SL pump was varied from 27 dBm to 30 dBm and the delayed signal shown by the OSA. Lastly, temperature of the SL medium was varied from 300K to 380K and the OSA used to show the delay.

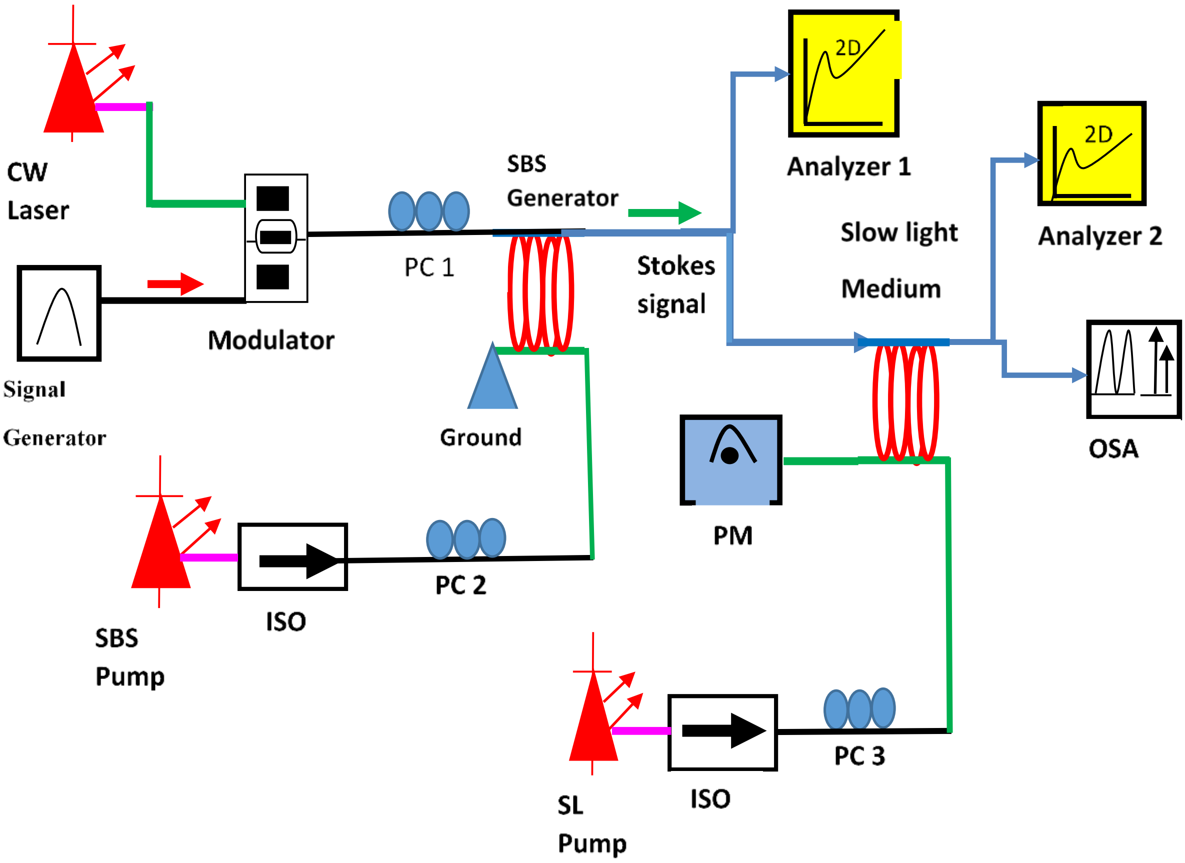

Figure 3. 1: Simulation setup for generating SBS based slow light. The PC: polarization controller, PM: power meter, ISO: Isolator, OSA: optical spectrum analyzer. SL: slow light

CHAPTER FOUR

RESULTS AND DISCUSSIONS

In this chapter results for the simulations are presented. The graphs were drawn and analyzed using ORIGIN software. Stokes power as a function of Brillouin pump power and relation between Brillouin threshold and length is presented. This characterization result was essential in finding the optimized power for the pump laser. Results of variation of Stokes power with fibre length, Stokes power with pump linewidth and effect of pump power on signal delay are also reported. Lastly, variation of temperature and slow light is presented.

4.1. Effect of Input Power on Stokes Power in Different Fibres at Different Linewidth.

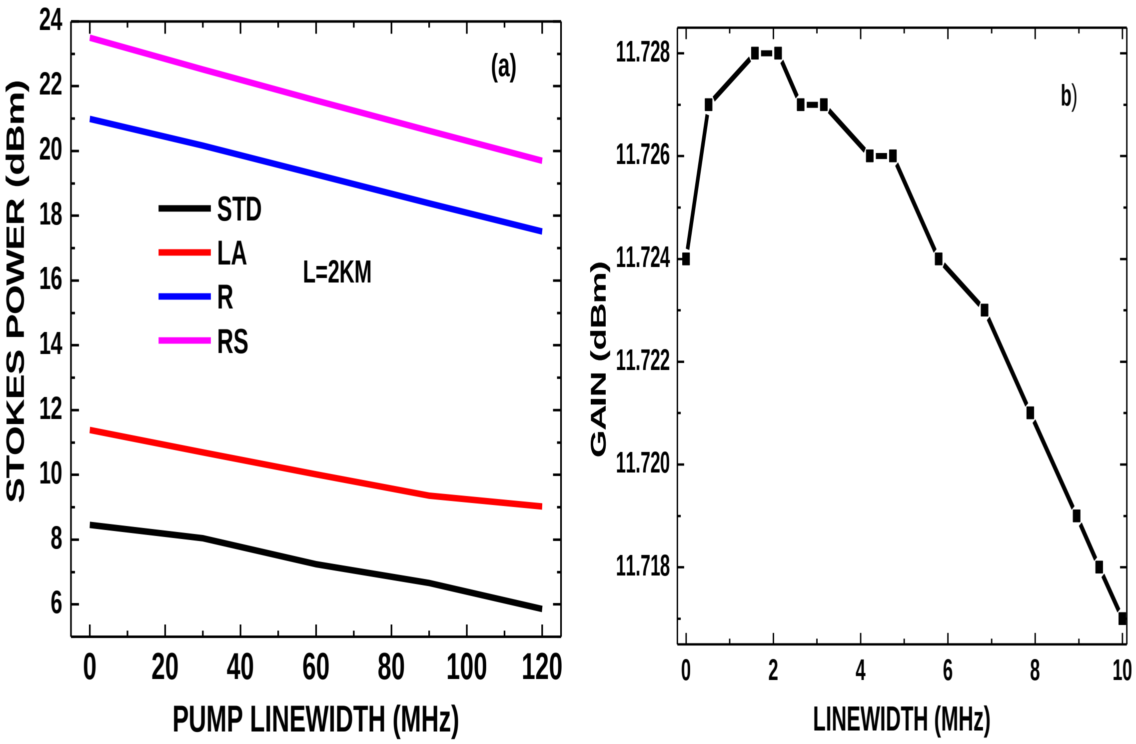

Figure 4. 1: (a) Effect of pump line width on Stokes power for LA RS and R. (b) Optimization of Stokes gain with linewidth for STD fibre.

Fig.4.1 (a) above shows that Stokes Power decreases as the pump linewidth is increased. Increase in linewidth reduces the interaction of counter propagating pump power and probe signal which in turn reduces the strength of interaction within the fibre. Thus Stokes power reduces as linewidth is increased. Backscattered power is lowest in standard fibre (STD) because it has the largest effective area hence, least interaction and consequently low power. Linewidth extension requires an increase of pump power to maintain power of the signal wave. From the optimized results in Fig.4.1 (b) linewidth of 2MHz gives maximum Stokes gain of 11.728 dBm.

4.2Stokes Power and Pump Power in Different Types of Fibre at Given Lengths

The Stokes signal power dependence on the Brillouin pump power in different single mode fibres (SMF) has been studied. The characteristic of SBS threshold power with respect to fibre length has also been investigated.

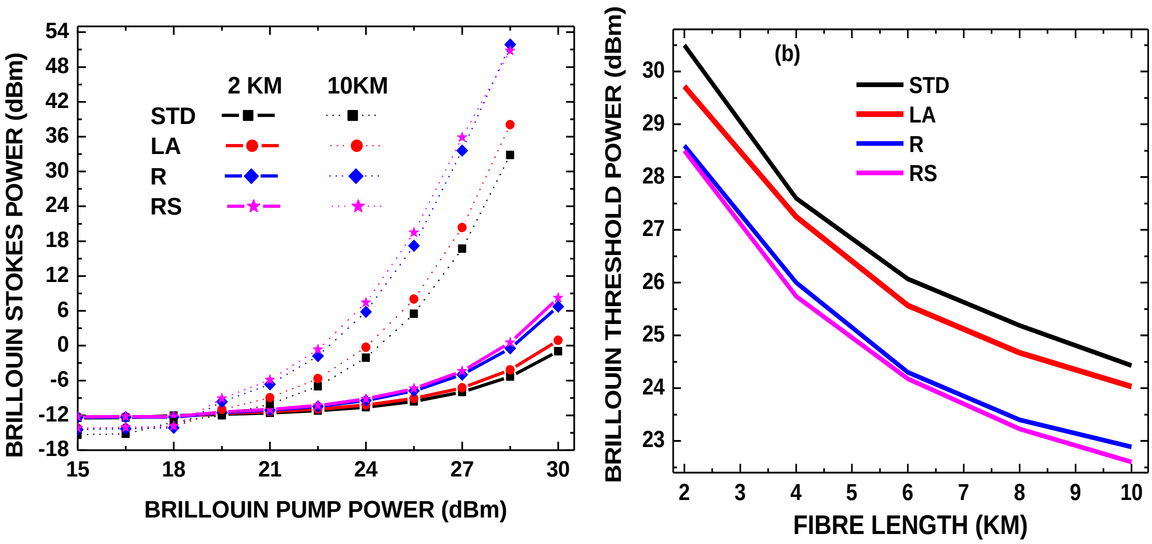

Figure 4. 2: (a) Brillouin Stokes power as a function of Brillouin pump power for different single mode fibres at probe signal power of -10 dBm. (b) Brillouin threshold power as a function of fibre length for SMF_ reduced slope (RS), large area (LA), standard (STD) and reach (R).

It can be seen in figure 4.2 (a) that increasing the pump power, increased the backward scattered Stokes power exponentially in all fibres. Both the reach fibre and reduced slope fibre showed enhanced Brillouin activity for pump powers above 21 dBm. At low input powers small fraction of the power is backscattered and when the input power is increased to a certain value (threshold power) the backscattered power increases rapidly. This is because at low input powers Brillouin scattering results due to the interaction between optical pump wave and acoustic wave generated by pump field via electrostriction. When the input power reaches threshold, an additional acoustic wave is excited within the fibre enhancing index grating which scatters most of pump power to Stokes power. Therefore the maximum power that can be transmitted by an optical fibre is limited by the process of SBS. Figure 4.2 (b) shows the threshold power for four fibres namely, standard (STD), large area (LA), reach (R), and reduced slope (RS). It can be seen that when fibre length was increased from 2km to 10km, the threshold power for STD, LA, R and RS fibre decreased from 30.5 to 24.4 dBm, 29.8 to 24.0 dBm, 28.7 to 22.9 dBm and 28.5 to 22.6 dBm respectively. Since Brillouin threshold depends on effective length which is a function of fibre length, then increasing the length would cause a corresponding decrease in the threshold. Consequently the threshold is reached faster for longer fibres than shorter ones. With fibre attenuation taken into account, the backscattered Stokes intensity distribution in the fibre has a strong dependence on the pump power coupled into the fibre. Threshold power for standard fibre was higher compared to large area (LA), reach (R) and Reduced slope (RS) fibre. This is due to low interaction in standard fibre since it has the largest effective area and hence, more pump power is required for the process.

4.3. The variation of Stokes Power with Fibre Length for Different Types of Fibres

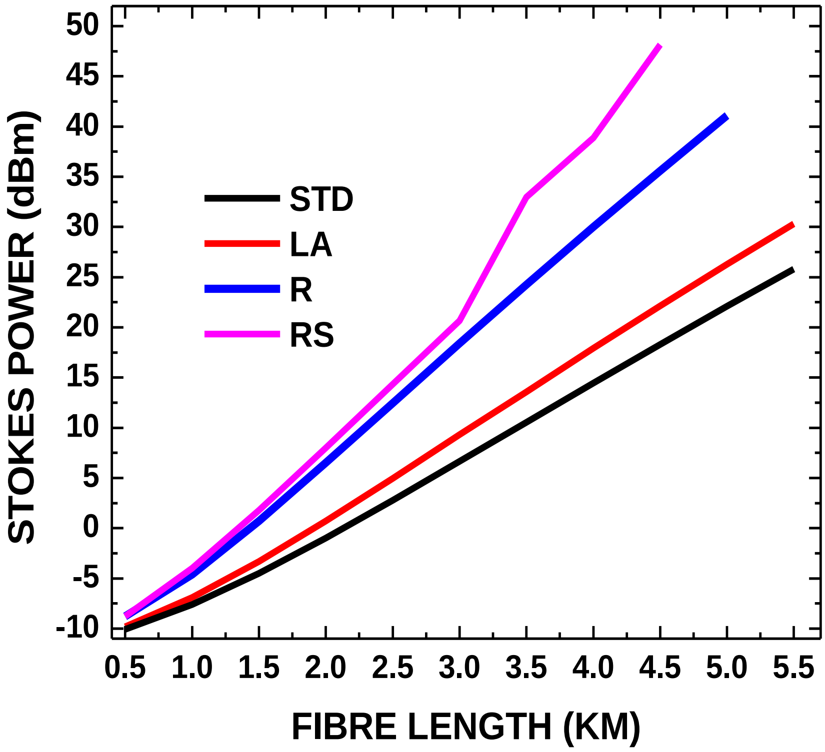

Figure 4. 3: Stokes power variation with fibre length for STD, LA, R and RS fibre.

Figure 4.3 shows that Stokes power increases with length for all types of fibres. However, reduced slope (RS) fibre gave the highest Stokes power. The trends observed in all the fibres result from the fact that interaction length for Brillouin scattering process increases with fibre length and, thus more power is backscattered. Reduced slope (RS) fibre has the lowest effective area thus experiencing more interaction and saturates faster at fibre length of 3km. It therefore means that there will be more interactions compared to Reach (R), large area (LA) and standard (STD) fibres which have increasing area respectively. Consequently, most pump power is backscattered for RS followed by R, LA and STD in that order. Thus, using length of more than 4.5km for RS results to Brillouin gain saturation as well as saturation of the Stokes power at the end of fibre output.

4.4. Total Power and Temperature.

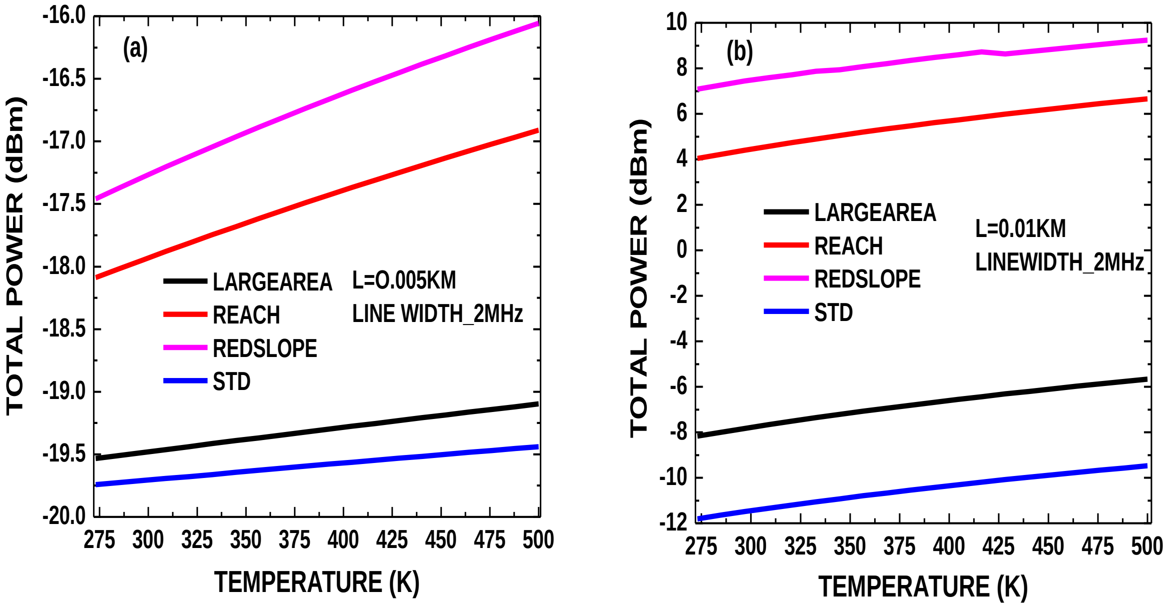

Figure 4. 4: Effect of temperature on Stokes power for (a) 0.005km and (b) 0.01km SMF_Reach fibre, Large Area fibre, Standard fibre and Reduced Slope fibre.

Figure 4.4(a) and (b) shows that increase in temperature causes a corresponding increase in Stokes power. The warmer the fibre, the more the excited molecules will be encountered. This temperature increase causes variation in birefringence thus more power is transferred to Stokes. At high pumping SBS nonlinearity is induced hence more interaction in the fibre causing more power to be backscattered. Owing to the fact that effective area increases in the following order RS<R< LA<STD, it therefore means more interaction for SBS process will occur in RS and Brillouin threshold is reached faster for RS fibre. The slope for the fibres at 0.005km are 0.0058 $dBmK^{-1}$, 0.0047 $dBmK^{-1}$, 0.002 $dBmK^{-1}$ and 0.0014 $dBmK^{-1}$ for RS, R, LA and STD respectively. While the slope for the fibres at 0.01km are 0.0084 $dBmK^{-1}$, 0.011 $dBmK^{-1}$, 0.011 $dBmK^{-1}$ and 0.0098$dBmK^{-1}$ for RS, R, LA and STD respectively. Thus, RS and R fibre have larger slope than STD and LA at 0.005km meaning they are more sensitive to temperature. For 0.01km R and LA have higher slope than RS

and STD. Short fibres are more sensitive to temperature and temperature dependence is linear.

4.5 Effect of Pump Power on Signal Delay

The simulation results below show the characteristic of Stokes power with time for large area fibre, standard fibre, reach fibre and reduced slope fibre at different pump powers for 1km, 1.5km and 2km. Time delay was determined by measuring the time of the peaks of the delayed signal.

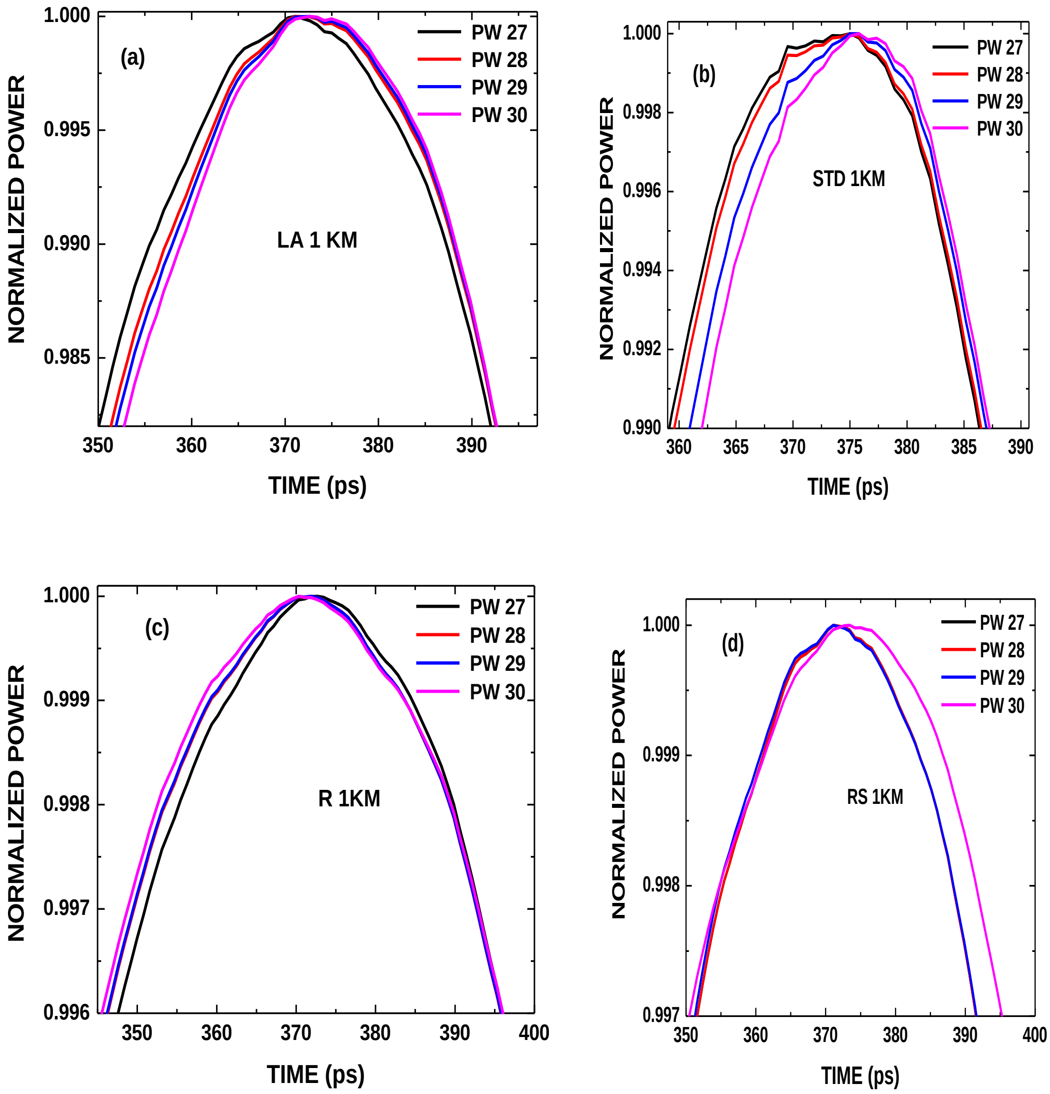

Figure 4. 5: Variation of total power with time for different pump power for 1km SMF (a)Large Area (b) Standard fibre (c) Reach and (d)Reduced Slope.

As is evident in figure 4.5, there was observable signal shift with pump power. This shift is due to large normal dispersion induced by SBS process which gives rise to a strong change in the group index. As a result, the group velocity at which a signal travels through the fibre decreases, leading to the generation of slow light and signal delay.

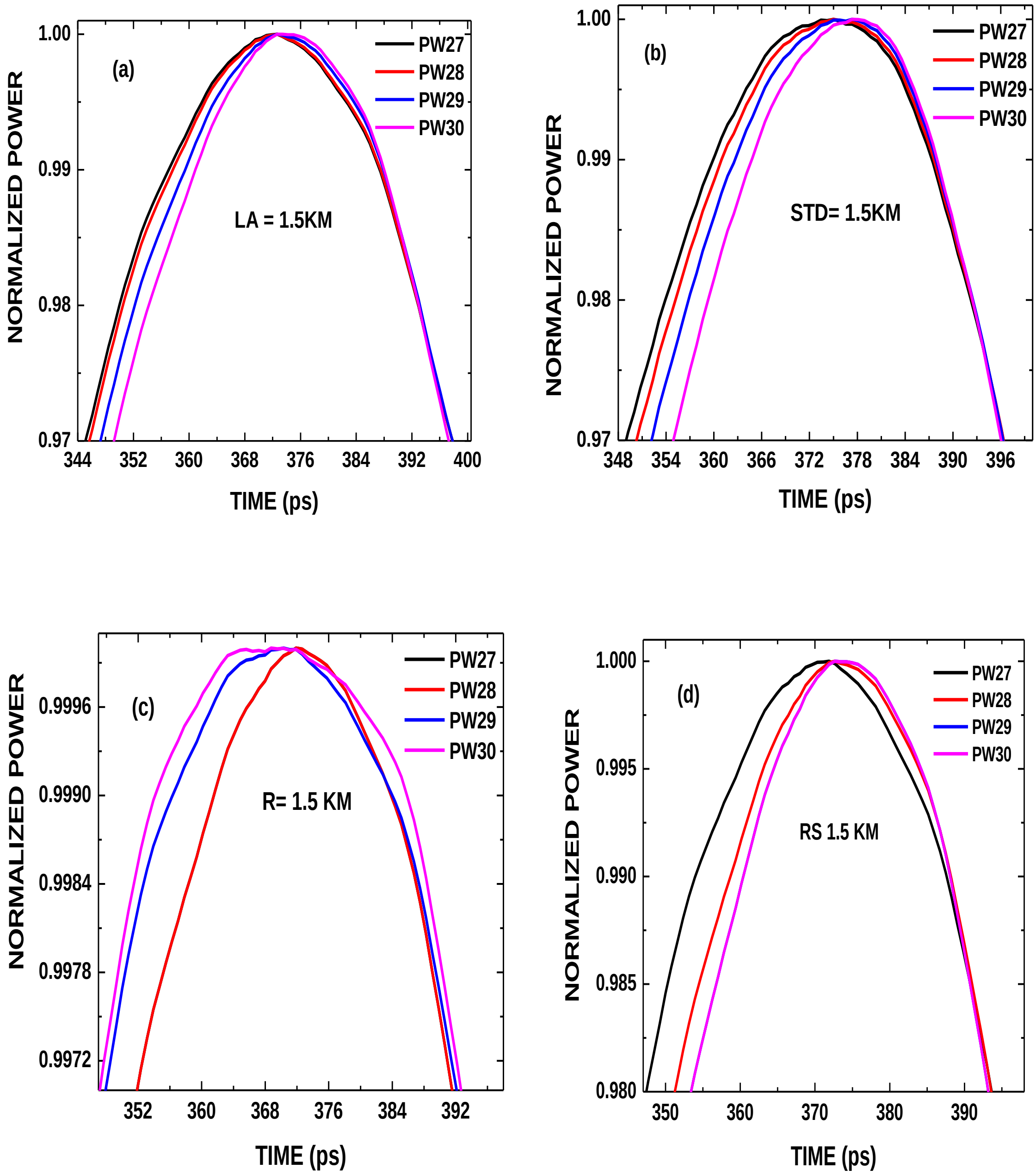

Figure 4. 6: Variation of total power with time for different input power for 1.5km SMF (a) Large Area (b) Standard fibre (c) Reach and (d)Reduced Slope.

Figure 4.6 (a-d) above shows a signal shift with pump power. There is increase of time delay with pump power for STD, LA and RS with maximum delay for varying power from 27 dBm to 30dBm being4.2ps, 1.5ps, and 3.5ps respectively. However, time delay decreases with increase in pump power(signal speed up of 4.2ps)for R fibre. The delay is due to large normal dispersion induced by SBS process giving rise to a strong change in the group index. This resulted to decrease in the group velocity of the signal.

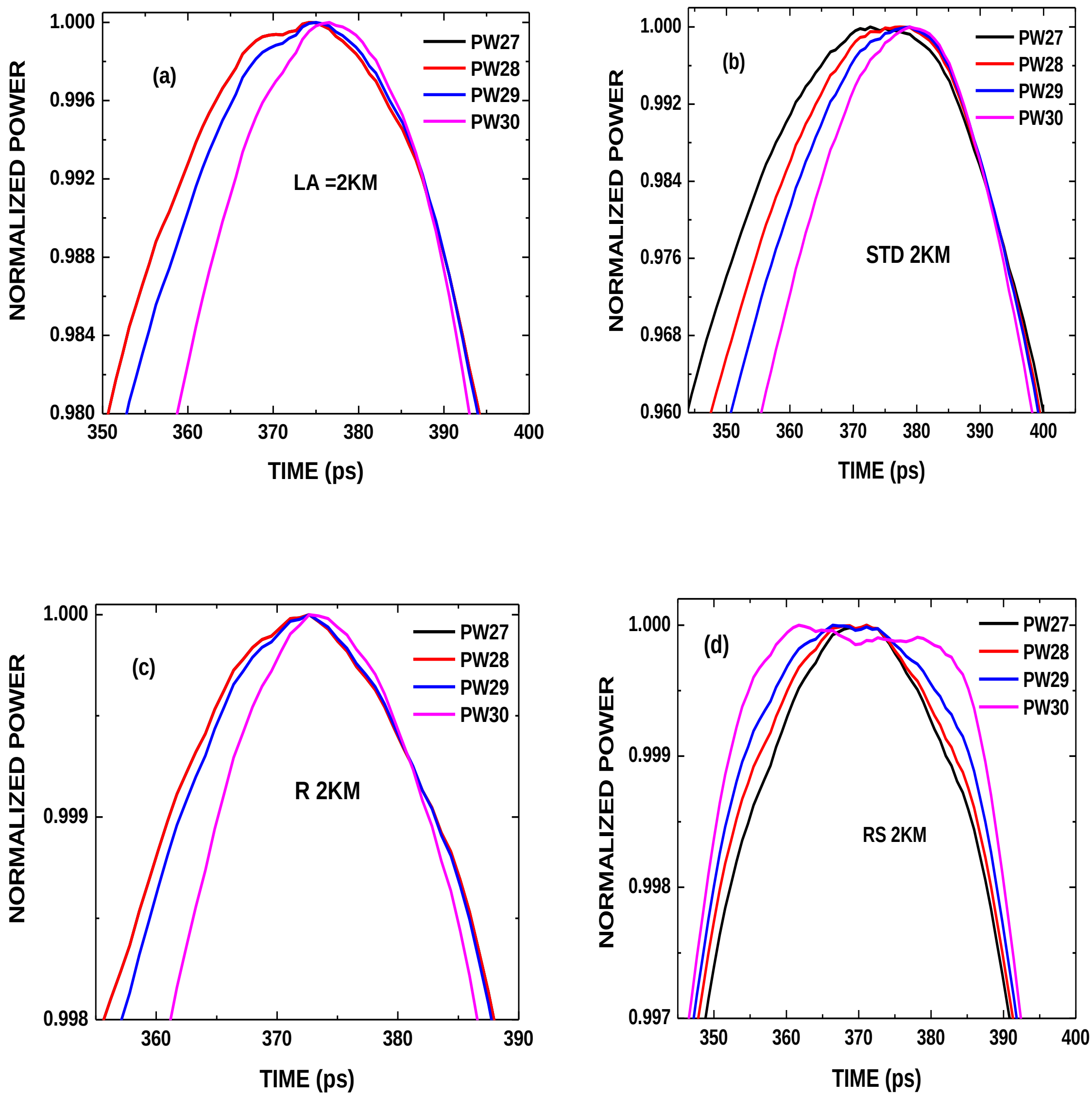

Figure 4. 7: Variation of power with time for different input power for 2km SMF(a)Large Area signal delay 4.1 ps (b) Standard fibre signal delay of 7.6 ps (c) Reach signal delay 1.7 ps and (d)Reduced Slope signal delay 0.02 ps.

Figure 4.7 shows the results obtained for varying power from 27 dBm to 30dBm. Time delay increases with pump power for LA, STD, R and RS. Since induced time delay is linearly dependent on the pump power, thus signal was delayed by varying the pump power.

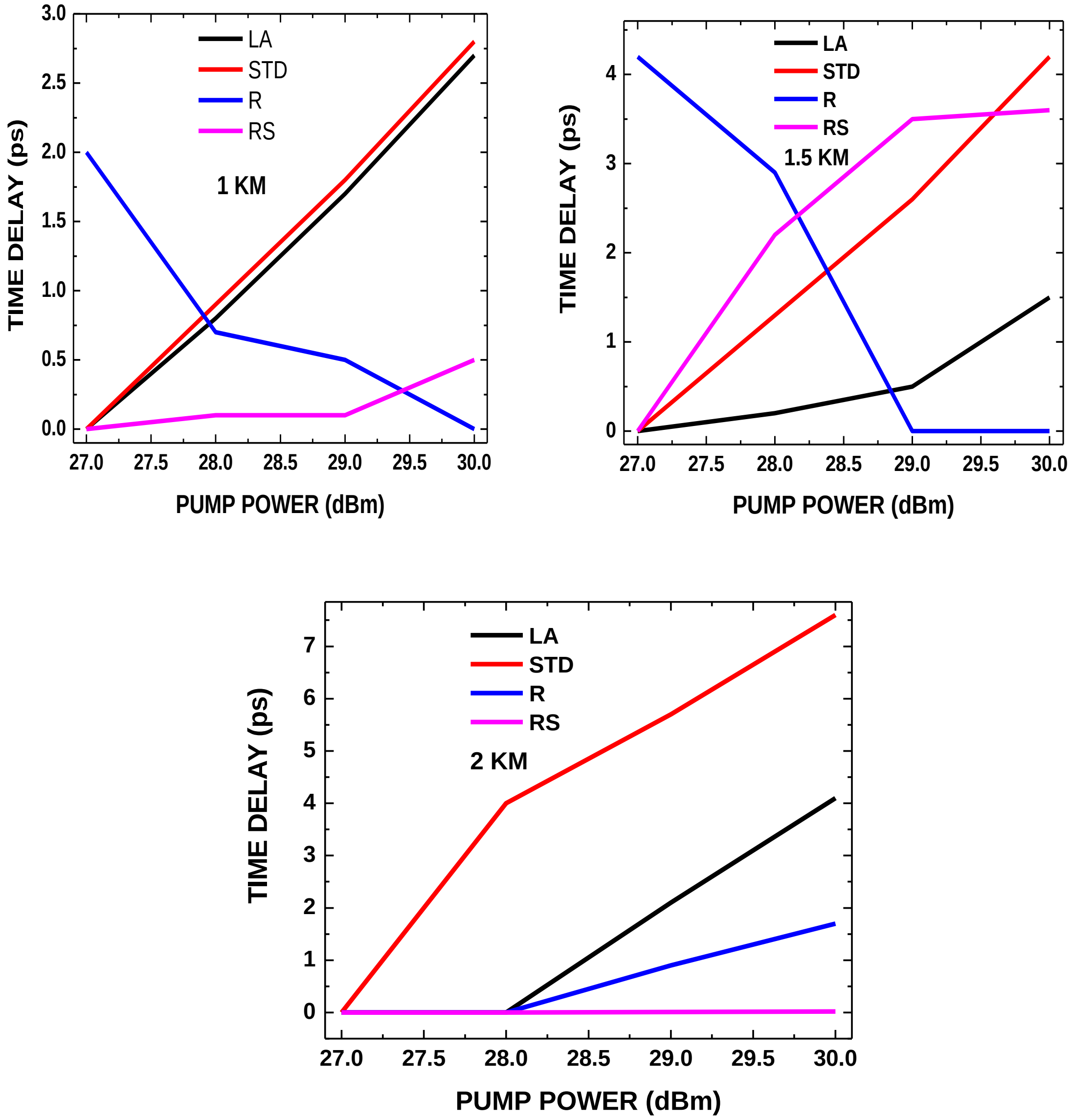

Figure 4. 8: Relationship between time delay with pump power for STD, LA, R and RS at 1km, 1.5km and 2km.

Results in figure 4.8 shows that there was time delay with increase in pump power for 1km, 1.5km and 2km. There was no delay for LA and R at 2 km between 27 dBm and 28dBm.

Maximum delay obtained for STD, LA and RS fibre was 7.6ps,4.1 ps and 3.5ps respectively. The delay for RS was very small at 1 km and 2km fibres, whereas there was signal speed up for R of 2 ps and 4.2 ps at 1km and 1.5km respectively. However, for 2 km R fibre the signal delay of 1.5ps was achieved.

4.6 Effect of Length on Signal Delay

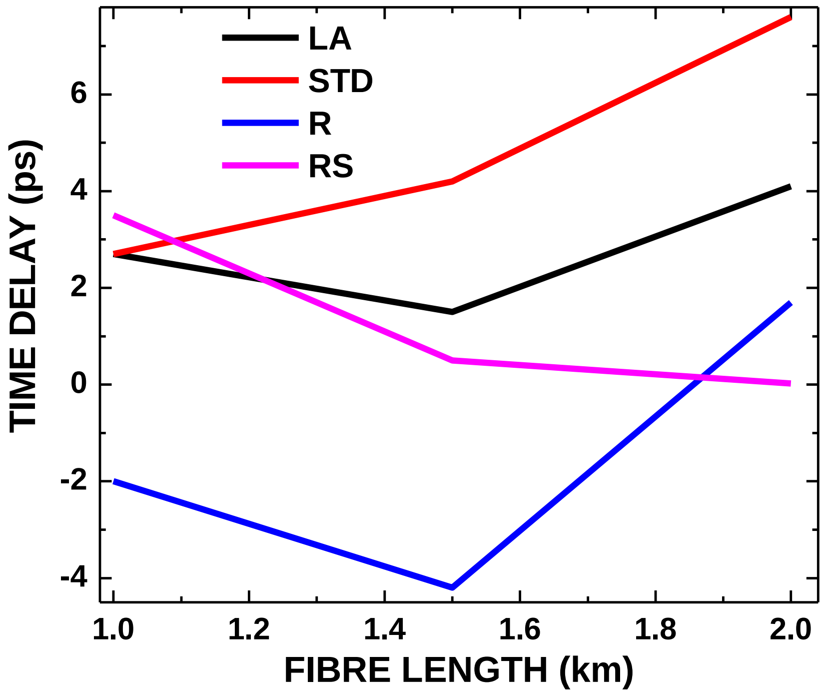

Figure 4. 9: Variation of signal delay with length for LA, STD, R and RS fibres.

The results in figure 4.9 above indicates that signal delay increases with increase in fibre length for STD and decreases for RS. However, for LA and R the delay reduces when length is increased to 1.5 km and starts increasing as the fibre length increases. The signal delay increases with length because after the signal passing through the fibre, the signal arrives at the end of the fibre with a transit time $T = L/v_g$ hence; there is more delay for longer fibres. Thereby, a large change of time delay for a pulse can be observed after the pulse propagates through the material.

4.7 Temperature and Slow Light

During SBS process, the beating between the pump and Stokes waves creates a modified density change. This density variation is associated with a mechanical acoustic wave; and it may be affected by local temperature, strain and vibration which induce changes in the fibre effective refractive index and sound velocity. The higher the temperature of the fibre, the more the excited molecules will be encountered within the fibre. Because of these temperature dependence, the relative strength of the signal can be used to calculate the temperature at a point of scattering.

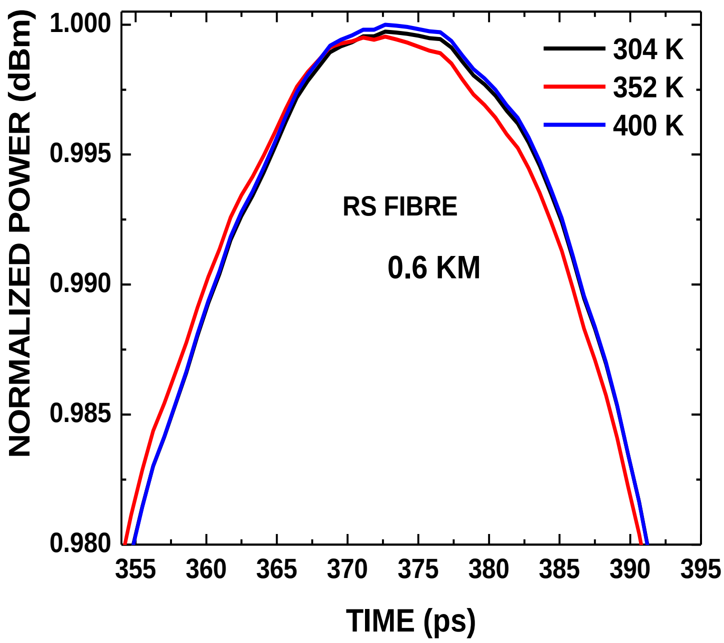

Figure 4. 10: Variation of power with time for different temperature for 0.6km SMF_Reduced Slope. The time delay is 1.6ps.

The fundamental principle here is the temperature dependence of the Brillouin frequency shift in the fibre, hence, the delay time of an input probe pulse as a result of SBS-based slow light. When temperature is changed, the probe frequency will no longer be aligned to the Stokes downshift frequency, leading to different values of δ and hence different probe delays.

$\Delta t = \left(\frac{g_p L P_p}{\Gamma_B A_{eff}}\right) \frac{1-\delta^2}{\left(1+\delta^2\right)^2}$, $\delta = \Delta\Omega \Big/ \left(\Gamma_B/2\right)$ where δ is the temperature-dependent parameter. Temperature sensitivity of the delay for RS is $0.0333 psK^{-1}$. Temperature change causes delay in RS, showing that RS can be used as temperature sensor by measuring the delay.

Delay attained for RS at 1.5km is 1.2ps as shown in Fig. 4.11.

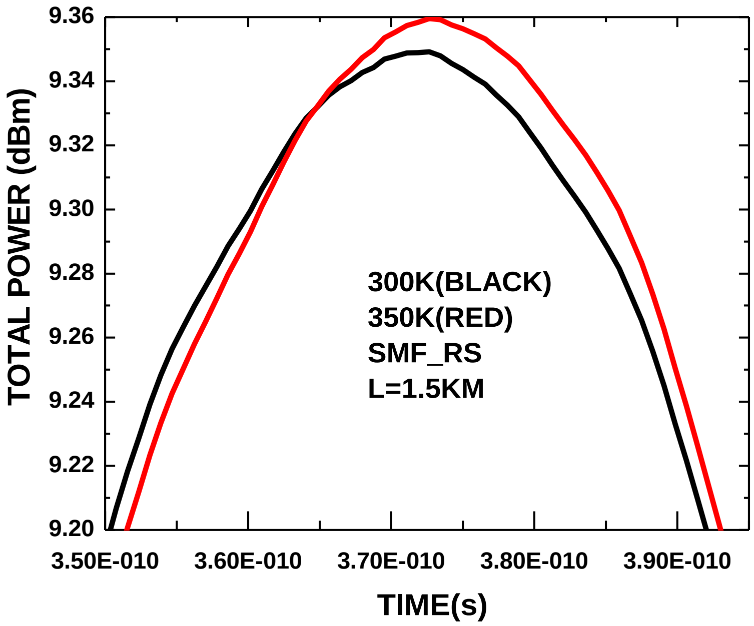

Figure 4. 11: Variation of power with time for different temperature for 1.5km SMF_Reduced Slope.

Constant power was used to counter-propagate into the slow light medium to ensure the delay is caused by the temperature. The delay determines the crossover (sensing) point of the two counter-propagating pulses in the medium, where SBS slow light is introduced. Finally, higher SBS gain is favorable in providing a higher sensitivity.

CHAPTER FIVE

CONCLUSIONS AND RECCOMMENDATIONS

5.1 Conclusions

Stimulated Brillouin scattering (SBS) is a nonlinear phenomenon that occurs in optical fibres at input power levels much lower than those needed for stimulated Raman scattering (SRS). At the same time Brillouin effects in optical fibre are very attractive for developing nonlinear devices. The four single mode fibre (SMF) investigated in this work showed that Brillouin effects depends on the optical characteristics of the fibre. Both the reach fibre and reduced slope fibre showed the highest back scattered power for a given fibre length. However Standard fibre and large area fibre showed moderate Brillouin effects. It has been shown that slow light can be achieved within a Brillouin gain resonance for standard fibre STD, large area fibre LA, reach fibre R and reduced slope fibre RS. The group velocity can be altered in every fibre length as long as the Brillouin gain is available. Time delay increases with length, pump power and temperature. However, for 1km and 1.5km of R there was signal speed up. Slow light via SBS has shown great flexibility and capacity to reach high data bit rates needed for use in present communications systems. Effects of pump power, fibre length and temperature on SBS slow light have been studied.

Brillouin scattering occur in SMF and results shows that Brillouin threshold decreases with increase in length for STD fibre, LA fibre, R fibre and RS fibre, thus threshold is reached faster for longer lengths than shorter one. Increasing pump power from 27 dBm to 30 dBm causes signal delay with the maximum delay for STD, LA, R and RS being 7.6ps, 4.1ps, 1.7 ps and 3.5ps respectively. Since frequency shift depends on temperature, its change slows down the signal with a delay of 1.6ps for RS. However, there was a fascinating result of pulse speed up of 4.2ps during the study for Reach fibre. Due to normal dispersion by SBS process modulation in group index causes decrease in group velocity of the signal and hence slow light. Simulation results reveal that increasing pump linewidth causes decrease in Stokes power. Thus, pump linewidth of 2 MHz gave highest Brillouin gain. Lastly, temperature varies directly with Brillouin gain thus, increase in temperature leads to increase in Stokes power. Since temperature causes signal delay and affect Stokes power directly, sensing for temperature can then be realized by measuring the peak of the delayed signal. Change in the Brillouin frequency shift of silica fibres can be advantageously utilized for temperature sensing. Since STD fibre gave maximum delay of 7.6ps it can be therefore the best SMF for generating slow light on the other hand, maximum delay when varying temperature was realized in RS fibre making it the best candidate for temperature sensing. It is worth noting that SBS slow light scheme is potentially useful for all optical signal processing due to its advantages of room temperature operation, compatibility with existing systems and sensing.

5.2 Recommendations

This research work recommends the use of 2 km STD fibre to generate SBS slow light for applications in signal processing and 0.6 km RS fibre for fibre sensing. Fast light for Reach should be investigated. The results presented need to be validated experimentally with pulse width >1ns. Also, this field should be explored in order to extend the number of application fields which may take advantage of SBS based systems. The implementation of this scheme should be investigated. Finally, application of slow light in the domain of computing and communication should be explored since slowing down light can lead to faster computing.

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APPENDICES

Appendix 1

Conference Presentation and Publications

1. **Osiemo**, **D. M.,** Waswa, D. W. & Muguro, K.M. "Stimulated Brillouin Scattering characterization and slow light generation technique in modern fibres", vol. 5 *International Journal of Emerging Technology and Advanced Engineering*, ISSN: 2250-2459, PP. 39- 43, Issue 9. September 2015.
2. **Osiemo**, **D. M.,** Waswa, D. W., Muguro, K.M., Isoe, G. M., Kirui, E. & Cherutoi, H. "Brillouin Threshold Measurement in Optical Fibres," Proceedings of 2014 international conference on Sustainable Research and Innovation (SRI), Vol. 5, ISSN: 2079-6226, pp. 243-246, May 2014.

3. **Osiemo**, **D. M.,** Waswa, D. W., Muguro, K.M., Isoe, G. M. & Cherutoi, H. "Investigation of slow light in Single Mode Fibres (SMF) for the Basis of Stimulated Brillouin Scattering and the application in sensing" Annual International Sustainable Research and Innovation (SRI) 6^{th} -8^{th} May 2015-Published.

Workshop attended

1. ALC Workshop on Lasers in Teaching and Research, 8th -13th September, 2013.

Egerton University, Njoro.