"Higher Order Approximation to Achieve Almost Constant Modulated SRS Power including Pulse Walk off Effect and Data Transmission Formats"

Dissertation Submitted towards the partial fulfilment of requirement for the award of degree of

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In

Electronics and Communication Engineering

Submitted by

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DECLARATION

I, Kamini Kumari, hereby declare that the work, which is being presented in this dissertation entitled "**Higher Order Approximation to Achieve Almost Constant Modulated SRS Power including Pulse Walk off Effect and Data Transmission Formats**" by me in partial fulfilment of the requirements for the award of degree of Master of Engineering in Electronics and Communication Engineering from Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Dr. Hardeep Singh.

I have not submitted the matter presented in the thesis for award of any other degree of this or any other university.

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Abstract

The nonlinear effects degrade the performance of system. When optical power is very high nonlinear effect occurs, there study became important in DWDM system. The two types of nonlinearities occur in optical fibers are:-

- Stimulated scattering such as SRS and SBS
- Optical Kerr effect, due to changes in the refractive index of fiber with optical power.

Depending upon the type of input sign Kerr-non-linearity represented in three different types of 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). if the incident power exceeds a certain threshold value the intensity vary linearly.

Difference between SRS and SBS are:-

1. SRS generated optical phonon are incoherent while SBS generated acoustic phonon are coherent.
2. SRS threshold is close to 1 w which is 100 times higher than SBS threshold.
3. Scattered light shifted in frequency is 13 THz in SRS while in SBS is 10 GHz. Hence frequency shift is maximum in SRS.
4. SRS is much less problem than SBS.
5. SRS bandwidth is 572 mW and in SBS bandwidth is narrow i.e. 1.289 mW.

In this Dissertation stimulated Raman scattering model has been study and presented a higher order approximation to achieve almost constant modulated SRS power including pulse walk off effect and data formats. The data format such as RZ, NRZ and optical Manchester discussed in briefly. Constant modulated power is produce using pulse walk off. Due to SRS effect, channel at shorter wavelength act as pump for the longer channel act as

stokes. To reduce SRS effect or to achieve almost constant modulated power pulse walk off rule is applied. Power tilt Because of SRS effect has been calculated at RZ, NRZ and optical Manchester format. Power has been varied from 1 to 60 mW. Using pulse walk off rule effect on channel was done. Pulse walk off rule limit the effective length and number of channels increases. Using this algorithm, efficiency is also increased.

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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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Chapter 1

Introduction to Optical Communication

Optics communication played important rule in telecommunication. The properties of optical fibers i.e. information carrying capacity, cheapest, and possess immunity from many disturbances. The optical fiber information carrying capacity is greater than its competitors: wires, coaxial cable and microwave link.

- Optical fiber are less expensive to produce
- Do not conduct electricity
- Small size

Frequency transmitted for voice communication is 50 Hz to 20 KHz. The main reason that optical fiber carrying very much large information than other media. Hence information carrying capacity is large. The frequency of light that travel along fiber is approximately 200 trillion cycle per second (Hz). PCS (personal communication service) cellular wireless system approximately 2,000,000,000 cycles per second at frequency of 2 GHz.

The actual bandwidth needed for voice communication is approximately 4KHz. 50 billion voice conversation is possible on single laser beam in optical. Optical fiber used in high speed telecommunication system internal and LAN to get larger bandwidth.

1.1 Repeaters

Optical fiber is extremely transparent over a long distance transmission some data may be lost but due to repeater long distance transmission is possible because by applying repeater regenerate the signal that distort by transmission loss.

It is electronics device that receive a signal and retransmit the signal at higher level or power on other side of obstruction so that signal can cover large distance. An optical repeater is optoelectronic circuit that amplifies the light beam. But disadvantage of repeater is that they cannot distinguish pulse is at one wavelength, this limit information carrying capacity. This complexity is reduced by erbium doped amplifier.

1.2 EDFA (Erbium doped fiber amplifier)

EDFA obtained by adding impurities of ion erbium in optical fiber. If energy is fed into section of this fiber, which uses pump laser than stream of optical pulse passes through the amplifier. By passing through amplifier pulse will be amplified or boosted in size [1].

This process occurs at 1.55 nm wavelength many different messages being carried on laser beam. All these beam are of different wavelength can be amplified simultaneously. 40 different wavelength are separated from each in frequency by 100 GHZ each wavelength carry 10 Gb/s data, so that total carrying capacity of fiber increased to 400Gb/s. EDFA only amplify the signal but does not considered pulse width broadening problem that result from dispersion.

1.3 Optical Communication Network

Most long distance lines use single mode fibers and in order to increase data rate networking is applied e.g. maximum data rate 2.488 Gb/s occur in SONET.

1.4 History of Optical Communication

In 1880, alexander graham bell established the world's India's largest wireless telephone transmission between two objects such as 213 m apart. This is the 1st invention. Optical communication properly developed in 1970 by corning glass works low attenuation for communication purpose. In 1791, Chapel from France developed semaphore which is limited for information transfer [6].

First generation system worked on at bit rate of 45 mbps with repeater spacing upto 10 km. fiber optics operated at 0.8 μm used in GaAs.

Second generation 1980, fiber optics operated at 1.3 μm used in InGaAsP semiconductor laser and limited to multimode fiber. In 1981 single mode fiber is revealed.it greatly improving system performance. In 1987, this system works on a bit rate of 1.7 Gb/s with repeater spacing of 75 Km.

Third generation system worked on 1.55 μm and fiber losses is approximated of 0.2 dB/Km. it discover the indium arsenide and indium gallium arsenide photodiode by Pearsall. The pulse spreading difficulty is overcome at that wavelength using InGaAsP. Scientist overcame this difficulties using dispersion shifted fiber at 1.55μm. This development allowed third generation system to work commercially at 2.5 GB/s with repeater spacing of 100 Km.

Fourth generation system used optical amplifier to reduce need for repeater and WDM to increase data capacity. Using optical amplifier in 2001 10 Tb/s capacity increases, in 2006 bit rate is reached 14 Tb/s with 160 Km range.

Fifth generation system focus on extending range of wavelength over which WDM can operate. Conventional band (c-band) cover wavelength range of 1.53-1.57 μm and dry fiber has low loss window extension rate to 1.3 μm to 1.65 μm. Other development include concept of optical soliton that preserve the shape of the pulse by the effect of dispersion with the nonlinear effects.

1.5 General Overview of Fiber Optic Communication

The primary objective of optical fiber communication system is to transfer the signal information from source to destination i.e. (voice, data, and video). The source provides information to transmitter in the form of electrical signal. This electrical signal applied to optical source that produce modulated light wave carrier. The optical source here is LED and LASER. The information carried in the form of light passes through the optical fiber cable. At the receiver side photo detector demodulates the optical signal and obtained electrical output. The types of optical detector used at receiver side are phototransistor, photoconductor etc.

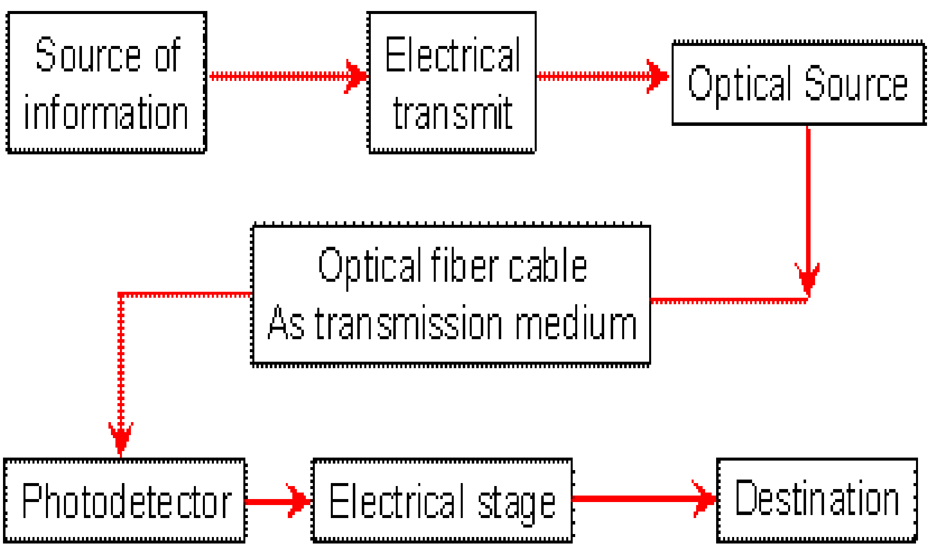

Figure 1.1 General fiber optical Communication

1.6 Technology

today fiber optic communication include transmitter to convert an electrical signal into optical signal to send it into optical fiber, a cable consist bundle of fiber, numbers of amplifier and to recover the signal at the receiver side an optical receiver .

1.6.1 Transmitter

Optical transmitter is semiconductor devices such as LED and laser diode. Difference between LED and laser is that

1. LED produce incoherent light, laser produce coherent light.
2. Light emitted from LED is coherent with spectral width of 30-60nm very useful for low application. Coherence means a constant phase difference between two waves. Laser produce light incoherent with spectral width <5nm.
3. In LED, the principle of emission is spontaneous, but in laser stimulated emission.
4. Output power is low as compared to laser.
5. The laser is highly directional as compared with LED.
6. The speed of operation is slow, but in laser speed of operation is high.
7. LED is easier to use less complex. Laser, complex circuitry need thermal and optical stabilization circuits due to light amplification.
8. Life time of LED is longer as compared with Laser.
9. LED Cost is cheaper, LASER is expensive.

1.6.2 Drive Circuit:

It is used to switch the current varied in the range of 10 to 1000 mA. For LED there are drive circuit like common emitter, low impedance matching, coupled emitter switched, trans-conductance drive circuit. For LASER shunt drive circuit, bias control circuit, ECL compatible drive circuit.

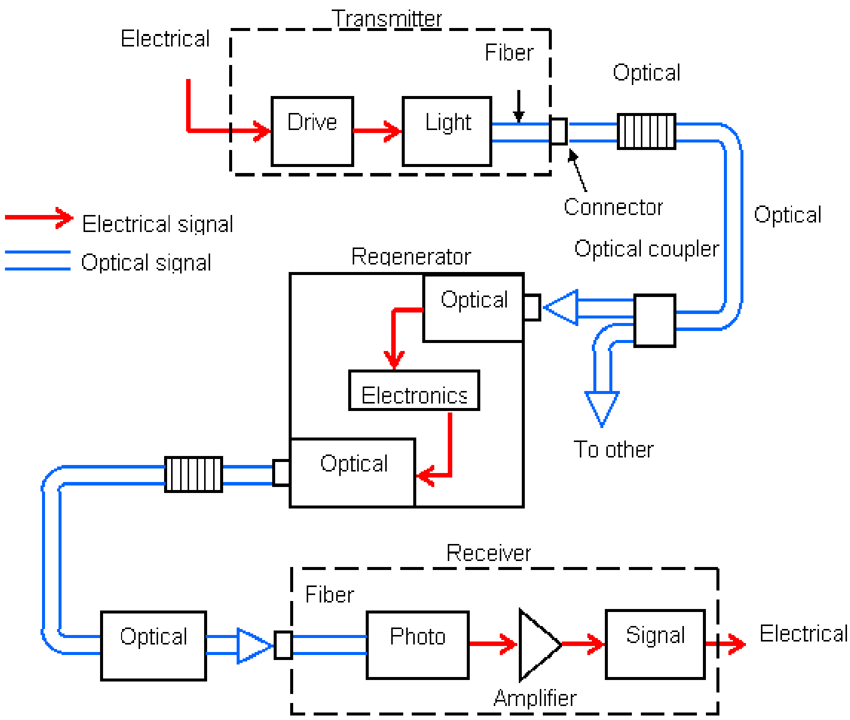

Figure 1.2 Major element of fiber communication

1.6.3 Receiver

It include photodetector, voltage amplifier, a decision circuit that gives the exact information signal that is transmitted at transmitter side. Photodetector convert light into electricity using photoelectric effect. Optical-electrical converter produce a digital signal in electrical domain, in electrical domain the signal attenuated and distorted when passing through the other channel. Such clock recovery from data performed by PLL applied before the data is passing through the other channel. The two most common photodetector are p-i-n and avalanche diode.

Important requirement of an optical receiver are sensitive of the signal, bit rate data compression, does not depend on bit pattern, particular range defined, holding time.

1.7 Types of optical fibers used in communication

According to refractive index profile optical fiber divided into two categories namely:

a. Step index fibers
b. Graded index fibers

1.7.1 Step index fibers

Step change in core cladding interface called as step index fibers. A multimode step index fiber has large core diameter of which is around 50μm. It limits bandwidth and introduces distortion. It is expensive and higher attenuation, a multimode step index shown in fig.3. a single mode fiber core diameter is 2 to 10 μm and propagation of light shown in figure 4. It has advantage over step index fiber is low intermodal dispersion. Multimode step index fibers used spatially incoherent optical sources and low forbearance requirement on fiber connectors.

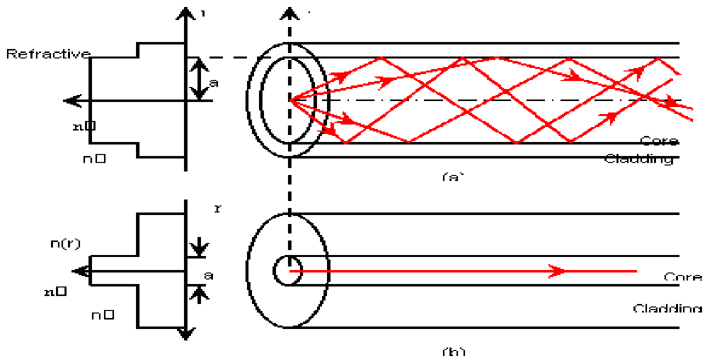

Figure 1.3 Multimode and Single mode step index fiber

1.7.2 Graded index fibers

The figure show, graded index fiber have core index of n(r) which is less than core index of step index fiber with a distance i.e. a from maximum value of n1 to a constant value of n2. For multimode graded index fiber gives best results for parabolic refractive index profile. Multimode graded index fiber has less intermodal dispersion than its multimode step index fiber.

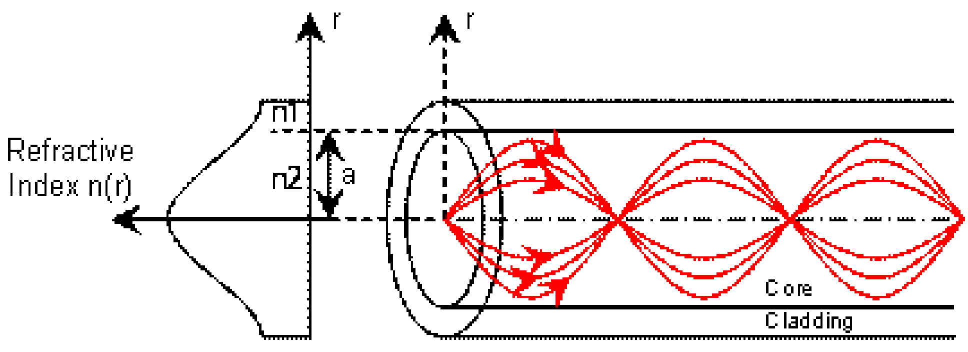

Figure 1.4 Graded index fiber

1.8 Comparison between optical fiber and electrical transmission

Optical fiber generally chosen because system requires high bandwidth and longer distance transmission than electrical transmission can accommodate. Main benefit of fiber is low loss, dielectric nature of cable, high data carrying capacity. In electrical transmission thousands of fiber needed to replace single high bandwidth fiber cable. Another advantage of fiber is that it is used for long distance, experience no cross-talk but in electrical transmission cross talk possible. In high EMI (electromagnetic interference) fiber can be installed. To avoid high lightning strike incidence dielectric cables is ideally used.

Electrical transmission in short distance and low bandwidth preferred because of its:

- Lower material cost
- Low cost transmitter and receiver

The fiber may be used for short distance and low bandwidth application due to other important features such as:

- No sparks
- Higher electrical resistance

Advantages

1. **Immunity to electromagnetic interference:** fiber optics is immune to EMI (electromagnetic interference). Since signal are transmitted as light instead of current. They can carry signal where EMI would block transmission.

2. **Data security:** fiber is most safe medium available for carrying the data that is easily affect by reaction occur in fiber i.e. shielding wire as in cable can reduce the problem of leaking the signal.

3. **Non-conductive cable:** metal can encounter problem of signal transmission. But an conductive cable reduce the transmission problem if semiconductor have large volts, they cannot damage the component hence signal transmission is possible without any damage.

4. **Eliminating spark hazards:** some electrical transmission create small spark, these small spark can make larger damage. These spark no longer danger but bad in chemical plant or oil refinery. In oil refinery little spark create a big explosion. To

avoid this spark cable is made of dielectric. These fiber optics cable do not create spark since they cannot carry current.

5. **Ease of installation:** by increasing capacity of transmitting more signal of fiber cable make fiber thicker and more rigid. Thick cable is difficult to install or expensive.

   Fiber cable is easy to install since they have small size, lightweight, flexible and small radii. It also makes them easier to be used in temporary and installation is easy to carried. Fiber cable is best for copper cable because of its storage, durability, strength and handling [1].

6. **High bandwidth over long distance:** it carry high speed signal over a long distance without any use of repeater. The information carrying capacity increases with frequency but does not mean infinite bandwidth greater than coaxial cable i.e. few MHz/Km but fiber cable has bandwidth of 400 MHz/Km.

1.9 Multiplexer

Multiplexer is a device that combines multiple signals into a single line of transmission. At receiver side the combined signal are separated by the help of de-multiplexer. It enhances the efficiency use of bandwidth.

1.9.1 Types of multiplexer technique:

1) TDM (time division multiplexing)
2) FDM (frequency division multiplexing)
3) WDM (wavelength division multiplexing)

1) **TDM:** it is used in digital technology but it is also applied for analog technology, in these technique different cable share same channel on the basis of time. During the transmission different cable is assigned a specific time slot during which signal is allowed from one end to other end and during this slot no other cable is allowed to send data. TDM is first developed for application in telegraphy to route multiple transmission over single transmission line.

2) **FDM:** it is generally used in analog technology.it is achieve by combining several signal into one medium by sending signal in different frequency range. Mostly used

application for FDM is radio, TV broadcast mobile or satellite. Service provider sends multiple channels simultaneously to all subscribers without any interference and at the receiver end subscriber must tune frequency to the accurate frequency to access channel.

3) **WDM:** different cable shares the same fiber on the basis wavelength. FDM and TDM operate in electrical domain but WDM operate in optical domain.by using WDM bit rate can be increased beyond 10 Tb/s and hence information capacity increased. WDM operate in single mode fiber with core diameter of 9μm, also used in multimode which is a core diameter vary from 50 or 62.5 μm.WDM is expensive and complicate to run [7].

Uses

- It is useful in signal processing and transmission optical. Multiplexing is also used in image processing and it also used in scan the entire signal.

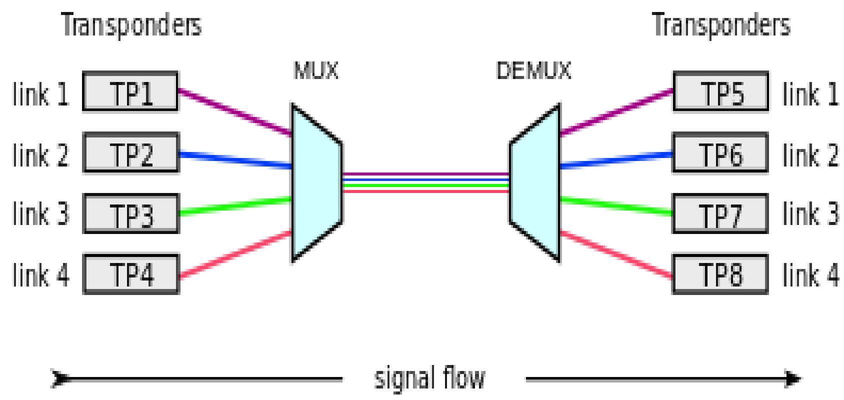

Figure 1.5 WDM operating principle

WDM divided into different wavelength:

1) CWDM (conventional or coarse wavelength division multiplexing)
2) DWDM (dense wavelength division multiplexing)

1) CWDM

At 1550 nm, CWDM given up to 8 channels in 3rd transmission window of silica fiber. CWDM uses increased channel spacing i.e. less sophisticated and thus less costly in the design of transceiver. CWDM uses two signals multiplexed onto single fiber, where one signal at the 1510 nm band and another at the 1310nm band.

2) DWDM

Same transmission but denser channel spacing. For 40 channels it uses channel spacing 100 GHz, 80 channels at 50 GHz. The channel spacing at 12.5 GHz called ultrashort dense wavelength.

WDM, CWDM and DWDM based on concept of multiple wavelengths on single fiber but different in spacing and number of channel. EDFA provide wideband amplification in c-band. Raman provides amplification in L-band. In CWDM no amplification is occurring.

1.10 Dispersion and losses in fibers

The pulse broaden as it travel through fiber is called dispersion. This pulse broadening is reducing the bandwidth or information carrying capacity over longer distance. The signal is passing through the fiber. It limits how fast the information is transferred. Dispersion of transmitted optical signal can cause distortion for both analog and digital signal transmission.

It spread in time domain thus they can interference with adjacent pulse results in what commonly known as ISI (inter symbol interference).

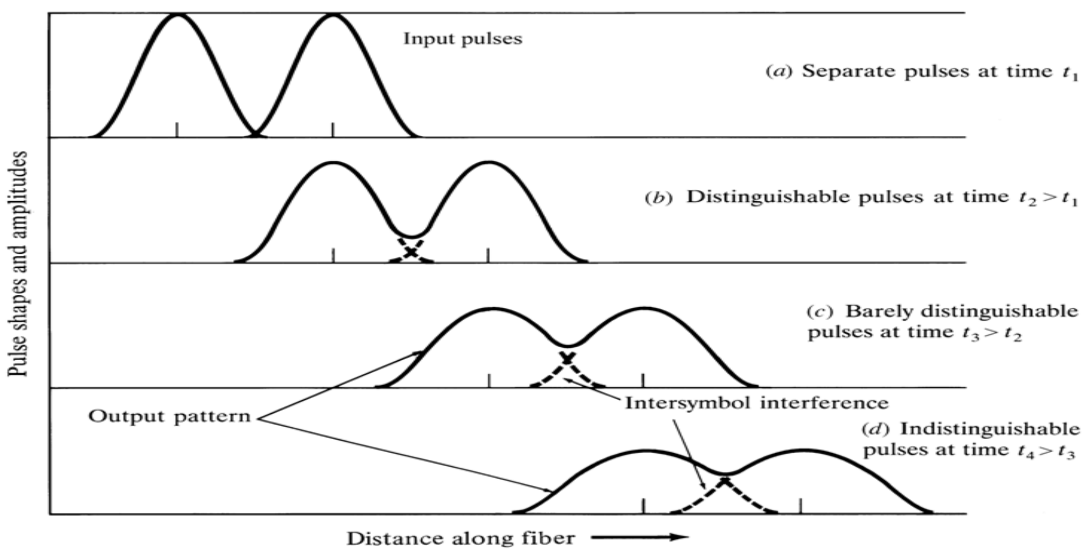

Figure 1.6 Pulse spread and attenuation due to dispersion

1.10.1 Types of dispersion

1. Intermodal dispersion
2. Intra-modal dispersion : a) material dispersion

   b) Waveguide dispersion

1) Intermodal dispersion

It occurs in multimode fiber. It arises when ray follow different path and arrive at other end at different times. The core of multimode fiber is large i.e. 50 to 62.5 μm ,the ray follow different path, travel with the same speed as travelling close to core-cladding interface. The ray covers all paths with same speed and reaches other side at different time. This lead to temporal broadening called intermodal dispersion

Intermodal dispersion reduced by different way such as:

1. Use single mode fiber where no modal dispersion.
2. Use small core diameter.
3. Graded index fiber is used so that ray travels danger path and also faster velocity and thereby arrives at same time as ray follow shorter path.

2) Intra-modal dispersion: spectral component travel with different group of velocity called GVD (group velocity dispersion) and intra-modal dispersion.

a. Material dispersion: this type of dispersion arises due to variation of refractive index with frequency of light.

Material dispersion $D_M = 122\left(1 - \frac{\lambda_{ZD}}{\lambda}\right)$

At 1300nm wavelength dispersion is zero. 600nm to 800nm dispersion is varying exponentially.

b. Waveguide dispersion: it is chromatic dispersion which arises due to difference in the refractive index of the core and cladding. It is occur in single mode fiber because optical energy travels through the core and cladding with different indices.

Total dispersion= material dispersion + waveguide dispersion

1.11 Group velocity dispersion

GVD is phenomenon is that group velocity of light depend upon frequency and wavelength

$$GVD = \frac{\partial}{\partial\omega}\frac{1}{v_g} = \frac{\partial}{\partial\omega}\left(\frac{\partial k}{\partial\omega}\right) = \frac{\partial^2 k}{\partial\omega^2}$$

k is frequency dependent. Basic unit of GVD is ${s^2}/{m}$. In term of optical fiber it is usually defined as derivative with respect to wavelength i.e.

$$D_\lambda = \frac{2\pi c}{\lambda^2}.GVD$$

Two regime of dispersion is normal dispersion and anomalous dispersion. In normal dispersion, group velocity decreases for increasing optical frequency.

GVD has several important effects such as:

I. It is responsible for temporal broadening.
II. Effect of nonlinearities, depend upon GVD. For example spectral broadening.
III. Dispersion responsible for group velocity mismatch.

1.12 Dispersion Shifted Single Mode Fiber

It is used to optimize both low attenuation and low dispersion. DSF is a single mode fiber; it exhibits the zero chromatic dispersion in the region 1.3 μm wavelength. 1.5 μm Wavelength region is important because the fiber losses is low at this region, EDFA operate at this region.

At 1.5 μm region DSF occur at zero dispersion wavelengths. DSF is modified waveguide dispersion i.e. shift the wavelengths into zero dispersion region. This is achieved by modified the refractive index of core and cladding. Triangular, Gaussian and trapezoidal shape are the index profile of DSF.

1.13 Dispersion Compensating Fiber

Compensation means control the chromatic dispersion. To avoid temporal broadening or distortion of signal compensation is needed. It is applied in telecommunication and pulse compression.

At high data rate, excessive dispersive broadening of modulated signal can occur. Without dispersion compensation, temporal broadening is in excess hence symbols is overlap with neighborhood symbol. For moderate broadening, inter symbol interference can distort the signal very strongly. Hence therefore dispersion compensation is essential to avoid this problem [1].

1.14 Attenuation in the optical Fiber

Attenuation defines as Light energy losses or optical power losses in fiber. Fiber with low attenuation reaches to the receiver with more power than a fiber with higher attenuation. Attenuation is directly proportional to length of the cable. It also decides the number of repeater required between transmitter and receiver.

$$\alpha = 10log\frac{P_i}{P_o}$$

P_i is input power and P_o is output power.

1.15 Motivation and Goal of Work

The motivation behind this work is to analyze effect of SRS (stimulated Raman scattering) and to analyze the effect of pulse walk off on SRS. Most of the work has been done in nonlinearities. SBS and SRS these two types of nonlinearities has been study, the SRS threshold is close to 1 w which is larger than SBS threshold. SBS provide gain in back reflected light. For the development of optical communication system SRS model has been studied. SRS provide forward and backward gain. In order to increase efficient use of bandwidth SRS can be used to make distributed amplifier. In this paper model of SRS and few observation of modified power have been taken. In this paper different data formats and its effect on SRS has been studied. Power is varied from 1 to 60mw and number of channel varied from 3 to 99 was done. Our goal is to reduce SRS effect by applying pulse walk off rule and different data formats.

1.16 Objective of Dissertation

The main objectives of dissertation are:

1. To develop SRS model.
2. To analyze the modulated power among all different wavelength channels.

3. To develop an algorithm of SRS for optical communication.
4. To analyze the pulse walk off and data format such as NRZ, RZ and optical Manchester.
5. Comparative analysis of different data transmission formats.

1.17 Outline of dissertation

This dissertation is divided into five chapters

Chapter 1 describes basics of optical fiber communication, history, optical networks, technology used in communication, advantages and uses. The various type of multiplexer such as TDM, FDM, and WDM are discussed. Different type of fiber, dispersion and types of dispersion, and attenuation caused by dispersion is mentioned in brief.
Chapter 2 describes in brief the optical nonlinearities, its basics, Kerr effect and two types of nonlinear effect such as elastic or inelastic phenomenon. SPM, XPM, and FWM are the Non-linear refractive index effect. The two scattering nonlinear affect also studied in brief such as SRS and SBS and their difference is also discussed.

Chapter 3 includes literature survey.

Chapter 4 includes model of SRS and power transfer among four different channels, general expression of modulated power, and walk off length. General expression of Data format such as RZ, NRZ and optical Manchester are discussed. Simulation results are discussed. Some Observation is also taken.

Chapter 5 describes the conclusion and future work.

Chapter 2
Nonlinearities

Due to increase in optical fiber data rate, number of wavelength, power level and number of wavelength nonlinearity arose. In early days optical fiber was easily affected by fiber attenuation and dispersion; however by using number of dispersion avoidance and cancellation techniques this problem is easily solved. Fiber nonlinearities cause many disturbance that must be overcome. The various effect of non-linearity are SRS (stimulated Raman scattering), SBS (stimulated brillouin scattering), SPM (self-phase modulation), XPM (cross-phase modulation), FWM (four wave mixing), and intermodulation. It appeared in undersea installation. It limits the amount of data transmitted on single optical fiber [1].

The change in refractive index of the medium with change in optical intensity nonlinearity occurs. Linear and nonlinear is two type of term. Linear means intensity independent and nonlinear means intensity dependent. The refractive index is depend on power hence it produce Kerr-effect. In response of electric field refractive index changes this phenomenon is called Kerr effect.

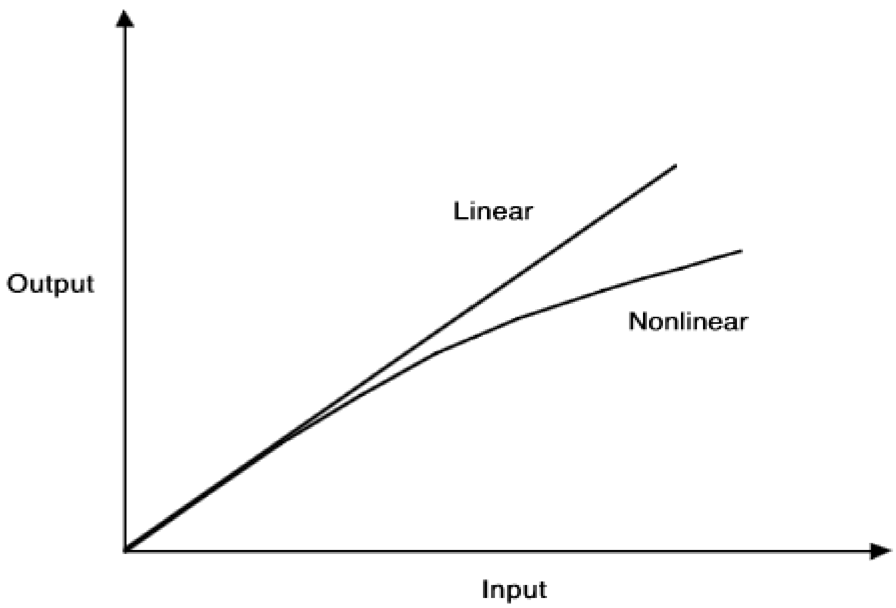

Figure 2.1 Interactions of linear and nonlinear

SPM and CPM cause spectral broadening and effect the phase only hence dispersion occurs. All nonlinear provide increased number of channel with the cost of depleting power except SPM and CPM. High threshold Power lead to scattering effect such as SRS [4, 5, 8, 9].

Difference between SRS and SBS are:-

1. SRS generated optical phonon are incoherent while SBS generated acoustic phonon are coherent.
2. SRS threshold is close to 1 watt which is 100 times higher than SBS threshold.
3. Scattered light shifted in frequency is 13 THz in SRS while in SBS is 10 GHz. Hence frequency shift is maximum in SRS.
4. SRS is much less problem than SBS.
5. SRS bandwidth is 572 m W and in SBS bandwidth is narrow i.e. 1.289 m W.

Table1 1.1

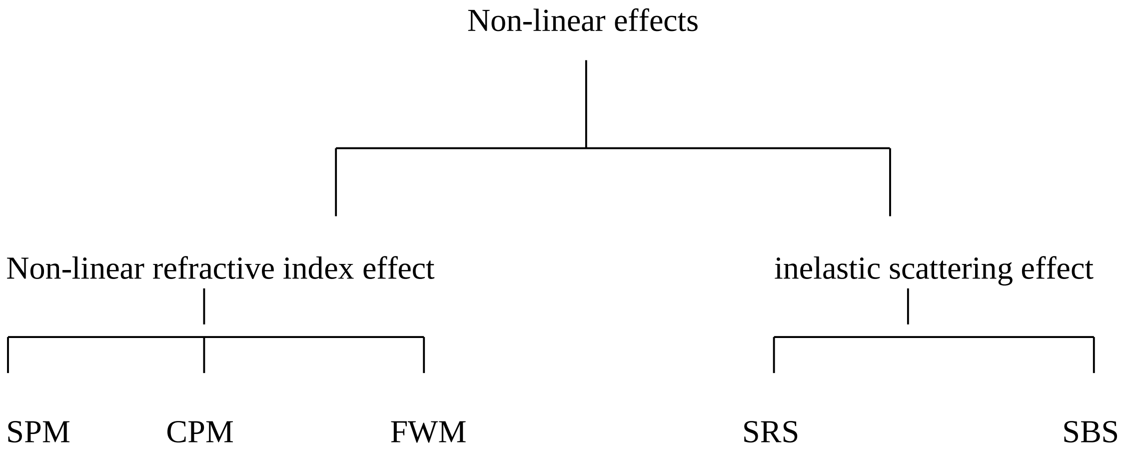

Table 1.1 Types of nonlinear effects

2.1 Basics of Nonlinearity

For intense electromagnetic interference device is sensitive called susceptibility and at this field dielectric medium is like non-linear. At this field there is harmonic motion in electron. Due this motion polarization is obtain and expressed by general expression such as:

$$P = \varepsilon_0 \chi^1 E + \varepsilon_0 \chi^2 E + \varepsilon_0 \chi^3 E \ldots.. \quad (2.1)$$

χ^1,χ^2, χ^3 ... ... is first order susceptibility, 2nd order susceptibility, 3rd order susceptibility and so on. For symmetric molecule χ^2 is vanishing. For electric and magnetic dipole second order non-linear effect is weak hence it is clear to say that in this type of optical fiber second order nonlinear effect is not possible. Lowest order nonlinear effects occur in 3rd order susceptibility [5].

$$E = E_0 \cos(\omega t - kZ) \tag{2.2}$$

Using trigonometric formulas P becomes

$$P = \frac{1}{2}\varepsilon_0\chi^2E^2 + \varepsilon_0\chi^1 + \frac{3}{4}\chi^3E^2\cos^2(\omega t - kZ) + \frac{1}{2}\varepsilon_0\chi^2E_0^2\cos 2(\omega t - kZ) + \frac{1}{4}\varepsilon_0\chi^3E_0^3\cos 3(\omega t - kZ) + \cdots \dots. \tag{2.3}$$

ω is known as fundamental harmonics of polarization. 2ω is second order harmonics of polarization, 3ω is third order harmonics of polarization. χ^2 Is vanishes hence equation (2.3) becomes

$$P = \varepsilon_0\chi^1E_0\cos(\omega t - kZ) + \frac{3}{4}\varepsilon_0\chi^3E_0^3\cos(\omega t - kZ) \tag{2.4}$$

The term 1 is linear and term 2 is non-linear in equation (2.4). Intensity (I) is defined as:

$$\mathrm{I} = \frac{1}{2c\varepsilon_0 n E_0^2} \tag{2.5}$$

From equation (2.5) equation (2.4) become

$$P = \varepsilon_0\chi^1E_0\cos(\omega t - kZ) + \frac{3}{4}\frac{\chi^3}{c\varepsilon_0 n_1}E_0^3\cos(\omega t - kZ) \tag{2.6}$$

Effective susceptibility i.e.

$$\chi_{eff} = \frac{P}{\epsilon_0 E} = \chi^1 + 4\pi|E(\omega)|^2\chi^3 \tag{2.7}$$

Equation (2.5) put in equation (2.7)

$$\chi_{eff} = \chi^1 + \frac{3}{2c\epsilon_0 n_1}\chi^3 I \tag{2.8}$$

Effective refractive index

$$n_{eff} = 1 + 4\pi\chi_{eff} \tag{2.9}$$

Equation (2.8) put in equation (2.9)

$$n_{eff} = \sqrt{1 + \chi^1 + \frac{3}{2c\varepsilon_0 n_1}\chi^3 I} \tag{2.10}$$

$$n_{eff} = n_1 + n_2 I \tag{2.11}$$

$$n_{eff} = n_1 + \frac{3}{4c\varepsilon_0 n_1}\chi^3 I \tag{2.12}$$

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

The change in refractive index is

$$\Delta n = n_2 I \tag{2.13}$$

2.2 Self-phase Modulation (SPM)

Non-linear phase shift results from dependence of refractive index on optical intensity while propagating through fiber. The phase shift (ϕ) is defined as:

$$\phi = \frac{2\pi}{\lambda} nL \tag{2.2.1}$$

Where λ is wavelength, n is refractive index, l is length of the fiber. nL is called optical path length.

SPM modifies only phase shift which is varies with time. In SPM spectrum is changes when pulse propagate through fiber [9]. The frequency spectrum (ω) i.e.

$$\omega = \frac{d\phi}{dt} \tag{2.2.2}$$

In dispersive medium, the new instantaneous frequency becomes

$$\omega' = \omega_0 + \frac{d\phi}{dt} \tag{2.2.3}$$

The refractive index change with intensity hence frequency spectrum is changed. Effective refractive index is defined as n_{eff}

$$n_{eff} = n_1 + n_2\, I \tag{2.2.4}$$

Put above equation in (2.2.1) and $L = L_{eff}$

$$\phi = \frac{2\pi}{\lambda}(n_1 + n_2 I)L_{eff} \tag{2.2.5}$$

From equation (2.2.5) is clear that ϕ depend on I.

Phase shift in SPM is negative hence

$$\omega' = \omega_0 - \frac{2\pi}{\lambda}L_{eff}(n_1 + n_2 I)\frac{dI}{dt} \tag{2.2.6}$$

The leading edge of pulse $\frac{dI}{dt} > 0$ so

$\omega' = \omega - \omega(t)$

Trailing edge $\frac{dI}{dt} < 0$ so

$\omega' = \omega + \omega(t)$

The leading or trailing edge of pulse leads to pulse chirped this type of chirping results to spectral broadening.

For Gaussian pulse, the I (t) and $\frac{dI}{dt}$ variation is shown in figure 2.2 and 2.3 [15].

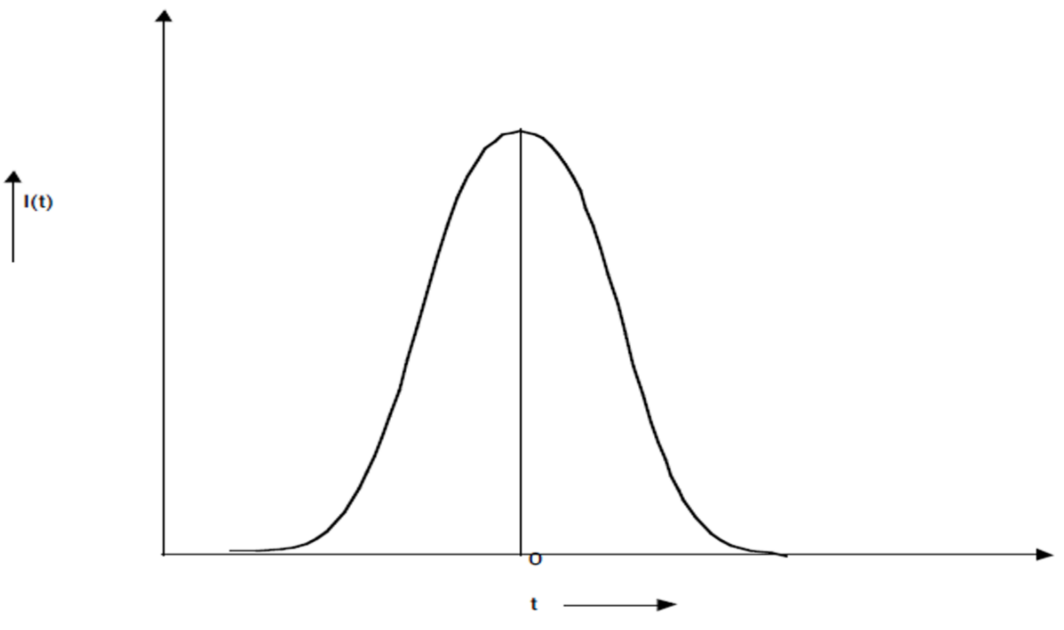

Figure 2.2 Intensity varying with time

With time I is varied, this increase the size of frequency spectrum hence pulse broadening occur. This type of broadening is called dispersion. The spectrum depends upon input and shape of the pulse. The chirp induced by SPM modifies the dispersion.

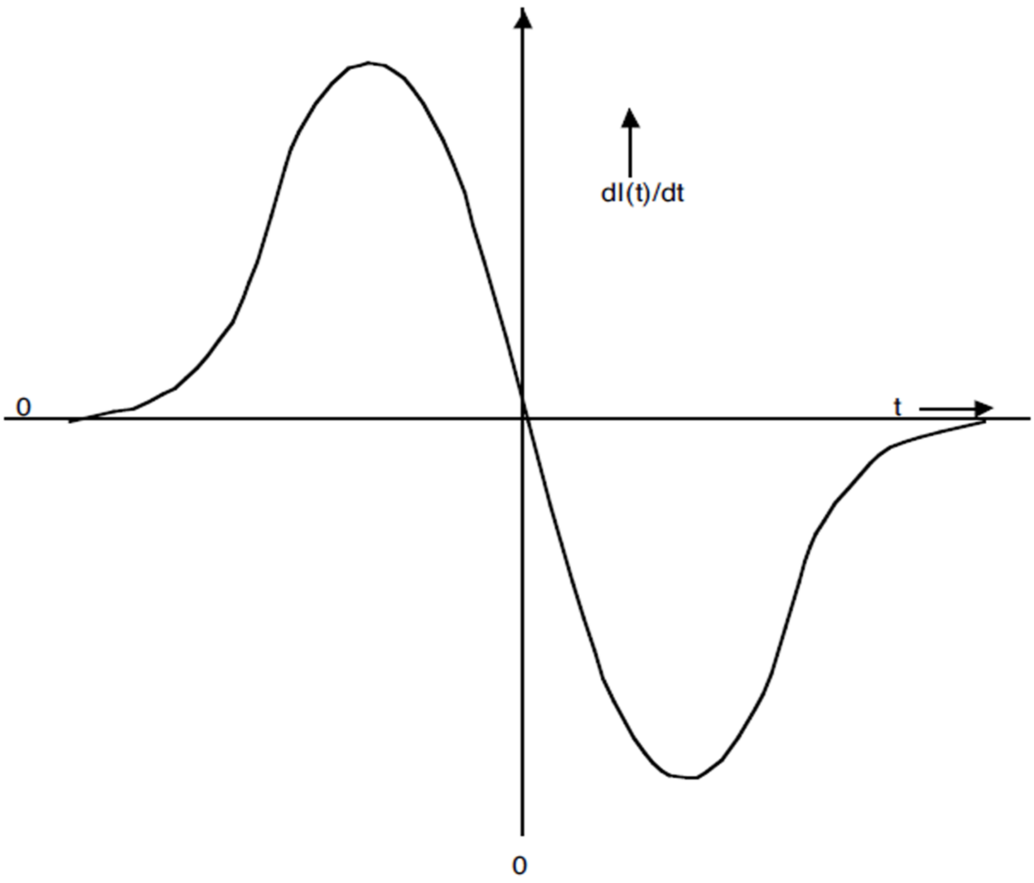

Figure 2.3 $\frac{dI}{dt}$ is varying as function of time

SPM changes phase only, the changed phase depends only upon its own pulse shape.

Disadvantages

- SPM degrade the performance of light-wave system. The modulation instability produces noise.

Advantages

- Ultra-short pulses are produced at high repetition rate. Modulation instability is defined as when two continuous wave travel with different velocity.

Applications

- Optical switching, pulse compression, pulse chirping, passive mode locking, all optical regeneration for WDM channel.

The combination of SPM and anomalous GVD called soliton. Anomalous pulse is defined as index of refraction decrease with angular frequency. Soliton preserve the shape of the pulse.

When $L_{NL} = L_D$ it balance the dispersive and nonlinear effects. Where nonlinear length $L_{NL} = \frac{1}{\gamma P_0}$ and dispersion length$L_D = T_0^2/|\beta_2|$. For$\beta_2 < 0$, the continuous wave is unstable.

Long fibers and high peak power is needed for optical switching.

2.3 Cross phase Modulation (XPM)

SPM limit to single channel but XPM uses two channel. The intensity of one beam change the phase of other co-propagating beam called XPM [13]. The two pulse propagating side by side the intensity of first beam change the refractive index of co-propagating beam.

CPM cause asymmetric spectral broadening and it distort the pulse shape. Asymmetric means it convert the power of one channel into phase fluctuation in other channel.

$$n_{eff} = n_1 + n_2 \frac{P}{A_{eff}} \tag{2.3.1}$$

Nonlinear effect depends on ratio of area and power. Propagation constant (k) depend on power. Propagation constant defined as:

$$k_{eff} = k_1 + k_2 P/A_{eff} \tag{2.3.2}$$

k_1 And k_2 are the linear and nonlinear propagation constant, A is core area, P is power.

Phase shift caused by nonlinear propagation constant is defined as

$$\phi_{n_2} = \int_0^L \left(k_{eff} - k_1\right) dZ \tag{2.3.3}$$

Using (2.3.2) in equation (2.3.3)

$$\phi_{n_2} = k n_2 P_{in} L_{eff} \tag{2.3.4}$$

In two pulse propagation $\phi_{n_2'}$ is nonlinear phase shift of first channel depend on power. $\phi_{n_2'}$ is defined as

$$\phi_{n_2'} = k_{n_2} L_{eff}(P_1 + 2P_2) \tag{2.3.5}$$

For i^{th} channel

$$\phi_{n_2'} = k_{n_2} L_{eff}(P_1 + 2\sum_{n\neq i}^{N} P_n) \tag{2.3.6}$$

Same power as in SPM, CPM is twice effective than SPM. CPM is effective when one signal impose to other signal in time [5].

Disadvantages

1. Inter-channel crosstalk in WDM System
2. Produce timing jitter and amplitude

Advantages

1. Nonlinear pulse compression
2. De-multiplexing of OTDM channel
3. Passive mode locking: approximated 100 fs pulses is produce
4. Ultrafast switching: long fiber needed and mach-zehnder is used for switching, switching time is greater than 1 ps.
5. Wavelength conversion of WDM channel

CPM is degrading the performance of system more than SPM. For larger channel CPM adversely affect the system. Power limit in CPM is 0.1 mw per channel for 100 channels.

2.4 Four Wave Mixing (FWM)

Interaction between two wavelengths produces two extra wavelengths. Let $\lambda_1, \lambda_2, \lambda_3$ are the three wavelengths the sum of their wavelength produce fourth wavelength.

$$f_{FWM} = f_i + f_j + f_k \tag{2.4.1}$$

Number of side band M is defined as

$$M = \frac{1}{2}(N_{Ch}^3 - N_{Ch}^2) \tag{2.4.2}$$

FWM efficiency can be expressed as

$$n \propto \left[\frac{n_2}{A_{eff} D (\Delta\lambda)^2}\right]^2 \tag{2.4.3}$$

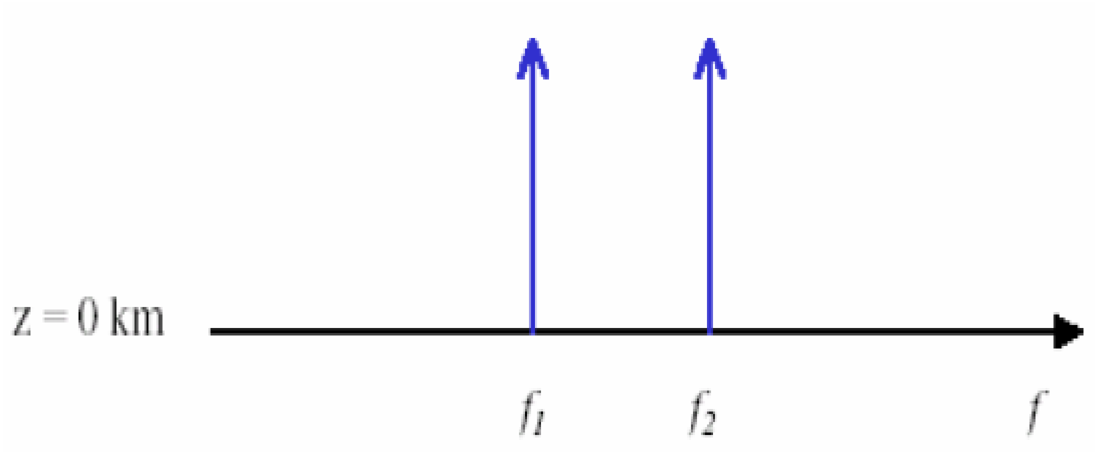

Figure 2.4 f_1 and f_2 are put inside the fiber

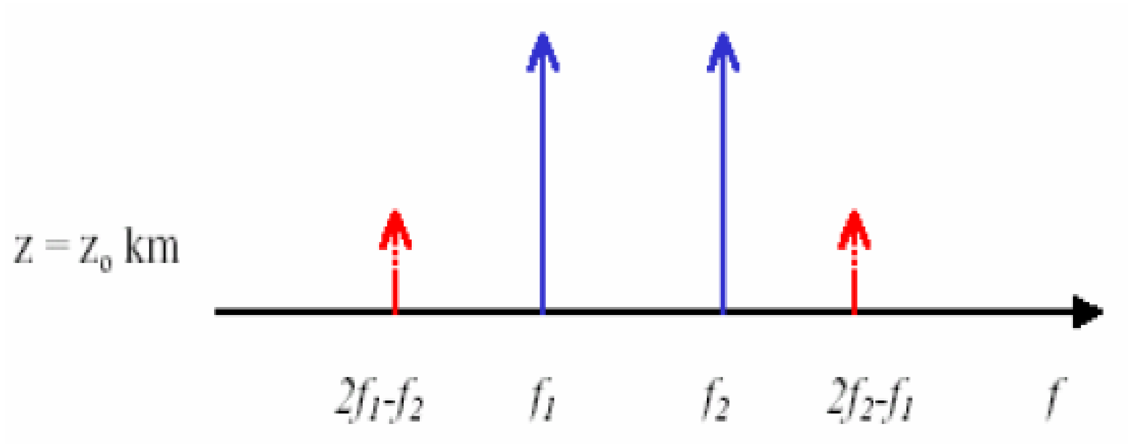

Figure 2.5 Generation of side band

It is clear from equation (2.4.3) that by increasing channel spacing or dispersion FWM is suppressed.

High power penalties occur for high dispersion. Hence system is design carefully.

2.5 Scattering nonlinearities

Inelastic phenomenon is defined as some of the energy loses. Energy transfer from lower to higher is called pump wave and energy transfer from higher to lower be called stokes wave. Two nonlinear effects are SRS and SBS. SRS generated optical phonon and SBS generated acoustic phonon. In SRS frequency shift occur in forward or backward direction but in SBS frequency shift occur in backward.

2.5.1 Stimulated Brillouin Scattering (SBS)

Thermal generation in medium is responsible for scattering of light. Light is scattered from non-propagating component. The energy is transmitted back when transmitted energy is greater than threshold power. At larger intensity SBS occur. For high speed transmission it is necessary to control SBS. Threshold power is defined as at which nonlinear effects occur. For SBS threshold level is approximately 1mw. Effect of SBS is shown in figure 2.6

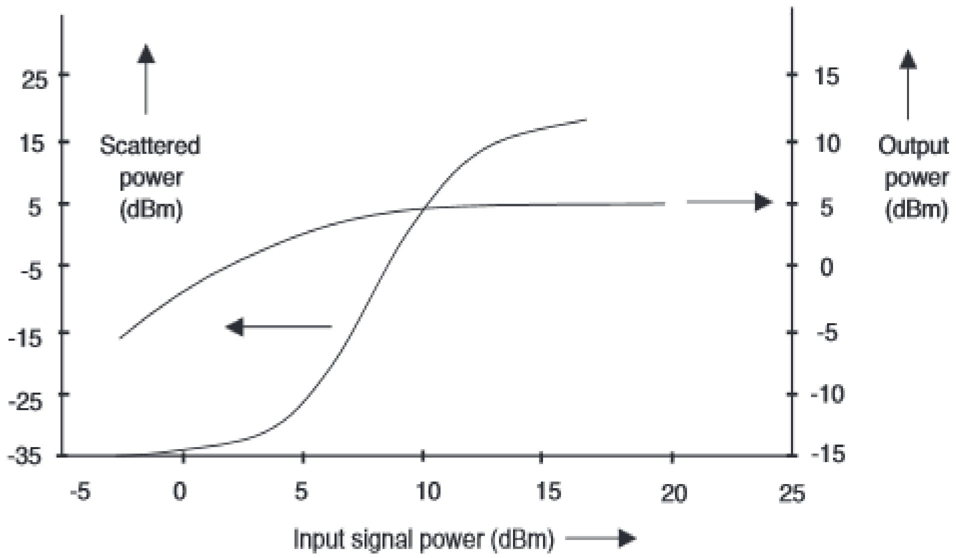

Figure 2.6 SBS effect when threshold is reached

When the transmitted power is low than threshold power, the transmitted power is linearly increases. Transmitted power become constant when threshold is reached or transmitted power is not depends on input power [25].

Some of power is needed at transmitter in absence of nonlinear effect to maintain the same BER. There is many ways to reduce power penalty i.e.

1. Power level is below the SBS threshold. Amplifier spacing is reduced in long haul system.

2. By increasing linewidth decrease the small gain of bandwidth. By chirping effect linewidth is increased, Dispersion is introduced by this. Hence dispersion management is applied to reduce dispersion penalty.

SBS threshold is decreased by adding EDFA. Optical spectrum with phase modulation is shown in figure 2.7 in this figure central carrier is above the threshold it degrade the performance of the system.

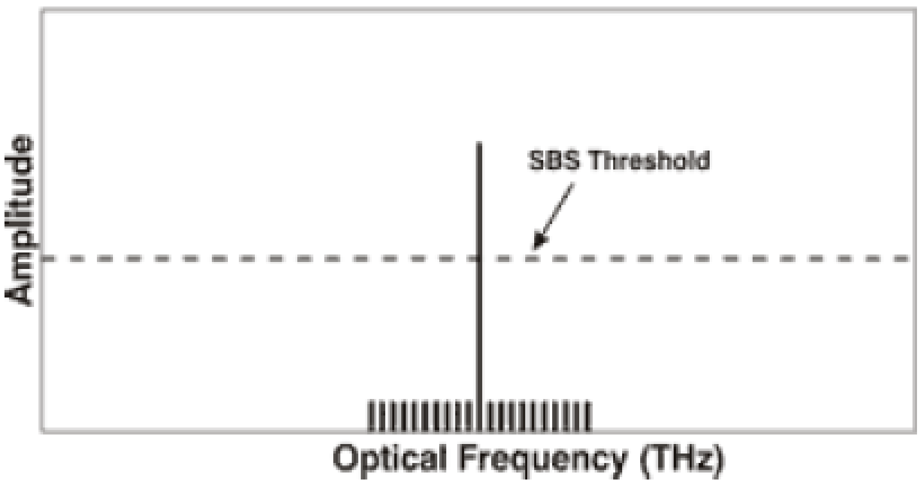

Figure 2.7 without phase modulation optical spectrums

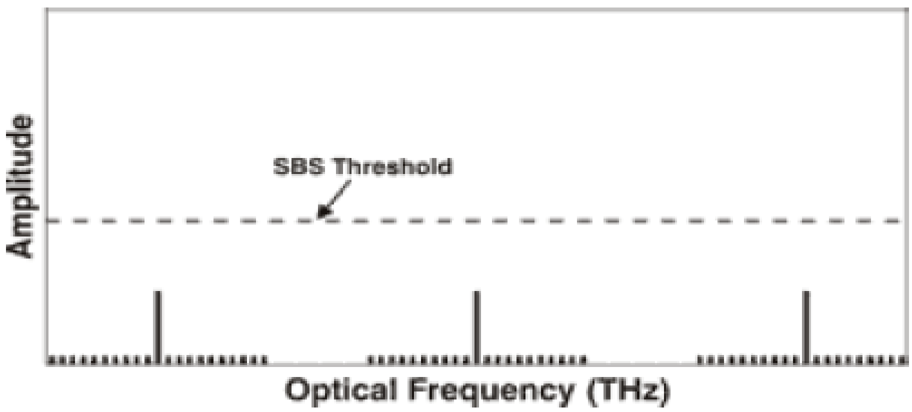

Figure 2.8 with phase modulation optical spectrum

Figure 2.8 shows optical spectrum with phase modulation [25]. The figure shows that the entire signal is below the SBS threshold. It increases SBS power by 10 dB [25].

Applications of SBS

1. **Fiber sensor:** it sense temperature and strain. Refractive index change with change with temperature, results in brillouin shift. This shift sense the temperature change over long distance hence called distributed fiber sensor.

2. **Brillouin fiber amplifier**: it amplifies the weak signal. Frequency shift of weak signal is occurring from pump frequency because of narrow bandwidth. Brillouin fiber amplifier is not suitable for in line amplifier or power amplifier but it is useful in coherent and multichannel communication. It generate for short fiber.

3. **Beam combiner:** beam combiner combines the long multimode fiber or it increases the brightness of the fiber.

4. **Pulse delaying and advancement:** control GVD

5. **Pipelining bucking detection**

2.5.2 Stimulated Raman scattering (SRS)

It generate optical phonons when light is incident the light is scattered some of loses their energy or gain energy. SRS compared with SBS, SRS have much less problem than SBS. The threshold power is close to 1W.

Figure 2.8 shows transmitted spectrum of six channel DWDM systems. Figure shows amplitude is same for six channels. The transmission window used is at 1550nm. Figure 2.9 shows SRS effect. From this figure it is clear that short wavelength have low power and longer wavelength have high power it is called SRS effect. Brillouin gain bandwidth is narrow in comparison of Raman gain bandwidth [28].

Difference between Kerr effect and nonlinearity is that in Kerr elastic scattering occur means no energy transfer occur but in nonlinearity in elastic scattering occur where energy transfer occur from higher to lower or lower to higher. No population inversion is possible in Kerr effect. The main difference between SRS and SBS is that SBS is limited to single channel but SRS have no limitation for single light-wave system.

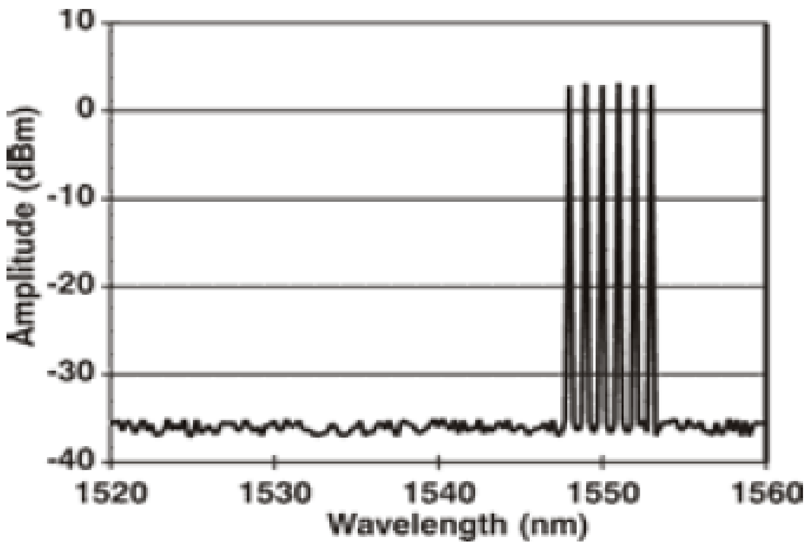

Figure 2.9 Six channel DWDM system optical spectrum

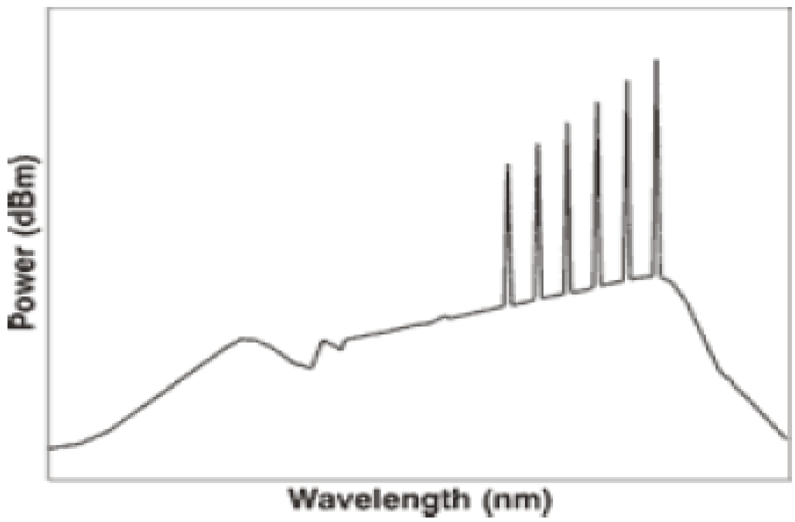

Figure 2.10 SRS effects

Applications of SRS

1. Raman fiber laser
2. Raman fiber amplifier
3. Eye safe laser

Chapter 3

Literature Survey

M Arumugam [1] gives the overviews of fiber optic communication. In this paper the history of optical communication has been discussed. The features and different types of fiber such as step index fiber, graded index fiber, single mode fiber, multimode fiber of optical communication has been discussed. Some aspects of losses in fiber, advantages, total internal reflection, refractive index profile, dispersion and dispersion compensating fiber are mentioned. The limitation of fiber is also mentioned. The soliton pulses are highlighted in optical communication. This paper discusses that how optical pulses are useful for high quality telecommunication at a lower cost.

The book "Nonlinear Fiber Optics" by G. P. Aggarwal provided the mathematical model of nonlinear effects. Types of nonlinear effect such as SPM, XPM, FWM is discussed in brief. The effect of GVD and dispersion induced in fiber and its effect also studied in brief. The scattering effect such as SRS, SBS is discussed in brief. The main point discuss in SRS and SBS is gain, threshold level, frequency shift, advantages, disadvantages and uses.

J. Toulouse [3] proposed the types of nonlinearities and the parameters. This parameter varied to determine the nonlinear effect. The parameter of SPM, XPM, SRS and SBS is varied and the nonlinear effect also studied. The application of each system is also mentioned.

S. Bigo [4] proposed dispersion management techniques and how power penalty is reduced discussed. The fast growth of the optical fibers the system is more complex to reduce this complexity dispersion management technique is applied it make system less complex and reduction of power penalty. The experiment is worked at 5.12 Tbit/s. in C and L band self-induced distortion and trade of vestigial side band has been discussed.

Haruo Akimaru et. al. [5] proposed the different network services such as telephone, internet, cable TV that contain the broadband highway and also mention the comparison between these different network and also discuss techniques used. Different component used in these networks discussed. In this paper connection modalities, controlling scheme and routing algorithm protocol, quality of service and digital broadcast satellite has been studied.

Neal S. Bergano [7] presented newly installed transoceanic which is very flexible and have a large capacity in terabit per second. Large capacity is help in improvement on many WDM transmission techniques. Larger capacity helpful and very important in different areas such as gain equalization, error correcting codes, dispersion management and modulation formats. long haul transmission system used in WDM technologies has been progressed.

A.R Chraplyvy [10] describe in brief SRS limitation to transmitted power in WDM system. In this paper general expression of transmitted power and its limitation due to SRS in WDM system. Two cases where maximum transmitted power per channel has been discussed. The general expression provides roughly constant channel separation in WDM system.

Ivan B. Djordjevic [12] present simple expression of transmission limitation of WDM was derived. In line optical amplifier is also applied.in the presence of ASE noise two nonlinear FWM and SRS are considered. Different parameters are applied and find one that increase the transmission distance. Different parameters are number of channel, spacing and bandwidth. Optimum spacing in two important nonlinear FWM and SRS in ASE noise which maximize the transmission distance. Different configuration of dispersion compensating fiber is discussed. The transmission distance is depend on bit rate are mentioned and optimum spacing is independent on bit rate.

N. Kikuchi, K. Sekine and S. Sasaki [13] proposed a paper that describe by using simulation and experiments derived the effect of CPM on WDM transmission performance. The authors also analyze the effect of dispersion compensation on XPM. By dispersion compensation technique XPM degradation affected strongly. Along transmission large Dispersion variation occurs.

S. P. Singh et. al. [15] described the basics of nonlinear effects, types of nonlinear effect which degrade the performance of system and comparison between different nonlinear effects such as SPM (Self phase modulation), XPM (Cross phase modulation) and FWM (four wave mixing). In FWM dispersion shifted fiber is applied because effect of FWM is reduced if dispersion is present. Applications and threshold management also mentioned in this paper. If power is below 19.6mw SPM effect is negligible.

Jia Lu et. al [16] gave a paper about theoretical and experimental expression of polarization insensitive signal used orthogonal signal pump four-wave mixing (FWM) in nonlinearities optical fiber. Power penalty of 2.5 Gb/s OOK intensity and 10Gb/s for DPSK are less than 0.5 and 0.8 dB occur after wavelength conversion used 1 km distance. High nonlinear optical fiber is polarization insensitivity. In this paper 3 polarization multiplexing is generated, two is polarization sensitive and one insensitive.

Gurmeet Kaur [17] presented a work about combination of SRS and FWM in ASE (amplifier spontaneous noise) noise produce optimized inter-channel separation. In the presence of ASE minimum noise is achieved. Two advantages of WDM system is enhanced capacity and flexible optical networks. Without the use of electrical regenerator transmission is possible for long distance by using EDFA (erbium doped fiber amplifier). Effect of SRS, ASE and FWM on transmitted power has been discussed. In this paper an algorithm for optimization of inter-channel separation has been discussed. Transmission distance depends on different parameter such as number of channels, channel spacing, fiber length and amplifier spacing. By varying this parameter maximum transmission distance is calculated.

Andrew R. Chraplyvy [18] in this paper light-wave limitation has been discussed. The nonlinearities degrade the performance of light-wave system. FWM, SRS, SBS nonlinearities are discussed here and discuss which one is least likely affect light-wave system or degrade the performance of light-wave system. SRS least likely affect light-wave system is concluded in this paper. Maximum power per channel plotted as function of number of channels. This paper concluded that if the transmitted power in long haul system is exceeded 10mw will degrade the system performance.

R. W. Tkach et. al [19] presented a work about FPM and use of high bit rates. High bit rate in dispersion shifted fiber to reduce penalties of dispersion. Wavelength multiplexing is used in optical amplifiers, it increase system capacity. if these two method are used together what is effect due to nonlinearities occur in system. FPM put some limitation on wavelength multiplexed that operates in fiber with low chromatic dispersion.

S. P. Singh, et. al [21] this paper describe about Four-wave mixing (FWM) i.e. using dispersion shifting fiber. By using dispersion shifting fiber effect of FWM is reduced. FWM effect is reduced by placing signal unequally spaced frequencies, it lead to increase the bandwidth. With lesser number of FWM component better bandwidth is obtained.

Masahiro daikoku et al [22], presented a work about combination of SPM and XAM effect with 3R regenerator. At signal rate of 40 Gb/s performance of 3R regenerators is investigated. 3R regenerators provided 3 dB improvement of Q-factor.3R regenerator chromatic dispersion tolerance is also discussed. Chromatic dispersion tolerance increases twice by introducing pre-distortion block. Among all optical network 3R regenerators are strong candidates.

M. N. Peterson et. al. [23] describes the dispersion monitoring technique by applying wavelength conversion. This paper concludes that after or before wavelength conversion 40 Gbit/s NRZ signal of dispersion are monitored. This paper has been demonstrated wavelength conversion and subcarrier monitoring.

C. A. Brackett [24] presented architectural of different networks, device technologies, network layers, issues, benefits and advantages. The proposed architecture uses both optical and electronics technologies which is independent of number of wavelength and nodes. This type of architecture introduces true scalability and modularity high density WDM, wavelength routing and wavelength selection switching are the different approached for network architecture. Different technologies are described in this paper are OEIC receiver, subcarrier multiplexing. Architecture focus on routing algorithm, controlling algorithm and throughput.

Roger M. stolen and Anthony M. Johnson [26] proposed the SRS power different fiber length.in this paper in single mode fiber SRS is experimentally investigated. SRS threshold directly depend on area and length of the fiber. Raman stoke pulse is produced within first 3-4 periods for large pulse walk off. Pulse of same duration as the input pulse raman produced about 2 walk of length for 20 percent conversion. For large Raman stokes effect of GVD are discussed. By using Nd : YAG laser 36 ps duration pulses at 532nm are produced. In this paper also mentioned that Strong frequency chirp is produced by Raman pulses.

D. N. Christodoulides and R. B. Jander [27] proposed a stimulated Raman cross talk in single mode fiber, also proposed triangular approximation. The expression of raman crosstalk has been mentioned in this paper. Crosstalk limits the small inter-channel power exchange. To detect the Raman gain spectrum triangular approximation technique is used. For multi-wavelength fiber Raman penalty is also predicted in this paper.

Z. Zirngib [28] studied a model of WDM system including the effect of stimulated Raman scattering (SRS). The gain saturation effect also described.in SRS spectral distortion occur and depend not only power distribution but also total input power. For input power distribution this model gives the solution and gives gain saturation effect.

Sanjeev Kumar Raghuwanshi and Srinivas Talabattula [29] proposed effect of GVD on SRS by applying different modulation technique. To solve the nonlinear Raman gain equation finite difference time domain method is used. In case of DWDM pulse walk off phenomenon asymmetrically distort the data. In DWDM large pulse walk off reduce the crosstalk. In this paper numerical technique of channel addition and removal is discussed. The main problem in pulse phenomenon is that pulse distorted continuously, data may be lost.

X. Zhang et. al. [30] studied expression of input power limit and capacity. In this paper maximum capacity is calculated at different input power due to SRS effect. Only considering effect of SRS intensity of WDM light wave system are calculated. A new version of input power and maximum capacity expression are derived.

S. Bigo et. al. [31] presented a paper about 32 multiplex channels and also describes power distribution of 32 multiplex. In this paper Raman gain coefficient is calculated and impact of SRS on power distribution is also mentioned.

Chapter 4

Proposed Work

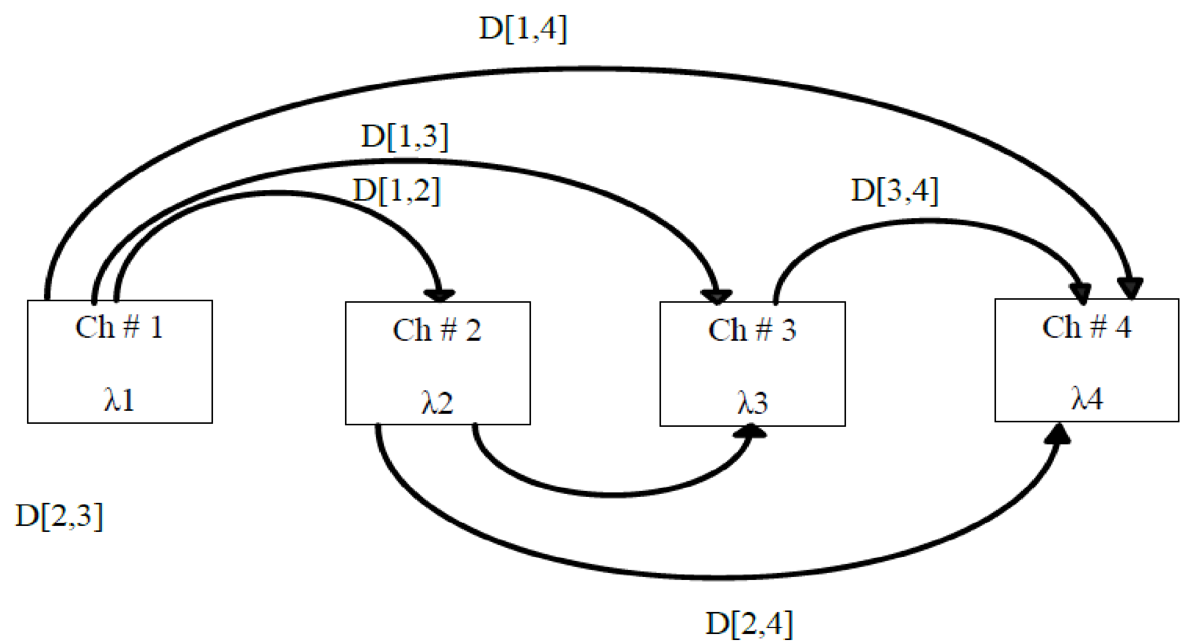

Figure 4.1 Power Transfer among different channel due to SRS

Figure 4.1 shows the model of power transfer among different wavelength channel. Figure shows four wavelength channel i.e. $\lambda_1, \lambda_2, \lambda_3$ and λ_4. λ_1 act as pump wave because of short wavelength and λ_4 act as stokes because of longer wavelength. The power transfer among three co-propagating wavelength channel is considered by the equation as:

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

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

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

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

$P_T[i]$ is transmitted power, $P_M[i]$ is modified power in the i^{th} channel where i=1,2,3,4. i=1means lowest wavelength channel with λ_1 center frequency.

$P_T\ [j]$ is Power launched in the j^{th} channel. By combining above equation in one form or modified power is defined as:

$$P_M[k] = P_T[k] - P_T[k]\sum_{i=k+1}^{N} D[k,i] + \sum_{j=1}^{k-1} P_T[j]D[j,k] \qquad (4.5)$$

Where D [k, i] =0 For $i > N$ and D [j, k]=0 for k=1

$P_T[k]\sum_{i=k+1}^{N} D[k,i]$ is optical launched power by higher wavelength and $\sum_{j=1}^{k-1} P_T[j]D[j,k]$ is optical power launched by lower wavelength.

At receiver side power received is defined by equation as:

$$P_R[k] = P_M[k] \times exp\{-\alpha(\lambda_k) \times L\} \qquad (4.6)$$

$D[i,j]$ is power depleted in i^{th} by j^{th} channel. For j>i means j channel is greater wavelength than i channel.

$$D[i,j] = \left(\frac{\lambda_j}{\lambda_i}\right) P_T[j]\{(f_i - f_j)/1.5 \times 10^{13}\} g_{R\,max} \times \{\left(L_e(\lambda_j) \times 10^5\right)/(b.A_e)\}$$

for $(f_i - f_j) \leq 1.5 \times 10^{13}$ Hz and $j > i$ (4.7)

$$D[i,j] = 0 \text{ for } (f_i - f_j) > 1.5 \times 10^{13} \text{ Hz and } j \leq i \qquad (4.8)$$

$g_{R\,max}$ is maximum gain, A_e is effective area of the fiber, $f_1\ and\ f_2$ are the center frequencies, $\lambda_i\ and\ \lambda_j$ are the wavelength in i^{th} and j^{th} channel. b=1,2 is depend on polarization state, here b=2 for scrambled polarization [10].

L is fiber length, $L_e(\lambda_j)$ is effective length which is depend on wavelength i.e. λ_j. $L_e(\lambda_j)$ is defined as:

$$L_e(\lambda_j) = \left\{1 - \exp\left[-\frac{\alpha(\lambda_j)L}{4.343}\right]\right\}[4.343/\alpha(\lambda_J)] \qquad (4.9)$$

$\alpha(\lambda_j)$ is loss coefficient depend on wavelength in dB/km, $\alpha(\lambda_j)$ is calculating by equation (4.10) at 25 nm by taking variation in loss coefficient upto 0.7 dB and L=100 km [31].

$$\alpha(\lambda_j) = \{\alpha_{max} - \lfloor(\lambda_j - \lambda_1)/\Delta_{wdm}\rfloor(\alpha_{max} - \alpha_{min})\}$$

$$\alpha_{max} = \alpha + \alpha_{var}/2$$

$$\alpha_{min} = \alpha - \alpha_{var}/2$$

$$\alpha_{var} = \left(\frac{0.007}{25}\right).\Delta_{wdm} \qquad (4.10)$$

Δ_{wdm} is spectral width and it is difference between shortest wavelength and longest wavelength. $\alpha_{var}$is in dB/km and α is loss coefficient and it varies linearly with wavelength so the 0.007/25 is changed according With equation (4.10). This method help to calculating the spectral distortion induced SRS in DWDM.

4.2 Pulse walk off effect and data formats effect

When the pulse in both the channel overlaps power transfer take place among the propagating channel. Power transfer not occur when pulse walk off completely. Power transfer again start when wavelength channel align. It is explained in figure 4.2

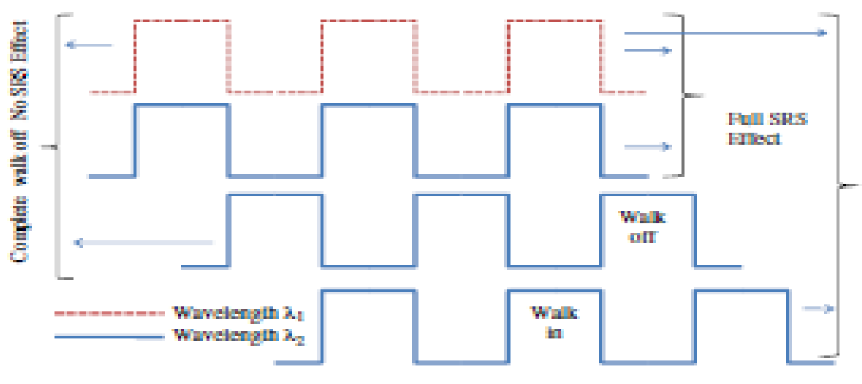

Figure 4.2 Graphical representation Pulse walk off and walk in for two co-propagating wavelength

Length of the fiber decreases because of pulse walk off. Length is function of data rate, dispersion coefficient of the fiber, data formats and inter-channel separation. After walk off completely, the propagation distance is known as walk off length and calculated as:

$$L_{walkoff} = \frac{10^3}{B \times D \times (\lambda_i - \lambda_j) \times 10^9} \quad (4.11)$$

Where D is dispersion coefficient calculated in ps/nm km, B is data rate in Gb/s and $(\lambda_i - \lambda_j)$is the wavelength separation between i^{th} and j^{th} channel. $L_{walkoff}$ calculated in km.

4.2.1 Non Return to Zero Format (NRZ)

For Given Data signal Rate i.e. bit rate. The NRZ require only half bit rate. The baseband bandwidth required by Manchester code is half of the NRZ.

Case:

1. Effective length $L_e$is less than or equal to $L_{Walkoff}$

No change in the L_e because of pulse walk off i.e $L_e = L_{Walkoff}$

2. $L_e > L_{Walkoff}$

Sub-case A. if

$$\frac{L_e}{L_{Walkoff}} = A + R$$

Where r is remainder, A is odd integer other than 1

$$L_e = \left(\frac{A+1}{2}\right) L_{Walkoff} + R$$

For A=1, $L_{e_{new}} = L_{Walkoff}$

Sub-case B. if

$$\frac{L_e}{L_{Walkoff}} = B + R$$

Where B is any even integer

$$L_{e_{new}} = \left(\frac{B}{2}\right) L_{Walkoff} + R$$

4.2.2 Optical Manchester Format

Manchester has transition at middle of each period and has transition at start of period. The direction of mid bit transition indicate data. Transition period boundaries do not carry information. This format is same as NRZ (non-return to zero) format except for the time shift of half bit periods. The occurrence of 1's and 0's the width of the pulse representing 1's in Manchester format is half the width of the pulse representing 1's in NRZ. This factor of 2 is used in the nominator while evaluating $L_{walkoff}$ as given below:

$$L_{walkoff} = \frac{10^3}{2\times B\times D\times(\lambda_i - \lambda_j)\times 10^3} \quad (4.12)$$

4.2.3 RZ (Return To Zero) Format

$L_{walkoff}$ will be calculated by using equation eq. (4.12)

Because pulse representing '1' in RZ format is half the width of pulse representing '1' in NRZ.

Case 1. When $L_e < L_{walkoff}$

No changes in the effective length because of pulse walk off i.e. $L_{enew} = L_e$

Case 2. When $L_e > L_{walkoff}$

Sub-case A. if

$$\frac{L_e}{L_{Walkoff}} = A + R$$

Where R is remainder and quotient A is any integer

$$L_e = \left[\left(\frac{A+1}{2}\right) - z\right] L_{Walkoff} + R$$

Where Z=0 for A=1

Z=1 for B= any odd umber other than 1

Sub-case B. if

$$\frac{L_e}{L_{Walkoff}} = B + R$$

Where B is any even integer

$$L_{e_{new}} = \left[\left(\frac{B}{2}\right) - Z\right] L_{Walkoff} + R$$

Z=0 for B=2 or 4.

Z=1 for B= any integer other than 2 or 4.The entire above model become capable of evaluating the SRS effect and pulse walk off effect.

4.3 Simulation Results

Power distributed linearly across the channel. Number of channel directly proportional to slope and inversely proportional to intercept means as number of channel increases intercepts decreases and slope is increases. At transmitter side power is transmitted constant or fixed but according to SRS properties power is linearly distributed. As shown in figure (4.13)

Corrected modulated power = [slope × wavelength + {power + (slope × wavelength of 3rd channel)}] (4.13)

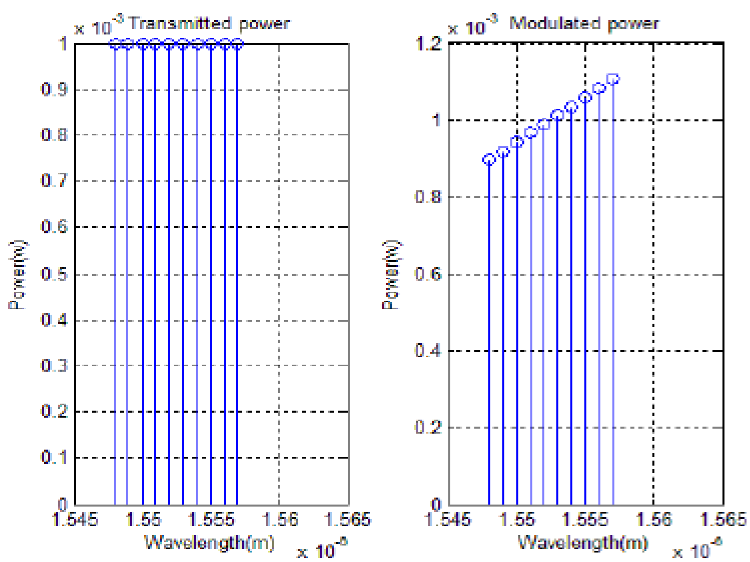

Figure 4.3 Transmitted and modulated power for 10 channels

By the equation (4.13) approximate constant power is obtained across all channels. As shown in figure 4.3

Figure 4.3 shows linearly varying modulated power produced by the constant power due to SRS effect, variation decreases by using eq. (4.13)

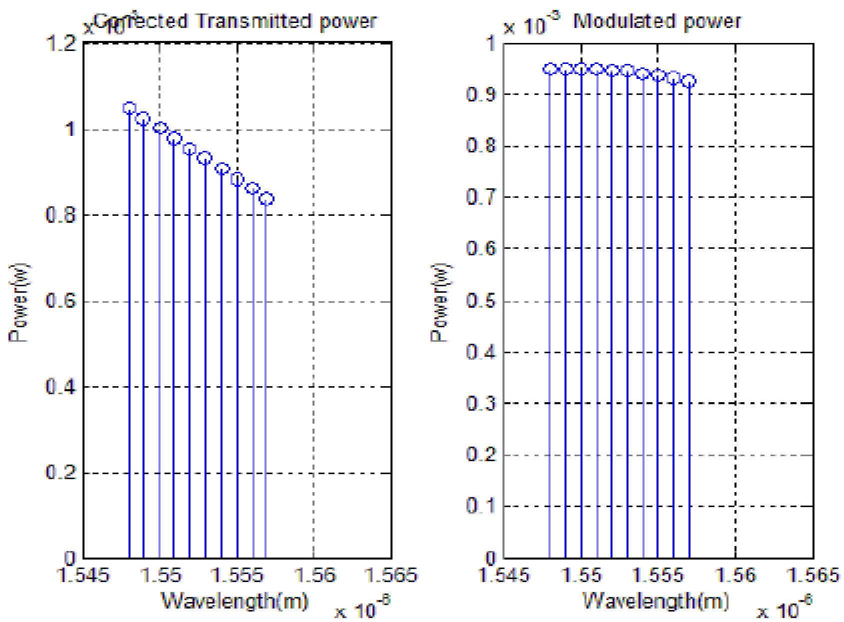

Figure 4.4 Corrected power and modulated power for 10 channels

Figure 4.4 shows if there is no SRS effect modulated power are nearly become constant for 10 channels.

Table 1.2

Power(mw)	Channel length(km)	Amplifier distance(km)	Without pulse walk off rule(no.of channels wavelength)
1mw	2,000	100	20
2mw	2,000	100	16
5mw	2,000	100	10
10mw	2,000	100	8

20mw	2,000	100	6
25mw	2,000	100	5

Table 1.2 maximum no. of channels that can be corrected for a given power

Table 1.2 shows maximum no. of corrected channel by applying algorithm such as:

1. Set the number of channel
2. Calculate modulated power
3. Approximate slope and intercept
4. Set transmitted power
5. Calculated new modulated power

With pulse walk off and data formats

NRZ data format

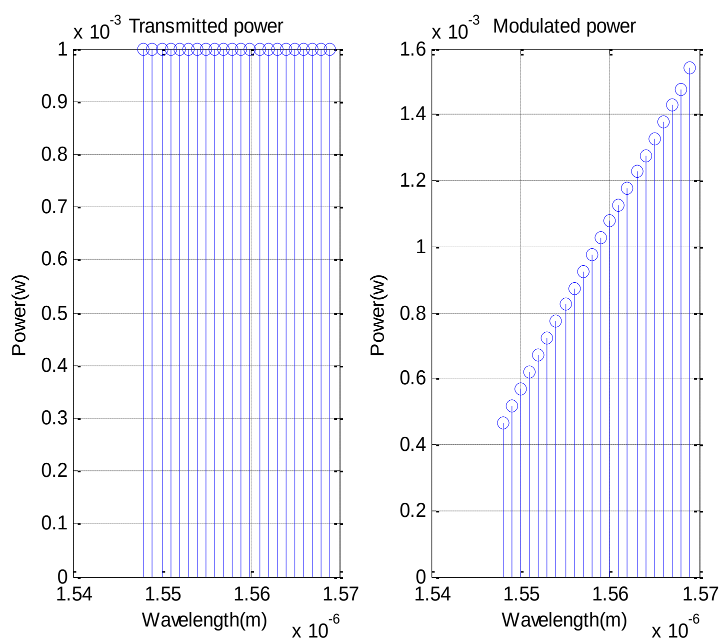

Figure 4.5 Transmitted and modulated power of NRZ for 23 channels at 1 mw power

Walk off distance depend on length and dispersion coefficient.

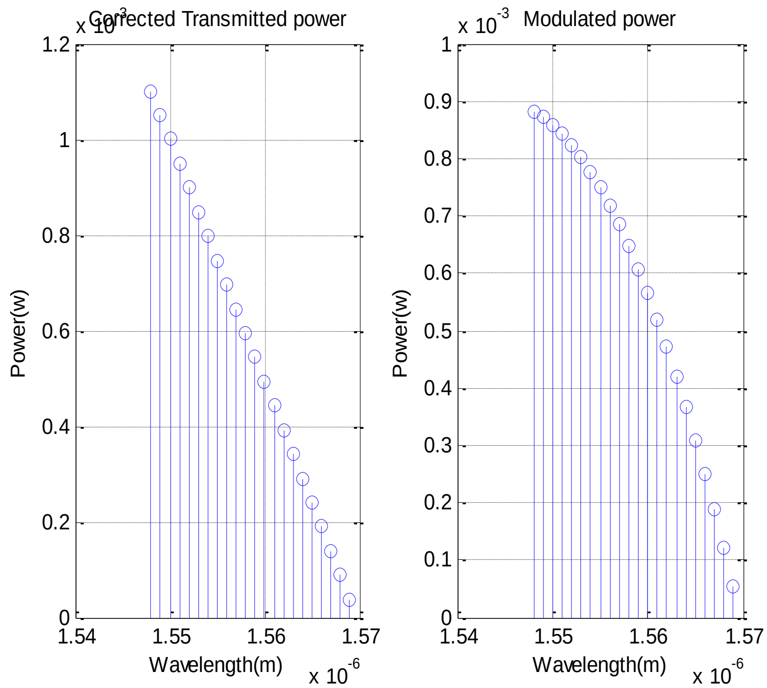

Figure 4.6 Corrected and modulated power of NRZ for 23channel at 1mw power

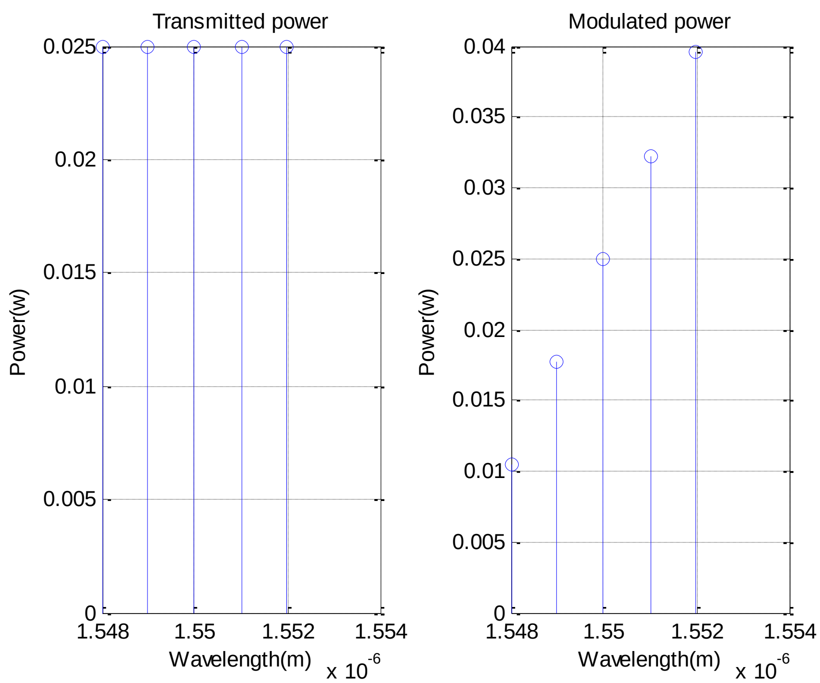

Figure 4.7 Modulated and corrected power of NRZ for 5channel at 25mw power

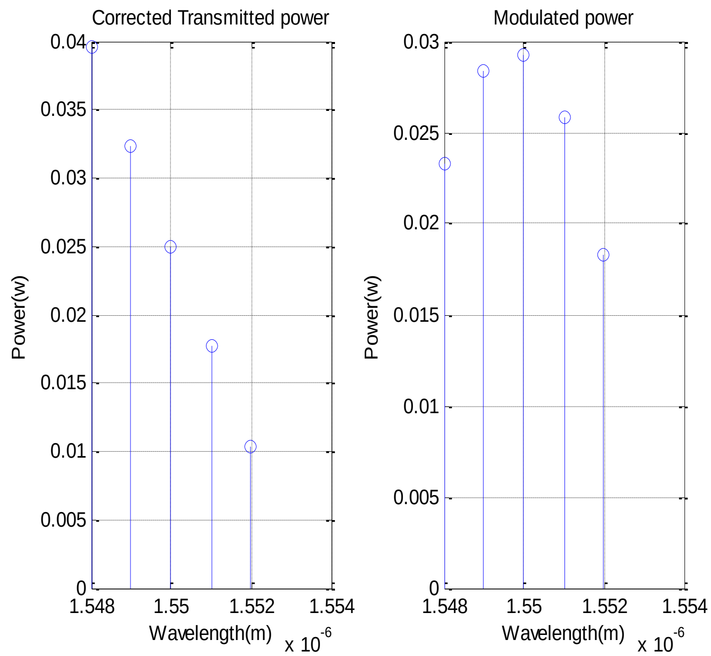

Figure 4.8 Corrected and modulated power of NRZ for 5 channels at 25mw power

Figure 4.5 and 4.6 show transmitted or corrected power for 23 channel. By using equation (4.13) corrected power is calculated for NRZ only 23 channel are corrected at 1mw.

Optical Manchester

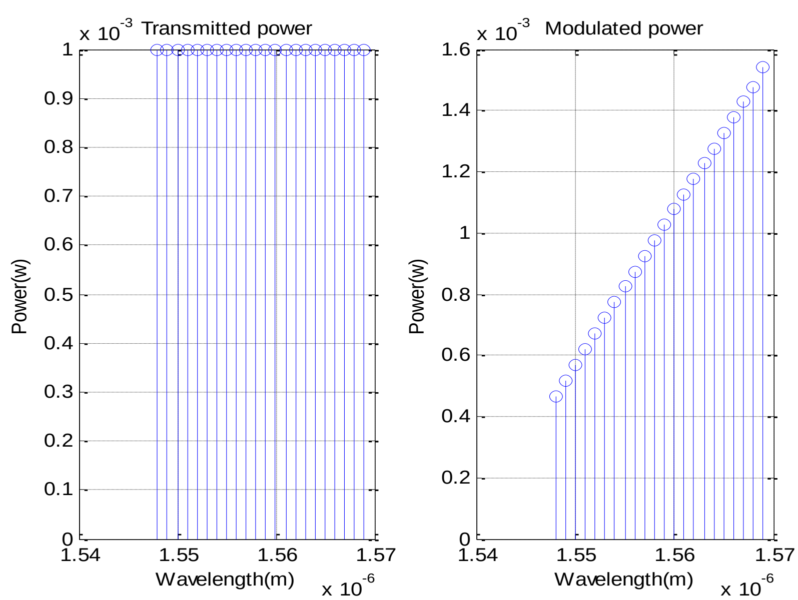

Figure 4.9 Transmitted and modulated power of Optical Manchester for 22 channels at 1mw

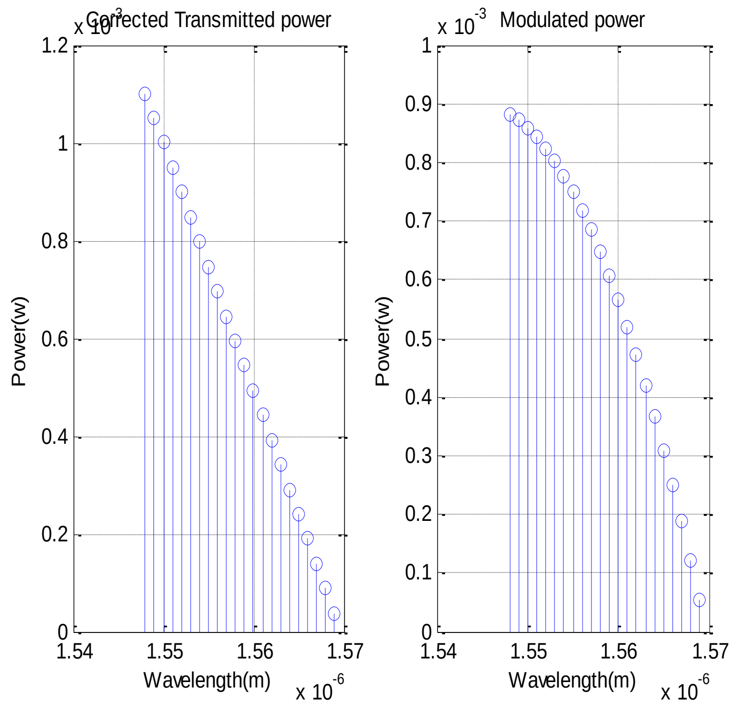

Figure 4.10 Corrected and modulated power of Optical Manchester for 22 channels at 1mw

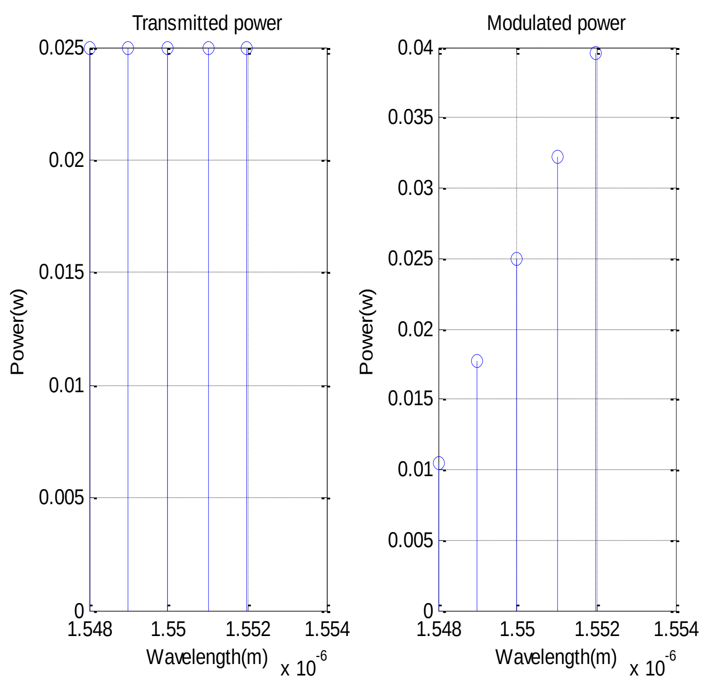

Figure 4.11 Transmitted and modulated power of Optical Manchester for 5 channels at 25mw

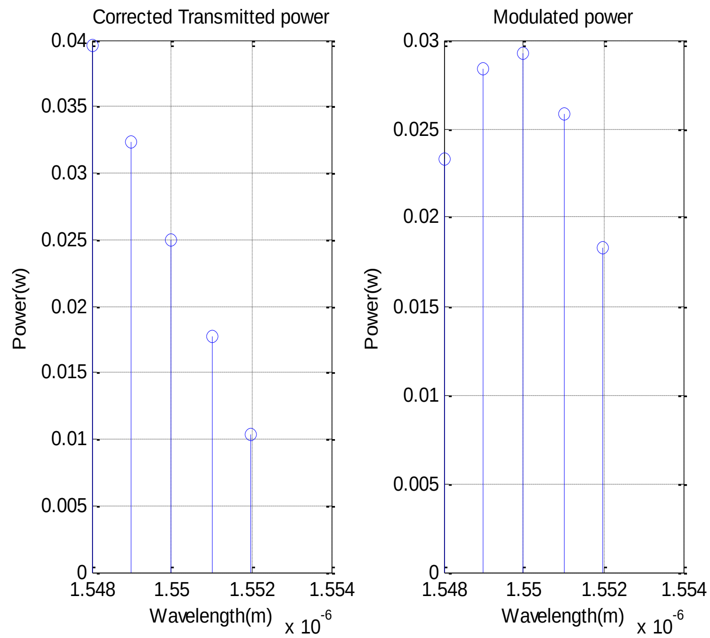

Figure 4.12 Corrected and modulated power of Optical Manchester for 5 channels at 25mw

Channel corrected in optical Manchester is same as that in NRZ but half of the NRZ. Hence there is little change in power tilt.

RZ (Return to zero) data format

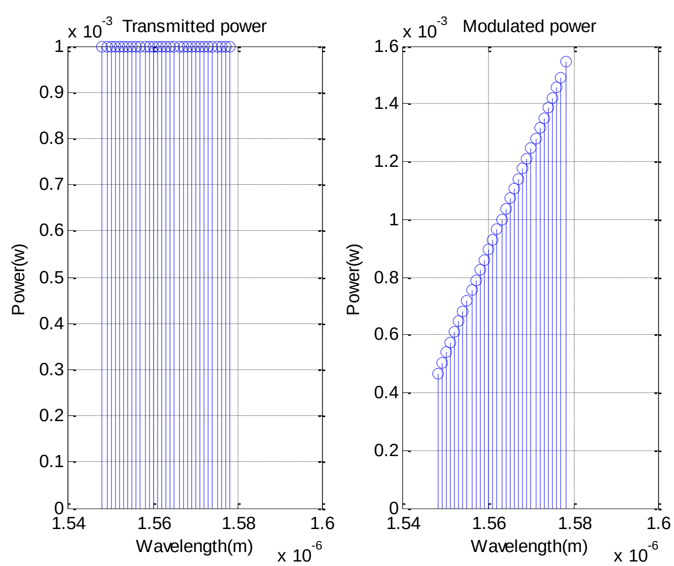

Figure 4.13. Transmitted and modulated power of RZ for 31 channel at 1mw power

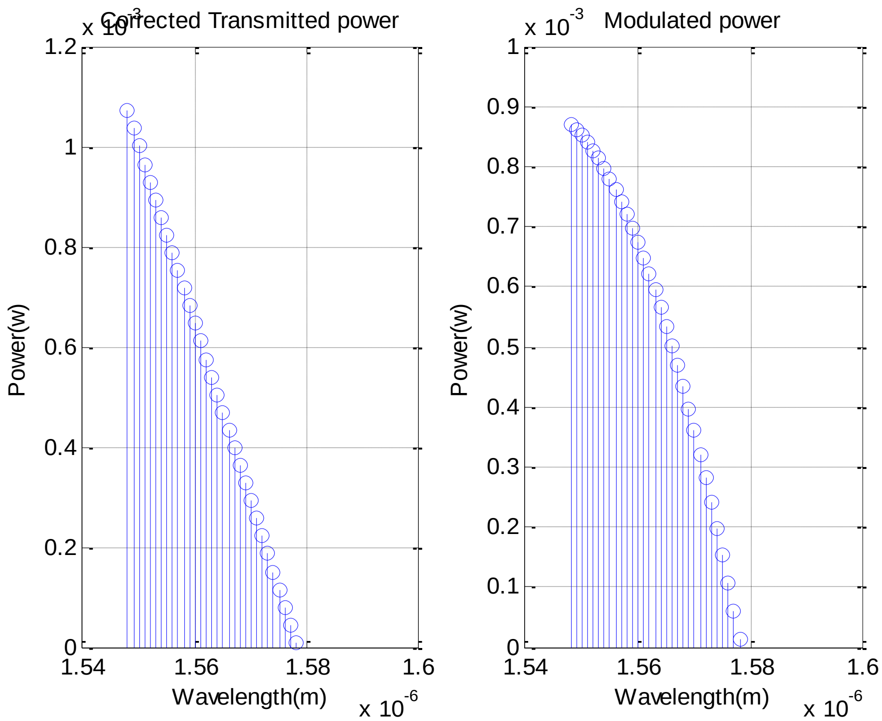

Figure 4.14 Corrected and modulated power of RZ for 31 channels at 1mw power

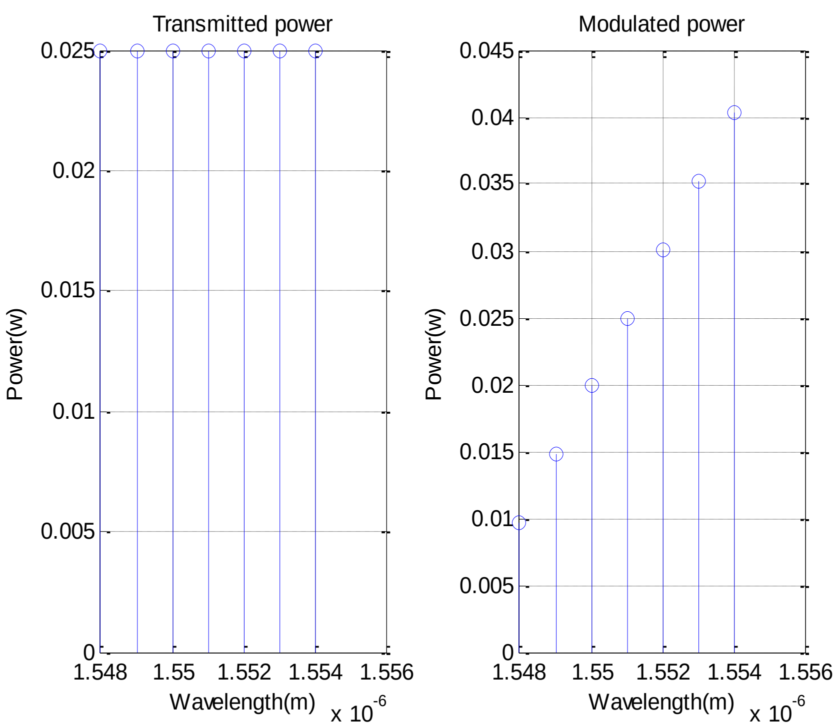

Figure 4.15 transmitted and modulated power of RZ for 5 channels at 25mw power

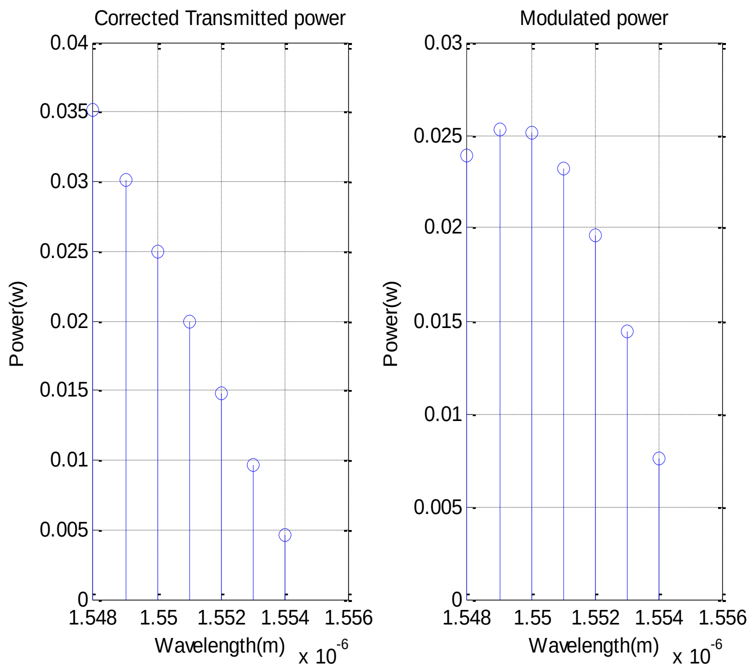

Figure 4.16 corrected and modulated power of RZ for 7channels at 25mw power

Above figure shows that RZ corrected 31 channels at 1mw and 7 channel at 25 mw whereas in NRZ and optical Manchester 23 channels corrected at 1mw and 5 channel at 25 mw. Hence RZ is most effective data format to reduce SRS effect in comparison to NRZ and optical Manchester.in NRZ and Optical Manchester small SRS effect is reduce. Effect of SRS is that for shorter wavelength small power is occur and for larger wavelength power transfer is large. Power is linearly varying to reduce these variations or to reduce SRS effect equation (4.13) is introduced hence power distributed constant all over the channel. Without pulse walk of channel corrected or used upto 20 channels, by using pulse walk off number of channel is increased.

Table 1.3

power	Channel length(km)	Amplifier distance	With walk off effect		
			RZ	NRZ	Optical Manchester
1mw	2,000	100	31	23	23
2mw	2,000	100	22	17	17

5mw	2,000	100	14	12	12
10mw	2,000	100	9	9	9
20mw	2,000	100	8	7	7
25mw	2,000	100	7	5	5

Table 1.3 Number of channels used for with walk off effect and data format such as RZ, NRZ and optical Manchester

Chapter 5

Conclusion and future scope

Conclusion

As shown in results, by using pulse walk off and data transmission formats (such as RZ, NRZ and Optical Manchester) almost constant modulated has been achieved across all wavelengths. With decrease in SRS, induced power tilt data rate has been increased upto 10 Gb/s. beyond 10 Gb/s there is small change in power because pulse walk off varies rapidly and this results in smll changes in length.

RZ helps in reducing SRS effect in DWDM system and it gives lower SRS induced power tilt in comparison with NRZ and optical Manchester data transmission formats. The data rate increase with decrease in SRS induced power tilt. Using pulse walk off number of channel and efficiency are increased.

Future Scope.

- Work has been done on 1550 nm where fiber loss coefficient varies linearly. There is a scope for analysis on 1350 nm window where fiber loss coefficient varies nonlinearly.
- Work has been done on data transmission formats such as NRZ, RZ and optical Manchester, further study could be done on CSRZ (carrier suppressed RZ).

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List of publications

1. Research paper titled "Pulse Walk off Effect and Data Format for Stimulated Raman Scattering and Comparison between Different Data Formats", published in international journal for innovative research in science and technology.
2. Research paper titled "Pulse walk off effect on Stimulated Raman scattering", published in Advance in computer science and technology (ACSIT), April-June, 2015.
3. Research paper titled "Power division approximation for stimulated Raman scattering including walk off effect", published in OPTO 2015 conference, May 27-30, 2015.