

**A  
Dissertation  
On  
“An algorithm development of impairment stimulated Raman scattering  
for efficient optical communication system”**

**Submitted in partial fulfilment of  
requirement for the award of degree of**

**MASTER OF ENGINEERING  
IN  
ELECTRONICS AND COMMUNICATION**

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**DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING**

**THAPAR UNIVERSITY**

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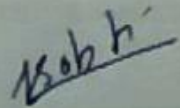
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### Declaration

I hereby declare that the work, which is being presented in the report, entitled "An algorithm development of impairment stimulated Raman scattering for efficient optical communication system" in partial fulfilment of the requirements for the award of Master of Engineering in Electronics and Communication at Electronics and Communication Engineering Department of Thapar University, Patiala which is an authentic record of my own work carried out under the guidance of **Dr. Hardeep Singh** Assistant Professor, Electronics and Communication Department during the fourth semester, June-2014.

The matter presented in this Dissertation has not been submitted in any other University/Institute for the award of Master of Engineering.

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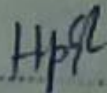


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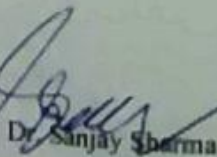
This is to certify that the above statement made by the student is correct to the best of my knowledge and belief.

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## Abstract

The nonlinear effects degrade the performance of system. Because nonlinear effects tend to manifest themselves when optical power is very high, there study became important in DWDM system. The nonlinearities in optical fibers fall into two categories. One is stimulated scattering (Raman and Brillouin), and the other is the optical Kerr effect which causes due to changes in the refractive index of fiber with optical power. Depending upon the type of input signal, kerr-non-linearity manifests itself in three different effects such as Self-Phase Modulation (SPM), Cross-Phase Modulation (CPM) and Four-Wave Mixing (FWM). At high power level, the inelastic scattering phenomenon can induce stimulated effects such as Stimulated Brillouin-Scattering (SBS) and Stimulated Raman-Scattering (SRS). The intensity of light grows exponentially if the incident power exceeds a certain threshold value. The difference between Brillouin and Raman scattering is that the Brillouin generated phonons (acoustic) are coherent and give rise to a macroscopic acoustic wave in fiber, while in Raman scattering the phonons (optical) are incoherent and no macroscopic wave is generated, SRS is much less of a problem than SBS. Its threshold is close to 1 Watt, nearly a thousand times higher than SBS. But real systems are being deployed with EDFAs having optical output powers of 500 mW (+27 dBm), and this will only go higher. A fiber optic link that includes three such optical amplifiers will reach this limit since the limit drops proportionally by the number of optical amplifiers in series.

In this Dissertation stimulated Raman scattering modal has been study and presented a linear power division algorithm to achieve almost constant modulated SRS power. This assumes a linear variation of power in channel with respect to each other which is a result of experimental verification. During this study variation of signal power from 1 to 60 mW was done and number of channels varied from 3 to 99.

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## List of Abbreviations

WDM	Wavelength Division Multiplexing
TDM	Time Division Multiplexing
FDM	Frequency Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
SPM	Self-Phase Modulation
XPM	Cross Phase Modulation
FWM	Four Wave Mixing
SRS	Stimulated Raman Scattering
SBS	Stimulated Brillion Scattering
SOA	Semiconductor Optical Amplifier
EDFAs	Erbium-Doped Fiber Amplifier
APD	Avalanche Photodiode
LED	Light Emitting Diode
GVD	Group Velocity Dispersion
LAN	Local Area Network

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### Introduction

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Twenty first century is the era of 'Information technology'. In twenty first century the information technology had a sharp growth through the modern telecommunication systems. Mostly, optical fiber communication played a important role in the development of high quality and high-speed telecommunication systems. Today, optical fibers are used in telecommunication links and in the Internet and local area networks (LAN) to get large channel bandwidth. In today's world, the advent of erbium-doped fiber amplifier (EDFAs) is one of the most notable breakthroughs in the fiber optical communication technology [1]. When EDFAs were not developed, the most widely method of compensating fiber loss was to space electronic generators periodically along the transmission link. A regenerator consists of photo-detectors, processing is done in electronic domain, amplifier for amplifying the signal and a transmitter for transmitting signal. Functionally, it performs optical to electronic conversion, processing done in electronic domain, electronic domain to optical domain conversion, and transmission of new generated signal. The advantages of regenerative systems are that transmission impairments such as noise, dispersion, and nonlinearities do not cause any problem in transmitting the signal. However electronic blocks in regenerators do not allow to use the complete bandwidth of optical fiber. Electronics components are normally designed for the specific bit rate and modulation format, it is necessary to replace all the regenerative repeaters along the link when the capacity of the system is need to be increased. On the other hand, optical amplifiers like EDFAs simply amplify the optical signal by several orders of magnitude without being limited by electronic speed. In addition amplification is bit rate and modulation format independent, which implies that optically amplified links can be upgraded by replacing terminal equipment alone. The optically amplified transmission lines are consider as transparent pipe which are transparent to data rates and format of modulation. However, transmission impairments, which are general not significant in a regenerative system, accumulate along the transmission link when amplifiers are used, so that they cannot be simply ignored, and this puts a new challenge to first order transmission design. Among those impairments, dispersion, fiber nonlinearities and noise accumulation from the optical amplifiers are the key limited factors. Dispersion a linear phenomenon is relatively well understood, and various

effective dispersion compensation techniques have been devised to cope with dispersion induced performance degradation. Fiber nonlinearities, on the other hand, have not been fully analyzed and understood especially when other impairments like dispersion are also present.

### **1.1 Historical Perspective of Optical Communication**

The use of light for transmitting information from one place to another place is a very old technique. In 800 BC., the fire and smoke signals were used by Greek for sending information of victory in a war, call for help, etc. Mostly a single signal was send. During the second century B.C. optical signals were converted using signalling lamps so that any message could be sent. There was no growth in optical communication till the end of the 18th century. The speed of the optical communication link was limited due to the requirement of line of sight transmission paths, the human eye as the receiver and unreliable nature of transmission paths affected by atmospheric effects such as fog and rain. In 1791, Chappe from France developed the semaphore for telecommunication on land. But that was also with limited information transfer [6]. In 1835, Samuel Morse invented the telegraph and the era of electrical communications started throughout the world. The use of wire cables for the transmission of Morse coded signals was implemented in 1844. In 1872, Alexander Graham Bell proposed the photophone with a diaphragm giving speech transmission over a distance of 200 m. But within four years, Graham Bell had changed the photophone into telephone using electrical current for transmission of speech signals. In 1878, the first telephone exchange was installed at New Haven. Meanwhile, Hertz discovered radio waves in 1887. Marconi demonstrated radio communication without using wires in 1895. Using modulation techniques, the signals were transmitted over a long distance using radio waves and microwaves as the carrier. During the middle of the twentieth century, it was realized that an increase of several orders of magnitude of bit rate distance product would be possible if optical waves were used as the carrier. Table 1 shows the different communication systems and their bit rate distance product. Here the repeater spacing is mentioned as distance [1]. In the old optical communication system, the bit rate distance product is only about 1 (bit/s)km due to enormous transmission loss ( $10^5$  to  $10^7$  dB/km). The information carrying capacity of telegraphy is about hundred times lesser than telephony. Even though the high-speed coaxial systems were evaluated during 1975, they had smaller repeater spacing.

Microwaves are used in modern communication systems with the increased bit rate distance product. However, a coherent optical carrier like laser will have more information carrying capacity. So the communication engineers were interested in optical communication using lasers in an effective manner from 1960 onwards. A new era in optical communication started after the invention of laser in 1960 by Maiman. The light waves from the laser, a coherent source of light waves having high intensity, high monochromaticity and high directionality with less divergence, are used as carrier waves capable of carrying large amount of information compared with radio waves and microwaves.

### 1.2 Unguided Optical Communication

The optical communication systems are different from microwave communication systems in many aspects. In the case of optical systems, the carrier frequency is about 100 THz and the bit rate is about 1T bit/s. Further the expanding of optical beams is always in the forward direction due to the short wavelengths. Optical communication is not suitable for broadcasting applications; it may be suitable for free space communications above the earth's atmosphere like inter satellite communications. For the terrestrial applications, unguided optical communications are not suitable because of the scattering within the atmosphere, atmospheric turbulence, fog and rain. The unguided optical communication systems played

System /km	Bit rate distance product (bits/sec)
Old optical communication	1
Telegraph	10
Telephone	$10^3$
Coaxial cables	$10^5$
Microwaves	$10^6$
Laser light in open air	$10^9$

Table 1.1 Bit rate distance product

an important role in the research between 1960 and 1970. For longer range unguided optical communication systems the neodymium laser (1.06  $\mu\text{m}$ ) and the carbon dioxide laser (10.6  $\mu\text{m}$ ) were the most favorable sources. Using narrow band gap compound semiconductors like indium sulphide (for neodymium laser) and cadmium mercury telluride (for  $\text{CO}_2$  laser) one can have better detection using heterodyne detection techniques.

### **1.3 The Birth of Fiber Optic Systems**

To guide light in a wave-guide, initially metallic and non-metallic wave-guides were fabricated but they have a large amount of loss so they were not suitable for telecommunication. Tyndall discovered the optical fibers and light could be transmitted by the phenomenon of total internal reflection in fiber. During 1950s, the optical fibers with large diameters of about 1 or 2 millimeters were used in endoscopes to see the inner parts of the human body. Optical fibers can provide a much more reliable and versatile optical channel than the atmosphere; Kao and Hockham published a paper about the optical fiber communication system in 1966. But the fibers produced an enormous loss of 1000 dB/km. But in the atmosphere, there is a loss of few dB/km. Immediately Kao and his fellow workers realized that these high losses were a result of impurities in the fiber material. Using a pure silica fiber these losses were reduced to 20 dB/km in 1970 by Kapron, Keck and Maurer. At this attenuation loss, repeater spacing for optical fiber links become comparable to those of copper cable systems. Thus the optical fiber communication system became an engineering reality.

### **1.4 Basic Optical Fiber Communication System**

Figure 1.1 shows the essential components in the optical fiber communication system. The input electrical signal regulates the intensity of light from the optical source. The optical carrier can be regulated internally or externally using an electro-optic modulator (or) acousto-optic modulator. Today electro-optic modulators are widely used as external modulators, which modulate the light by changing its refractive index through the given input electrical signal. In the digital optical communication system, the input electrical signal is in the form of coded digital pulses from the encoder and these electric pulses modulate the intensity of the light from the laser diode or LED and convert them into optical pulses. In the receiver stage, the photo detector likes avalanche photodiode (APD) or positive-intrinsic-negative (PIN) diode converts the optical pulse into electric pulse. A decoder converts the electrical pulses into the original electric signal.

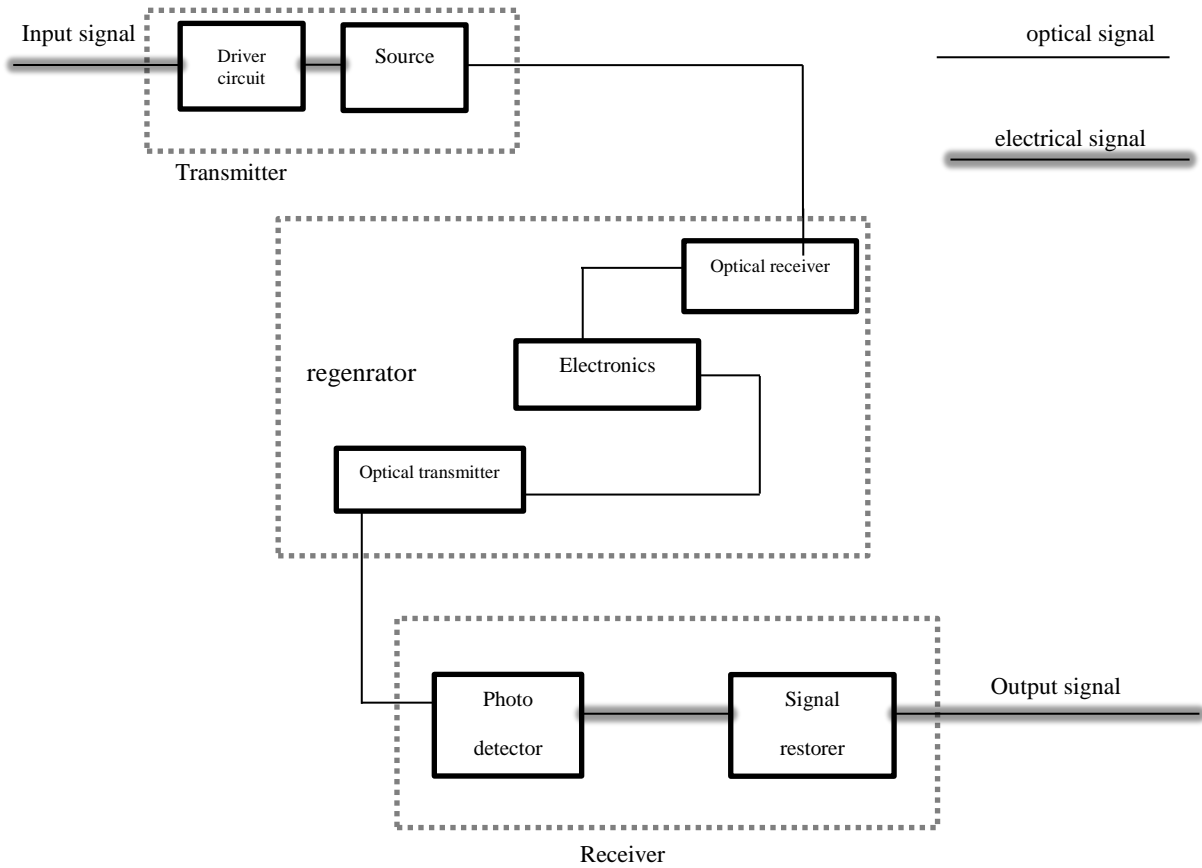


Figure 1.1 Major elements of the basic optical communication system

Generation	Wavelength (μm)	Bit rate Mb/s	Repeater spacing (km)	Loss dB/km	Existed up to
1	0.8	45	10	1	1980
2	1.3	$1.7 \times 10^2$	50	<1	1987
3	1.55	$1.0 \times 10^4$	70	<0.2	1990
4	1.55	$1.0 \times 10^5$	100	<0.02	2000
5	1.55	$>1.0 \times 10^9$	>100	<0.002	

Table 1.2 Different generations of optical fiber communication systems

## 1.5 Multiplexers

The transmission of multiple optical channels over the same fiber is a simple way to increase the transmission capacity of the fiber against the fiber dispersion, fiber nonlinearity and speed of electronic components, which limit the bit rate. Multiplexing means many signals at a given time. Suppose for each channel the bit rate is 100 Gb/s and by accommodating 100 channels through multiplexing technique the total bit rate through a single fiber can be increased to 10 Tb/s (1 Tera =  $10^{12}$ ): Thus the information carrying capacity of a fiber is increased by the multiplexing technique.

**There are three types of multiplexing techniques:**

- (i) **TDM** – Time division multiplexing
- (ii) **FDM** – Frequency division multiplexing
- (iii) **WDM** – Wavelength division multiplexing

**(i) Time division multiplexing (TDM):** In time division multiplexing, different communication links share the same channel on the basis of time. In TDM high bit rate data stream is constructed directly by time multiplexing several lower bit rate optical streams. Similarly, at the receiver end of the system, the very high bit rate signal is demultiplexed to several lower bit rate signals before detection. Each specific link is assigned specific time slots during which it is allowed to send its data from end to other end and during this slot no other link is allowed to send data. TDM works best when it is dealing with links all of the same type and all given permanents assigned time slots of equal time interval.

**(ii) Frequency Division Multiplexing (FDM):** FDM is possible when the useful bandwidth of the transmission medium exceeds the required bandwidth of signals to be transmitted. In the frequency division multiplexing increases transmission capacity and flexibility by utilizing the very large bandwidth potential of the radio frequency. In FDM, a number of frequency channels can be placed adjacent to each other to provide a large capacity of transmitted signals. Several messages can be simultaneously along the channel. To prevent interference, the channels are separated by guard bands, which are TDM and FDM techniques are operated in the electrical domain and are widely used in the conventional radio wave communication. WDM technique is very useful in the optical

domain and by WDM the bit rate can be increased beyond 10 Tb/s in the optical fiber communication.

**(iii) Wavelength division multiplexing (WDM):** With wavelength division multiplexing different communication links share the same fiber on the basis of wavelength. Information associated with each link first goes through a modulation process. The result is the generation of light modulated by the information [7]. The light from the links can be coupled into a single fiber optic and then transmitted together down the fiber. At the receiving end different links can be separated on the basis of wavelength using demultiplexing operation. The resulting received information is then directed to the appropriate data device destination.

In the Figure 1.2 different wavelengths carrying separate signals are multiplexed by the multiplexer and then they are transmitted through a single fiber. At the receiver end, the separate signals at different wavelengths are demultiplexed by the demultiplexer and are given to separate receivers. From the receiver side also the signals can be transmitted in the same manner through the same fiber. Thus instead of handling a single channel with single wavelength and limited bit rate (10 Gb/s), the bit rate is raised to about 10 Tb/s, hence the information capacity of the fiber is increased by WDM technique. In principle any optical wavelength demultiplexer can be also used as a multiplexer. Thus for simplicity the word ‘multiplexer’ is often used as a general term to refer to both multiplexers and demultiplexers, except when it is necessary to distinguish the two devices or functions.

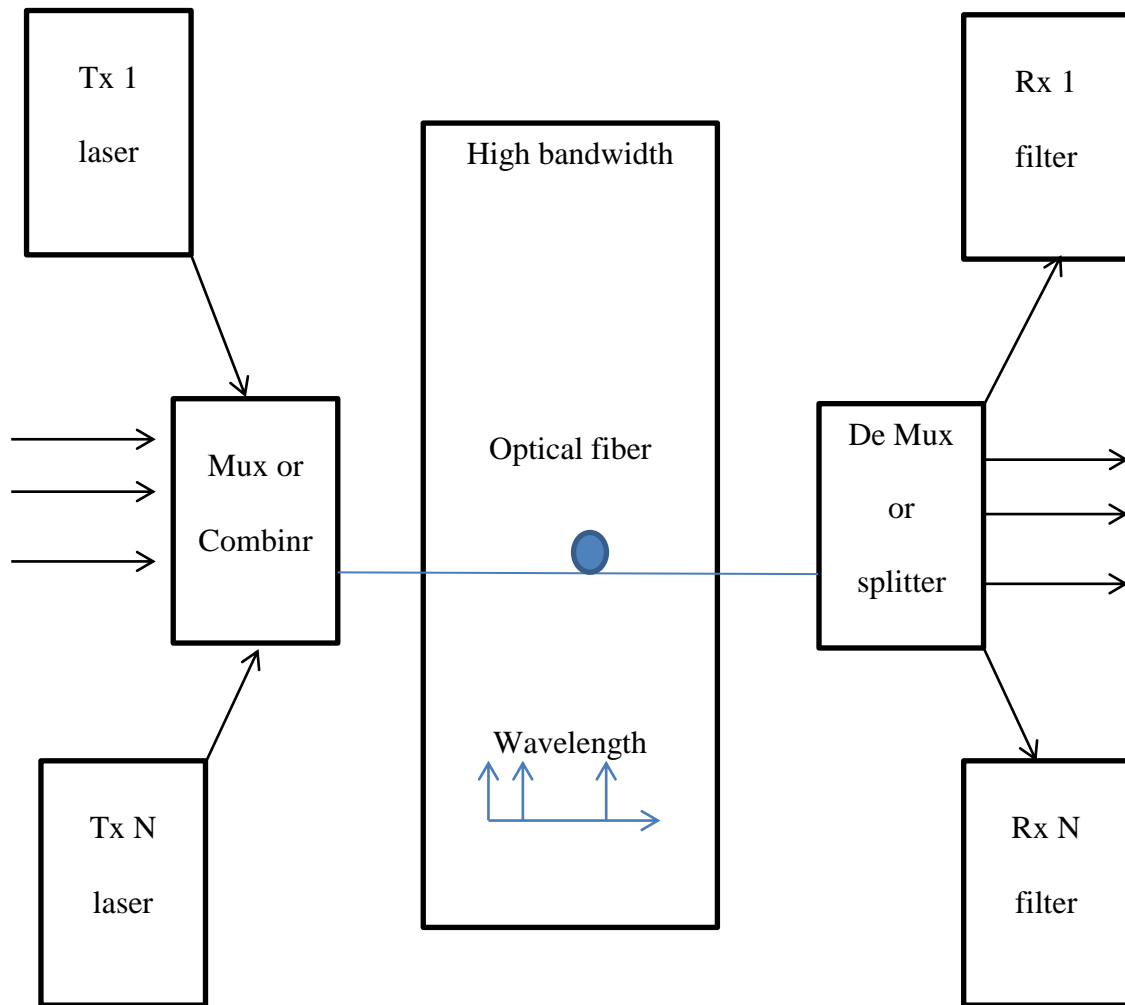


Figure 1.2 Basic principle of WDM technique

## 1.6 Advantages of optical fiber communication

**1. Wider bandwidth:** The information carrying capacity of a transmission system increases as carrier frequency increases and it is directly proportional to the carrier frequency of the transmitted signals. The optical carrier frequency is in the range  $10^{13}$  to  $10^{15}$  Hz while the radio wave frequency is about  $10^6$  Hz and the microwave frequency is about  $10^{10}$  Hz. Thus the optical fiber yields greater transmission bandwidth than the conventional communication systems and the data rate or number of bits per second is increased to a greater extent in the optical fiber communication system. Further the wavelength division multiplexing operation by the data rate or information carrying capacity of optical fibers is enhanced to many orders of magnitude.

**2. Low transmission loss:** Due to the usage of the ultra-low loss fibers and the erbium doped silica fibers as optical amplifiers, one can achieve almost lossless transmission. In the modern optical fiber telecommunication systems, the fibers having a transmission loss of 0.002 dB/km are used. Further, using erbium doped silica fibers over a short length in the transmission path at selective points, appropriate optical amplification can be achieved. Thus the repeater spacing is more than 100 km. Since the amplification is done in the optical domain itself, the distortion produced during the strengthening of the signal is almost negligible.

**3. Dielectric waveguide:** Optical fibers are made from silica which is an electrical insulator. Therefore they do not pick up any electromagnetic wave or any high current lightning. It is also suitable in explosive environments. Further the optical fibers are not affected by any interference originating from power cables, railway power lines and radio waves. There is no cross talk between the fibers even though there are so many fibers in a cable because of the absence of optical interference between the fibers.

**4. Signal security:** The transmitted signal through the fibers does not radiate. Further the signal cannot be tapped from a fiber in an easy manner. Therefore optical fiber communication provides hundred per cent signal security.

**5. Small size and weight:** Fiber optic cables are developed with small radii, and they are flexible, compact and lightweight. The fiber cables can be bent or twisted without damage. Further, the optical fiber cables are superior to the copper cables in terms of storage, handling, installation and transportation, maintaining comparable strength and durability [1].

### **1.7 Dispersion and losses in fibers**

Dispersion in the fiber means the broadening of the signal pulse width due to dependence of the refractive index of the material of the fiber on the wavelength of the carrier. If we send digitized signal pulses in the form of square pulses, they are converted into broadened gaussian pulses due to dispersion. The dispersion leads to the distortion (or) degradation of the signal quality at the output end due to overlapping of the pulses. There

are two kinds of dispersion mechanisms in the fiber: (i) Intramodal dispersion and (ii) Intermodal dispersion.

The dispersion effects can be explained on the basis of behavior of group velocities of the guided modes in the optical fiber. Group velocity is the velocity, at which the energy in a particular mode travels along the fiber,

The propagation constant  $\beta = n_1 \frac{2\pi}{\lambda} = \frac{n_1 \omega}{c}$  therefore

Group velocity  $v_g = \frac{d\omega}{d\beta} = \frac{d\lambda}{d\beta} \frac{d\omega}{d\lambda}$

Since  $\beta = n_1 \frac{2\pi}{\lambda}$ ,

$$\frac{d\beta}{d\lambda} = \frac{2\pi}{\lambda} \frac{dn_1}{d\lambda} - n_1 \frac{2\pi}{\lambda^2}$$

$$\omega = \frac{2\pi c}{\lambda},$$

$$\frac{d\omega}{d\lambda} = -\frac{2\pi c}{\lambda^2}$$

Therefore

$$v_g = \frac{d\lambda}{d\beta} \frac{d\omega}{d\lambda} = \frac{\frac{2\pi c}{\lambda^2}}{\left(\frac{2\pi}{\lambda} \frac{dn_1}{d\lambda} - n_1 \frac{2\pi}{\lambda^2}\right)} = \frac{c}{n_1 - \lambda \frac{dn_1}{d\lambda}} = \frac{c}{N_g}$$

Where  $N_g = n_1 - \lambda \frac{dn_1}{d\lambda}$  is called the group index of the fiber. Thus the group velocity and phase velocity  $v_p = c/n_1$  are different in the optical fiber. Otherwise an optical fiber is a dispersive medium. Intramodal dispersion arises due to the dependence of group velocity on the wavelength. Further it increases with the increase in spectral width of the optical source. This spectral width is the range of wavelengths emitted by the optical source. For example in the case of LED, it has a large spectral width about 40 nm since it emits wavelengths from 830– 870 nm with the peak emission wavelength at 850 nm. In the case of laser diode which has a very narrow spectral width, the spectral width is about 1 or 2 nm only. Thus the intramodal dispersion can be reduced in an optical fiber using single mode laser diode as an optical source. Intramodal dispersion arises due to the dispersive

properties of the optical fiber material (material dispersion) and the guidance effects of the optical fiber (waveguide dispersion).

### **1. Intramodal dispersion:**

**(a) Material dispersion:** This dispersion arises due to the variation of the refractive index of the core material with the wavelength or frequency of light. It is directly proportional to the frequency bandwidth of the transmitted pulse. The material dispersion tends to zero at the wavelength of 1300 nm. Further by using an optical source with a narrow spectral width, the material dispersion can be reduced. For shorter wavelengths around 600 nm to 800 nm, the material dispersion exponentially rises to a higher value.

**(b) Waveguide dispersion:** This dispersion arises due to the finite frequency bandwidth and the dependence of the mode group velocity on the frequency of light. Higher the frequency bandwidth of the transmitted pulse, higher will be the waveguide dispersion. The amount of waveguide dispersion depends on the fiber design like core radius, since the propagation constant 'β' is a function of  $\frac{\alpha}{\lambda}$ . In the case of single mode fibers,

waveguide dispersion arises when  $\frac{d\beta^2}{d\lambda^2} \neq 0$ . In the case of multimode fibers, most of the modes propagate far from the cutoff value. Therefore then all are almost free from waveguide dispersion.

**2. Intermodal dispersion:** Intermodal dispersion or multimode dispersion arises due to the variation of group velocity for each mode at a single frequency. Different modes arrive at the exit end of the fiber at different times. So there is multimode dispersion and hence there is broadening of the signal pulses.

Based on the dispersion effects, one can get the following results:

(i) The multimode step index fibers exhibit a large value of dispersion due to the enormous amount of multimode dispersion which gives the greatest pulse broadening. At the same time the multimode graded index fiber exhibits an overall dispersion which is 100 times lesser than the multimode step index fiber's dispersion. This is due to the shaping of the refractive index profile in a parabolic manner.

(ii) In the case of single mode step index fibers, they have only intramodal dispersion. Further among the intramodal dispersions, the waveguide dispersion is the dominant one. The material dispersion in them is almost negligible due to axial ray propagation and

small core radius. When we compare it with the dispersion in the multimode graded index fiber, the dispersion in the single mode fiber is negligible. That is why single mode fibers are highly useful in long distance communication systems.

### **1.8 Dispersion-shifted single mode fibers**

Generally in single mode fibers, zero dispersion is obtained at a wavelength of about 1300 nm. Since there is a finite loss in the silica fiber at 1300 nm, today the fibers are designed such that there is zero dispersion at 1550 nm with a minimum loss. At 1550 nm, the material dispersion in single mode fiber is positive and large, while the waveguide dispersion is negative and small. So to increase the waveguide dispersion equal to that of material dispersion, the relative refractive index difference ' $\Delta$ ' may be slightly increased by adding more  $\text{GeO}_2$  in the core (which increases the refractive index of the core) or adding more fluorine in the cladding (which decreases the refractive index of the cladding) or instead of parabolic refractive index profile, a triangular refractive index profile can be designed. Thus the dispersion-shifted fibers have minimum loss and zero dispersion at 1550 nm.

### **1.9 Dispersion compensating fibers**

At present the installed fiber optic links are operating at the wavelength of 1300 nm using conventional single mode fibers. Instead of 1300 nm wavelength if one wants to use 1550 nm wavelength to reduce the transmission loss, then the whole fiber optic link should be replaced with the new dispersion-shifted fibers. This will require an enormous expenditure. To avoid this huge expenditure and to use the old fiber optic links dispersion compensating fibers were evolved. These fibers have a large negative dispersion at 1550 nm, while the conventional single mode fibers operating at 1300 nm have positive dispersion at 1550 nm. By suitably replacing 1 km length of conventional single mode fiber in the fiber optic link with the dispersion compensating fiber for every 100 km length of conventional single mode fiber optic link, one can achieve minimum loss and zero dispersion also [1].

### Literature survey

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M. Arumugam [1], has given an overview about the fiber optic communication. This paper deals with the historical development of optical communication systems and their failures initially. Then the different generations in optical fiber communication along with their features has been discussed. Some aspects of total internal reflection, different types of fibers along with their size and refractive index profile, dispersion and loss mechanisms are also mentioned. Finally the general system of optical fiber communication is briefly mentioned along with its advantages and limitations. Future soliton based optical fiber communication is also highlighted. This paper explained that how high quality telecommunication at a lower cost using solitons can be achieved.

The book “Nonlinear Fiber Optics” by G. P. Agrawal provided the background material and the mathematical tools needed for understanding the various nonlinear effects. Starting from the Maxwell’s equation, the wave equation in a nonlinear dispersive medium is used to discuss the fiber modes and to obtain the basic propagation equation. The main effect of GVD and dispersion induced broadening is also explained in detail. This book also explained the nonlinear phenomenon of SPM occurring as a result of intensity dependence of the refractive index. Study of higher optical solitons is introduced together with the inverse scattering method used to solve the nonlinear Schrödinger equation. Also focus other nonlinear effects such as XPM, SRS, and SBS. During the description of theory SBS Dr. Agrawal describes the important features such as the Brillouin threshold, pump depletion, and gain saturation. This book also explains the application of nonlinearities in industry and in telecommunications system.

J. Toulouse [3], proposed the different kinds of optical nonlinearities encountered in fibers, pointing out the essential material and fiber parameters that determine fiber nonlinear effects and describe the effects produced by each kind of nonlinearity, emphasizing their variations for different values of essential parameters on nonlinear effects.

S. Bigo [4], introduced the fast growth of optical fiber communication system in last 30 years, along with the growth the optical linear and nonlinearities make system complex,

it became a challenge for system engineers to design the optical fiber with these complexity, dispersion management is one of good technique to make system less complex but it required more time consuming stimulation done optimally, the author described the two rule which provide insight in these matter.

Haruo Akimaru et. al. [5], introduced general design considerations for the broadband Information highway of the future are given in the context of interactive broadband services to the home. As potential precursors to this highway, the telephone, the Internet, and cable television networks are examined. Several emerging technologies are also examined as candidates for the future local subscriber loop. For the information highway, classes of network services are proposed that are independent of the specific network technologies used. It has been suggested that the information highway be partitioned logically or physically so as to provide a variety of service levels according to the subscriber's cost and quality of service requirements.

A.R Chraplyvy [10], introduced idea about the limitation provided by SRS to transmitted power in wavelength division multiplexing optical communication system, This paper gave a general expression for transmitted power estimation for system containing an random number of channels with random channel separation but channel separation should be equal. The expressions are applicable to any WDM system provided the channel separations are roughly constant.

Ivan B. Djordjevic [12], proposed simple expressions appropriate to study the transmission limitations of WDM systems with dispersion compensated links using inline optical amplifiers imposed by fiber nonlinearities are derived in this paper. Two important nonlinear effects, FWM and SRS in the presence of ASE noise are taken into consideration. The maximum possible transmission distance has been discussed in terms of various system parameters such as wavelength spacing, number of channels, total bandwidth, etc. Optimum channel spacing to maximize the transmission distance is found as a compromise between conflicting requirements imposed by FWM and SRS in the presence of ASE noise.

S. P. Singh et. al. [15], described the various types of nonlinear effects based on first effect such as self-phase modulation cross-phase modulation and four-wave mixing. The thresholds, managements and applications have been discussed, and comparative study of these effects has been presented.

M. N. Peterson et. al. [23] described the first demonstration of chromatic dispersion monitoring in optical networks having employed all-optical wavelength conversion. Their experimental results confirmed that dispersion monitoring based on an in-band subcarrier tone combined with wavelength conversion based on four-wave mixing (FWM) render dispersion monitoring possible in an optical network utilizing wavelength conversion.

C. A. Brackett et. al. [24] presented an architectural approach for very-high-capacity wide-area optical networks, and described a proposed program of research to address key system and device issues. The network was based on dense multi-wavelength technology and was scalable in terms of the number of networked users, the geographical range of coverage, and the aggregate network capacity. They employed a distributed optical interconnect that is wavelength-selective and electronically controllable, permitting the same limited set of wavelengths to be reused among other access stations.

## **2.2 Motivation**

According to the literature survey, it has been observed that the most of work has been in optical nonlinearities effects. The stimulated nonlinearities like SBS and SRS has been study, the SBS threshold is very low but it provide gain in back reflected light so it can be eliminated by using optical isolators whereas in SRS its threshold is very high compare to SBS but in current scenario the use of DWDM system make the threshold level of SRS reach very easily, the SRS model has been study a lot for development of optical communication system as the forward gain provided by SRS can be used to make distributed amplifiers to increase the efficient use of optical bandwidth. In this paper, the development model of SRS has been studied in detail and taken few observations while calculation of modified power due to SRS indicating almost linear variation of power in channel with respect to each other. During this study variation of signal power from 1 to 60mw was done and number of channels varied from 3 to 99.

### **2.3 Objective of Dissertation**

The following main objectives of dissertation are:

1. To develop the model of SRS.
2. To investigate the modulated power due to SRS with different power level and different number of channels for equal spacing.
3. An algorithm development of impairment stimulated Raman scattering for efficient optical communication system.

### **2.4 Organization of Dissertation**

This dissertation is divided into five parts chapters.

First chapter presents a brief introduction to optical communication system, history of optical communication. In this various multiplexing techniques such as Time Division Multiplexing, Frequency Division Multiplexing, and Wavelength Division multiplexing are discussed in brief. These techniques are used to increase the capacity of the system. Also discuss the generation and various developments done the field of optical communication system. The attenuation caused by dispersion is also discussed in detail. Second chapter include the literature survey of various optical nonlinear effects, its application and management, its effect on optical DWDM system.

Third chapter include the basics of optical nonlinear effects are discussed, the two nonlinearity Kerr effect and stimulated scattering has been discussed in brief with their effects on optical fiber communication.

Fourth chapter include the development model of SRS and the effects of SRS on transmitted power for four channel is shown, after that the generalised equation of modulated power for N number of channels shown and a proposed algorithm is given to negate the SRS effect in DWDM system in the last of this chapter stimulation results are the discussed with some observation gives strength to our result.

Finally, in the last chapter fifth, conclusion and future scope is discussed on work done.

### Introduction to Non-Linearities

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Nonlinearity effects arose as optical fiber data rates, transmission lengths, number of wavelengths, and optical power levels increased. The only worry that affects optical fiber in the early time was fiber attenuation and, sometimes, fiber dispersion; however, these issues are easily dealt with using a number of dispersion avoidance and cancellation techniques. Fiber nonlinearities give a new realm of obstacle that must be overcome. These nonlinearities earlier appeared in specialized applications such as undersea installations. However, the new nonlinearities that need unique attention when designing state-of-the-art fiber optic systems include stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), four wave mixing (FWM), self-phase modulation (SPM), cross-phase modulation (XPM), and intermodulation. Fiber nonlinearities represent the fundamental limiting mechanisms to the amount of data that can be transmitted on a single optic fiber. System designers must have knowledge of these limitations and the steps that can be taken to minimize the detrimental effects of fiber nonlinearities. The term linear and nonlinear (Figure 3.1), in optics, mean intensity independent and intensity dependent phenomena respectively. Nonlinear effects in optical fibers (Figure 3.2) occur due to (1) change in the refractive index of the medium with optical intensity and, (2) inelastic scattering phenomenon. The power dependence of the refractive index is cause for kerr-effect. Depending upon the type of input signal, kerr-non-linearity manifests itself in three different effects such as Self-Phase Modulation (SPM), Cross-Phase Modulation (CPM) and Four-Wave Mixing (FWM). Except for SPM and CPM, all nonlinear effects provide increase to some channel at the cost of depleting power from other channels. SPM and CPM affects only the phase of signals and can produce spectral broadening, which leads to more dispersion. At high power level, the inelastic scattering phenomenon can generate stimulated effects such as like Stimulated Brillouin-Scattering (SBS) and Stimulated Raman-Scattering (SRS). The intensity of light grows exponentially if the incident power exceeds a certain threshold value. The difference between Brillouin and Raman scattering is that the Brillouin generated phonons (acoustic) are coherent and give rise to a macroscopic acoustic wave in fiber, while in Raman scattering the phonons (optical) are incoherent and no macroscopic wave is generated [1]

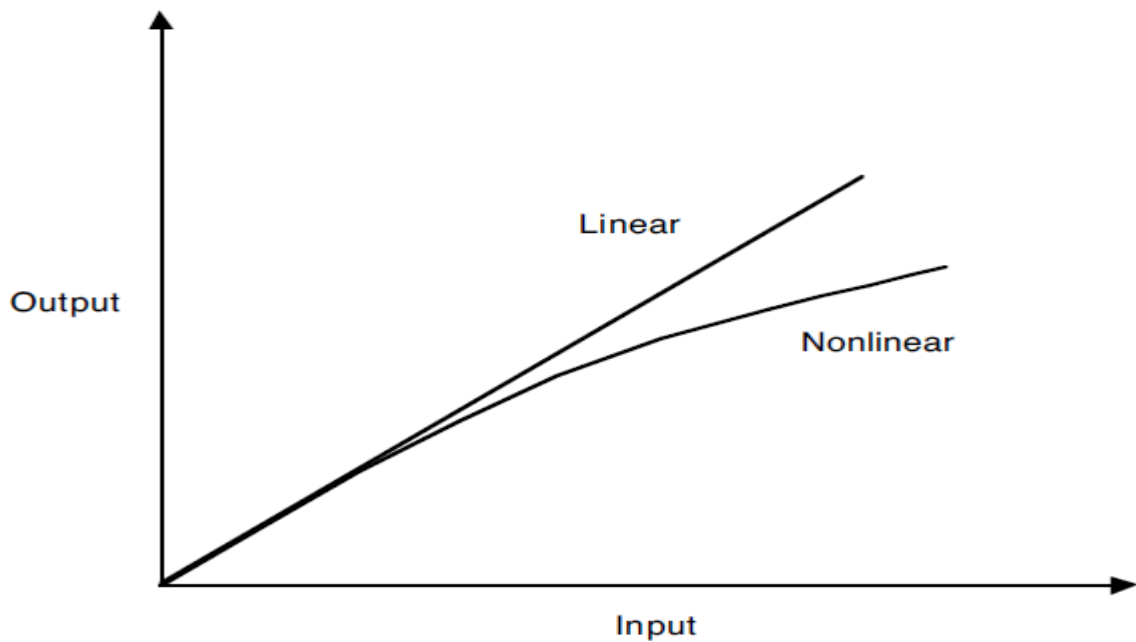


Figure 3.1 Linear and nonlinear interactions

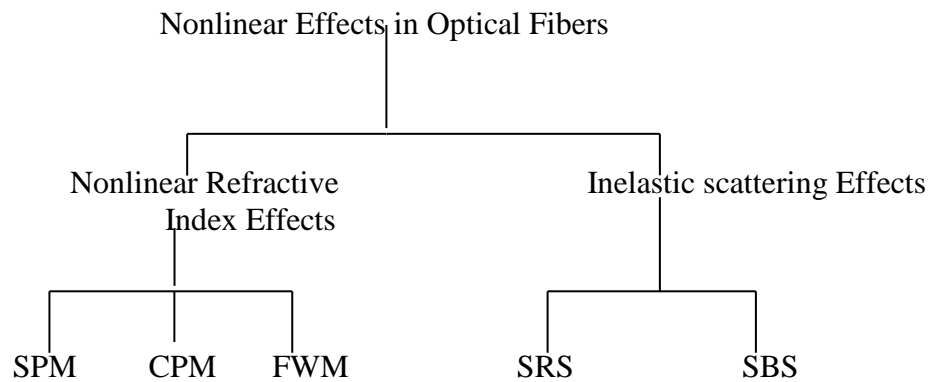


Figure 3.2 Nonlinear effects in optical fiber

SRS is much less of a problem than SBS. Its threshold is close to 1 Watt, nearly a thousand times higher than SBS. But real systems are being installed with EDFAs having optical output powers of 500 mW (+27 dBm), and this will only rise higher. A fiber optic link that includes three such optical amplifiers will reach this limit as the limit drops proportionally by the number of optical amplifiers in series [4, 5, 8, 9].

### 3.1 Basics

For intense electromagnetic fields, any dielectric medium acts like a nonlinear medium. Fundamentally, origin of nonlinearity is in an harmonic motion of bound electrons under the effect of an applied field. Due to this an harmonic motion the total polarization  $P$  induced by electric dipoles is not linear but satisfies more general relation as

$$P = \epsilon_0 \chi^{(1)} E + \epsilon_0 \chi^{(2)} E^2 + \epsilon_0 \chi^{(3)} E^3 + \dots \quad (3.1)$$

where  $\epsilon_0$  is the permittivity of vacuum and  $\chi^{(k)}$  ( $k = 1, 2, \dots$ ) is  $k$ th order susceptibility. The dominant contribution to  $P$  is provided by linear susceptibility  $\chi^{(1)}$ . The second order susceptibility  $\chi^{(2)}$  is cause for second harmonic generation and sum-frequency generation. A medium, which lacks inversion symmetry at the molecular level, has non-zero second order susceptibility. However for a symmetric molecule, like silica,  $\chi^{(2)}$  vanishes. Therefore optical fibers do not contain second order nonlinear refractive effects. It would be right to mention here, the electric quadrupole and magnetic-dipole moments can produce weak second order nonlinear effects. Defects and colour centers inside the fiber core are responsible to second harmonic generation under particular conditions. Obviously the third order susceptibility  $\chi^{(3)}$  is cause of lowest-order nonlinear effects in fibers [5]. For isotropic medium, like optical fiber, polarization vector  $P$  will always be in parallel of electric field vector  $E$ . So one may use scalar notations rather than of vector notations. For an electric field,

$$E = E_0 \cos(\omega t - kZ) \quad (3.2)$$

the polarization  $P$  becomes

$$P = \epsilon_0 \chi^{(1)} E_0 \cos(\omega t - kZ) + \epsilon_0 \chi^{(2)} E_0^2 \cos^2(\omega t - kZ) + \epsilon_0 \chi^{(3)} E_0^3 \cos^3(\omega t - kZ) + \dots \quad (3.3)$$

Using some trigonometric relations, equation (3.3) can be written as

$$P = \frac{1}{2} \epsilon_0 \chi^{(2)} E_0^2 + \epsilon_0 \chi^{(1)} E_0 \cos(\omega t - kZ) + \frac{3}{4} \epsilon_0 \chi^{(3)} E_0^3 \cos^3(\omega t - kZ) + \frac{1}{2} \epsilon_0 \chi^{(2)} E_0^2 \cos 2(\omega t - kZ) + \frac{1}{4} \epsilon_0 \chi^{(3)} E_0^3 \cos 3(\omega t - kZ) + \dots \quad (3.4)$$

The effect of first term is of little practical importance as the term does not change and gives a dc field across the medium. The second term oscillating at frequency  $\omega$  is known

as first or fundamental harmonic of polarization. The third term oscillating with frequency  $2\omega$  is called the second harmonic of polarization. Similarly fourth term with frequency  $3\omega$  is known as third harmonic of polarization. For optical fibers,  $\chi^{(1)}$  vanishes, and hence equation (3.4) becomes

$$P = \varepsilon_0 \chi^{(1)} + \frac{3}{4} \chi^{(3)} E_O^2 E_O \cos(\omega t - kZ) + \frac{1}{4} \varepsilon_0 \chi^{(3)} E_O^3 \cos 3(\omega t - kZ) \quad (3.5)$$

Here higher order terms are neglected because their contribution is negligible. Due to changes in refractive index of the fiber there is reduction of phase between frequencies  $\omega$  and  $3\omega$ . Due to this phase mismatch the second term of equation (3.5) can be neglected and polarization can be written as

$$P = \varepsilon_0 \chi^{(1)} E_O \cos(\omega t - kZ) + \frac{3}{4} \varepsilon_0 \chi^{(3)} E_O^3 E \cos(\omega t - kZ) \quad (3.6)$$

This equation contains both linear (first term) and nonlinear (second term) polarizations. For a plane wave represented by equation (3.2), the intensity ( $I$ ) is defined as,

$$I = \frac{1}{2} c \varepsilon_0 n_1 E_O^2 \quad (3.7)$$

where  $c$  is velocity of light and  $n_1$  is linear refractive index of the medium at low fields. Hence,

$$P = \varepsilon_0 \chi^{(1)} + \frac{3}{2} \frac{\chi^{(3)}}{c \varepsilon_0 n_1} I E_O \cos(\omega t - kZ) \quad (3.8)$$

### 3.2 Effective Susceptibility and Effective Refractive Index

$$\chi_{eff} = \frac{P}{\varepsilon_0 E} = \chi^{(1)} + \frac{3}{2} \frac{\chi^{(3)}}{c \varepsilon_0 n_1} I \quad (3.9)$$

Therefore, effective refractive index  $n_{eff}$  can be written as

$$n_{eff} = (1 + \chi_{eff})^{\frac{1}{2}}$$

Or  $n_{eff}$  can be written as

$$n_{eff} = (1 + \chi^{(1)} + \frac{3}{2} \frac{\chi^{(3)}}{c \varepsilon_0 n_1} I)^{\frac{1}{2}} \quad (3.10)$$

The last term is usually very small even for very intense light beam. Hence above expression for  $n_{eff}$  can be approximated with help of

Taylor's series expansion as

$$n_{eff} = n_1 + \frac{3}{4} \frac{\chi^{(3)}}{c\epsilon_0 n_1^2} I \quad (3.11)$$

Or

$$n_{eff} = n_1 + n_2 I \quad (3.12)$$

In equation (3.12) first term  $[n_1 = (1 + \chi^{(3)})^{\frac{1}{2}}]$  is linear refractive index and second term

$n_2 = + \frac{3}{4} \frac{\chi^{(3)}}{c\epsilon_0 n_1^2}$  is nonlinear refractive index. Higher order terms are negligible and hence

neglected. For fused silica fibers  $n_1 = 1.46$  and  $n_2 = 3.2 \times 10^{-20} m^2 / W$ .

For the propagation of a mode carrying 100 mW of power in a single mode fiber with an effective mode area  $\approx 50 \mu m^2$ , resultant intensity is  $2 \times 10^9 W / m^2$  and the change in refractive index due to nonlinear effect is,

$$\Delta n = n_2 I \approx 6.4 \times 10^{-11}$$

Although, this change in refractive index is very small MINUTE, but due to very long interaction length (10–10,000 km) of an optical fiber, the total effects (nonlinear) become significant. It is worth to mention that, this nonlinear term is causes for the formation of solitons.

### 3.3 Self-Phase Modulation (SPM)

The dependence of the refractive index on optical intensity results a nonlinear phase shift while propagating through an optical fiber. The phase ( $\phi$ ) introduced by a field  $E$  over a fiber length  $L$  is given by

$$\phi = \frac{2\pi}{\lambda} nL \quad (3.13)$$

where  $\lambda$  is wavelength of optical pulse propagating in fiber of refractive index  $n$ , and  $nL$  is known as optical path length.

For a fiber containing high-transmitted power  $n$  and  $L$  can be replaced by  $n_{eff}$  and  $L_{eff}$  respectively i.e.

$$\phi = \frac{2\pi}{\lambda} n_{eff} L_{eff} \quad (3.14)$$

Or

$$\phi = \frac{2\pi}{\lambda} (n_1 + n_2 I) L_{eff} \quad (3.15)$$

If intensity is time dependent i.e., the wave is temporally modulated then phase ( $\phi$ ) will also depend on time [9]. This variation in phase with time is responsible for change in frequency spectrum, which is given by

$$\omega = \frac{d\phi}{dt} \quad (3.16)$$

In a dispersive medium an alteration in the spectrum of temporally varying pulse will change the nature of the variation. To observe this, consider a Gaussian pulse, which modulates an optical carrier frequency  $\omega$  (say) and the new instantaneous frequency becomes,

$$\omega' = \omega_0 + \frac{d\phi}{dt} \quad (3.17)$$

The sign of the phase shift due to SPM is negative because of the minus sign in the expression for phase,  $(\omega t - kz)$  i.e.,

$$\phi = -\frac{2\pi}{\lambda} L_{eff} (n_1 + n_2 I)$$

And therefore  $\omega$  becomes,

$$\omega' = \omega_0 - \frac{2\pi}{\lambda} L_{eff} n_2 \frac{dI}{dt} \quad (3.18)$$

Clearly at leading edge of the pulse clearly at leading edge of the pulse  $\frac{dI}{dt}$  hence

$$\omega' = \omega_0 - \omega(t) \quad (3.19)$$

And at trailing edge  $\frac{dI}{dt} < 0$  so

$$\omega' = \omega_0 + \omega(t) \quad (3.20)$$

This shows that the pulse is chirped i.e., frequency varies across the pulse. This chirping phenomenon is generated due to SPM, which leads to the spectral broadening of the

pulse. Figures 3.3 and 3.4 show the variation of  $I(t)$  and  $\frac{dI}{dt}$  for a Gaussian pulse [15].

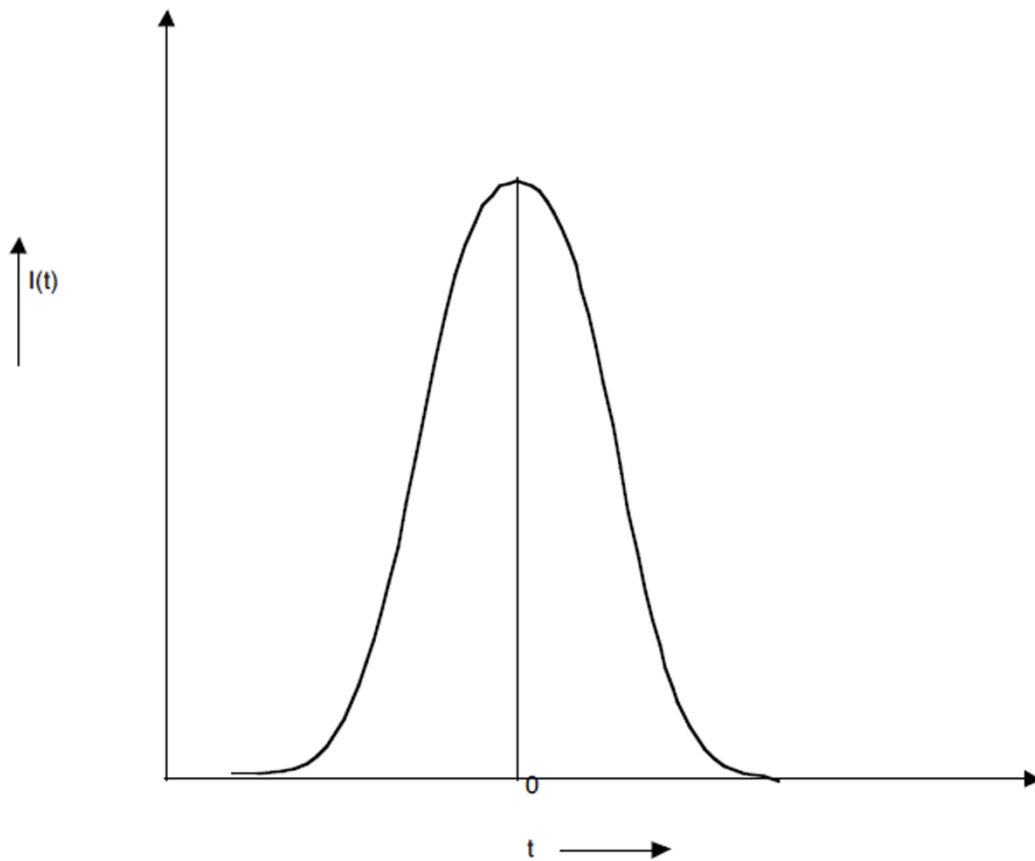


Figure 3.3 Pulse with intensity varying as function of time

There is increasing size of the spectrum without any change in temporal distribution in case of self-phase modulation but in case of dispersion, there is broadening of the pulse in time domain and spectral contents are not changed. In other words, the SPM by itself leads only to chirping, regardless of the pulse shape. It is dispersion that is responsible for pulse broadening. The SPM induced chirp modifies the pulse broadening effects of dispersion.

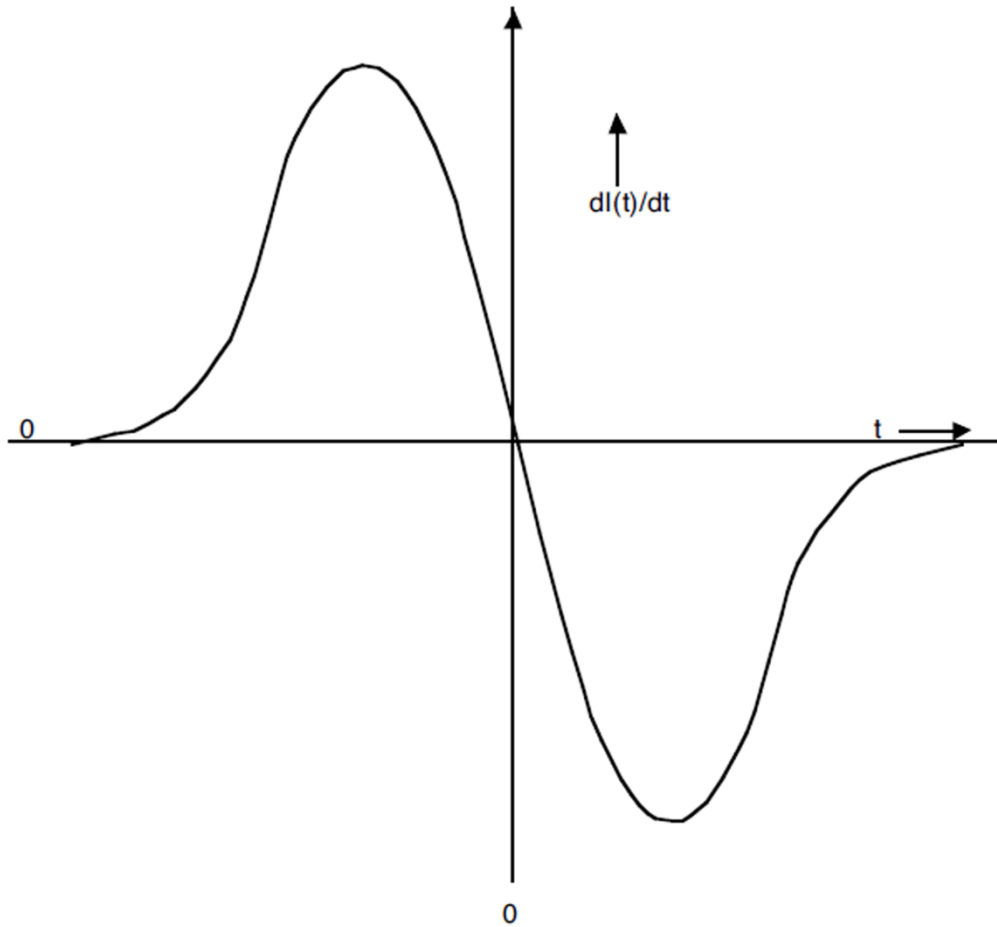


Figure 3.4 Pulse with  $\frac{dI}{dt}$  varying as function of time

Since the nonlinear phase shift is dependent on its own pulse shape, it is called self-phase modulation (SPM).

### 3.4. CROSS PHASE MODULATION (CPM)

SPM is the major nonlinear limitation in a single channel system. The intensity dependence of refractive index further causes to another nonlinear phenomenon known as cross-phase modulation (CPM). When two or more optical pulses propagate side by side, the cross-phase modulation is always has SPM and occurs because the nonlinear refractive index viewed by an optical beam depends not only on the intensity of that beam but also on the intensity of the other co-propagating beams [13]. In fact CPM converts power fluctuations in a certain wavelength channel to phase fluctuations in other co-propagating channels. The result of CPM may be asymmetric spectral broadening and

distortion of the pulse shape. The effective refractive index of a nonlinear medium can be expressed in terms of the input power ( $P$ ) and effective core area ( $A_{eff}$ ) as

$$n_{eff} = n_1 + n_2 \frac{P}{A_{eff}} \quad (3.21)$$

The nonlinear effects depend on ratio of light power to the cross sectional area of the fiber. If the first-order perturbation theory is used to investigate how fiber modes are affected by the nonlinear refractive index, it is found that the mode shape does not change but the propagation constant becomes power dependent.

$$k_{eff} = k_1 + k_2 \frac{P}{A_{eff}} \quad (3.22)$$

where  $k_1$  is the linear portion of the propagation constant and  $k_2$  is nonlinear propagation constant. The phase shift caused by nonlinear propagation constant in traveling a distance  $L$  inside fiber is given as

$$\phi_{n_2} = \int_0^L (k_{eff} - k_1) dz \quad (3.23)$$

Using equations (3.22) nonlinear phase shift becomes,

$$\phi_{n_2} = k_{n_2} P_{in} L_{eff} \quad (3.24)$$

When many optical pulses propagate side by side the nonlinear phase shift of first channel  $\phi_{n_2}^1$  (say) depends not only on the power of that channel but also on signal power of other channels. For two channels,  $\phi_{n_2}^1$  can be given as,

$$\phi_{n_2}^1 = k_{n_2} L_{eff} (p_1 + 2p_2) \quad (3.25)$$

For  $N$ -channel transmission system, the shift for  $i^{\text{th}}$  channel can be given as [8],

$$\phi_{n_2}^i = k_{n_2} L_{eff} (p_i + 2 \sum_{n \neq i}^N P_n) \quad (3.26)$$

The factor 2 in above equation has its origin in the form of nonlinear susceptibility [5] and shows that CPM is twice as effective as SPM for the same amount of power. The first term in above equation represents the indulgence of SPM and second term that of CPM. It can be seen that CPM is effective only when the interacting signals Super impose in time.

CPM hinders the system performance through the same mechanism as SPM: chirping frequency and chromatic dispersion, but CPM can damage the system performance even more than SPM. CPM influences the system deeply when number of channels is large. Theoretically, for a 100-channels system, CPM imposes a power limit of 0.1 mW per channel.

### 3.5 Four-Wave Mixing (FWM)

Four-wave mixing (FWM), also known as four-photon mixing, is a parametric interaction among optical waves, which is similar to intermodulation distortion in electrical systems. In a multi-channel system, the actions between two or more channels transcend generation of one or more new frequencies at the value of power reduction of the original channels. When three waves at frequencies  $f_i$ ,  $f_j$  and  $f_k$  are put into a fiber, new frequency components are produced at  $f_{FWM} = f_i + f_j + f_k$  [19]. In a normal case where two continuous waves at the frequencies  $f_1$  and  $f_2$  are put into the fiber, as shown in figure 3.5 the beget of side bands due to FWM is given in Figure 3.6

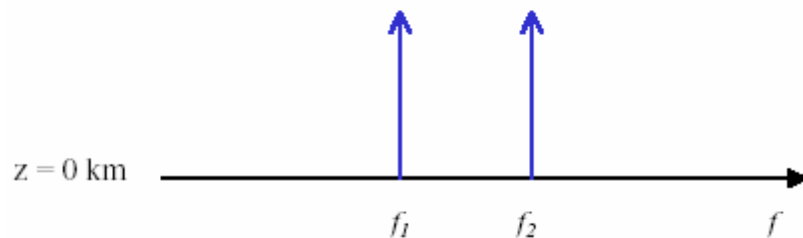


Figure 3.5 the frequencies  $f_1$  and  $f_2$  are put into the fiber

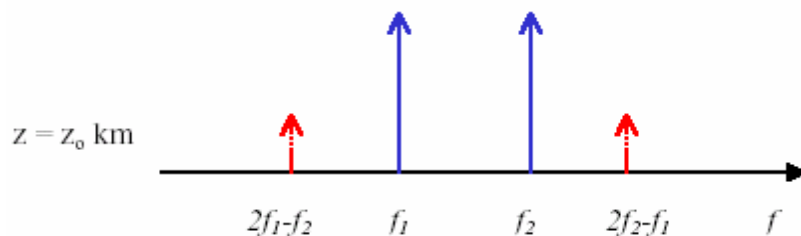


Figure 3.6 generation of side bands due to FWM

The number of side bands due to FWM increases geometrically, and is given by

$$M = \frac{1}{2}(N_{ch}^3 - N_{ch}^2)$$

where  $N_{ch}$  is the number of channels, and  $M$  is the number of newly beget sidebands. For example, eight channels can produce 224 side bands. Since these mixing products can fall directly on signal channels, proper FWM suppression is required to shun significant interference between signal channels and FWM frequency components. When all channels have the same input power, the FWM efficiency,  $h$ , can be expressed as the ratio of the FWM power to the output power per channel, and is proportional to

$$n\alpha \left[ \frac{n_2}{A_{eff} D(\Delta\lambda)^2} \right]^2$$

where  $A_{eff}$  is the effective area of fiber. This shows that FWM of a fiber can be suppressed either by increasing channel spacing or by increasing dispersion. Large dispersion can cause unacceptable power penalties especially in high bit rate systems. However, careful design of the dispersion map (often called dispersion management) which allows large local dispersion but limits the total average dispersion to be below a certain level is found to be very effective to combat both dispersion and FWM induced abasement.

### 3.6 Scattering Nonlinearities

When light is incident on material it undergoes various scattering process. Most of the scattering is elastic, and the scattered wave has the same frequency as the incident wave. However, this scattered light is, in general, at some arbitrary angle to the forward direction of propagation. Hence, if one measures the transmitted light in the forward direction, there is a reduction in intensity as a result of the scattering into other directions. This loss is known as Rayleigh scattering loss. In addition to the elastically scattered component, a small fraction (about 1 to  $10^6$ ) of the incident photons undergo inelastic scattering. The scattered photon emerges with a frequency shifted below or above the incident photon frequency. The difference in energy between the incident and scattered photons is deposited in, or extracted from, the scattering medium. The frequency shifts\* can be small (approximately  $1 \text{ cm}^{-1}$ ) or large (greater than  $100 \text{ cm}^{-1}$ ). When the frequency shift is small, the process is known as Brillouin scattering. The larger frequency shifts characterize the regime of Raman scattering.

### 1) Stimulated Brillouin Scattering (SBS):

Stimulated Brillouin Scattering (SBS) sets an upper limit on the amount of optical power that can be usefully launched into an optical fiber. When the SBS threshold for optical power is exceeded, a significant amount of the transmitted light is redirected back to the transmitters. In addition to causing a saturation of optical power in the receiver, problems also arise with back reflection in the optical signal, and noise that degrades the BER performance. It is particularly important to control SBS in high-speed transmission systems the use external modulators and continuous wave (CW) laser sources. It should be noted that 1550 nm CATV signals in the high-speed transmitters often possess the characteristics that trigger the SBS effect. Brillouin scattering is the time-varying electric fields within a fiber interacting with the acoustic vibrational modes of the fiber material which in turn scatter the incident light. Stimulated Brillouin Scattering is when the source of the high intensity electric fields is the incident lightwave. The periodic variation in in the refractive index, caused by the high power incident lightwave, cases backreflection similar to the effect of Bragg gratings. An increasing portion of light is backscattered because of the increasing optical level beyond the SBS threshold. This creates an upper limit to the power levels that can be carried over the fiber. Figure 3.7 [25] illustrates this phenomenon. As the launch power is increased above the threshold, there is a dramatic increase in the amount of backscattered light. Wavelength (the threshold is lower at 1550 nm than 1310 nm) and the linewidth of the transmitter, among other parameters, govern the precise threshold for the onset of the SBS effect. Values of +8 to +10 dBm are typical for direct modulated optical sources operating at 1550 nm over standard single-mode fiber.

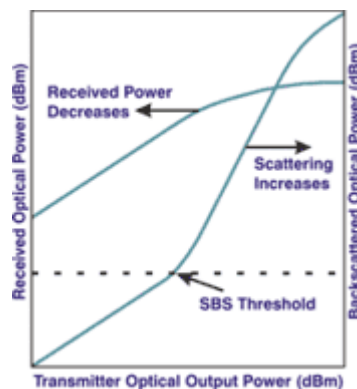


Figure 3.7 SBS threshold effects

The SBS threshold is strongly dependent on the linewidth of the optical source with narrow linewidth sources having considerably lower SBS thresholds. Extremely narrow linewidth lasers (e.g. less than 10 MHz wide), often used in conjunction with external modulators, can have SBS thresholds of +4 to +6 dBm at 1550 nm. Figure 3.8 [25] illustrates how the SBS threshold increases proportionally as the optical linewidth increases. Broadening the effective spectral width of the optical source minimizes SBS. Externally modulating the transmitter provides one way to broadening the linewidth. This involves adding a small AC modulation signal to the DC current source used drive to laser. This broadens the spectral linewidth of the transmitter and increases the threshold for the onset of SBS. This option also increases the dispersion susceptibility of the transmitter, primarily a concern when operating at 1550 nm over non dispersion-shifted single-mode fiber. Practical implementations of SBS suppression circuitry based on laser drive dithering can increase the SBS threshold by 5 dB.

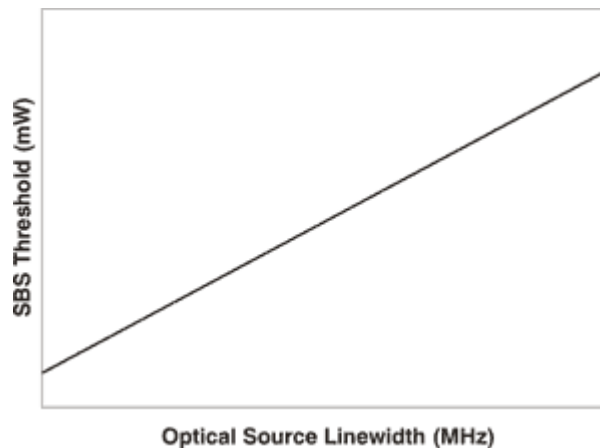


Figure 3.8 SBS threshold versus source linewidth

Phase dithering the output of the external modulator provide another common means of increasing the SBS threshold. In this case, a high frequency signal, usually twice that of the highest frequency being transmitted, is imposed onto both output legs of the external modulator. This modulates the phase of the light, effectively spreading out the spectral width. Figure 3.9 [25] shows the optical spectra of a VSB/AM transmitter without phase dithering. The central carrier exceeds the SBS threshold, causing serious system degradation.

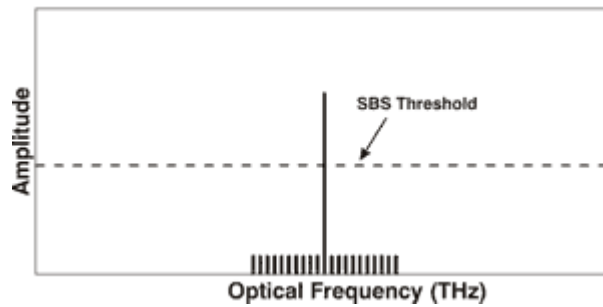


Figure 3.9 Optical spectrum without phase modulation

In Figure 3.10 [25], a high frequency dither signal has been applied to the phase modulation input of the external modulator. It can be seen that all of the lines are now comfortably below the SBS threshold. This technique can raise the SBS threshold optical power by about 10 dB.

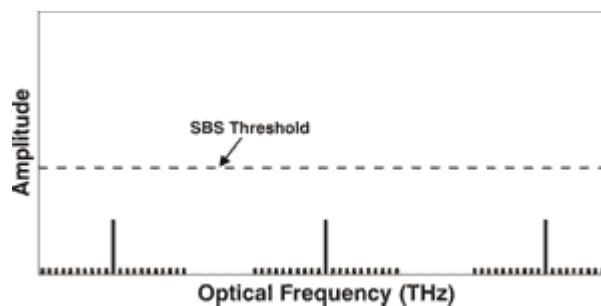


Figure 3.10 - Optical spectrum with phase modulation

Adding EDFAs to a signal path greatly decrease the SBS threshold. The SBS threshold for a system containing  $N$  amplifiers is the threshold without amplifiers in mW divided by  $N$ . This can result in very low SBS thresholds that can seriously impair system performance.

## 2) Stimulated Raman Scattering (SRS):

Stimulated Raman Scattering (SRS) is much less of a problem than SBS. Its threshold is close to 1 Watt, nearly a thousand times higher than SBS. But real systems are being deployed with EDFAs having optical output powers of 500 mW (+27 dBm), and this will

only go higher. A fiber optic link that includes three such optical amplifiers will reach this limit since the limit drops proportionally by the number of optical amplifiers in series. SRS can cause scattering like SBS, but usually the effect first seen is that the shorter wavelength channels are robbed of power, and that power feeds the longer wavelength channels. This is similar to the operation of EDFAs where a 980 nm pump wavelength provides the energy that amplifies the signals in the longer wavelength, 1550 nm, region.

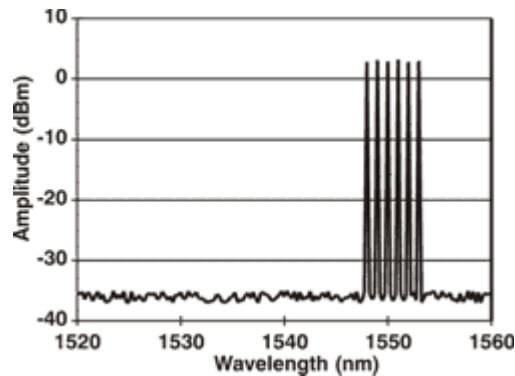


Figure 3.11 Six channel DWDM transmitted optical spectrum

Figure 3.11 [25] shows the typical transmit spectrum of a six-channel DWDM system. Note that all of the six wavelengths have identical amplitudes. These signals are all in the 1550 nm window. Figure 3.12 [25] illustrates the SRS effect. It can be seen that the short wavelength channels have much smaller amplitude compared to the longer wavelength channels. Plain silica fiber can provide similar gain using the Raman gain mechanism. Raman amplifiers are only now becoming mainstream additions to long-haul telecommunications system.

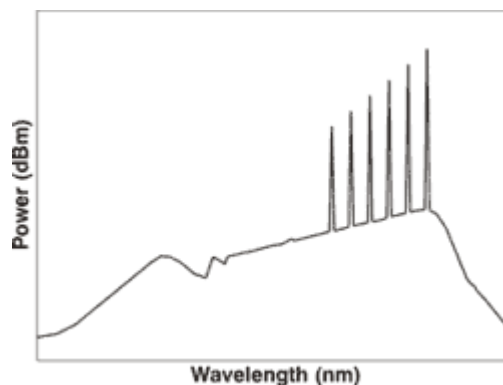


Figure 3.12 - SRS effect on six channels DWDM transmitted optical spectrum

## Proposed work

### 4.1. Development of the model

In DWDM systems due to SRS effect, channels at lower wavelengths act as pump for the channels at higher wavelengths that act as stokes. This leads to power transfer among the different wavelength channels. The graphical representation of depletion and amplification of optical power at different wavelength channels due to SRS has been shown in Figure 4.1 for a four channel DWDM system.

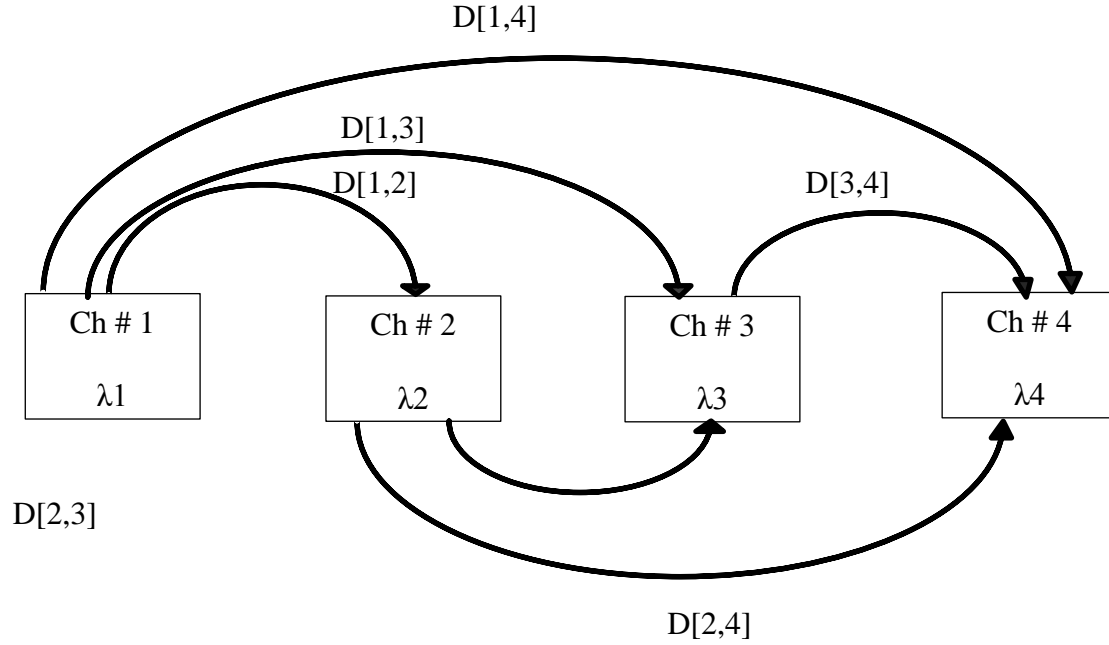


Figure 4.1 Optical power transfer among different wavelength channel due to SRS

A simple case of a DWDM fiber optic system having four co-propagating channels is considered first and mathematical expressions for depletion and amplification of power at different wavelength channels due to SRS are obtained as given in equations (4.1) – (4.4). A generalized expression for N channel system is then obtained from these equations.

$$P_M[1] = P_T[1]\{1 - \sum_{i=2}^4 D[1, i]\} \quad (4.1)$$

$$P_M[2] = P_T[2]\{1 - \sum_{i=3}^4 D[2, i]\} + P_T[1]D[1,2] \quad (4.2)$$

$$P_M[3] = P_T[3]\{1 - D[3,4]\} + \sum_{j=1}^2 \{P_T[j]D[j, 3]\} \quad (4.3)$$

$$P_M[4] = P_T[4] + \sum_{j=1}^3 \{P_T[j]D[j, 4]\} \quad (4.4)$$

where  $P_T[i]$  and  $P_M[i]$  are the optical power launched in the  $i$ th channel and the modified power in the  $i$ th channel due to SRS effect after propagation over a given length of optical fiber respectively for  $i=1,2,3,4$ . Channel # 1 is the lowest wavelength channel with centre wavelength  $\lambda_1$ .  $D[i,j]$  represents the fraction of power depleted from the  $i^{\text{th}}$  channel by the  $j^{\text{th}}$  channel for  $j>i$ , i.e.,  $j^{\text{th}}$  channel is at a wavelength longer than that of the  $i^{\text{th}}$  channel. The value of  $D[i,j]$  is evaluated using equation (4.5) that is developed by modifying the expression in [10, 14].

$$\begin{aligned} & \text{for } (f_i - f_j) \leq 1.5 \times 10^{13} \text{ Hz and } j > i \\ & D[i, j] = 0 \\ & \text{for } (f_i - f_j) > 1.5 \times 10^{13} \text{ Hz and } j \leq i \end{aligned} \quad (4.5)$$

$g$  is peak Raman gain coefficient (cm/W).  $L_i, L_j$  are the wavelengths (nm) of  $i$ th and  $j$ th channels and  $f_i, f_j$  are the centre frequencies (Hz) of the  $i^{\text{th}}$  and  $j^{\text{th}}$  channels.  $A_e$  is effective core area of optical fiber in  $\text{cm}^2$ .  $P_T[j]$  is optical power in watts launched in the  $j$ th channel and value of  $b$  varies from 1 to 2 depending upon the polarization state of the signals at different wavelength channels,  $b=2$  is considered for scrambled polarisation [10].  $L$  is actual fiber length in km and  $L_e[1, j]$  is wavelength dependent effective length in km which is calculated using equation (4.6) given below

$$L_e(\lambda_j) = \left\{ 1 - \exp \left[ \frac{-\alpha(\lambda_j)L}{4.343} \right] \right\} \left[ \frac{4.343}{\alpha(\lambda_j)} \right] \times \frac{\text{total length}}{\text{inter channel separation}} \quad (4.6)$$

Where  $\alpha(\lambda_j)$  is wavelength dependent linear loss coefficient of optical fiber in dB/km. For calculating  $\alpha(\lambda_j)$ , equation (4.7) is developed by taking into account the variation in linear loss coefficient with wavelength up to 0.7 dB, over 25 nm bandwidth (in 1550 nm transmission window) and 100 km fiber length confirmed by the experimental results [11].

$$\begin{aligned} \alpha(\lambda_j) &= \{ \alpha_{\max} - [(\lambda_j - \lambda_1)/\Delta_{\text{WDM}}](\alpha_{\max} - \alpha_{\min}) \} \\ \alpha_{\max} &= \alpha + \alpha_{\text{var}}/2 \\ \alpha_{\min} &= \alpha - \alpha_{\text{var}}/2 \\ \alpha_{\text{var}} &= (0.007/25)\Delta_{\text{WDM}} \end{aligned} \quad (4.7)$$

Where  $\Delta_{\text{WDM}}$  is spectral width of DWDM signal (i.e. separation between the shortest wavelength channel and the longest wavelength channel) in nm,  $\lambda_j$  and  $\lambda_1$  are wavelengths of channel #  $j$  and channel# 1 respectively in nano meters and  $\alpha_{\text{var}}$  is in dB/km and  $\alpha$  is fiber loss coefficient in dB/km at centre wavelength. It is assumed that  $\alpha$

varies linearly with wavelength. However, in transmission windows other than 1550 nm window the variation of fiber loss coefficient with wavelength will differ and so the factor 0.007/25 in equation (4.7) will have to be changed accordingly. This makes the model capable of taking into account the effect of wavelength dependent linear loss coefficient of fiber while calculating SRS induced spectral distortion in DWDM fiber optic systems. The equations (4.1) to (4.4) are combined together to form a single equation, which is further generalized for N channel systems as given below [4.8].

$$P_M[k] = P_t[k] - P_t[k] \sum_{i=k+1}^N D[k, i] + \sum_{j=1}^{k-1} P_t[j] D[j, k]$$

for  $k = 1, 2, \dots, N$  (4.8)

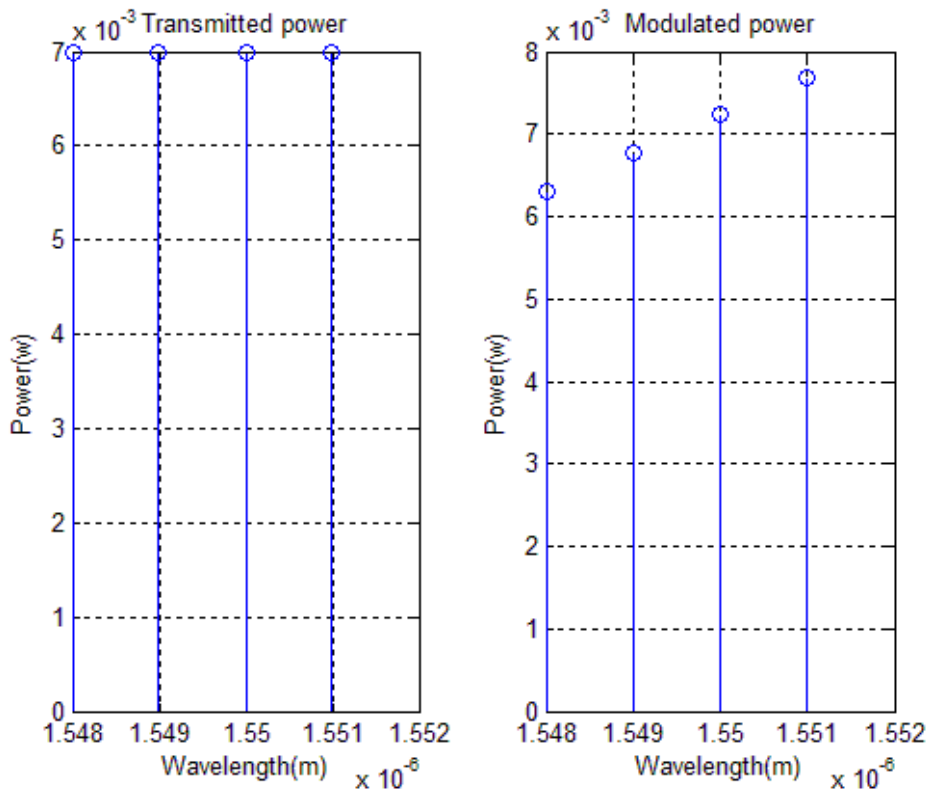


Figure 4.2 Power transmitted and modulated power due to SRS.

Figure 4.2 shows the typical transmit spectrum of a four channel DWDM system. Note that all the four wavelengths have identical amplitudes (power). These signals are in 1550 nm window and illustrate the SRS effect. It can be seen modulated power that short wavelength channels have much smaller amplitude compared to the longer wavelength channels.

## 4.2 Algorithm

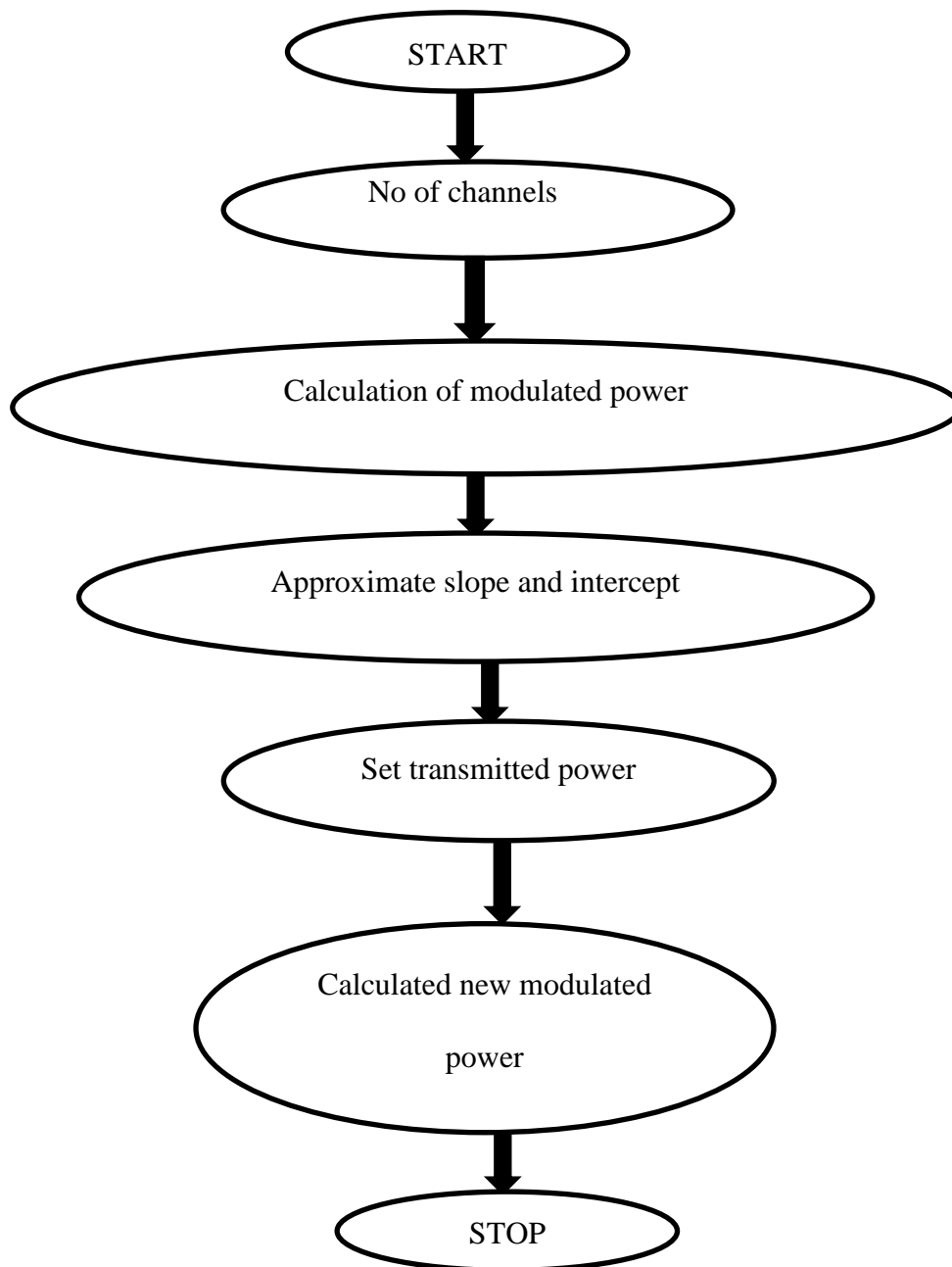


Figure 4.3 Flow chart of algorithm

### 4.3 Simulation results

SRS causes a distribution of power across all channels linearly. As the number of channels increase the slope linearly increases and the intercept linearly decreases, for a fixed power transmitted across each channel. By using these properties of SRS to transmit power linearly across channels we can set the transmitted power according to eq (4.9) which provides an approximate constant power across all channels according to the specified power value.

$$\text{Corrected modulated power} = [\text{slope} * \text{wavelength} + \{\text{power} + (\text{slope} * \text{wavelength of 3}^{\text{rd}} \text{ channel})\}] \quad (4.9)$$

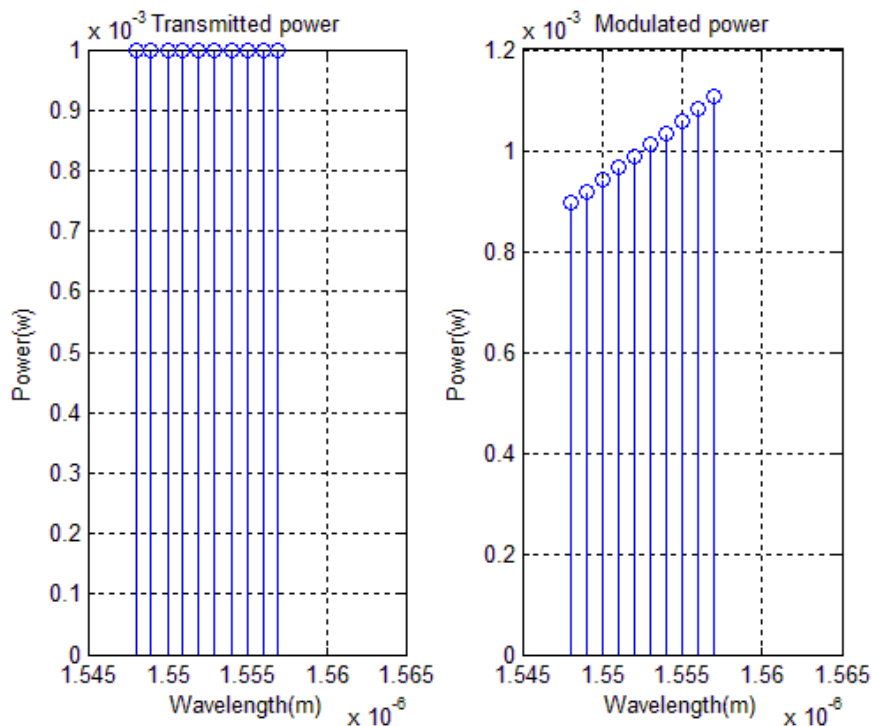


Figure 4.4 Transmitted power and modulated power for 10 channels

Figure 4.4 shows 10 channel DWDM system for constant power transmitted across channel. As shown clearly in Figure 4.4 the constant power across the wavelengths produces a linearly varying modulated channel due to SRS. We can decrease this variation using the power specified by eq (4.9).

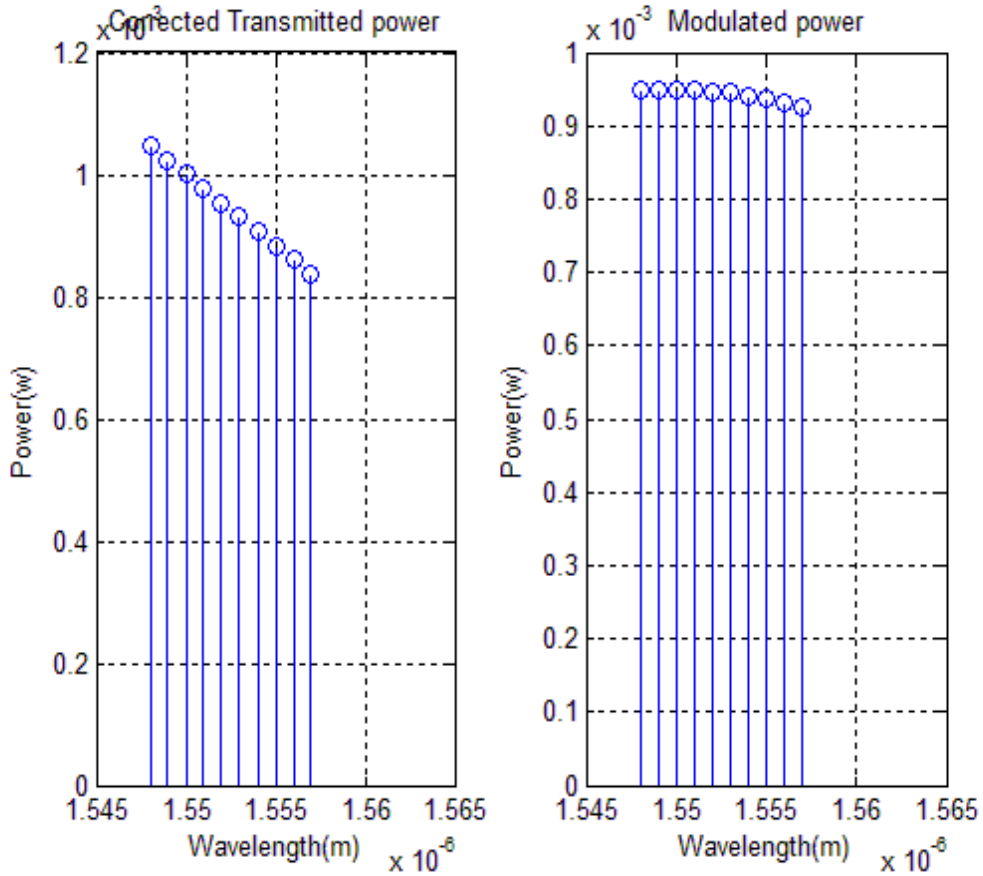


Figure 4.5 Corrected power and modulated power for 10 channels

Figure 4.5 shows that the modulated power for 10 channels nearly becomes constant as if there is no effect of SRS in the channel.

Power (mW)	Channel length (km)	Amplifier distance (km)	No of channel wavelengths
1	2000	100	20
2	2000	100	16
3	2000	100	13
4	2000	100	11
5	2000	100	10
10	2000	100	8

15	2000	100	7
20	2000	100	6
25	2000	100	5

Table 1.3 Maximum no of channels that can be corrected for a given power

Table 1.3 shows the maximum no of channels that can be corrected for a given power value using our algorithm.

### CONCLUSION AND FUTURE SCOPE

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#### Conclusion

The result in Figure 4.5 and Table 1.3 show that the use of linear approximation results in almost constant modulated power on given no of channel wavelengths and given power eg. For 1 mW of power we can use a 20 channel DWDM system negating the effect of SRS in channel length of 2000 km just by efficient power division. Thus, we can say that using linear approximation on the transmitted side can negate the effect of SRS in DWDM system. It can be said that efficient power division algorithms can help to achieve almost constant power across all the wavelengths.

#### Future scope

- Optical distributed amplifier can be design using Raman gain with proper use of channel separation.
- Higher order approximation at the transmitter side can improve the result.
- Fiber loss coefficient used in this dissertation vary linearly because work is done on 1550 nm optical window, further study can be done on nonlinearly varying fiber loss coefficient on 1350 nm window.

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## **List of Publication**

1. "Linear power division approximation for stimulated Raman-scattering", *Fiber and Integrated optics journal*, Taylor & Francis Inc (accepted on 8 April 2014 )
2. "Effect of SRS on transmitted signal power", *International conference on Emerging technology in electronics and communication under TEQIP-II GRANT*, 20-22 Dec 2013