Suppression of Stimulated Brillouin Scattering Effect Using Self-Phase and Cross-Phase Modulation

By
Fahmida Hossain Tithi

MASTER OF SCIENCE IN INFORMATION AND COMMUNICATION TECHNOLOGY

Institute of Information and Communication Technology
Bangladesh University of Engineering and Technology
July 2011

The thesis titled **"Suppression of Stimulated Brillouin Scattering Effect Using Self-Phase and Cross-Phase Modulation"** submitted by Fahmida Hossain Tithi, Roll no: M04083113P, (Session April/2008) has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Information and Communication Technology on 23 July, 2011.

BOARD OF EXAMINERS

1. ____

Dr. Md. Saiful Islam
Professor
Institute of Information and Communication Technology
BUET, Dhaka- 1000

Chairman
(Supervisor)

2. ____

Dr. S. M. Lutful Kabir
Professor and Director
Institute of Information and Communication Technology
BUET, Dhaka- 1000

Member
(Ex-officio)

3. ____

Dr. Md. Liakot Ali
Professor
Institute of Information and Communication Technology
BUET, Dhaka- 1000

Member

4. ____

Dr. Md. Hossaim-e-Haider
Instructor (Class A)
Department of EECE, MIST
Mirpur, Dhaka-1216

Member
(External)

CANDIDATE'S DECLARATION

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

Fahmida Hossain Tithi

DEDICATED TO MY PARENTS

Contents

CHAPTER 1: Introduction

CHAPTER 2: Fiber Impairments and Stimulated Scattering

3. THEORITICAL ANALYSIS FOR SUPPRESSION OF SBS EFFECT

4. Results and Discussion

5. Conclusion and Future Work

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

SBS	Stimulated Brillouin scattering
SRS	Stimulated Raman scattering
SPM	Self phase modulation
XPM	Cross phase modulation
FWM	Four wave mixing
WDM	Wavelength division multiplexing
DCF	Double-clad fiber
RoF	Radio-over-fiber
FBG	Fiber Bragg grating
NLSE	Nonlinear Shroedinger Equation
SSFM	Split step Fourier method
LEM	Local error method
EDFA	Erbium doped fiber amplifier
MOPA	Master oscillator power amplifier
Gbps	Giga Bit Per Second
RI	Refractive index
TIR	Total internal reflection
SMF	Single mode fiber
MMF	Multi mode fiber
PMD	Polarization mode dispersion
DSF	Dispersion shifted fiber

LIST OF SYMBOLS

n	Refractive index
n_{eff}	Effective refractive index
n_1	Core refractive index
n_2	Cladding refractive index
$\mathrm{n_l}$	Linear refractive index
$\mathrm{n_{nl}}$	Nonlinear refractive index
c	Velocity of light in vacuum
v	The velocity of light in medium
θ_1	Incident angle
θ_2	Refraction angle
θ_c	Critical angle
α	Attenuation constant
L	Fiber length.
$\mathrm{L_{eff}}$	Effective fiber length
I	Intensity of light
γ	Nonlinear coefficient
N	No. of channel.
P_m	Received power
λ	Wavelength
A_{eff}	Effective Area
b	Polarization factor

ACKNOWLEDGEMENTS

This thesis is the most significant accomplishment in my life. First of all I would like to thank almighty Allah for providing me the strength and patience that carried me through the work and enabled me to complete this work. Next, I would like to thank my parents for their continuous support, encouragement and sacrifice throughout the period and I will be indebted to them forever for all they have done.

This is my immense pleasure to express my sincere and profound gratitude to my supervisor Dr. Md. Saiful Islam of IICT, BUET for providing me the opportunity to conduct postgraduate research in area of optical fiber communication. I convey my heartfelt and cordial thank to him for his continuous guidance, kind help and encouragement without which this work would never be possible.

Finally, I would like to exceed way sincere thanks all the teachers and staffs of IICT, BUET for their cordial help and assistance during my study period.

ABSTRACT

Stimulated Brillouin scattering (SBS) is a resonant nonlinear optical interaction with the material that results in transmitted light being scattered back towards the input. Although high power lasers are available to overcome the intrinsic loss of standard single mode optical transmission fibers (0.2 to 0.3 dB/km) but SBS places an upper limit on the optical power that can be transmitted through the link. This optical power limitation gets worse as the length of the fiber is increased. It is totally undesirable for many other applications because it limits the amount of optical power that can be used in a fiber. Recently, there is an increasing interest in reducing the SBS effect for applications such as optical links, fiber amplifiers and lasers, nonlinear devices, fiber to the home etc. where high optical power is required. Usually, SBS normally has a lower threshold power (≤1.4 mW) than other nonlinear effects. In this thesis work, we have studied a novel SBS suppression mechanism in optical transmission system utilizing the effects of self phase- and cross phase modulation which causes spectral broadening of the propagating signal and thereby suppress the SBS effect.

We have established the analytical model for spectrum broadening factor using self phase modulation (SPM) and cross phase modulation (XPM) by solving the nonlinear Schrödinger equation. SBS threshold is dependent on optical sources spectral width and spectral broadening due to SPM and XPM ultimately enhances the threshold level. Our numerical simulation results show that this method will increase the SBS threshold power significantly through choosing the proper fiber length; such high level SBS threshold power can suppress the SBS sufficiently and even completely. The results are evaluated at different input power and varying transmission distance and it is found that XPM effect plays more active role than SPM for same amount of channel power. Our findings of this research will be useful to design a fiber-optic based wavelength division multiplexing system where transmission of higher power is an important factor.

CHAPTER 1

INTRODUCTION

Communication is the process of transferring of information from one point to another. People need to communicate with another. For that reason communication system is necessary for sending message or information from one place to another. Optical fiber communication is one of the most popular and efficient system because of its potential bandwidth, low transmission loss, small size and weight.

1.1 General Communications System

The block diagram of general communication system is shown in Fig. 1.1. From the Fig. 1, we see that information signal is sent to transmitter, where the transmitter worked as a modulator. Transmitter modulates or multiplexed original signal. The original signal may be voice, data, video etc. This original signal is converted to electrical signal by the transmitter. Then the modulated signal travels through transmission medium. The transmission medium may be a cable, wire etc. At the receiving end, the receiver converts the electrical signal to their original signal. The receiver worked as a demodulator or demultiplexer [1].

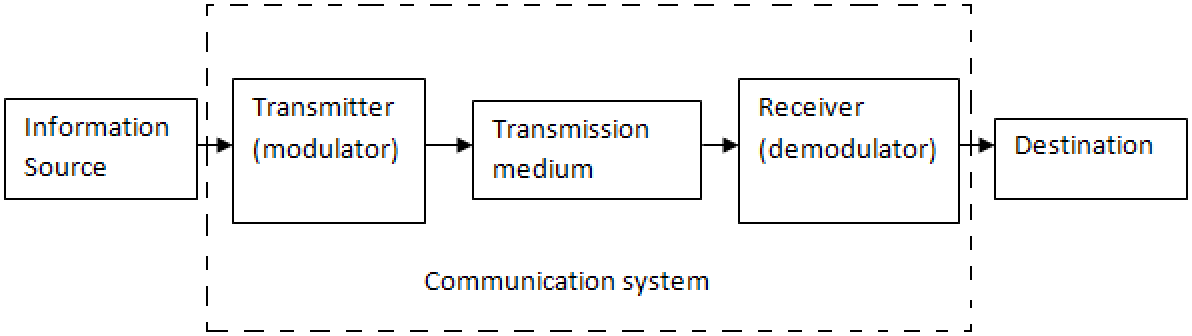

Fig. 1.1: Model of a general communication system

1.2 Optical Fiber Communications System

Optical fiber communication system is used for long distance. The block diagram of optical fiber communication system is shown in Fig. 1.2. The information signal may be voice, data, video etc and the information signal is converted to electrical signal through the transmitter. Here electrical transmitter works as a modulator or multiplexer. In this block diagram, optical source is used. The main function of this optical source is to convert the electrical signal to optical signal. Laser diode (LD) or light emitting diode (LED) is used as an optical source in optical fiber communication system. They are called optical oscillator, they provide stable, single frequency waves with sufficient power for long distance propagation.

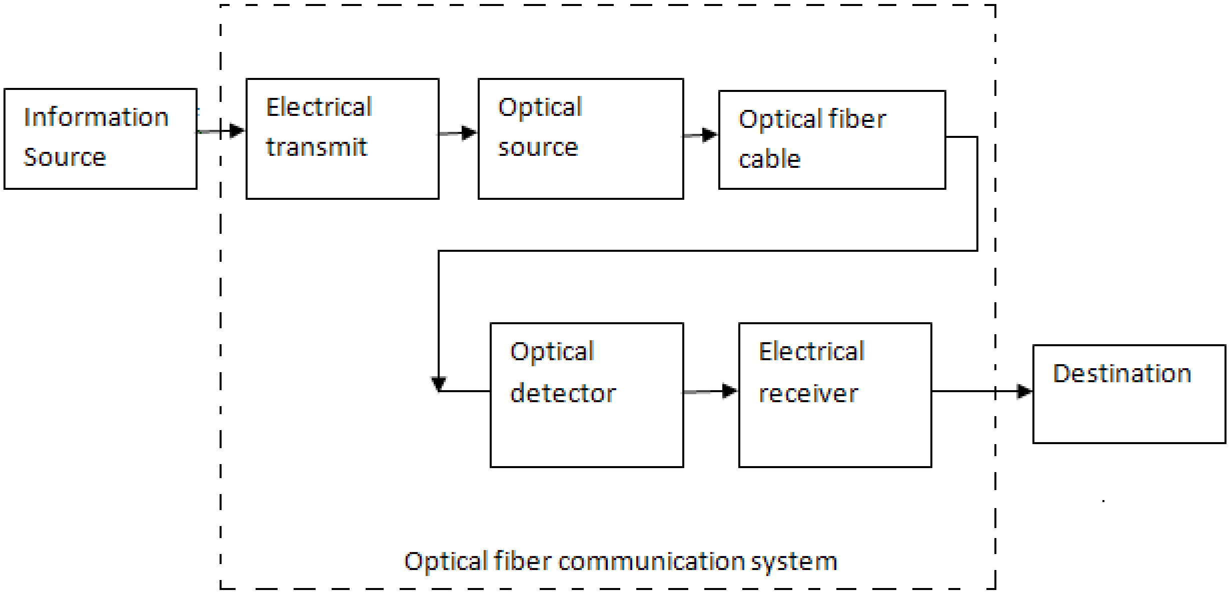

Fig. 1.2: A typical optical fiber communication system

The output of the optical signal pass through the transmission medium and this transmission medium is an optical fiber cable. The optical fiber creates connection between transmitter and receiver. After traveling the optical signal enters to the optical detector and the main functions of this optical detector is to convert optical signal to electrical signal. Semiconductor photodiode is mainly used as an optical receiver.

Detector output contains the transmitted information. These photodetectors are small size, low power consumption, high sensitivity and usually cost effective. Finally, this electrical signal is received by an electrical receiver and convert electrical signal to original signal [2]. For long distance transmission reshaping and amplifying is necessary for getting accurate signal [3]. For that's reason optical amplifiers and signal generators are used.

Between optical transmitter and optical receiver optical filters, couplers, switches are used. The function of a coupler is to combine light into or split light out of a fiber. A splitter is a coupler that divides the optical signal on one fiber to two or more fibers [4]. The receiver detecting the weakened and/or distorted signal and receiver also contains electronic amplification devices which restore the signal.

1.3 Historical Development

The mode of propagation of optical wave through optical fiber is evaluated by Snitzer [4]. In 1960s Kao and Hockham studied on the practical feasibility of fiber as a light guide for communication applications [5]. Kao studied on dielectric fiber waveguide for communication purpose [6]. At early stage, there have some limitations on rate of data transmission. But day by day bit rate and repeater spacing also increased. [7].

In first generation, GaAs is used as a semiconductor laser which has 0.85 μm operating wavelength. Bit rate and repeater spacing was very low. First generation uses multimode fiber for light propagation. Core diameter of multimode fiber is about 50 μm or greater. Due to this large core diameter intermodal dispersion and chromatic dispersion (CD) effects are observed in first generation [7].

Bit rate : 45 Mb/s
Repeater spacing : 10 km

Second generation uses GaAsP as a semiconductor which has operating wavelength is 1.31 μm. Data rate transmission and repeater spacing increased than first generation. Second generation used single mode fiber. Core diameter of this single mode fiber was 2 -10 μm. So, intermodal dispersion was not observed but chromatic dispersion surfaced as a new challenge. Some attenuation exists in this generation [7].

Bit rate : 100 Mb/s to 1.7 Gb/s
Repeater spacing : 50 km
Operating wavelength: 1.3 µm
Semiconductor : In GaAsP

Third generation has 1.55 µm operating wavelength, bit rate and repeater spacing is increased than previous generations. To avoid some attenuation dispersion shifted fiber and conventional fiber are used in third generation [7].

Bit rate : 10 Gb/s
Repeater spacing : 100 km
Operating wavelength: 1.55 µm

The fourth-generation optical fiber communication system uses 1.45 µm to 1.62 µm wavelength in single mode optical fiber. In this generation, coherent optical communication system is developed to avoid attenuation [7].

Bit rate : 10 Tb/s
Repeater spacing : >10000 km
Operating wavelength: 1.45 to 1.62 µm

In 1990s, light wavelength division multiplexing was introduced to improve bit rate in the same transmission distance with the light waves which enlarges the system capacity greatly, for the fifth-generation optical fiber communication system. In this system, coupled with optical fiber amplifiers, it is possible to achieve very high rates and very long-distance optical fiber communications [7].

Bit rate	: 40-160 Gb/s
Repeater spacing	: 24000 – 35000 km
Operating wavelength	: 1.53 – 1.57 µm

1.4 Different Transmission Windows in Optical Fiber Communication Systems

The wavelength bands for transmission are called transmission windows. The first window at 800 nm –900 nm was originally used. The fiber losses are relatively high in this region and fiber amplifiers are not well developed for this spectral region. For that reason, first window is used only for short distance transmission. The second window at 1.3 µm was used. This is used for long distance transmission system. The third window is now widely used. The third window is at around 1.5 µm. These windows have been standardized and the second and third telecom windows are further subdivided into the following wavelength bands:

Table 1.1 Different transmission windows

Band	**Description**	**Wavelength range**
O band	Original	1260–1360 nm
E band	Extended	1360–1460 nm
S band	Short wavelengths	1460–1530 nm
C band	Conventional (“Erbium window”)	1530–1565 nm
L band	Long wavelengths	1565–1625 nm
U band	Ultralong wavelengths	1625–1675 nm

The middle windows (S and C) around 1500 nm are the most widely used. This region has the lowest attenuation losses and this window is used in long distance transmission. It does also have some dispersion, so dispersion compensator devices are used to remove this.

1.5 Review of Previous Works

Fiber nonlinearities become a problem when several channels coexist in the same fiber and results high optical power. Interactions among propagating light and the fiber can lead to interference, distortion or excess attenuation of the optical signals. Nonlinear effects are determined by the total power per channel. The most important types of nonlinear scattering within optical fibers are stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). The non-linear phenomenon of SBS, first observed in 1964 [1, 8].

Once the power launched into an optical fiber exceeds a certain level, which is known as threshold level or threshold power, most of the light is reflected backward direction due to SBS. While light is started scattering in the backward direction and at higher transmitted power, the amount of backscattering light also increased as a result it is impossible to transfer larger amount of power to the receiving end and fiber span length become short [9-10] . Over the years, many research works have been carried out to analyze impact of SBS on transmission performance and developed many techniques to suppress its effect.

Jaworski *et al*. (2001) has shown that threshold power can be increased using two methods. One method is optical phase modulation (dithering) and another is initial pulse modulation and spectrum scattering by propagating in double-clad fiber. By applying these methods optical signal spectrum is widened and suppressed due to four wave mixing in the fiber. The simulation results provide satisfied output result [11].

Lee *et al.* (2003) has used fiber Bragg grating (FBG) for SBS suppression. For suppressing the SBS effect they used a FBG fabricated within the ‘photosensitive’ fiber. They used a sampled FBG consisting of 4-cm-long samples over 1m long optical fiber with 10 cm sampling period [12]. They reported that 15 ns pulses with 2 KW peak power can be transmitted though a 1-m long fiber with little energy loss. Finally they proved through numerical simulation that SBS effect can be suppressed with a proper design of a fiber Bragg grating.

Raman fiber amplifier based SBS suppression with dispersion shifted fiber is reported in [13]. The method uses the spectral broadening of the signal due to cross phase modulation induced by the pump. They showed that experimental method to suppress the SBS effect by using the advantages of Raman fiber amplifier.

As the bandwidth of the scattered wave due to SBS is smaller (≥25 MHz) and it also distorts the signal of individual channels [14]. Hu *et al.* (2005) studied the SBS effect on the radio-over-fiber (RoF) distribution systems. They demonstrated that the modulation depth of the optical micro-wave signal can suppress the SBS effect. They proposed how the position of the optical filter can influence the performance of a RoF system due to SBS and also discussed the overcoming the SBS effect by the eye-diagram of received signal with pre-filtering and post-filtering. The experimental results showed that SBS threshold increases with the modulation index.

Hedge *et al.* (2007) studied the effect of a photonic bandgap in a photonic crystal fiber. They demonstrated an analytical model for SBS effect and showed that SBS effect can be minimized by using the elastic grating structure model [15]**.** Their analytical solution showed that SBS threshold increases with elastic-grating coupling coefficient and they verified the analytical results by numerically solving equations for the variety of different photonic bandgap sizes**.**

Gray *et al*. (2007) demonstrated 502 Watts of power from a pump limited, single mode, narrow linewidth fiber amplifier [16]. To achieve high power operation in a narrow linewidth amplifier a double-clad Erbium doped fiber was fabricated. They reduced SBS effect by minimizing the overlap between the optical and acoustic fields in the fiber core.

Lei *et al.* (2009) analyzed and showed that SBS effect can be eliminated using the nonlinear effect through simulation [17]. They solved the modified nonlinear Schrödinger equation (NLSE) in the Erbium doped fiber amplifier (EDFA) and NLSE in the passive fiber by using the split step Fourier and Local error method (SSFM-LEM). They used master oscillator power amplifier (MOPA) for their research work. From their simulation result they have showed that wavelength broadening is increased with fiber length and spectrum broadening is also increased with fiber length.

Multi-frequency phase modulation is also reported to improve threshold power and eliminate the SBS effect. Liu *et al.* (2009) investigated the effect of SBS on the equal-amplitude spectral lines based on multi-frequency phase modulation numerically and experimentally. The SBS threshold of three, five, seven, and eleven equal-amplitude spectral lines are obtained [18].

Du *et al.* (2010) theoretically treated the SBS effect [19]. In this paper, a two-stage amplification all-fiber amplifier system is set up to investigate SBS effect in multitone-driven high-power amplifiers. In one case the system is seeded with a 1064 nm single frequency laser with output power of 43 mW. In another case the system is seeded with a narrow-linewidth laser with center wavelength around 1064 nm and output power of 45 mW. They showed that the SBS threshold in multitone-driven narrow-linewidth high-power amplifiers can be enhanced.

We have already observed from the above mentioned works that different researchers investigated and developed different methods, techniques and tools to eliminate SBS effect. Some of the research works were carried out analytically, numerically and / or experimentally. From the above literature review, we have observed that most of the research works have addressed SBS suppression using fiber Bragg grating, photonic crystal fiber, Raman fiber amplifier, master oscillator power amplifier, double-clad fiber etc. Various proposed methods suppressed SBS effect in different amounts. They were able to improve SBS threshold power for SBS reduction. In this thesis work, we have suppressed the SBS effect through raising the threshold power using nonlinear effect like- self phase modulation (SPM) and cross phase modulation (XPM).

1.6 Research Objectives

In this research work we have shown that it is possible to reduce SBS effect in optical fiber over a much wider range accurately compared to various conventional techniques. The main goal of this work is to suppress the SBS effect by improving SBS threshold power. We have analyzed and solved non-linear Schrödinger equation considering self phase- and cross phase modulation which enhances the spectral width of the propagating signal. The larger spectral width ultimately helps to raise SBS threshold power. The salient objectives of this research are:

a) To derive analytical models for spectral broadening of the propagating signal due to self phase- and cross phase modulation.

b) To evaluate the effect of spectral broadening on signal for different input power using the above models.

c) To observe the effect of spectral broadening on SBS threshold power improvement and thereby suppression of SBS effect due to SPM and XPM.

d) To compare the evaluated results with related published works.

1.7 Outline of the Thesis

This thesis is divided in five chapters. At the beginning of **Chapter 1** general communication system and optical fiber communication system is presented. Then historical development of optical fiber communication system is presented. Then an elaborate record of previous works on the analysis of suppression of SBS effect in optical fiber communication system.

Chapter 2 provides the different types of fiber nonlinearities and stimulated scattering effect.

Chapter 3 includes the theoretical analysis of SBS suppression using SPM and XPM.

Chapter 4 presents simulation results of the analytical expressions. We plot some graph based on our analysis and also compare our result with other published works.

Chapter 5 concludes this thesis. Recommendations of future research are presented in this chapter.

CHAPTER 2
Fiber Impairments and Stimulated Scattering

Optical fiber communication is a method of transferring information through an optical fiber. Light rays carry information and pass through the fiber. Optical fiber is used by many telecommunications companies to transmit telephone signals, Internet data and cable television signals. It has huge advantages over copper wire. Due to lower attenuation and interference it is used in long distance and high bandwidth applications.

In this chapter, we have discussed how light rays propagate through an optical fiber. When light rays propagate in optical fiber they show some linear and nonlinear characteristics. Fiber nonlinearities represent the fundamental limiting mechanism to the amount of data that can be transmitted on a single optical fiber. We have also discussed fiber impairment like attenuation, different types of dispersions and nonlinear effect of fibers.

2.1 Light Propagation through Optical Fiber

Fiber optic communication systems hold some advantages over other systems. The advantages are large bandwidth, small size, greater information-carrying capacity, lower cost per bit etc. [20]. Fiber optic plays an important role in modern communication system.

2.1.1 Basic of Optical Fiber

An optical fiber is a thin, flexible and transparent fiber. Optical fibers are widely used in fiber-optic communications, which permits transmission over longer distances and at higher bandwidths (data rates) than other forms of communication.

The basic structure of an optical fiber is shown in Fig. 2.1.

Fig. 2.1: Basic structure of an optical fiber

Mainly optical fiber has two parts. One is core and another is cladding. The transparent core of an optical fiber is surrounded by a transparent cladding material. Core and cladding are made from same material but they differ from their refractive indexes [2]. Refractive index of a core is higher than the refractive index of a cladding. External coating also exists to protect and strengthen the fiber [21].

2.1.2 Basic Propagation of Guided Light in an Optical Fiber

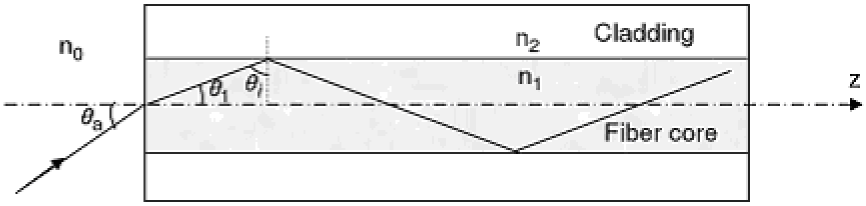

Fig. 2.2: Light propagate through an optical fiber

Here, we have discussed how light ray propagates through an optical fiber. Fig. 2.2 illustrates how light propagates through an optical fiber. Here n_0 is refractive index of air, n_1 is the core refractive index and n_2 is the cladding refractive index. Suppose, light ray enters from air medium to fiber core. These ray incidents at the core cladding interface and creates an incident angle to the normal. If this incident angle is lower than critical angle then it passes through the fiber cladding. If the incident angle is equal to the critical angle then it passes to the core-cladding boundary. But when light ray incident to the normal greater than the critical angle then total internal reflection is occurred *i.e.,* light ray is back reflected to the fiber core. This phenomenon occurred repeatedly for propagation through fiber. Here θ_a is called acceptance angle. The acceptance angle is the maximum angle to the axis of the fiber that light entering the fiber is propagated. The value of the angle of acceptance depends on fiber properties and transmission conditions**.**

2.2 Fiber Impairments

In optical fiber communication systems, several types of impairments may be introduced to the signal. These impairments result in degraded system performance, high bit-error-rate or power penalty etc. Now we discuss different types of fiber impairments like attenuation, losses, different types of dispersions etc. Attenuation and dispersion are known as linear fiber effects because can be described by a linear relationship between the fields of the light waves at the input and output of the fiber.

2.2.1 Attenuation

Attenuation is one of the most important characteristics of optical fiber communication systems. Attenuation in an optical fiber is caused by absorption, scattering, and bending losses. Each mechanism of loss is influenced by fiber-material properties and fiber structure. Attenuation is the loss of optical power as light travels along the fiber. If P_{out} is the optical output power and P_{in} is the optical input power then we can write

$$\text{Loss} = P_{out} / P_{in} \text{ --- } (2.1)$$

Attenuation is denoted by A and it measures in db/km. So we can write

$$A(db/km) = -(1/L)10\log_{10}(P_{out}/P_{in}) \text{ --------------------------------- } (2.2)$$

where P_{out} and P_{in} expressed in watt and L is fiber length expressed in km.

2.2.2 Absorption

Absorption is a major cause of signal loss in an optical fiber. Absorption is defined as the portion of attenuation resulting from the conversion of optical power into another energy form, such as heat.

Absorption in optical fibers is explained by three factors:

1. Imperfections in the atomic structure of the fiber material
2. The intrinsic or basic fiber-material properties
3. The extrinsic (presence of impurities) fiber-material properties

2.2.2.1 Intrinsic Absorption

Intrinsic absorption is caused by basic fiber-material properties. If an optical fiber were absolutely pure, with no imperfections or impurities, then all absorption would be intrinsic. Intrinsic absorption sets the minimal level of absorption. The main cause of intrinsic absorption in the infrared region is the characteristic vibration frequency of atomic bonds. The interaction between the vibrating bond and the electromagnetic field of the optical signal causes intrinsic absorption.

2.2.2.2 Extrinsic Absorption

Extrinsic absorption is caused by impurities introduced into the fiber material. Trace metal impurities, such as iron, nickel and chromium, are introduced into the fiber during fabrication. Extrinsic absorption is caused by the electronic transition of these metal ions from one energy level to another.

2.2.3 Bending Losses

Bending the fiber also causes attenuation. There are two types of bending losses. One is macrobending loss and another is microbending loss. Microbending and macrobending losses are very important loss mechanisms.

2.2.3.1 Macrobending Loss

Macrobending losses are caused by curvature of the fiber axis. These losses are observed when a fiber bend's radius of curvature is large compared to the fiber diameter. These bends become a great source of loss when the radius of curvature is less than several centimeters. Light propagating at the inner side of the bend travels a shorter distance than that on the outer side. To maintain the phase of the light wave, the mode phase velocity must increase. When the fiber bend is less than some critical radius, the mode phase velocity must increase to a speed greater than the speed of light. However, it is impossible to exceed the speed of light. This condition causes some of the light within the fiber to be converted to high-order modes. These high-order modes are then lost or radiated out of the fiber.

2.2.3.2 Microbending Loss

Microbending losses stem from microdeformations of the fiber axis. These losses are caused by small discontinuities or imperfections in the fiber. Uneven coating applications and improper cabling procedures increase microbending loss. External forces are also a source of microbends. An external force deforms the cabled jacket surrounding the fiber but causes only a small bend in the fiber. Microbends change the path that propagating modes take. Microbending loss increases attenuation because low-order modes become coupled with high-order modes that are naturally lossy.

2.2.4 Dispersion

Dispersion is defined as the signal broadening or spreading while it propagates inside the fiber. The phenomenon of spreading of the optical pulse as it travels along the fiber and limits the information capacity of the fiber is known as dispersion. It will cause the signal to spread out, lose it is shape and become difficult to detect by receivers at the end of a fiber span, thus dispersion will causes bit error rate (BER) to increase to unacceptable levels. Dispersion causes pulse spreading and distortion and thus can lead to system penalties.

There are many different types of dispersion in optical fibers. These types are:

1. Modal dispersion or intermodal dispersion.
2. Chromatic dispersion or intramodal dispersion.
3. Polarization mode dispersion.

2.2.4.1 Modal Dispersion

Modal dispersion occurs in multimode fiber. It does not exist in single mode fibers. Single mode fibers propagate only the fundamental mode. Therefore, single mode fibers exhibit the lowest amount of total dispersion. Single mode fibers also exhibit the highest possible bandwidth.

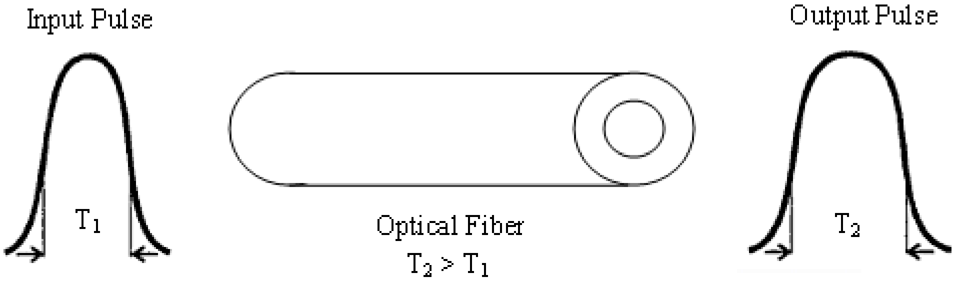

Fig. 2.3: Modal dispersion

Pulse widening caused by the mode structure of a light beam inside the fiber is called modal or intermodal dispersion. In modal dispersion various modes of light traveling down the fiber arrive at the receiver at different times, it causes signal to spread out. Pulse spreading is proportional to the fiber length. As the length of the fiber increases, modal dispersion increases. The phenomenon of modal dispersion is depicted in Fig. 2.3. We can use single mode fiber optics to overcome this effect. We also use graded index fiber to reduce modal dispersion. The core refractive index of a graded index fiber is not constant. We know that c = vn, where c is the light velocity in the vacuum, v is the light velocity within core and n is the refractive index of a core. So in shortest distance, light ray travel at the lowest speed due to the highest refractive index and in longer distance, light ray travels higher speed due to the lower refractive index. Thus using graded index fiber modal dispersion can be removed.

2.2.4.2 Chromatic Dispersion

The word ‘chromatic’ is associated with colors. Different colors light ray has different wavelength and different wavelengths of light ray has different refractive index. Chromatic dispersion occurs as a result of the range of wavelengths is the light source. Each of these wavelengths travels at a slightly different speed. So at the fiber output, the varying wavelength speeds cause the light pulse to spread in time. Chromatic dispersion can be compensated or mitigated using dispersion shifted fiber (DSF).

Chromatic dispersion is measured in ps/nm-km. There are two types of chromatic dispersion. These are:

1. Material dispersing
2. Waveguide dispersion

Material dispersion exists due to change in index of refraction for different wavelengths. Waveguide dispersion is caused by the difference in the index of refraction between the core and cladding. Waveguide dispersion is significant only in fibers carrying fewer than 5-10 modes [31]. Since multimode optical fibers carry hundreds of modes, they will not have observable waveguide dispersion. Waveguide dispersion depends on the shape, design and chemical composition of the fiber core.

In a single mode fiber chromatic dispersion parameter is sum of the material and waveguide dispersion.

$$D(\lambda) = D_{mat}(\lambda) + D_{wg}(\lambda) \text{--} (2.3)$$

where as $D_{mat}(\lambda)$ is material dispersion and $D_{wg}(\lambda)$ is waveguide dispersion parameter.

2.2.4.3 Polarization Mode Dispersion

Pulse spreading caused by a change of fiber polarization properties is called polarization mode dispersion (PMD). Different frequency component of a pulse acquires different polarization states such as linear polarization and circular polarization. This results in pulse broadening and creates PMD. PMD is caused by asymmetries and stress distribution in the core of the fiber because it occurs due to the polarization dependent refractive index. PMD occurs in fibers with a slightly elliptic core asymmetrical mechanical stress.

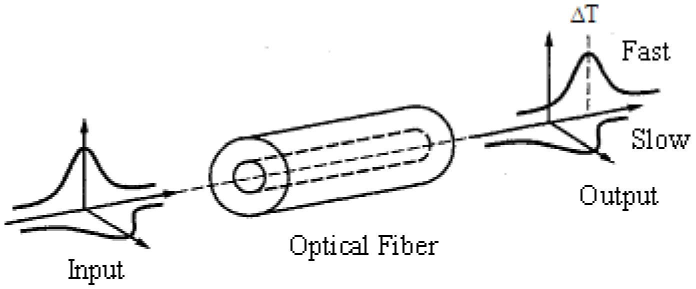

Fig. 2.4: Polarization mode dispersion

The phenomenon of PMD is shown in Fig. 2.4. From figure we see that horizontally and vertically polarized light propagates in a fiber at slightly different speeds. ΔT is the difference in arrival time and it is called differential group delay (DGD)

Due to PMD the pulse spreading is

$$\Delta t_{PMD} = D_{PMD}\sqrt{L} \text{ -- } (2.4)$$

where, D_{PMD} is the coefficient of polarization mode dispersion and L is the fiber length.

PMD is not an issue at low bit rates but becomes an issue at bit rates in excess of 5 Gbps.

2.3 Fiber Nonlinearities

An optical effect is called nonlinear if its parameters depend on light intensity. In optics the terms linear mean power independent and nonlinear mean power dependent phenomenon. The nonlinear effects depend on transmission length. In long length fiber the non linear effect is greater. The two types of nonlinear effects occur in fiber optics. These are

1. Kerr effect
2. Stimulated scattering

Stimulated scattering effect depends on threshold power and Kerr effect depends on nonlinear refractive index of a core. Nonlinear refractive indexes are caused by the dependence of electric susceptibility on the field strength.

2.3.1 Kerr Effect

Optical Kerr effect is the phenomenon in which the refractive index of the medium changes when the electron orbit is deformed by the strong electric field [24]. Kerr effect is occurred due to the intensity dependent phase shift of the optical signal.

There are three types of Kerr effects observe in fiber optics.

1. Self phase modulation (SPM)
2. Cross phase modulation (XPM)
3. Four wave mixing (FWM)

2.3.1.1 Self Phase Modulation (SPM)

Phase modulation of an optical signal by itself is known as self-phase modulation (SPM). It is a nonlinear optical effect and it increases with high power levels. Phase shift and nonlinear pulse spread occurs due to this nonlinear phenomenon. SPM effects observe in single channel system [25]. SPM acts along with chromatic dispersion to broaden pulse. SPM involves one pulse but XPM involves two pulses.

When a pulse coupled into a fiber, the instantaneous phase of optical pulse rapidly changes through optical Kerr effect. The effects are shown in Fig. 25 and Fig. 2.6.
The instantaneous angular frequency is defined as the derivative of phase (Φ) with respect to time.

$$\omega(t) = d(\Phi)/dt \quad \text{---} \quad (2.5)$$

The phase (Φ) is defined as,

$$\Phi = (2\pi/\lambda)nL \quad \text{---} \quad (2.6)$$

where as, λ = Wavelength of optical pulse
n = Refractive index
L = Fiber length.

Effective refractive index, $n_{eff} = n_l + n_{nl}I$ -- (2.7)

where as, n_l = Linear refractive index
n_{nl} = Nonlinear refractive index
I = Intensity of light

Effective length, $L_{eff} = (1 - e^{-\alpha L})/\alpha$ --- (2.8)

where as, α = Attenuation constant

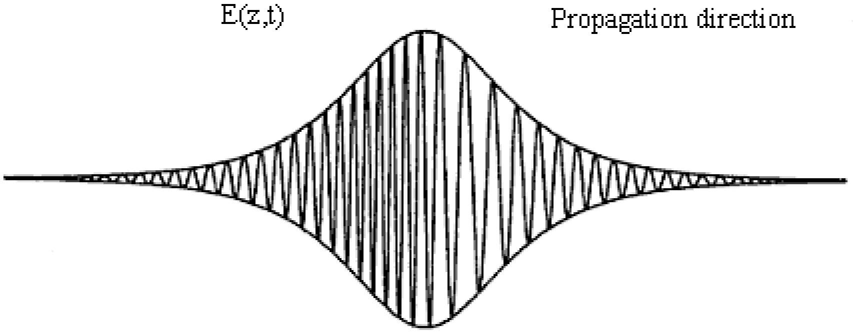

Fig 2.5: Modulated pulse waveform due to SPM

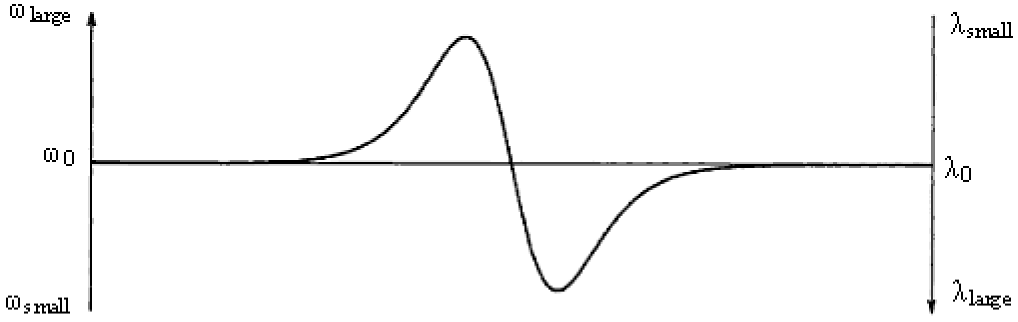

Fig 2.6: Instantaneous frequency change

If refractive indexed is replaced by effective refractive index and fiber length is replaced by effective length then we can write from equation (2.5),

$$\Phi = (2\pi / \lambda)(n_l + n_{nl} I)L \quad \text{--} \ (2.9)$$

If we consider a Gaussian pulse, then new instantaneous frequency is,

$$\omega' = \omega_0 - d(\Phi)/dt \ \text{---} \quad (2.10)$$

$$\omega' = \omega_0 - dI/dt \quad \text{---} \ (2.11)$$

If an optical pulse is transmitted through a medium, the Kerr effect causes a time-dependent phase shift according to the time-dependent pulse intensity. In this way, an initial unchirped optical pulse acquires a temporally varying instantaneous frequency.

A leading edge, $\omega' = \omega_0 - \omega(t) \quad [di/dt > 0]$ --- (2.12)

At trailing edge, $\omega' = \omega_0 + \omega(t) \quad [di/dt < 0]$ --- (2.13)

Due to this effect spectral broadening of pulse occurred. In SPM, the nonlinear refractive index causes a phase shift in the propagation pulse's optical wavelength, which is proportional to its own optical intensity. Thus SPM creates pulse broaden.

2.3.1.2 Cross Phase Modulation (XPM)

Cross-phase modulation (XPM) is a nonlinear optical effect where one wavelength of light can affect the phase of another wavelength of light. It occurs in multichannel system. If two pulse travels at different bit rates or with different group velocities walk across each other then XPM occurs due to walkover effect. Thus, slower pulse sees the walkover and induced a phase shift. Actually in XPM, when two pulses travel through an optical fiber due to change of refractive index as the optical power varies two pulses overlap and they introduce distortion into the other pulse [26]. XPM is a major performance limiting effect in high capacity WDM systems. Greater channel spacing and higher fiber core area minimize the effect of XPM.

The amount of phase modulation due to XPM in the *j*th channel is given by [27],

$$\theta_{XPM} = \frac{\gamma}{\alpha}\left(P_j + 2\sum_{m\neq j}^{N} P_m\right) \text{ -- } (2.14)$$

Where, γ = Nonlinear coefficient,

α = Attenuation constant,

P_j = jth channel power,

N = No. of channels.

The influence of XPM is much more important than the influence of SPM in WDM systems. From equation (2.14) we see that the effect of XPM at least twice than the effect of SPM. The first term of this equation is responsible for SPM and second term for XPM. XPM is the most important factor that determines the transmission capacity of optical fibers.

2.3.1.3 Four Wave Mixing (FWM)

Four wave mixing (FWM) phenomenon is one of the most important nonlinearities in optical fiber [28]. This nonlinear effect observes due to nonlinearity of refractive index of optical power. It is also a nonlinear effect of fiber optics. When three wavelengths interact in a nonlinear medium they create a fourth wavelength due to scattering of the incident photons. This phenomenon is known as FWM.

This phenomenon causes system degradation in multichannel transmission systems such as Wavelength division multiplexing (WDM) system [29]. The effects of FWM are pronounced with decreased channel spacing wavelengths and at high signal power levels [31].

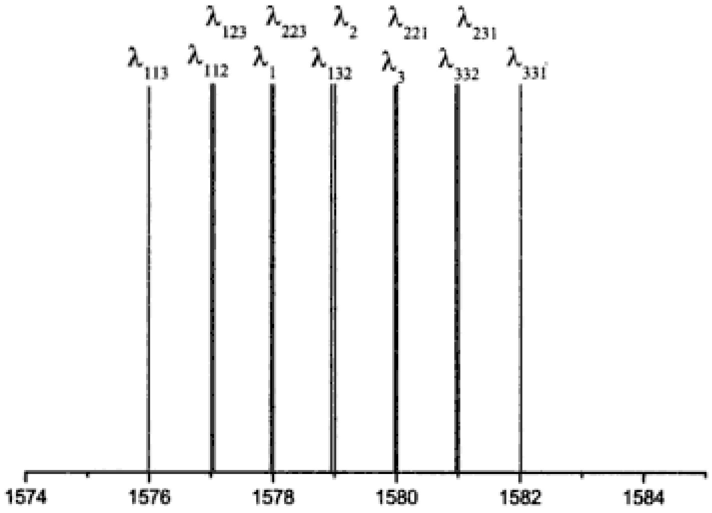

Fig. 2.7: Mixing frequencies due to FWM for equidistant wavelength spacing [31]

2.3.2 Stimulated Scattering Effect

In scattering effects, energy gets transferred from one light wave to another wave at a longer wavelength or lower energy. The lost energy is absorbed by the molecular vibrations, or phonons, in the medium. Stimulated scattering is affected by the threshold level. The most important types of nonlinear scattering within optical fibers are stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS).

2.3.2.1 Stimulated Raman Scattering (SRS)

SRS is a nonlinear parametric interaction between light and molecular vibrations. Optical phonon participates in SRS but acoustic photon participates in SBS. Due to SRS power transferred from shorter wavelength channels to the longer wavelength channels. SRS occurs in both directions, either forward or backward direction.

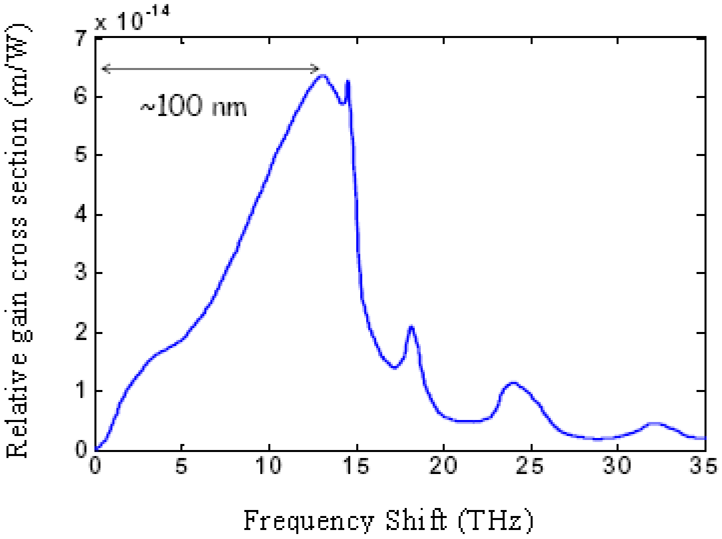

Fig. 2.8: Raman gain coefficient versus for fused silica with a pump at 1500 nm [35]

SRS effect occurred in multiple channel system. So it is a problem for WDM system, but it has almost no effect on single channel systems. In SRS scattered light is shifted by about 13 THz which is called Stokes shift.

2.3.2.2 Stimulated Brillouin Scattering (SBS)

The non-linear phenomenon of SBS, first observed in 1964 [30]. When launched power into an optical fiber exceeds threshold level, most of the light is reflected backward direction. This phenomenon is known as SBS. Input signal is known as pump wave and which signal is generated due to this scattering process that is known as Stokes wave. SBS occurs only in the backward direction *i.e.*, when input power exceeds threshold power, Stokes power shifted to the backward direction. Pump wave losses power while Stokes wave gains power.

In SBS scattered light is shifted to the backward direction by about 10 GHz which is called Stokes shift. Brillouin gain spectrum near about 20 MHz for SBS. SBS effect occurred in single channel system. So it is a problem for single channel system but it has almost no effect on WDM system because 10 GHz frequency is much smaller than channel spacing.

2.3.2.2.1 SBS Mechanism

Stimulated Brillouin scattering is a nonlinear process that can occur in optical fibers at large intensity. Quantum mechanically the Brillouin shift originates from the photon-phonon interaction. The basic mechanism of SBS phenomenon is illustrated in Fig. 2.9.

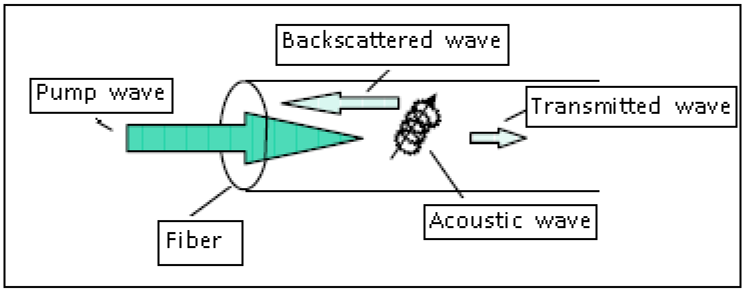

Fig. 2.9: Basic SBS mechanism

The pump wave creates acoustic wave in transmission medium through a process called electrostriction. The interaction between pump wave and acoustic wave creates the generation of back propagating optical wave which is called Stokes wave. When acoustic waves travel through the solid, transparent glass material, they induce spatially periodic local compressions and expansions which in turn cause local increases and decreases in the refractive index. This phenomenon is known as photoelastic effect. The magnitude of the photoelastic effect increases with increasing input optical power. When the input power reaches a SBS threshold level, the refractive index of the fiber has been acoustically altered to a degree such that a significant portion of the optical signal is back-scattered. So, we can say that the acoustic wave alters the optical properties of the fiber, including the refractive index. This fluctuation of refractive index scatters the incident wave and creates Stoke wave which propagates in the opposite direction.

2.3.2.2.2 Physical Process of SBS

From SBS mechanism, we have seen that there is annihilation of a pump photon, which results is creation of Stokes photon and an acoustic phonon simultaneously. The conservation law for energy and momentum must be followed in such scattering process. If ω_p is pump frequency and ω_s is Stokes frequency then according to energy conversion we can write,

Stokes shift, $\omega_B = \omega_p - \omega_s$ -- (2.15)

and $\mathbf{k}_A = \mathbf{k}_p - \mathbf{k}_s$ -- (2.16)

where , $\mathbf{k}_A$ is the momentum vector of acoustic wave,
$\mathbf{k}_p$ is the momentum vector of pump wave and
$\mathbf{k}_s$ is the momentum vector of Stokes wave

The frequency ω_B and the wave vector $\mathbf{k}_A$ of the acoustic wave satisfy the standard dispersion relation [9],

$$\begin{aligned}\omega_B &= \upsilon_A\, |\mathbf{k}_A| \\ &= \upsilon_A\, |\mathbf{k}_p - \mathbf{k}_s| \\ &\approx 2\upsilon_A\, |\mathbf{k}_p| \sin\left(\frac{\theta}{2}\right) \quad \text{-- (2.17)}\end{aligned}$$

So ω_B is maximum when $\theta = \pi$, *i.e.*, backward direction and ω_B is minimum when $\theta = 0^\circ$ *i.e.,* forward direction. From equation (2.17) we can write,

$$\begin{aligned}\upsilon_B &= \omega_B / 2\pi \\ &= 2n\upsilon_A/\lambda_p \quad \text{-- (2.18)}\end{aligned}$$

2.3.2.2.3 Brillouin Gain Spectrum

Brillouin gain can be written as [32],

$$g_B(\omega) = g_B(\omega_B)/1 + (\omega - \omega_B)^2 T_B^{\ 2} \quad \text{-------------------------- (2.19)}$$

The peak value of Brillouin gain occurs at $\omega = \omega_B$.

The gain $g_B(\omega)$ depends on many parameters like concentration of dopants in Fiber. Fig. 2.10 shows the gain spectra measured for three different fibers having different structures and different doping levels of Germania in their core

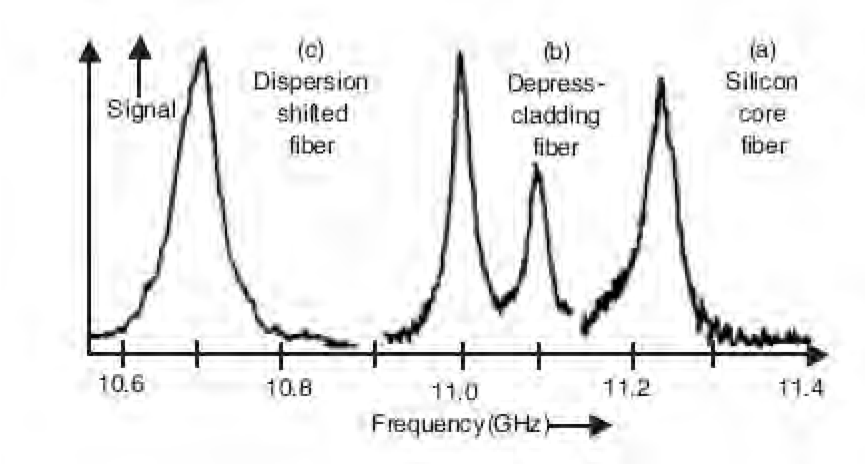

Fig. 2.10: Brillouin gain spectra at pump wavelength at 1525 nm [32]

Fig. 2.10 describes the Brillouin gain spectra at pump wavelength 1525nm for (a) silica-core fiber, (b) depress-cladding fiber and (c) dispersion shifted fiber. Brillouin shift is reduced for fibers b and c with nearly inverse dependence on the germanium concentration. The fiber b has a double-peak structure that results from an inhomogeneous distribution of germanium within the core.

2.3.2.2.4 SBS Threshold Power

We can write, $\frac{dI_s}{dz} = g_B I_p I_s$ -- (2.20)

Where, g_B = Brillouin gain coefficient,

I_p = pump wave intensities and

I_s = Stokes wave intensities.

From equation (2.20) we can write [9],

$$\frac{dI_s}{dz} = -g_B I_p I_s + \alpha_s I_s \qquad (2.21)$$

For pump wave,

$$\frac{dI_p}{dz} = -\frac{\omega_p}{\omega_s} g_B I_p I_s - \alpha_p I_p \text{ --- } (2.22)$$

For simplicity we can consider $\omega_p \approx \omega_s$ and therefore $\alpha_p \approx \alpha_s = \alpha$. We can write

$$\frac{dI_s}{dz} = -g_B I_p I_s + \alpha\ I_s \text{ -- } (2.23)$$

and $$\frac{dI_p}{dz} = -g_B I_p I_s - \alpha\ I_p \text{ -- } (2.24)$$

For $\alpha = 0$, from equation (2.23) and (2.24) we can write,

$$I_p - I_s = \text{constant -- } (2.25)$$

When stokes power is much smaller than pump power we can ignore the term $-g_B I_p I_s$ in equation (2.24),

$$\frac{dI_p}{dz} = -\alpha\ I_p \text{ -- } (2.26)$$

The solution of the equation (2.26) is,

$$I_p(z) = I_p(0)\exp[-\alpha z] \text{ -- } (2.27)$$

where $I_p(z)$ is the pump intensities at length z

and $I_p(0)$ is the pump intensities at $z = 0$

From equation (2.23) and (2.27),

$$\frac{dI_s}{dz} = -g_B\ I_p(0)\exp[-\alpha z] I_s + \alpha\ I_s \text{ --- } (2.28)$$

The solution of the equation (2.28),

$$I_s(0) = I_s(L)\exp[g_B I_p(0) L_{eff} - \alpha L] \text{ -- } (2.29)$$

Where, L_{eff} = effective length of interaction.

From equation (2.27) and (2.29),

$$P_s(0) = P_s(L)\exp(-\alpha L)\exp(g_B P_p(0) L_{eff} / A_{eff}] \tag{2.30}$$

and

$$P_p(L) = P_p(0)\exp[-\alpha L] \tag{2.31}$$

We can calculate SBS threshold power from equation (2.30) and (2.31). It can be approximated as [30],

$$P_{th} = 21\frac{A_{eff}}{g_B L_{eff}}\left(1 + \frac{\Delta V'_{source}}{\Delta V_B}\right) \tag{2.32}$$

where, A_{eff} = Effective cross-section area,

b = Polarization factor,

L_{eff} = Effective length,

g_B = Brillouin gain coefficient,

ΔV_B = Brillouin line width and

ΔV_{source} = Source line width

2.3.2.2.5 SBS Effect During Signal Transmission

The scattering effect transfers power from incident wave to the reflected wave. The lost energy is absorbed by molecular vibrations in the fiber. Due to this loss of energy, the reflected wave has a lower frequency than the incident wave.

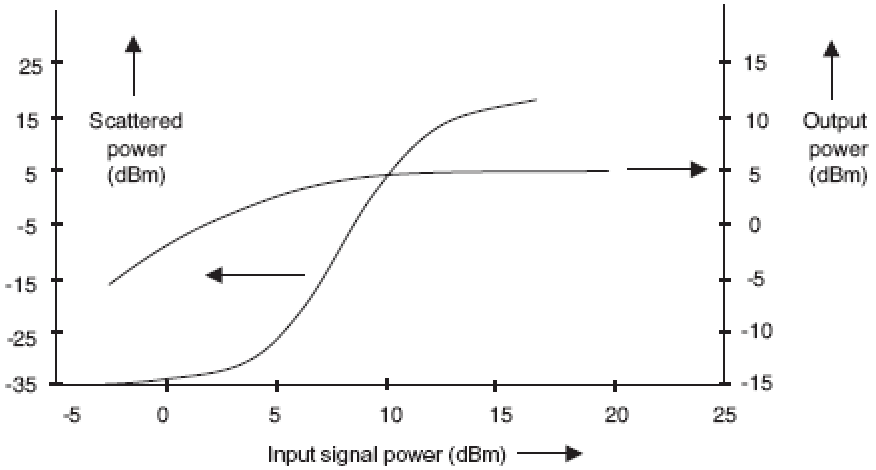

Fig. 2.11: Illustration of SBS effect [34]

The SBS effect is depicted in Fig. 2.11. From Fig. 2.11, we see that with increasing input power output power also increased. But at a certain point output power is saturated i.e., output power is not increased; most of the power is reflected to the backward direction with increasing input power. Due to the SBS effect high power transmission is not possible, we don't get expected output power due to the backscattering.

SBS is a problem for signal quality. It has some harmful effects such as attenuation, power saturation, back- propagation etc. Attenuation is due to the loss of energy *i.e.*, power transfer from pump wave to reflected wave. SBS limits maximum amount of power that can be transmitted through a fiber. At a certain point output power is not increase with input power *i,e,*; power is saturated. From Fig. 2.11, we see this effect of SBS clearly. Due to the SBS affect most of the power reflected to the backward direction when input power exceeds more 14 mW. It creates noise in transmitter and saturates amplifiers. SBS causes bit error rate degradation, for that reason it is a serious problem for single channel system. So, we need to suppress the SBS effect and enable the system to transmit larger amount of optical power at the receiving end.

2.4 Comparison of Different Types of Nonlinearities

In the preceding sections, we have described the characteristics of various nonlinear effects. We are summarizing their salient features in Table 2.1 and Table 2.2.

Table 2.1 Comparison between SBS and SRS Effect

Sl no.	**SBS effect**	**SRS effect**
1.	Brillouin shift originates from the photon-acoustic phonon interaction.	Raman shift originates from photon-optical phonon interaction.
2.	The SBS occurs only in backward direction.	The SRS can occur in both directions, *i.e.*, forward and backward.
3.	Frequency shift is near about 10 GHz.	Frequency shift is near about 10 THz**.**
4.	Brillouin gain bandwidth is near about 20 MHz.	Raman bandwidth is near about 5 THz.
5.	It effects on single channel system.	It effects on WDM channel system.

Table 2.2 Comparison between optical Kerr effect and stimulated scattering effect

Sl no.	**Optical Kerr Effect**	**Stimulated Scattering Effect**
1.	Kerr effects are due to intensity dependence of refractive index	Stimulated scattering effects are due to threshold power.
2.	In optical Kerr effect, there has no energy transfer.	In stimulated scattering effect, energy transfer from pump wave to Stokes wave.
3.	It is elastic process.	It is inelastic process.
4	SPM, XPM, FWM are example of optical Kerr effect.	SBS and SRS are example of stimulated scattering effect.

CHAPTER 3

THEORITICAL ANALYSIS FOR SUPPRESSION OF SBS EFFECT

In this chapter, we have analyzed the technique of SBS suppression. First of all, we have discussed about the threshold power at which the SBS start its action. Then we have derived spectrum broadening factor due to self phase- and cross-phase modulation. We have also analyzed how SBS threshold power is increased using these nonlinear phase modulation.

3.1 Threshold Power of SBS

The amount of SBS threshold power from equation (2.32),

$$P_{th} = 21\frac{A_{eff}\, b}{g_B L_{eff}}\left(1+\frac{\Delta V'_{source}}{\Delta V_B}\right) \text{ --- } (3.1)$$

where, A_{eff} = Effective cross-section area,

b = Polarization factor,

L_{eff} = Effective length,

g_B = Brillouin gain coefficient,

ΔV_B = Brillouin line width and

$\Delta V'_{source}$ = Total source line width.

In optical transmission system, if we can increase the P_{th} value then it is possible to transmit higher amount of power without SBS effect. From equation (3.1) we observe that threshold power of SBS depends on the source line width, effective area and gain coefficient. Keeping all other parameters constant, if we increase the source line width then it is possible to increase the threshold power of SBS. Using nonlinear effect like- SPM or XPM, the new spectral width of the source, $\Delta V'_{source}$ becomes,

$$\Delta V'_{source} = \Delta V_{source} + \Delta \omega_{SPM\,/\,XPM} \quad \text{---} \quad (3.2)$$

In the following sections, we have derived the spectral broadening of the propagating signal *i.e.,* the source line width using SPM and XPM effects.

3.2 Spectral Broadening Factor

Due to some nonlinear phenomenon source line width of input signal is increased. The intensity dependence of the refractive index in nonlinear optical media is manifested through self phase modulation. If this effect is expressed in terms of frequency then it is called spectral broadening. Here we discuss about spectral broadening for SPM and XPM.

3.2.1 Spectral Broadening Factor due to SPM

The optical pulse propagation in a dispersive media like- single mode fiber (SMF) can be described by nonlinear Schrödinger equation (NLSE). The NLSE is given by,

$$i\frac{\partial A}{\partial z} = -i\frac{\alpha}{2}A + \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + i\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3} - \gamma|A|^2 A \quad \text{-----------------------------------} \quad (3.3)$$

where, $z =$ Longitudinal coordinate of the fiber,

$t =$ Time in a framework moving at the group velocity,

$A =$ Complex electrical field envelope,

$\beta_2 =$ First order group velocity dispersion (GVD),

$\beta_3 =$ Second order GVD and

$\gamma =$ Nonlinear coefficient.

Now, we would like to solve the NLSE equation analytically to derive the expression for spectral broadening due to SPM effect. We assume input pulse is propagating through the fiber in Gaussian form. The Gaussian pulse assuming unit amplitude is given by,

$$f(t) = \exp\left(\frac{-t^2}{2T_0^{\,2}}\right) \text{ -- } (3.4)$$

Let, the incident optical field at $z = 0$ is of the form

$$A(0,t) = A_0 f(t) \text{ --- } (3.5)$$

Where, A_0^2 is the peak power, $f(t)$ is the pulse shape.

The SPM effect introduces the nonlinear phase shift as the optical carrier signal changes with respect to time because of the intensity changes over time. So, the phase factor θ_{eff} arising due to SPM can be written as,

$$A_{eff}(0,t) = A_0 f(t) \exp(i\theta_{eff}) \text{ --- } (3.6)$$

To solve the NLSE, we have considered the dispersion and nonlinear effect separately. First, putting $\beta_2 = \beta_3 = 0$ (assuming no dispersion effect and only nonlinear effect), the NLSE becomes,

$$i\frac{\partial A}{\partial z} = -i\frac{\alpha}{2}A - \gamma|A|^2 A \text{ --- } (3.7)$$

Let, $A = r\exp(i\theta)$

Equating real and imaginary parts we obtain,

$$r(z,t) = r_0(t)\exp\left(-\frac{\alpha}{2}z\right)$$

$$\theta(z,t) = \theta_0(t) + \gamma\, r_0^{\,2}(t) L_{eff}$$

$$\text{where, } r_0(t) = A_0 f(t),$$

$$L_{eff} = \frac{1 - \exp(-\alpha z)}{\alpha}$$

$$\theta_{eff} = \gamma\, A_0^{\,2} f^2 L_{eff} = \theta_m f^2(t)$$

$$\theta_m = \gamma\, A_0^{\,2} L_{eff}, \quad \text{when } t = 0$$

From equation (3.5),

$$A_{eff}(0,t) = A_0 f(t)\exp\left[i\theta_m f^2(t)\right] \text{ -- } (3.8)$$

Since attenuation has no effect on dispersion, we may use $\gamma = 0, \quad \alpha = 0$, A_{eff} as input field at distance $z = 0$, then becomes,

$$i\frac{\partial A_{eff}}{\delta z} = \frac{-\beta_2}{2}\omega^2 A_{eff} \text{ -- } (3.9)$$

By solving the equation we get,

$$\tilde{A}_{eff}(z,\omega) = \tilde{A}_{eff}(0,\omega)\exp\left(\frac{i}{2}\beta_2\omega^2 z\right) \text{ -------------------------------------- } (3.10)$$

$\tilde{A}_{eff}(z,\omega)$ is the Fourier transform of $A_{eff}(z,t)$ such that,

$$A_{eff}(z,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{A}_{eff}(z,\omega)\exp(-i\omega t)d\omega \text{ -------------------------------- } (3.11)$$

From equation (10), $A(z,\omega) = \tilde{A}_{eff}(0,\omega)\exp\left(\frac{i}{2}\beta_2\omega^2 z\right)$

$$= F\left[A_{eff}(0,t)\right]\exp\left(\frac{i}{2}\beta_2\omega^2 z\right)$$

$$A(z,\omega) = A_0 F\{f(t)\exp\left[i\theta_m f^2(t)\right]\}\exp\left(\frac{i}{2}\beta_2\omega^2 z\right) \text{ ---------------------- } (3.12)$$

From equation (3.12) we get,

$$A(z,\omega) = F\left[\exp\left(-\frac{t^2}{2T_0^2}\right)\exp\left(-\frac{t^2}{T_0^2}\right)\right]\exp\left(\frac{i}{2}\beta_2\omega^2 z\right) \text{ --------------------------------- } (3.13)$$

$$\Psi(\omega) = F\left[\exp\left(-\frac{t^2}{2T_0{}^2}\right)\exp\{i\theta_m \exp\left(-\frac{t^2}{T_0{}^2}\right)\}\right] \tag{3.14}$$

$$\tau(t) = \exp\left(-\frac{t^2}{2T_0{}^2}\right)\exp\left[i\theta_m \exp\{i\theta_m \exp\left(-\frac{t^2}{T_0{}^2}\right)\}\right] \tag{3.15}$$

$$\Psi(\omega) = F\left|\tau(t)\right| \tag{3.16}$$

The RMS width is related to the square root of the variance of the pulse and here. The RMS spectral width of the pulse due to SPM is given by,

$$(\Delta\omega)_{SPM} = \left\{\left\langle\omega^2\right\rangle - \left\langle\omega\right\rangle^2\right\}^{\frac{1}{2}} \tag{3.17}$$

Now, $$\left\langle\omega^2\right\rangle = \frac{\int_{-\infty}^{\infty}\omega^2\left|\Psi(\omega)^2\right|d\omega}{\int_{-\infty}^{\infty}\left|\Psi(\omega)\right|^2 d\omega} \tag{3.18}$$

$$\omega = \frac{\int_{-\infty}^{\infty}\omega\left|\Psi(\omega)\right|^2 d\omega}{\int_{-\infty}^{\infty}\left|\Psi(\omega)\right|^2 d\omega} \tag{3.19}$$

But for odd function,

$$\int_{-\infty}^{\infty}\omega\left|\Psi(\omega)\right|^2 d\omega = 0; \quad \text{So,} \left\langle\omega\right\rangle^2 = 0, \tag{3.20}$$

Now using Fourier Transform multiplication property we find out the value of $\int_{-\infty}^{\infty}\left|\Psi(\omega)\right|^2 d\omega$,

$$\int_{-\infty}^{\infty}\left|\Psi(\omega)\right|^2 d\omega = \frac{1}{2\pi}\int_{-\infty}^{\infty}\left|\tau(t)\right|^2 dt \tag{3.21}$$

Now,

$$\tau(t) = \exp\left(-\frac{t^2}{2T_0{}^2}\right)\exp\left[i\theta_m \exp\left(-\frac{t^2}{T_0{}^2}\right)\right]$$

$$\left|\tau(t)\right| = \exp\left(-\frac{t^2}{2T_0^{\ 2}}\right) \qquad \text{Since, } \left|re^{i\Phi}\right| = |r|$$

$$\left|\tau(t)\right|^2 = \exp\left(-\frac{t^2}{T_0^{\ 2}}\right)$$

$$\int_{-\infty}^{\infty} \Psi|\omega|^2 d\omega = \frac{1}{2\pi}\int_{-\infty}^{\infty} \exp\left(-\frac{t^2}{T_0^{\ 2}}\right)dt$$

$$= \frac{1}{2\pi}\frac{\sqrt{\pi}}{\sqrt{a}} \qquad \text{Since } \int_{-\infty}^{\infty} e^{-at^2}dt = \frac{\sqrt{\pi}}{\sqrt{a}}$$

$$= \frac{1}{2\pi}T_0\sqrt{\pi} \qquad \text{as, } a = \frac{1}{T_0^{\ 2}}$$

So, $$\int_{-\infty}^{\infty} \Psi|\omega|^2 d\omega = \frac{1}{2\sqrt{\pi}}T_0$$

Using multiplication and frequency derivative property,

$$\int_{-\infty}^{\infty} \omega^2 \left|\Psi(\omega)\right|^2 d\omega = \frac{1}{2\pi}\int_{-\infty}^{\infty} \left|\tau'(t)\right|^2 dt \quad \text{---} \ (3.22)$$

Again,

$$\tau(t) = \exp\left(-\frac{t^2}{2T_0^{\ 2}}\right)\exp\{i\theta m.\exp\left(-\frac{t^2}{T_0^{\ 2}}\right)\}$$

$$\tau'(t) = -\frac{t}{T_o^{\ 2}}.\exp\left(-\frac{t^2}{2T_0^{\ 2}}\right).\exp\{i\theta_m.\exp\left(-\frac{t^2}{T_0^{\ 2}}\right)\}\left[1 + 2i\theta_m \exp\left(-\frac{t^2}{T_0^{\ 2}}\right)\right]$$

$$\left|\tau'(t)\right| = -\frac{t}{T_0^{\ 2}}\exp\left(-\frac{t^2}{2T_0^{\ 2}}\right)\left[\sqrt{1 + 4\theta_m^{\ 2}\exp\left(-\frac{2t^2}{T_0^{\ 2}}\right)}\right]$$

$$\left|\tau'(t)\right|^2 = \frac{t^2}{T_0^{\ 4}}\exp\left(-\frac{t^2}{T_0^{\ 2}}\right)\left[1 + 4\theta_m^{\ 2}\exp\left(-\frac{2t^2}{T_0^{\ 2}}\right)\right]$$

Now,

$$\int_{-\infty}^{\infty}\omega^2\left|\Psi(\omega)\right|^2 d\omega=\frac{1}{2\pi}\int_{-\infty}^{\infty}\left|\tau'(t)\right|^2 dt$$

$$=\frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{t^2}{T_0^{\ 2}}\exp\left(-\frac{t^2}{T_0^{\ 2}}\right)[1+4\theta_m^{\ 2}\exp\left(-\frac{2t^2}{T_0^{\ 2}}\right)]dt$$

$$=\frac{1}{2\pi T_0^{\ 4}}[\int_{-\infty}^{\infty}t^2\, exp\left(-\frac{t^2}{T_0^{\ 2}}\right)dt+4\theta_m^{\ 2}\int_{-\infty}^{\infty}t^2\, exp\left(-\frac{2t^2}{T_0^{\ 2}}\right)dt$$

$$=\frac{1}{2\pi T_0^{\ 4}}[\frac{1}{2}.\frac{\pi}{a^{\frac{3}{2}}}+4\theta_m^{\ 2}.\frac{1}{2}\frac{\sqrt{\pi}}{a_2^{\ \frac{3}{2}}}]$$

Since, $\int_{-\infty}^{\infty}t^2a^{-at^2}dt=\frac{1}{2}\frac{\sqrt{\pi}}{a^{\frac{3}{2}}}$

$$\therefore\int_{-\infty}^{\infty}\omega^2\left|\Psi(\omega)\right|^2 d\omega=\frac{1}{4T_0\sqrt{\pi}}+\frac{\theta_m^{\ 2}}{\sqrt{\pi}}.\frac{1}{T_0\left(\sqrt{2}\right)^3}$$

Finally we get,

$$\int_{-\infty}^{\infty}\Psi\left|\omega\right|^2 d\omega=\frac{1}{2\sqrt{\pi}}T_0 \quad \text{---} \quad (3.23)$$

and

$$\int_{-\infty}^{\infty}\omega^2\left|\Psi(\omega)\right|^2 d\omega=\frac{1}{4T_0\sqrt{\pi}}+\frac{\theta_m^{\ 2}}{\sqrt{\pi}}.\frac{1}{T_0\left(\sqrt{2}\right)^3} \quad \text{-------------------------} \quad (3.24)$$

Now, substituting the value of equation (3.21) and (3.22) in equation (3.17),

$$(\Delta\omega)_{SPM}^2=\frac{\int_{-\infty}^{\infty}\omega^2\left|\Psi(\omega)\right|^2 d\omega}{\int_{-\infty}^{\infty}\left|\Psi(\omega)\right|^2 d\omega} \quad \text{---} \quad (3.25)$$

$$=\frac{\frac{1}{2\pi}\int_{-\infty}^{\infty}\left|\tau'(t)\right|^2 dt}{\frac{1}{2\pi}\int_{-\infty}^{\infty}\left|\tau(t)\right|^2 dt}$$

$$= \frac{1}{2T_0^{\ 2}}\left(1 + \frac{4}{3\sqrt{3}}\theta_m^{\ 2}\right) \quad \text{---} \quad (3.26)$$

Thus the RMS spectral broadening due to SPM effect of the propagating Gaussian pulse,

$$(\Delta\omega)_{SPM} = \left\{\frac{1}{2T_0^{\ 2}}\left(1 + \frac{4}{3\sqrt{3}}\theta_m^{\ 2}\right)\right\}^{\frac{1}{2}} \quad \text{---} \quad (3.27)$$

3.2.2 Amount of phase change due to XPM

For XPM, the derivation for spectral broadening will be as (3.27), but the amount of phase will be different. The amount of phase modulation due to XPM in the j^{th} channel is given by,

$$\theta_{XPM} = \frac{\gamma}{\alpha}\left(P_j + 2\sum_{m \neq j}^{N} P_m\right) \quad \text{-------------------------} \quad (3.28)$$

where, γ = The nonlinear coefficient,

α = Attenuation constant,

P_j = j^{th} channel power,

N = Number of channel.

If there are N channels with equal power, the nonlinear phase in the j^{th} channel becomes,

$$\theta_{\max(XPM)} = \frac{\gamma}{\alpha}(2N - 1)P_j \quad \text{---} \quad (3.29)$$

And for unequal channel power, suppose only 4 channels, the amount of maximum phase change in 3rd channel is given by,

$$\theta_{\max(XPM)} = \frac{2\pi n_2}{\lambda_3}.z.\left[I_3(t) + 2I_1(t) + 2I_2(t) + 2I_4(t)\right] \quad \text{--------------------------} \quad (3.30)$$

Thus, the RMS spectral broadening due to XPM is,

$$(\Delta\omega)_{XPM} = \left\{\frac{1}{2T_0^{\,2}}\left(1+\frac{4}{3\sqrt{3}}\theta_{XPM}^{\;\;2}\right)\right\}^{\frac{1}{2}} \text{ -- } (3.31)$$

3.3 Improving SBS Threshold Using SPM

Spectral broadening occurred due to SPM. We want to find out the spectral broadening by solving the NLSE. From equation (3.1), we have already seen that SBS threshold power depends on source linewidth. After spectral broadening, we get new source linewidth and total source linewidth from equation (3.2). We have derived the equation for spectral broadening. Now we may put the value of equation (3.27) into equation (3.2) and observe that if we increase source linewidth then is it possible to increase SBS threshold power or not. In the next chapter we have done numerical simulation and found that broadened linewidth due SPM and/ or XPM suppresses the SBS effect significantly.

3.4 Improving SBS Threshold Using XPM

Like SPM, XPM also enhances the spectral broadening. Interestingly, it is found that the effect of XPM is twice than that of SPM. It is clear from equation (3.28) that the spectral broadening is more than SPM for same channel power. We also observe the effect of XPM for both cases equal channel and unequal channel spacing with same and /or different amount of input optical power.

CHAPTER 4

RESULTS AND DISCUSSION

Following the analytical formulations in chapter 3, we have carried out numerical simulation and obtained results are depicted by different graphs. Here, at first we have observed different characteristics of SBS effect, spectral broadening due to SPM and XPM as a function of fiber length. Our analytically derived model of spectrum broadening improves SBS threshold power and we can transfer higher amount of optical power without BER degradation. We have found the improvement of SBS threshold power for both SPM and XPM. For XPM we have considered equal channel as well as unequal channel power. MATLAB software is used to plot different types of graph. The parameter values used in the theoretical computations are given in Table 4.1.

Table 4.1: Different types of parameters and their values

Parameter	**Value**
Effective area, A_{eff}	$5.5 \times 10^{-11}\ m^2$
Polarization factor, b	1
Non-linear coefficient, γ	$2.35 \times 10^{-20}\ m^2 / w$
Brillouin bandwidth, Δv_b	20 MHz
Brillouin gain coefficient, g_b	$4 \times 10^{-11} m / w$
Wavelength, λ	1550 nm

4.1 Relative Intensity Pump and Stokes Power

SBS scattered light moves backward and the phonons associated with it are acoustic in nature. It becomes a stimulated process when the input power exceeds the threshold level. Pump power produces density variations through electrostriction, resulting in an index grating which generates Stokes wave through Bragg diffraction.

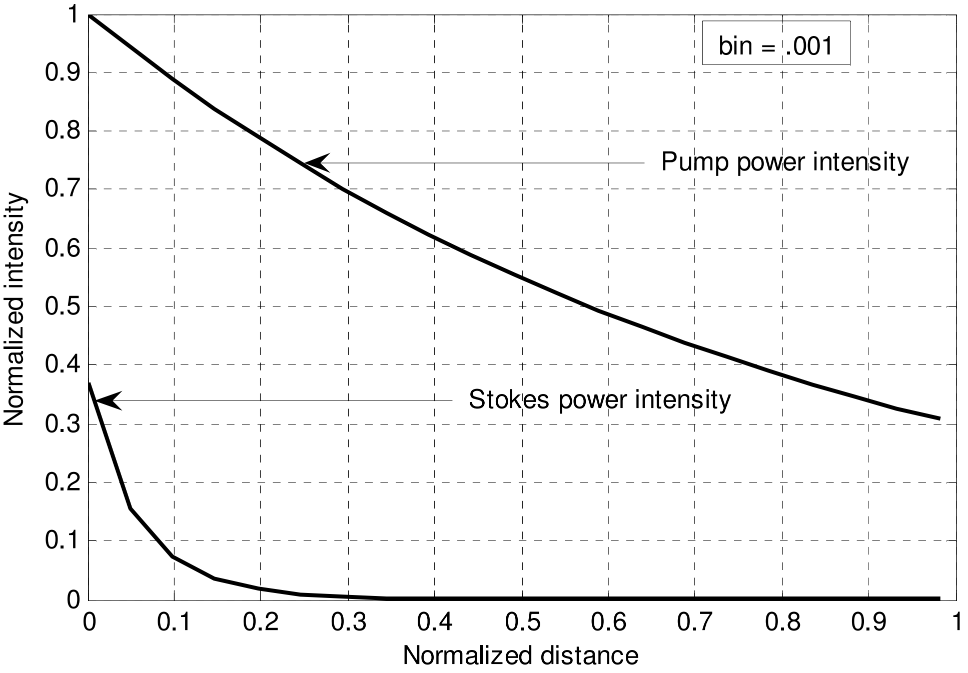

Fig.4.1: Variation of relative intensity of pump- and Stokes power along fiber length

In Fig. 4.1, we plot the relative intensity of pump- and Stokes power along fiber length based on equations (2.27), (2.29) and (2.31) which are derived and discussed in chapter 2. Here x-axis denotes normalized distance and y-axis denotes normalized intensity. At the input end, it is found that the nonlinear effects of pump wave and backscattered wave. Here, we use b_{in}=.1%, where, b_{in} is the ratio of Stokes power intensity at L distance to the pump power intensity at zero length.

From this figure we observe that 40% of the pump power is transferred to the Stoke power for b_{in}=.001 and it also remarkable that most of the power transfer occurred within the first 20-30% of the fiber length.

4.2 Backscattered Power as a Function of Input Power

This nonlinear effect is due to the interaction between the incident light and acoustic vibration in the optical fiber. Similar to SRS, SBS causes frequency down-conversion of the incident light, but the frequency shift in this case is equal to the frequency of the interacting acoustic wave.

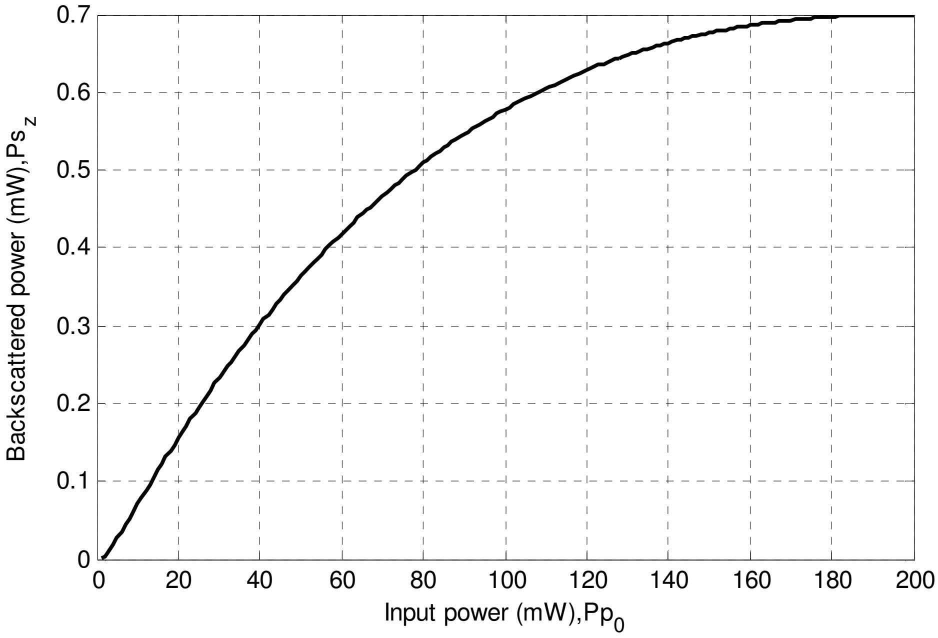

Fig. 4.2: Backscattered power versus input power

Fig. 4.2 shows the backscattered power versus input power. We have already seen that after SBS threshold most of the portion of pump power is scattered to the backward direction. From this Fig. 4.2, we observe that with increasing input power *i.e.*, backscattered power also increases. When the gain of the backscattered light is greater than the losses due to fiber attenuation, it reaches the SBS threshold. After this point, the amount of backscattered light increases very rapidly with increasing input power until nearly all the input power is reflected.

4.3 Ratio of Backscattered Power and Pump Power

Brillouin scattering manifests itself through the generation of a backward propagating Stokes wave downshifted from the frequency of the incident pump wave by an amount determined by the nonlinear medium. The stoke waves carries most of the input energy, once the Brillouin threshold is reached.

The process of SBS can be viewed as a parametric interaction among the pump wave, the Stokes and anti Stokes wave and an acoustic wave. The pump field generates sound waves in the fiber which induce a periodic modulation of the refractive index due to the pressure.

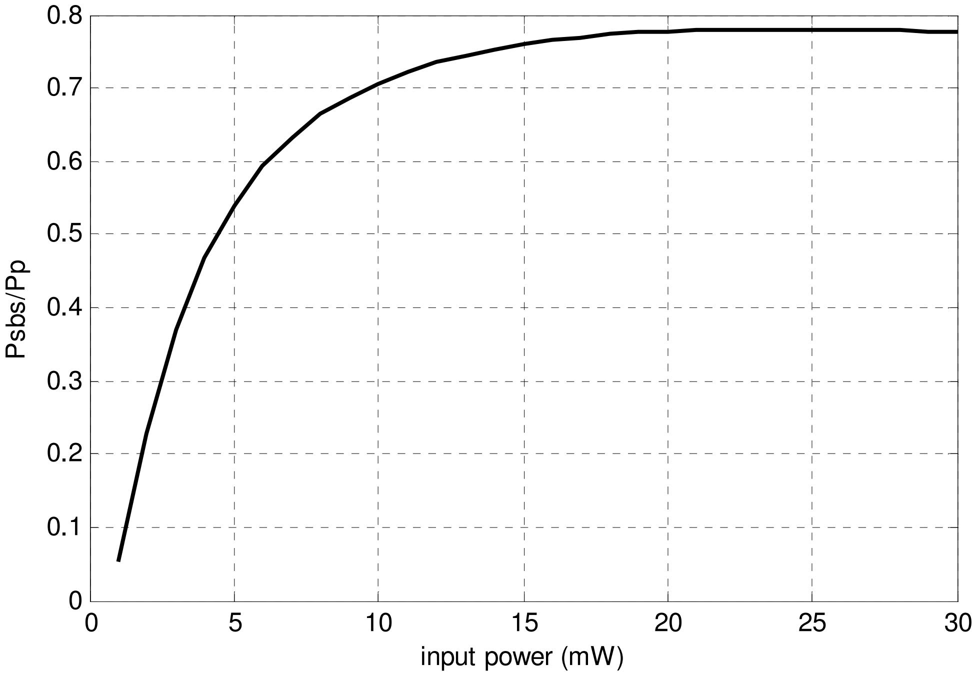

Fig. 4.3: P_{sbs}/P_p versus P_p

Fig. 4.3 shows the normalized Stokes power versus pump power. Here, P_{sbs} indicates backscattered power or Stokes power and P_p indicates input pump power. This plot is called the reflectivity curve. The power of SBS scattering light increases gradually as the fiber-launch power increased. When the fiber-launch power reached a certain point, the SBS scattering light power increased dramatically, indicating that it has crossed the threshold power of SBS. In Fig. 4.3, we have used the ratio of scattering light power, P_{sbs} to the fiber-launch power, P_p as the vertical axis and P_p as the horizontal axis and obtained the reflectivity curves of SBS.

4.4 Effect of Spectral Broadening

We would like to observe the effect of spectral broadening of the propagating signal on fiber link length from our derived equation. We plot the curves for different input power. Here we plot the curves to get the effect of spectral broadening on fiber length due to SPM and XPM.

4.4.1 Effect of Spectral Broadening Due to SPM

Fig. 4.4 shows the plots of spectral broadening versus fiber length for different amount of input power based on our derived equations in the previous chapter. From the Fig. 4.4, it is seen that at short distance the amount of spectral broadening is very small and almost linear irrespective of the input power. At relatively longer distance, spectral broadening becomes significant and also nonlinear. It is found that the spectral broadening is much higher for high power. We see that at 10 km fiber length, spectral broadening factor is 1.058, 1.217 and 1.443 for input power of 30 mW, 60 mW and 90 mW respectively.

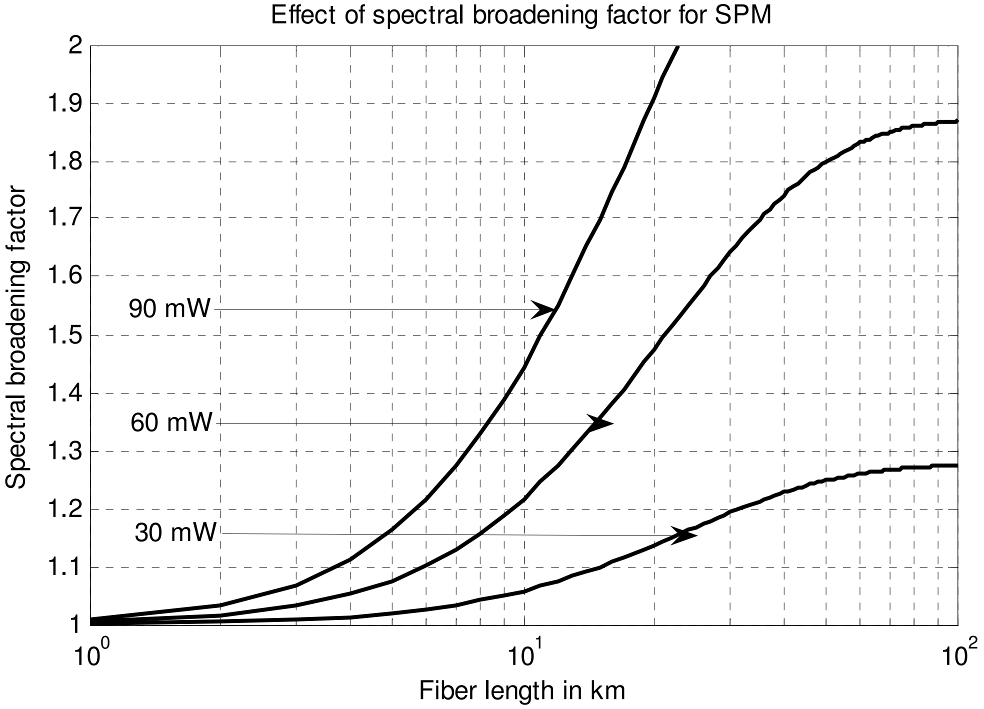

Fig. 4.4: Effect of spectral broadening due to SPM

4.4.2 Effect of Spectral Broadening Due to XPM (Equal Channel Power)

When more than one channel propagates through the fiber then the phase induced to the target channel is twice than SPM. In addition, the effect of SPM is also there. Here, we observe the effect of XPM on spectral broadening, we have considered only 3-channels and each channel is carrying equal amount of power. We have carried out three numerical simulation using 30 mW, 60 mW and 90 mW of input power in all the three channels. The plots are shown in Fig.4.5. It is seen that spectral broadening at 10 km link length is about 2.05, 3.61 and 5.29 for input power of 30 mW, 60 mW and 90 mW respectively. So, it is clear that the effect of spectral broadening factor due to XPM is much larger than SPM effect.

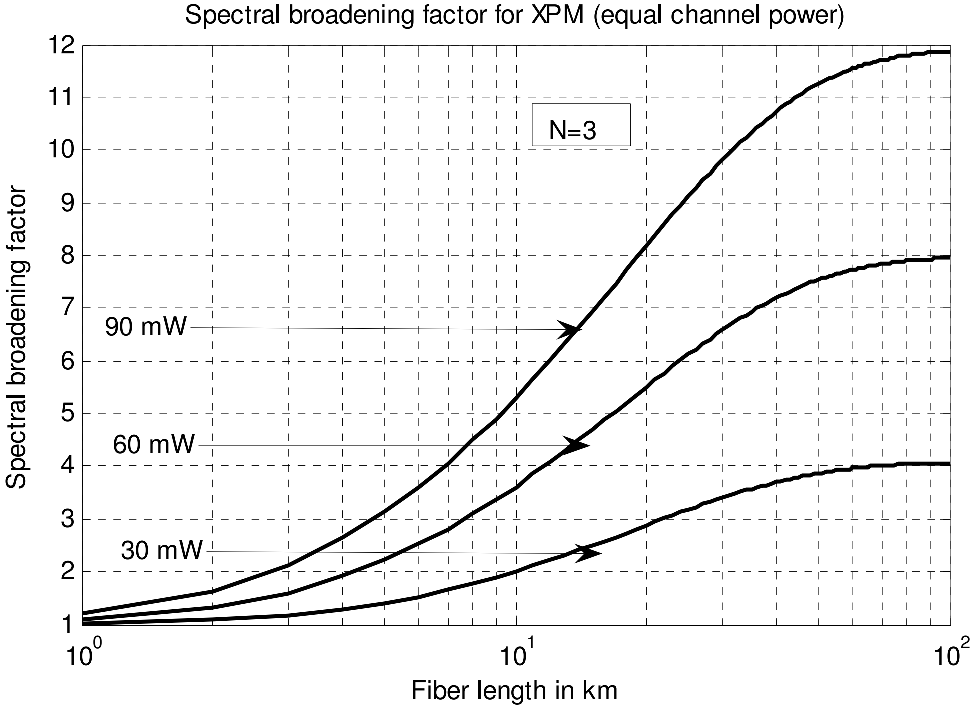

Fig. 4.5: Effect of spectral broadening due to XPM for equal channel power for 3-channels

4.4.3 Effect of Spectral Broadening Due to XPM (Unequal Channel Power)

We have also observed the effect of spectral broadening for unequal channel power and it is depicted in Fig. 4.6. Four channels are used for numerical simulation and we assumed that channel 2 as target the channel. Three simulations are run using use 30 mW, 60 mW and 90 mW of input power of the target channel (channel 2) power. From the plots, it is observed that spectral broadening is not same as equal power channels. For example, at 10 km fiber link length the spectral broadening factors are 3. 0, 3.4 and 4.0 for input power of 30 mW, 60 mW and 90 mW respectively.

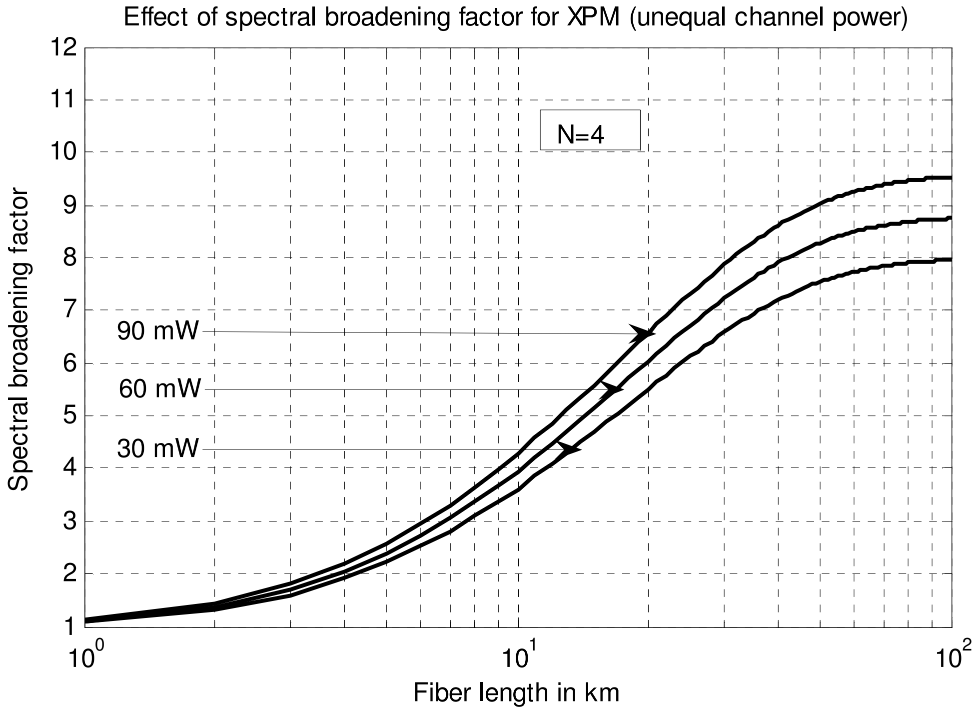

Fig. 4.6: Effect of spectral broadening due to XPM for unequal channel power (N=4)

4.4 Determination of Threshold Power Improvement

In the preceding 3-sections, we have evaluated the spectral broadening effect due to SPM and XPM. Now assuming the spectral broadening factor as propagation signal (source) broadening, we may use equation (3.1) to calculate the amount of threshold power improvement in each case.

4.4.1 Threshold Power Improvement Due to the Effect of SPM

We know that due to SBS effect, we cannot feed relatively high amount of optical input power to the fiber transmission link, because most of the power scattered to the backward direction due to SBS. By improving SBS threshold power, we can overcome this impairment of the system. Fig. 4.7 shows the improvement of SBS threshold power due to the spectral broadening of SPM effect. In this numerical simulation, we have used 30 mW, 60 mW and 90 mW of input power and found that with increasing input power SBS threshold power also increased. For example, at 220 MHz spectral width, the threshold power improvements are 3.75 mW, 4.5 mW and 6.25 mW respectively.

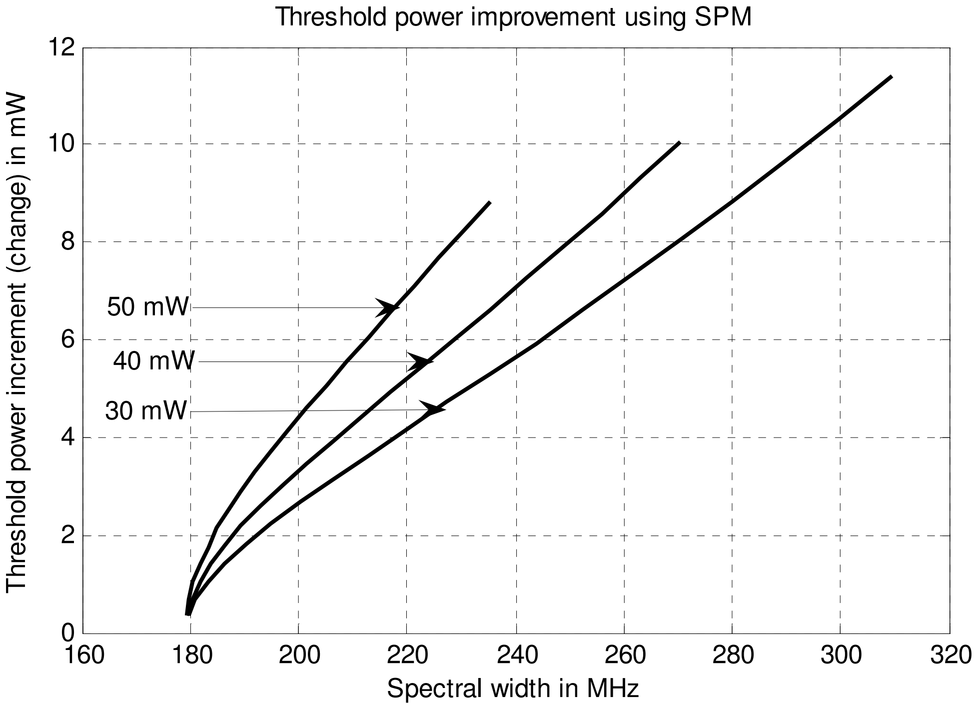

Fig. 4.7: Threshold power improvement using SPM

4.4.2 Threshold Power Improvement Due to XPM (Equal Channel Power)

Fig. 4.8 shows the SBS threshold increment power versus source spectral width due to XPM for equal channel power. Here, we have used values of 3-channels spectral broadening factor of Fig. 4.5. It is observed that spectral broadening and thereby the threshold power improvement is 1.5 times more than SPM effect for the same amount of power in all the 3-channels. For example, at 600 MHz source spectral width the amount of threshold power improvement are 7.5 mW, 10.2 mW and 14.5 mW for input optical power of 30 mW, 40 mW and 50 mW respectively.

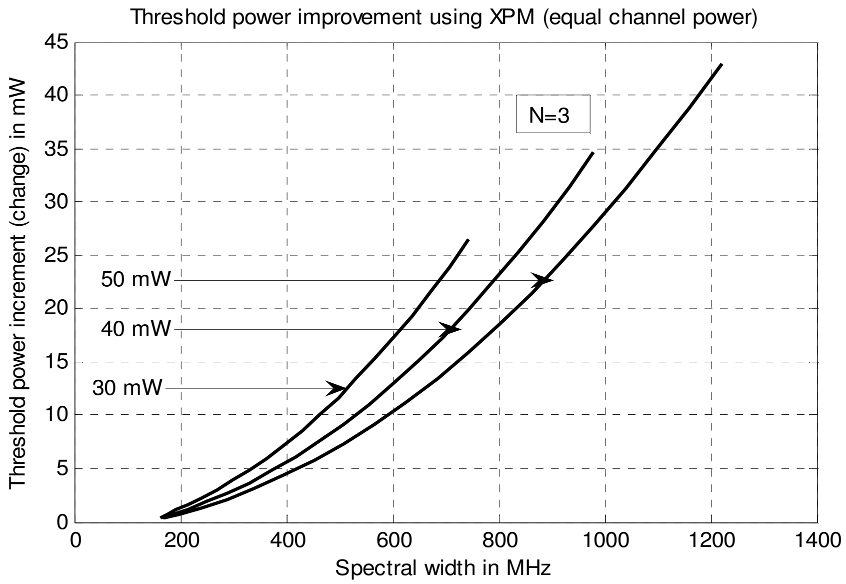

Fig. 4.8: Threshold power improvement due to XPM for equal channel (N=3)

4.4.3 Threshold Power Improvement Due to XPM (Unequal Channel Power)

Threshold power improvement due to XPM for unequal channel power is shown in Fig.4.9. We have noted that spectral broadening is significantly reduced in the case of unequal power and as a result threshold power improvement is also less in this case. For example, at 600 MHz spectral width is about 5 mW to 7 mW less than that of equal channel case of Fig. 4.8.

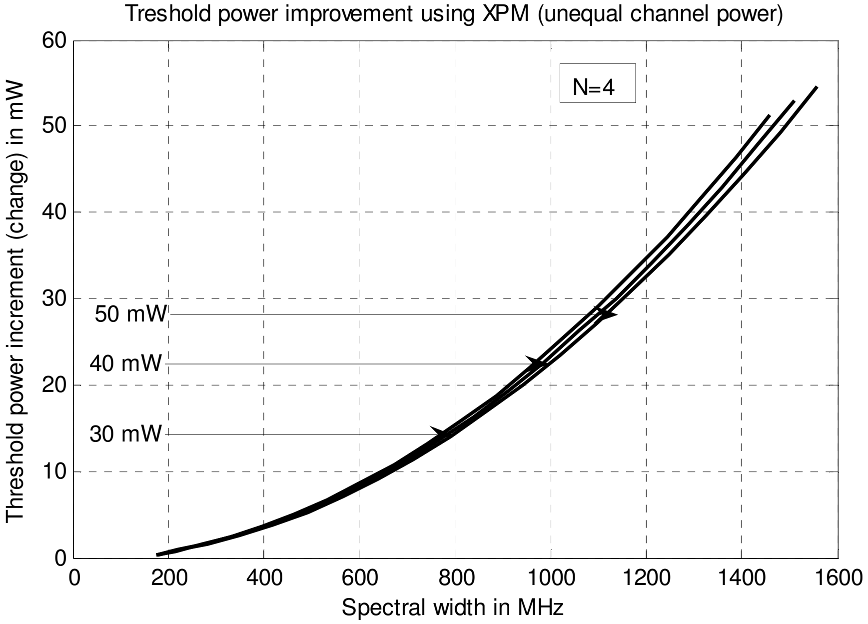

Fig 4.9: Threshold power improvement using XPM for unequal channel (N=4)

4.5 Comparison with Published Works

Over the years various works has been carried out to suppress the effect of SBS using different methods and techniques like- source frequency dithering, wide spectral width source power and nonlinear effect. Lei *et al.* have carried out simulation to suppress SBS by raising the threshold power using the SPM technique. In this section, we are comparing the performance of our proposed method with existing methods. A relative comparison is shown in Table 4.2.

Table 4.2 Comparison among different research works

Sl	**Method/Technique**	**Type of study**	**Length of the kink**	**Spectral broadening of pump wave**	**Threshold power improvement**
1.	Multi-frequency phase modulation [18]	Experimental	N/A	N/A	68 mW for three equal amplitude modulation signals
2.	SBS gain reduction [33]	Analytical	67.3 km	N/A	73 mW at modulation index 0.82
3.	Nonlinear SPM effect [17]	Simulation	100 km	Up to 18 MHz for SPM only	70 mW for SPM only
4.	Our proposed method	Analytical and numerical simulation	100 km	19.33 MHz for SPM 23.68 MHz for XPM [N=3]	72 mW for SPM 99.9 mW for XPM [N=3]

4.5.1 Comparison of Spectrum Broadening versus Fiber Length

Lei *et al.* have analyzed on SBS suppression using high power short pulse fiber amplifier using the SPM effect and have showed that with increasing fiber length spectrum broadening also increased [17]. Fig. 4.10 and Fig. 11 show the comparative frequency spectrum for SPM and XPM respectively. We have analyzed the SBS suppression and plotted the graph of spectral broadening as a function of fiber length using SPM and XPM nonlinear effect. It is seen from the Fig. 4.10 that our analytical result almost similar to the existing simulation work. It is found that the difference is only about 0.2 MHz at 70 km link length.

In the simulation work [17], they might have assumed some simple boundary conditions. This may be the probable cause for the small deviation between the simulation and our analytical work. From Fig. 4.11, SBS threshold power improvement is higher than SPM alone for the same link length.

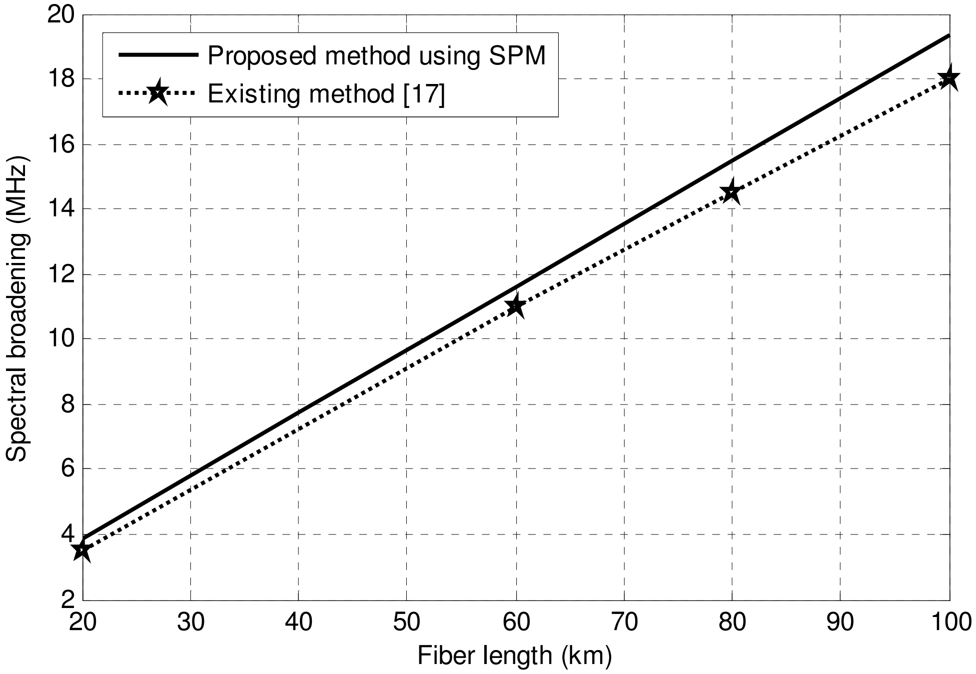

Fig.4.10: Spectral broadening versus fiber length for SPM

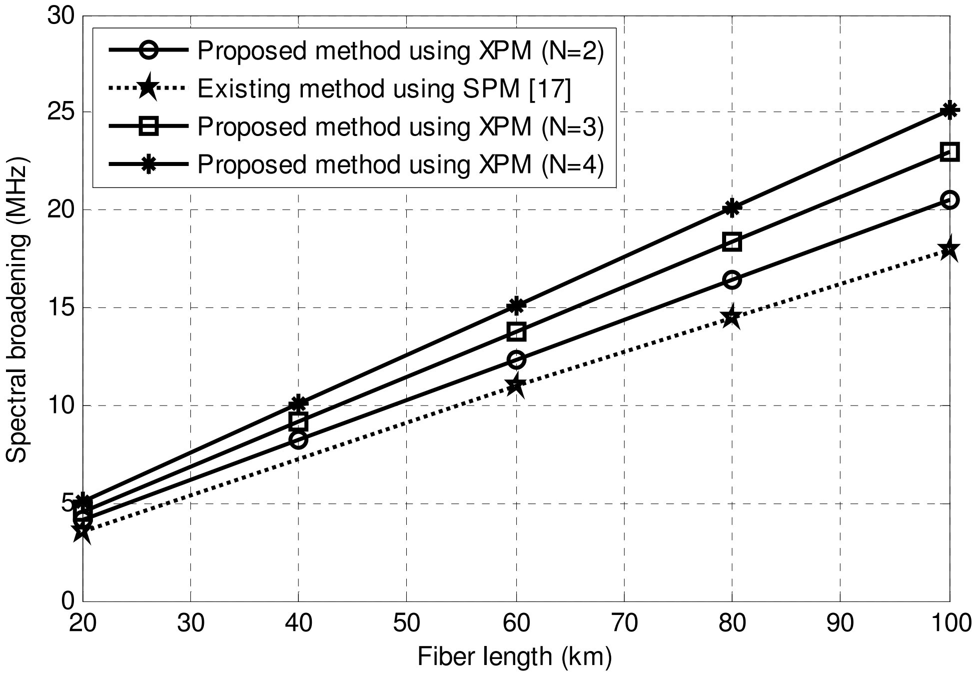

Fig. 4.11: Spectral broadening versus fiber length for XPM (Unequal channel power)

4.5.2 Comparison of Threshold Power Improvement

Fig. 4.12 in the next page shows the comparison of SBS threshold power based on our analysis. It is seen that threshold power is increased up to 72 mW at 100 km fiber length. Here, it is also noted that our analytical result shows almost a linear relationship of threshold power improvement with fiber link length. This deviation may result due to various boundary conditions under which simulation is carried out in [17].

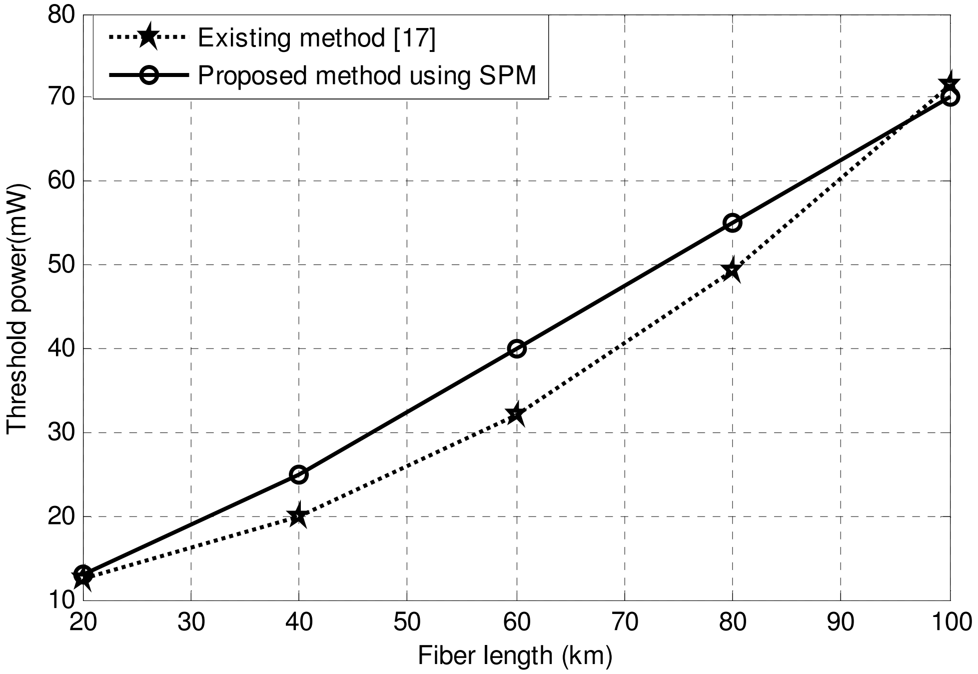

Fig. 4.12: Improvement of SBS threshold power versus fiber length using SPM

4.5.3 Overall Comparison with Related Work

In Table 4.2, we have established a comparison of our proposed work with published work. Liu *et al.* have experimentally worked SBS suppression based on multi-frequency phase modulation [18]. They have observed that the threshold power after modulation is in reverse proportion to the maximum square of amplitude moduli of fundamental frequency and the nth harmonic wave. For three equal amplitude modulation signals threshold power raised up to 68 mW. Hayashi *et al.* have analyzed on SBS threshold representing bit-error degradation in single-mode optical fiber transmission considering different boundary conditions [33]. They have improved SBS threshold power up to 73 mW at 0.82 modulation index. Lei *et al.* have raised the SBS threshold level using high power short pulse fiber amplifier [17]. They have improved threshold power up to 70 mW and spectral broadening up to 18 MHz at 100 km using SPM only. In our work,we found that threshold power improvements are up to 72 mW using SPM and 99.9 mW for XPM considering three channels. The spectral broadening of pump wave are up to 19.33 MHz and 23.68 MHz for SPM and XPM respectively.

4.6 Discussion

A detailed analytical formulation and numerical computation are carried out to evaluate the impact of SBS threshold power improvement in optical fiber communication systems. We have plotted the pump power intensity and Stokes power intensity along fiber length for different values of b_{in}. Initially, we have observed the effect of spectral broadening on fiber length due to SPM and XPM effect. Later on using those values of spectral broadening SBS threshold power improvement is determined. It is found that the effect of XPM is larger than SPM in suppressing the effect of SBS. Finally, we have compared our works with published works and found that threshold power improvement is almost same as those reported in literature.

Our analytical model is based on some boundary conditions and as a result we have seen a little deviation of the analytical result with the published simulation results. Our findings in this research may be useful in designing a high speed WDM system where higher amount of power handling is a critical factor.

CHAPTER 5

CONCLUSION AND FUTURE WORK

In this final chapter, we summarize the out-come of our intended research work to fulfill the desired objectives. Here, we also try to provide suggestions for future work.

5.1 Conclusion

In this thesis, we have first studied the fundamental characteristics and detrimental effect of SBS in optical transmission system. In optical transmission system, we always strive for larger span length by feeding higher amount of power at the transmitter end. But unfortunately due to the SBS effect, when the input power exceeds the threshold level, certain amount of power gets reflected in the backward direction thereby saturates the transmitter. From our analysis we found that about 40% of the pump power is transferred to the Stokes power for a ratio of 0.001, which is the Stokes power intensity at L distance to the pump power intensity at zero length and it is also notable that most of the power transfer occurs within the first 20 - 30% of the fiber length. So, the only way to transmit relatively higher power, we need to increase the SBS threshold level.

A detailed theoretical analysis is carried out to obtain the expression for spectrum broadening due to the nonlinear phenomenon like SPM and XPM. From the numerical simulation results, we have found that spectral broadening factor are 1.058, 1.217 and 1.443 for input power 30 mW, 60 mW and 90 mW respectively due to SPM effect at 10 km transmission length. Using these broadening factors and input optical powers, the amount of threshold power improvements are 2.1 mW, 3.2 mW and 4.5 mW respectively for a source spectral width of 200 MHz. In the case of XPM, we have considered equal and unequal channel power where it is observed that equal channel power does more spectral broadening than unequal channel power and thereby results more threshold power improvement.

5.2 Recommendations for Future Work

We have carried out our research to enhance the threshold power level of SBS using spectral broadening which ultimately suppress the SBS effect. Broadening due to SPM is observed for only single channel system and XPM for a limited number of channels for WDM system. Future work can be done in the following direction:

1. More number of channels may be considered for XPM effect which is contributing for the spectral broadening at data rate of 10 Gbps or higher.

2. One well known way to reduce the SBS effect is to increase the effective area. For fiber lasers, fibers with large mode area have been proposed to handle high laser power. Simulations may be done to increase the mode effective area by lowering the core refractive index and increasing the core diameter.

3. Another way to reduce the SBS is to reduce the overlap between the optical and acoustic field. The simple step index profile made of GeO_2 doping is not suitable for this purpose because the fundamental optical and acoustic mode has very similar field distribution. Appropriate doping materials may be searched to overlap the above mentioned fields.

4. Creating a non-uniform Brillouin spectrum along the fiber is also an effective way to reduce the SBS because it reduces the maximum effective gain coefficient. This can be done by changing the dopants level, applying distributed stress, or using a temperature gradient along the fiber during manufacturing. Before directly applying this approach in manufacturing, simulation or analytical study may be a viable option.

In summary, the SBS effect can be reduced by using different design methods to change the effective area, doping material, the effective gain coefficient as well as the polarization factor.

REFERENCES

[1] Senior J. M., “Optical Fiber Communications”, Chapter 1, Second Edition, Practice Hall International (UK) Ltd, 1993.

[2] Maynbaev D. K. and Scheiner L., “Fiber-Optic Communications Technology”, Chapter 1, Dorling Kinderley (India) Pvt. Ltd, Pearson Education in South Asia, 2001.

[3] Keiser G., “Optical Fiber Communications”, Chapter 1, Tata McGraw-Hill, 2008.

[4] Mukherjee B., “Optical WDM Networks”, Chapter 2, pp. 57-65, Department of Computer Science, University of California, Davis, CA 95616 USA, 2006.

[5] Guo Y., Kao, Lee E.H. and Chiang K.S., “Nonlinear Photonics: Nonlinearities in Optics, Optoelectronics, and Fiber Communications”, Chapter 1, The Chinese University Press, 2002.

[6] Kao D. and Hockham M., “Dielectric-fiber surface waveguides for optical frequencies”, Standard Telecommunication Laboratories Ltd, Proceedings of IEEE, vol. 113, no. 7, pp. 1151-1158, 1966.

[7] Bagad B.S., “Optical Communication”, Academy Press, New York, 2009.

[8] Shiraki K., Oshani M. and Tateda T., “Suppression of stimulated Brillouin scattering in a fiber by changing the core radius”, Electronics Letters, vol. 31, no. 8, pp. 668-669, 1995.

[9] Agrawal G. P., “Nonlinear Fiber Optics”, Chapter 9, Academic Press, Elsevier, Third Edition, pp. 355-360, 2009.

[10] Willems F. W. and Muys W., "Simultaneous suppression of stimulated Brillouin scattering and interferometric noise in externally modulated lightwave AM-SCM systems", IEEE Photonics Technology Letters, vol.6, no. 2, pp.1476-1478, 1994.

[11]Jaworski M. and Marcinial M., "Initial pulse modulation method for SBS counteracting in long distance optical fiber CATV link", Proceedings of 3rd International Conference on Transparent Optical Networks, pp. 279-282, 2001

[12] Lee H. and Agrawal G.P., "Suppression of stimulated Brillouin scattering in optical fibers using fiber Bragg gratings", Optical Express, vol. 11, no. 25, pp. 3467-3472, 2003.

[13] Ranet G., Fotiadi A.F., Blondel M. and Megret P., "Suppression of stimulated Brillouin scattering with a Raman fiber amplifier", Proceedings of IEEE Lasers and Electro Optics Society, Ghent (B), pp. 199-202, 2004.

[14] Hu L., Kaszubowska A. and Barry L.P., "Investigation of stimulated Brillouin scattering effects in radio-over-fiber distribution systems", Optics Communications, vol. 255, no. 4-6, pp.253-260, 2005.

[15] Hegde R.S., Winful H.G. and Galvanaskas A., "Suppression of stimulated Brillouin scattering in a photonic crystal fiber", Quantum Electronics and Laser Science Conference, QELS, pp.1-2, 2007.

[16] Gray S., Liu A., Walton D. T., Wang J., Li M. J., Chen X., Ruffin A. B., DeMeritt J. A. and Zenteno L. A., "Suppression of stimulated Brillouin scattering in high power, narrow linewidth fiber amplifiers" , Optical Express, vol. 15, no.25, pp. 17044-17050, 2007.

[17] Lei Z., Jiping N., Cheng C., Weiyi Z. and Juntao W., "Analysis of a novel stimulated Brillouin scattering suppression mechanism through self phase modulation process

in the high power short pulse fiber amplifier", Journal of Optoelectronics and Biomedical Materials, vol.1 no.1, pp. 157-164, 2009.

[18] Liu Y., Lii Z., Dong Y. and Li Q., "Research on stimulated Brillouin scattering suppression based on multi-frequency phase modulation", Chinese Optical Letters, vol. 7, no. 1, pp.29-31, 2009.

[19] Du W., Ma Y., Zhu J., Dong Wang, X., Zhou P. and Xu X., "Experimental study of the SBS effect in multitone-driven narrow-linewidth high-power all-fiber amplifiers", Photonics Global Conference, pp. 1-3, 2003.

[20] Downing N., "Fiber-Optic Communications", Academy Press.Third Edition, Chapter 2, pp. 25-26, 2004.

[21] Hui R. and Sulivan M. S., "Fiber Optic Measurement Techniques", Tata McGraw-Hill, Chapter 3, pp. 44-59, 2009.

[22] Selvarajan A., Kar S. and Srinivas T., "Optical Fiber Communication: Principles and Systems", Chapter 2, Tata McGraw-Hill Education, pp. 11-13, 2003.

[23] Kumar M. S., "Fundamentals of Optical Fiber Communication", PHI Learning Pvt. Ltd, Chapter 4, pp.58-60, 2005.

[24] Hellwarth R.W., "Third-order optical susceptibilities of liquids and solids", Quantum Electron, vol. 5, no. 1-A, pp.60-68, 1977.

[25] Alwayn V., "Optical Network Design and Implementation", Chapter 3, Cisco Press, USA, pp. 69-85, 2004.

[26] Goff D. R., Hansen K. S. and Stull M. K., "Fiber Optic Video Transmission: The Complete Guide", Chapter 6, Focal Press, pp. 67-68, 2003.

[27] Agrawal G.P., “Fiber Optic communication Systems”, Second Edition, New York, John Wiley & Sons, 1997.

[28] Hill K. O., Johnson D.C., Kawasaki B.S. and MacDonald R.I., “CW three-wave | mixing in single mode optical fibers”, Journal of Applied. Physics, vol.49, no.10, pp. 5098-5106,1978.

[29] Shibata N., Nosu K., Iwashita K. and Azuma Y., “Transmission limitation due to four-wave mixing in single mode optical fibers”, IEEE Journal of Selected Area in Communications, vol.8, pp.1068-1077, 1990.

[30] Boyd R.W., “Nonlinear Optics”, Chapter 8, Academic Press, San Diago, 1992.

[31] Sairam K. V., “Optical Communications”, Chapter 2, Firewall Media, 2007.

[32] Cotter D.,“Observation of stimulated Brillouin scattering in low loss silica fiber at 1.3 µm”, Electronics Letters, vol. 18, no. 10, pp.495–496, 1982.

[33] Hayashi Y. and Ohkawa N., “ Stimulated Brillouin Scattering Threshold Representing Bit- Error Ratio Degradation in Single-Mode Optical Fiber Transmission”, Electronics and Communications in Japan, Part 1, vol. 79, no.5, pp.15-26,1996.

[34] Mao X.P., Takach R.W., Jopson R.M. and Dorosier R.M., “Stimulated Brillouin threshold dependence on fiber type and uniformity,” IEEE Photonics Tech. Leett., vol.4, pp.66- 69, 1992.

[35] Mohammad N.I., “Raman Amplifiers for Telecommunications”, IEEE journal of selected topics in quantum electronics, vol.8 , no.3 pp.548-559 ,2002.

Outcome of This Research Work

1. **F.H.Tithi** and M.S.Islam, “Suppression of stimulated Brillouin scattering effect using nonlinear phase modulation”, 6th International Conference on Computer and Electrical Engineering (ICECE 2010), 18-20 Dec. 2010, Dhaka, Bangladesh.