INVESTIGATION AND SUPPRESSION OF FOUR WAVE MIXING IN WDM SYSTEMS

A Dissertation Submitted in Partial Fulfillment of the Requirement for the Award of the Degree of

MASTER OF ENGINEERING

In

Wireless Communication

Submitted By

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JULY, 2017

DECLARATION

I, Jaspreet Kaur hereby declare that the work presented in this dissertation entitled **"Investigation and Suppression of Four Wave Mixing in WDM System"** in partial fulfillment of the requirement for the award of degree of Master of Engineering in Wireless Communication submitted at Electronics and Communication Engineering department, Thapar University, Patiala is an authentic record of work carried out under supervision of Dr. Hardeep Singh (Assistant Professor, Electronics and Communication Engineering Department) Thapar University from 2015 to 2017. The matter presented in this dissertation has not been submitted either in part or full to any other university or institute for the award of any other degree.

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It is certified that the above statement made by the candidate is correct to the best of my knowledge and belief.

Date: 14-07-2017 **Dr. Hardeep Singh**

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ACKNOWLEDGEMENT

To discover, analyse and to present something new is to venture on an untraded path towards and unexplored destination is an arduous adventure unless one gets a true torch bearer to show the way. I would have never succeeded in completing my task without the cooperation, encouragement and help provided to me by various people. Words are often too less to reveal one's deep regards. I take this opportunity to express my profound sense of gratitude and respect to all those who helped me through the duration of this thesis. I acknowledge with gratitude and humility my indebtedness to **Dr. Hardeep Singh, Assistant Professor,** Electronics and Communication Engineering Department, Thapar University, Patiala, under whose guidance I had the privilege to complete this thesis. I wish to express my deep gratitude towards him for providing individual guidance and support throughout the dissertation work.

I convey my sincere thanks to **Head of the Department, Dr. Alpana Agarwal** as well as **PG Coordinator, Dr. Ashutosh Kumar Singh, Assistant Professor,** Electronics and Communication Engineering Department, entire faculty and staff of Electronics and Communication Engineering Department for their encouragement and cooperation.

My greatest thanks are to all who wished me success especially my parents. Above all I render my gratitude to the almighty who bestowed self-confidence, ability and strength in me to complete this work for not letting me down at the time of crisis and showing me the silver lining in the dark clouds. I do not find enough words with which I can express my feelings of thanks to my dear friends and seniors for their help, inspiration and moral support which went a long way in successful competition of the present study.

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ABSTRACT

In optical fiber communication, non-linear effects deteriorate the performance of the communication system. This is because of the condition that degrading effects of non-linearities start to emerge at high launched powers in ultra-dense wavelength division multiplexing and FWM is the major deteriorating issue as it becomes severe at low frequency spacing and at minimum pulse broadening (Dispersion) values.

The major emphasis of this dissertation is to investigate the emergence of FWM in WDM system at different distances and to study the behaviour of the system for different WDM channels. Performance of the proposed system is evaluated in terms of Q-factor, BER and FWM. Results revealed that maximum FWM emerges for 3.125 GHz WDM channel spacing and reduced as the spacing between channels increased. Moreover, small optical fiber effective areas exhibit more FWM and also more four wave mixing power induced in dispersion compensation fiber (DCF) as compared to single mode fiber (SMF).

Performance analysis of high capacity and high speed WDM has been done by incorporating different line-coding and advanced modulation formats. A 96 channels WDM system is investigated for different distances and validated in terms of Q- factor, BER. Results revealed that DRZ is maximum tolerant to FWM effects and NRZ is maximum prone to FWM. A suppression method for FWM using an optical phase conjugation (OPC) is proposed. Comparison of placements of OPC in two different cases has been done and it is observed that placement of OPC after laser source performs exceptionally well and suppresses FWM with ease of maintenance.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

WDM	*Wavelength Division Multiplexing*
FWM	*Four Wave Mixing*
TDM	*Time Division Multiplexing*
MZM	*Mach-Zehnder Modulator*
LASER	*Light Amplification by Stimulated Emission of Radiation*
LED	*Light Emitting Diode*
SPM	*Self-Phase Modulation*
XPM	*Cross Phase Modulation*
XGM	*Cross Phase Modulation*
SBS	*Stimulated Brillion Scattering*
SRS	*Stimulated Raman Scattering*
EDFA	*Erbium Doped Fiber Amplifier*
PMD	*Polarization Mode Dispersion*
MLSD	*Maximum Likelihood Sequence Detector*
SMF	*Single Mode Fiber*
FBG	*Fiber Bragg Grating*
DCF	*Dispersion Compensation Fiber*
CSRZ	*Compressed Spectrum Return to Zero*
DRZ	*Duo Binary Return to Zero*
MDRZ	*Modified Return to Zero*
NRZ	*Non Return to Zero*
RZ	*Return to Zero*
BER	*Bit Error Rate*
OPC	*Optical Phase Conjugate*
NR DCF	*Non Return Dispersion Compensation Fiber*
FDM	*Frequency Division Multiplexing*
OSA	*Optical Spectrum Analyzer*
CWDM	*Coarse Wavelength Division Multiplexing*
UDWDM	*Ultra Dense Wavelength Division Multiplexing*
DWDM	*Dense Wavelength Division Multiplexing*

CHAPTER 1

INTRODUCTION

1.1 OPTICAL FIBER COMMUNICATION (OFC): DEVELOPMENT AND OVERVIEW

Ever since the beginning of time, mankind has found different ways to communicate with each other. People were assigned the duties of messengers to carry the message from one place to another. Also, some took the positions at top of the hills with good quality acoustic points to yell the messages so that they can be carried in the form of resonance. With the development of science and technology things were entirely changed. Advances in the field of optical communication started with the discovery of lasers in the 1960's. The first optical fiber link was installed in the late 1970's and was used for transmitting telephony signals at about 6 Mbps over distance of approximately 10 km [1]. Optical Communication has been used since 90's for high speed transmission of data. Optical communication is the kind of communication that reliant on the light transmission from one end to other terminating point, despite the movement of electrons (electric current). First and foremost transmission block in OFC is transmitter that consists of modulators and a optical medium followed by receiver section. Owing to the several constructive effects of OFC over electrical transmission, it mainly substitutes copper wire transmission in the urbanized world. Transmissions reliant on optical fiber have given the paradigm shift in the communications as well as cater a prominent part in the initiation of the networking era. Today, optical fibers are also used in the LANs to achieve high signalling rates. There are several prominent advantages of fiber optic such as less attenuation, prolonged link lengths, and also speedy data streams carrying capacity that has a edge over electrical communication systems. In order to replace the high bandwidth optical fiber, typically 1000s of electrical copper wires are needed to incorporate. Also no cross talk is introduced in optical fibres running beside each other over large distances as compared to copper wires. The demand and need for optical fiber systems and optical fiber applications have grown tremendously. Nowadays, applications which are dependent upon the telecommunication are ubiquitous and widespread to personal computers (Desktops). Using the optical fiber strands few in number, triple play services can be transmitted over the span of hundreds of meters and kilometres [2]. The enormous large band of frequencies transmission space of fiber optic system can be used utmost by serving or cater the numerous users also called access techniques. In order to have the benefits of the fiber optic, main work is to use the bandwidth and send the multiple signals over the signal strand of fiber. This is referred as multiple access method. Access techniques are categorized as Asynchronous and Synchronous. In former stated method access is random and collisions occur. These are ambitiously suitable for LAN's [3]. But as the traffic intensity goes on increasing this asynchronous access method suffer from cumulative delay. On contrary, in later mentioned methods, the communication is utterly planned and therefore exhibit more superior performance [4]. Figure 1.1 illustrates the blocks of the basic transmission system using fiber optic.

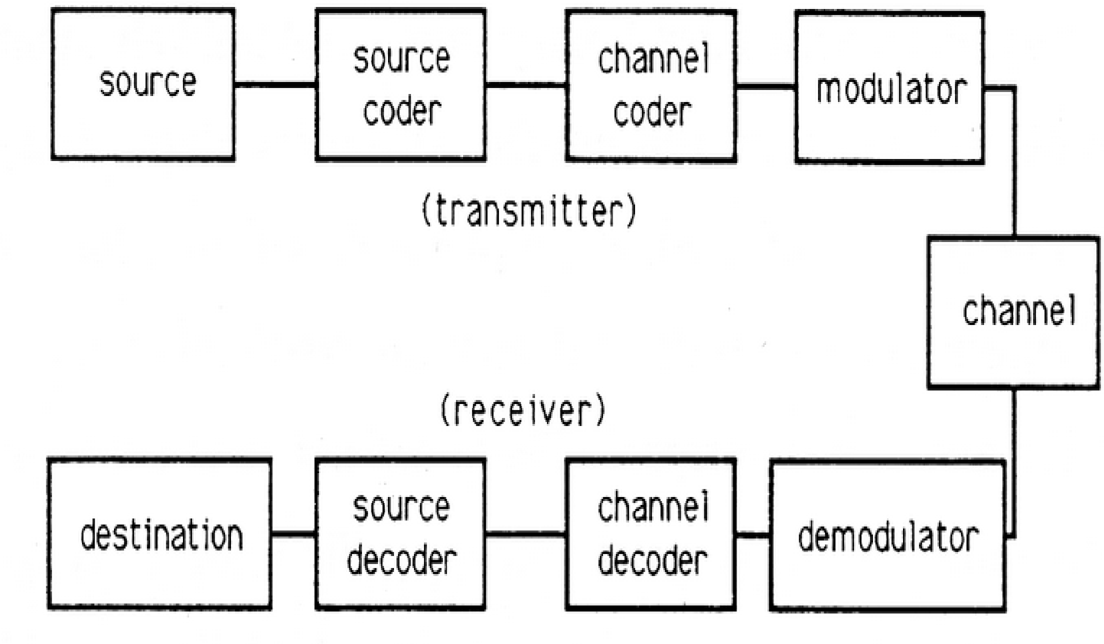


Figure.1.1 Representation of optical fiber communication system [7]

1.1.1 Essential Components of OFC:

- Transmitter: Signal generation and conversion of E/O is carried out at transmitter. Lasers, light emitting diodes are the general components used to generate light and act as intensity source for communication.
- Channel: The channel is composed of cable which consists of glass fibers that act as a waveguide through which optical signals (light) passes. Optical fiber provides special protection to the optical fiber inside. Total internal reflection is a main principle of communication inside optical fiber and there is an advantage of thin size of fiber that includes core and clad. Also, a buffer jacket to confine the light and help to accomplish TIR and moreover has used to provide protection.
- Receivers: Receivers part usually incorporated the component that is called photo-detector, which renovates light into electric signal using the photoelectric

effect. Most commonly used PD is the semiconductor reliant [5]. PIN and avalanche are the major two photo-detectors in optical communication.

Communication that use fiber optic and refers as OFC is a well competent way for the signal transmission over the longer distances. Basic principle in this technique is that data is transmitted from the sender to the recipient in one go over the fiber optic communication medium. It is acting as a paradigm in the communication networks because of its numerous benefits over copper wires or media based on electric current. So, OFC is far ahead of electric media and take advantage of low losses and better bandwidth. Also, a fiber-optic cable are immune to electromagnetic interference and exhibits no crosstalk when simultaneously transmitted inside fiber to make long haul system. The initial deployment of fiber-optic networks was mainly for large or prolonged distances but now they are currently being deployed in almost all metro-networks [6]. Thus, the requirements for more number of channels in regional, and in networks call for the up gradation of the existing backbone communication networks to utilize higher transmission rates.

1.2 MULTIPLEXING

1.2.1 Origin of Multiplexing

Since the origin of telegraphs in 18th century the steer has been to augment the sum of information in the time intervals. Since the development of communication means, the most observable way out was to include more lines of communication. However, this method was costly and motivate researcher to look forward for cost efficient method and maintenance. The researchers came back with the method called multiplexing, in which multiple channels can be sent over medium simultaneously [6].

1.2.2 Need of Multiplexing

It has been observed that the bandwidth of the communication media is generally very large however the transmitting devices need an operation for modest speed data streams. So the outcome is that the two communicating stations are not able to take advantage of wideband and high speed data. Furthermore, in order to utilize the data link efficiency, some techniques are needed to provide assessment to multi nodes in the network. When the bandwidth of a medium is more than the single channel which needs to be send over fiber optic, the available bandwidth can be distributed among more than one channel. The process of effectively utilizing the available medium bandwidth is referred as Multiplexing. The common way to accumulate the channels using copper and optical fiber in long distance transmission can be realized using multiplexing [7].

1.2.3 Multiplexing and its concepts

Figure 1.2 represents general operation of multiplexing. MUX is linked to de-multiplexer through a one link. It accumulates the data from 'n' number of input channels and broadcast over the large bandwidth medium, respective channels are transmitted to particular port according to frequency. So, multiplexing is a way out to pack several channels in transmission medium at the same time.

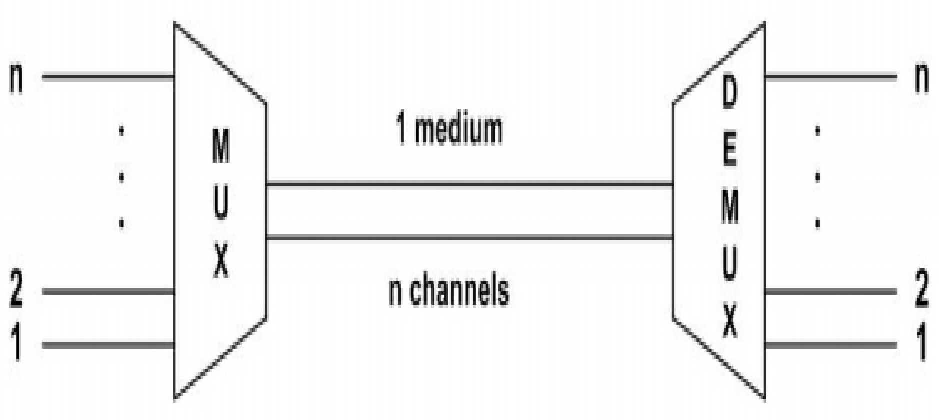


Figure 1.2 Block diagram of basic multiplexing [7]

1.2.4 Types of multiplexing techniques

1.2.4.1 *Time Division Multiplexing (TDM)*

In TDM, data tributaries from more than one channel are fed to communication medium with different temporal delays. This is not very efficient technology. Figure 1.3 illustrates the TDM form of multiplexing.

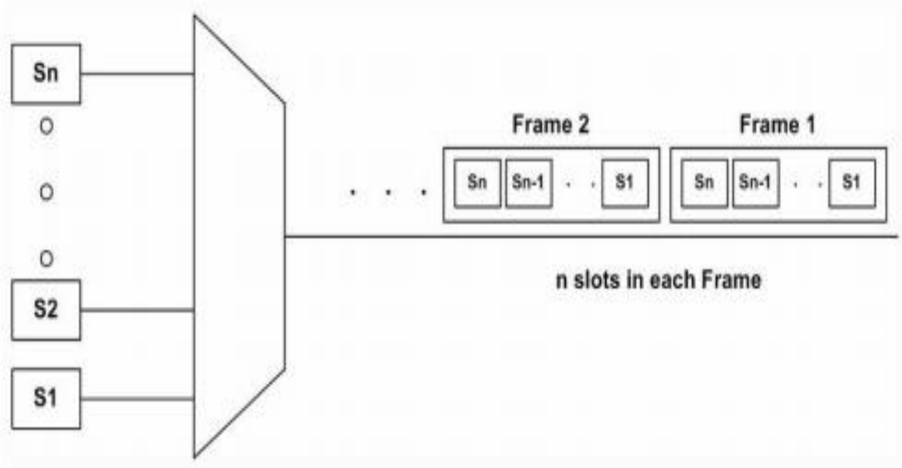


Figure 1.3: TDM operation [7]

Due to the less advantages of time division, it is not suggested on the priorty basis.If number of supported channels are large, then a new alternate should be used [6].

1.2.4.2 *Wavelength Division Multiplexing (WDM):*

Since frequency and wavelengths are closely related, so is also refered as the Frequency division multiplexing (FDM). Each WDM fiber has a definite bandwidth—the range of frequencies it can transmit. In case of WDM, major advantage is that each channel can carry the information at high speed or the data rate possible for channel to carry. Moreover, signal integrity cannot be disturbed in WDM system and does not change the speed of the system. Even with the new resolution to the bandwidth bottleneck, the position gained by WDM was lost quickly, and another step further had to be made [6]. WDM techniques are very useful in the optical domain and by WDM the data speed can be enhanced or improved to several terabits in the fiber optic signal transmission.

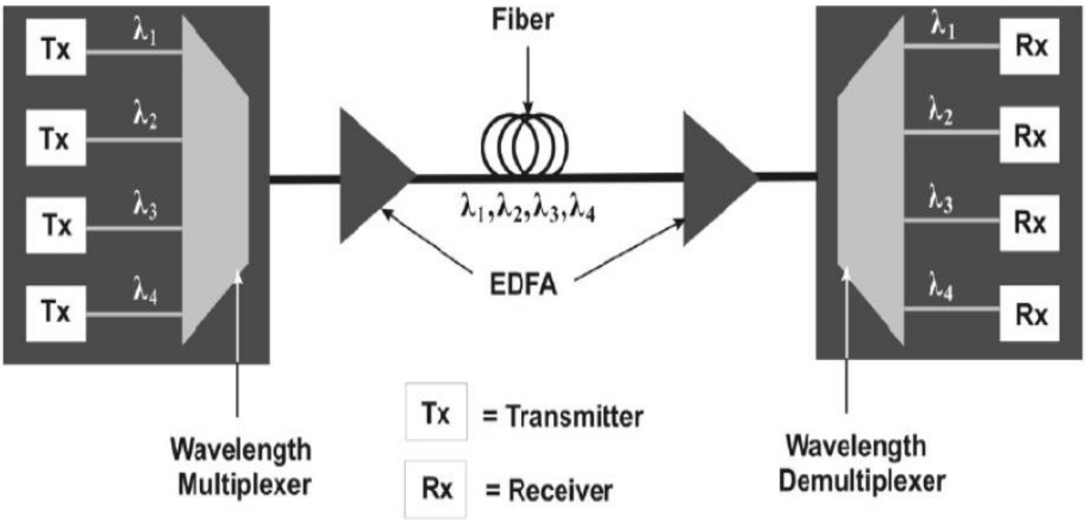


Figure 1.4: WDM system [8]

1.2.4.3 *Frequency division multiplexing (FDM):*

FDM is promising when the useful bandwidth of the transmission medium goes beyond the required bandwidth of signals to be transmitted. The FDM increases transmission capacity and flexibility by exploiting the very large bandwidth potential of the radio frequency. In FDM, a number of frequency channels are placed adjacent to each other and present a large capacity of transmitted signals.

A number of messages can be sent along the channel at the same time. Unused portion of the spectrum are used as guard bands to prevent interference.TDM and FDM techniques function in the electrical domain and are widely used in the conventional radio wave communication.

Further in order to improve the overall capacity of the system, more signals in a single fiber needs to be increased which can be accomplished by incorporating the WDM or Dense WDM (DWDM). But the linear and non-linear impairments become worse in such high-speed DWDM networks. Pulse broadening (dispersion) and PMD are the linear impairments; and the intensity and refractive fluctuation dependent effects include FWM (Four-Wave Mixing), SPM (Self-Phase Modulation) and XGM, XPM (Cross-Gain and phase Modulation).

1.3 NON-LINEARITIES IN OPTICAL FIBERS

In the fiber optic communication, with the use of multiple channels in the system called WDM, a major performance degrading factor exist called nonlinear effects. These issues play a very important role and also limit the launched power to be supported by the system without these effects. Moreover, it also limit the total speed, link length and channels spacing flexibility in the system [9].

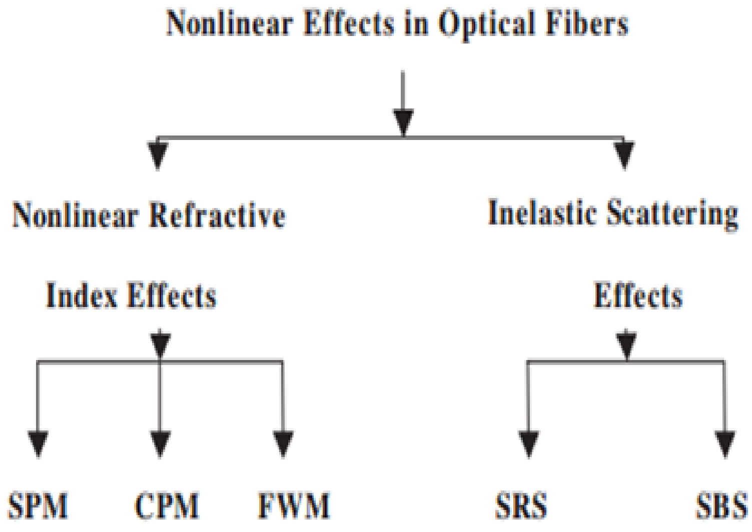


Table 1.1 Non- linear effects in optical fibers [9].

1.3.1 Basic cause of emergence of Non-linearities

Basically non-linear effects induces in the fiber arise fundamentally from two mechanisms. The most disadvantageous mechanism arises from the actuality that due to the property of reliance of refractive index of fiber on the transmitted intensity over the medium. Refractive index is expressed as:

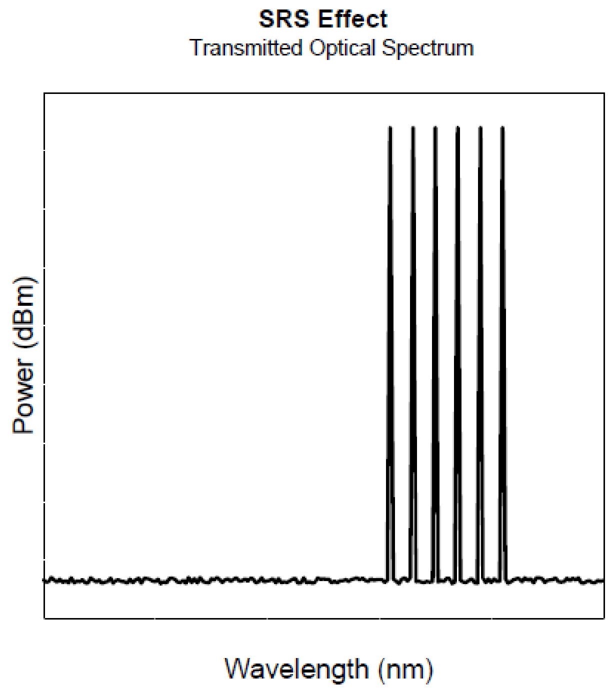
$$n = n_0 + n_2 * \frac{p}{A_{eff}}$$

Where n_0 is core refractive index, n_2 is the nonlinear refractive index coefficient, P is the launched power measured in decibel or Watts. Effective area is denoted by A_{eff} and is an important factor in nonlinear optics. From aforementioned expression it may be concluded that nonlinear effects can be suppressed by launching low power or by increasing the effective area of fiber. However, low input power limits the total reach of the system and the only way to suppress the effects is effective area. Most of the work is accentuated to increase the effective area of the optical fiber as the lesser diameter of effective area cause more nonlinearity [10].

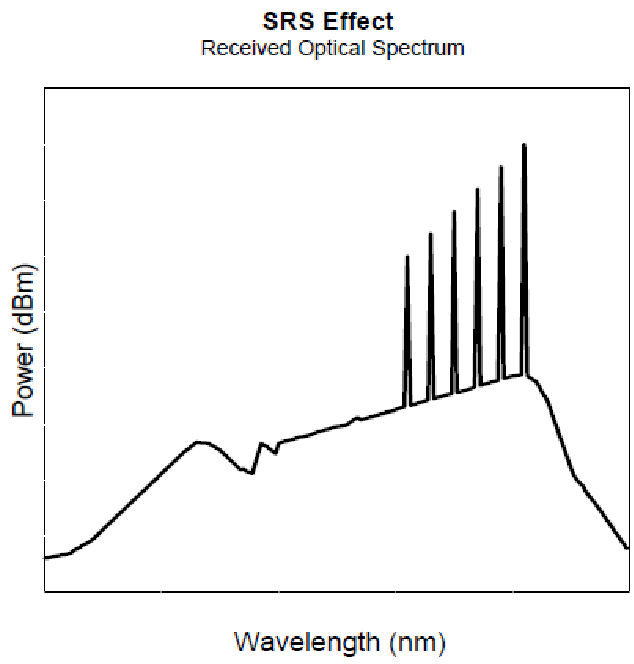
1.3.2 Types of non-linearities

1.3.2.1 *Stimulated Raman Scattering (SRS)*

SRS is less severe in degrading the performance of the system as compared to the SBS. Threshold of SRS is very high and typically of 1 Watt, about a 1000 times more than SBS effect [10]. SRS is generated by the interaction of light with molecular vibrations. Light incident on the molecules generates scattered light at a longer wavelength as compared to incident light. A fraction of the light traveling at each frequency in a fiber is downshifted across a region of lower frequencies. The light produced at the lower frequencies is called the Stokes wave. Frequency grid occupied by the Stokes wave is decided by the Raman gain spectrum which spans a range of about 40 THz below the frequency of the input light. At very high input power, SRS will cause nearly all of the power in the input signal to be shifted to the Stokes wave. To lessen the amount of loss, the power of each channel should be below a certain level [9]. But, practical systems are realized by incorporating EDFA's operating at 200mW and may go further powers.[10] SRS causes a signal wavelength to act as a — "pump" for longer wavelengths, either other signal channels or spontaneously scattered Raman-shifted light. The shorter wavelengths are attenuated by this process, which in turn amplifies longer wavelengths. Figure 1.5 shows the SRS effect on six wavelengths sent through the in-line amplifiers over long haul or great distance link length.



(a)



(b)

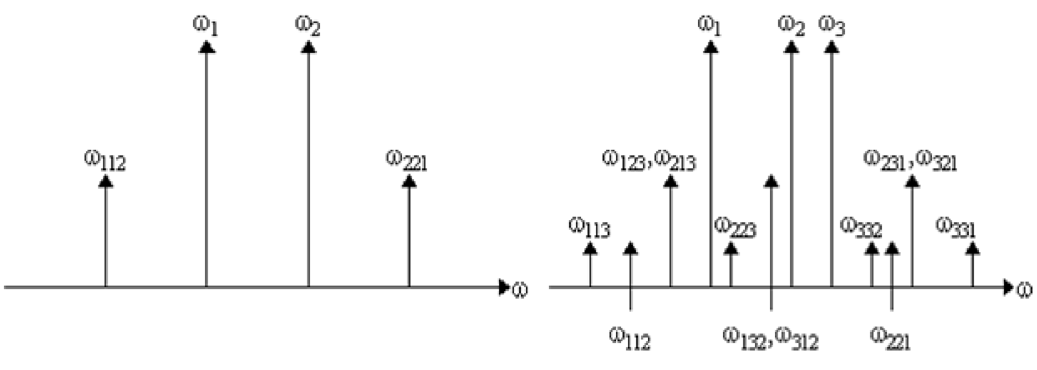
Figure 1.5 (a) Optical spectrum of transmitted signal (b) SRS Effect experienced at receiver [10]

1.3.2.2 *Stimulated Brillion Scattering (SBS)*

SBS is similar to SRS, the difference lies in the fact that the frequency shift is caused by sound waves rather than molecular vibrations. In SBS the Stokes wave propagates in the opposite direction of the input light, and SBS occurs at comparatively low input powers for broad pulses (greater than 1ps), but has insignificant effect for short pulses (less than 10 ns) . The intensity of the scattered light is larger in SBS than in SRS, although the frequency range of SBS is of the order of 10GHz, which is much lower than SRS. [9]. In addition, SBS may induce crosstalk between channels in multi wavelength systems. Crosstalk occurs when two counter propagating channels vary in frequency by the Brillion shift, which is about 11 GHz for wavelengths at 1550 nm. However, SBS crosstalk is fairly easy to avoid because of its narrow gain bandwidth.

1.3.2.3 *Four Wave Mixing (FWM)*

FWM is the major nonlinear effect in pulse propagation. This effect is commonly observed in multi-channel systems where more than one channel combine mutually to generate a extra or undesired new wavelengths, referred as interfering products. It occurs due to the dependence of the fiber refractive index. Interfering products that lies between the original signals wavelength tend to get mixed up with the signal, deteriorating the signal, and thus introduce amplitude loss. Signals emergence to the nearby carrier signal can be easily removed. Frequency of newly generated wave is determined by: $\omega_{123} = \omega_1 + \omega_2 - \omega_3$ where ω_1, ω_2 and ω_3 are the frequencies of the first, second and third wave respectively.



(a) (b)

Figure1.6 Additional frequencies generated through FWM in the (a) partially degenerate (b) and non-degenerate case

FWM is worst in the evenly separated WDM channels. The effect of FWM can be reduced by using fibers with high dispersion (SMF, NZDSF) or unevenly separated frequencies in multi-channel system. Yet, there are some significant drives that are taking the benefit of FWM in WDM networks. The most important one is wavelength conversion using FWM [9]. FWM is most dominant near the region where dispersion is null and in the ultra-dense frequency spacing's. It is categorized or stated as the third-order nonlinearity. In WDM systems, mechanism of third order produces third harmonics and cross products of FWM components. Cross products induce the major problems as they incident on the desired frequency. The total number of FWM components is expressed as $(n^3 - n^2)/2$. Figure 1.7 shows that this become very large number rapidly [10].

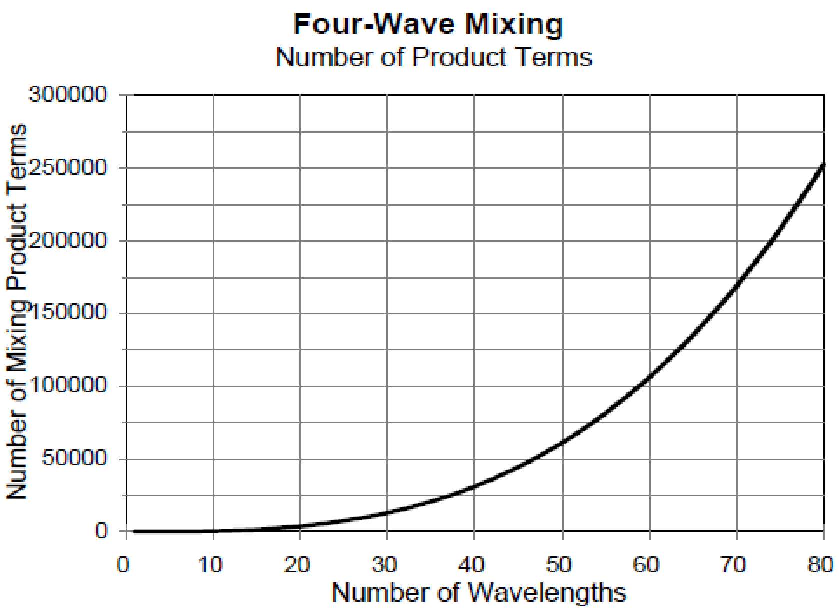


Figure 1.7 FWM Products v/s Channel Count [10]

FWM is measure in the decibel and efficiency is also represented in dB. The more negative values of FWM efficiency are better as it signifies lower efficiency of FWM. Magnitude of FWM products is strongly influenced by two factors namely: channel spacing in a WDM system and pulse broadening in medium. Mixing efficiency is increased severely as the channel spacing is reduced and varies opposite to the dispersion because of the maximum emergence at the null dispersion region. Figure 1.7 depicts the FWM mixing efficiency magnitude versus channel count. [10].

1.3.2.4 Self Phase Modulation (SPM)

The intensity reliant traits of optical medium or fiber are prominent cause to modulation of phase as well as self-focusing cramped pulse. In optical fiber, any other confinement that is generated by intense pulse is insignificant. Nevertheless, retardation at high pulse in contrast to the trailing edge and leading will augment in extensive communication and consequences in substantial modulation of phase. Pulse enlargement is more significant when associated with high launched power ultra- short pulse and link length.

1.3.2.5 Cross Phase Modulation (XPM)

XPM is very much identical to the effects of SPM, the only difference is that SPM is a single channel phenomenon and XPM emergence on the system where multiple channels are included. In XPM, more than one signal, each travelling down the fiber fluctuates the refractive index as the optical power changes. If these two pulses occur to overlap, they will initiate disturbance into the adjacent signal due to XPM. Contrasting to SPM, pulse broadening effects has minor impact on cross phase modulation. Effective area enhancement will reduce the XPM as well as other nonlinearities [10].

1.4 APPLICATIONS OF FWM

Multiwave mixing, especially FWM, is a characterised as a basic and important factor in optics. It basically generates the new components of frequencies by the mixing of multiple frequencies within the optical medium and generates the addition and difference of singles. Subsequently, two pump waves mix with original signal; produce new signals that are phase conjugated [25]. At the same time as pulse broadening introduces problems of phase matching; FWM has proved constructive in such applications as real time holography [26]. The most common configuration involves a self-focusing nonlinearity and a backward geometry, in which the initial pump beams counter propagate to create a reflection grating. [19].

Investigation of FWM effect on varying various parameters has been discussed in the further chapters.

CHAPTER 2
LITERATURE REVIEW

2.1 LITERATURE SURVEY

Hwang *et al.* [21] proposed the comparative investigation of 20 channels of WDM at equal and unequal channel spacing's in terms of the induced FWM powers. Results revealed that system incorporating modulation with on-off keying operating in bandwidth of 16 nano meter at zero decibel launched power per channel accomplish bit error rate 10^{-9} with an FWM components interference (crosstalk) power <1 db. System with even channel spacing was not able to accomplish similar performance with 100 GHz frequency spacing.

Song *et al.* [22] shown that the dispersion plays a major role in fiber transmission and at less pulse broadening values, more non-linear effects emerges. Moreover, stated that, the influence of self -phase and cross phase on FWM is more when the power launched in the fiber is large. Also power of each channel plays an important role along with channel spacing. Subsequently, the expression for validating the matching of phase conditions for FWM emerges considerable errors by not considering the cross and self-phase effects as well as a phase matching factor was derived including these factors.

Tang *et al.* [23] presented a common management of fiber spans of nonlinear effects reliant on Kerr's phenomenon and on Shannon channel competence for pulse broadening free fiber optic.

Miyamoto *et al.* [24] described current technological issues and the advancement towards the apprehension of the optical networks based on 43 Gbps channel. They proposed 43-Gbps carrying capacity of each WDM channel along with the incorporation of dispersion-managed transmission at dense frequency spacing's using CSRZ format.

Sinsky *et al.* [25] conducted an experiment of 42.7Gbps system based on the single polarization. They achieved single-channel transmission and 8 WDM transmissions with 300 GHz frequency spacing between the channels over the inter-city 200 km SMF by utilizing 42.7 Gbps RZ differential PSK signals as well as a simple dispersion compensation that induces due to polarization.

Sun *et al.* [26] demonstrated the suppression of FWM by introducing laser action in EDFAs. Appropriate lasing at appropriate wavelength converts the inverted population sharing as well as keeps the production and the addition of the four wave mixing signals. So, the FWM is suppressed and is effectively degenerated.

M. Arumugam [27] gives the overview of fiber communication system. In this paper, the history of optical communication has been discussed. The different types of fibers such as SMF (single mode fiber), MMF (multimode fiber), SI (step index fiber), and GI (graded index fiber) are discussed. The soliton pulses are highlighted in optical communication. This paper discusses how optical pulses are useful for high quality telecommunication at a lower cost.

Monika *et al.* [28] in this paper, the authors presented the design, implementation and performance analysis of FWM in transmission system. The system has been designed for different channels from 2-12 with the addition of two channels each time as well as for diverse frequency spacing's such as 6.25 GHz, 12.50 GHz, 25 GHz, 40 GHz, 50 GHz. The results show that as the number of users/channels is increased, the crosstalk in addition augmented and therefore, the FWM effect also increases. The eye diagram becomes less clear with the increase in WDM channels. Also, it increases the BER and decreases the Q-factor. The authors thus concluded that the effect of FWM is minimum when there exists least number of users.

S.P. Singh *et al.* [29] described the basics of non-linear effects which degrade the system performance and comparison between different non-linear effects such as SPM, XPM and FWM. In this effect DSF (dispersion shifted fiber) is applied because if dispersion is present then four wave mixing effect can be reduced. If power is below 19.6 mill watt SPM effect is negligible.

Surinder Singh *et al.* [30] described the FWM effect in 3-D, 2-D orthogonal modulation at even frequency spacing of 100 GHz and 50 GHz. In order to implement the prolonged link length WDM system, orthogonal formats are used. Additionally, the evaluation of degeneration of FWM is presented and projected and has been analyzed by altering the launched power from -10 decibel to 10 dBm. It is observed that FWM effect is more on three-dimensional orthogonal modulation format; it is difficult to design practical ultra- long reach WDM transmission system without the orthogonal formats.

David *et al.* [31] demonstrated the effects of FWM in SOA (semiconductor optical amplifiers) is an attractive mechanism for wavelength conversion in WDM since it gives the pulse shape (modulation) and data speed precision over large tuning ranges. They presented a series of experiments. Evaluated the various factor of the operation of these devices at data speed of 2.5 and 10 Gbps. They also presented the wavelength conversion and spectral investigation based on time resolving.

Yasin M. Karfaa *et al.* [32] presented a detailed study of the Kerr's effect based degrading issue i.e. four wave mixing in optical fiber. They integrated corresponding system of equations numerically and described the channels interface phenomena such as FWM. They validated the performance of the system by analyzing the BER with the transmission of the channels under the effect of FWM and calculated the crosstalk emerged in the system.

S Sugumaran *et al* . [33] discussed the realization of dense WDM system by considering the FWM for frequency spacing as well as dispersion values. Link length is also varied to accomplish the aim of investigation of FWM. For the accomplishment of the work, a premier and widely used tool optic system is used and bit error rate is also depicted with the help of analyzer present in the tool. Results revealed that FWM effect can be lower by setting uneven frequency spacing.

John M. Senior [34] explained the mathematical tools required for considerate study and to comprehend the non-linear effects. First and foremost, Maxwell's equation is discussed; general equation of transmission or propagation in nonlinear medium under the dispersive medium is considered.

S.P. Singh *et al.* [35] described about FWM and also stated the effects of dispersion shifted fiber. With the incorporation of DSF, effect of FWM is suppressed. FWM effect is diminished by placing unequally spaced frequencies; it leads to increase the bandwidth. With more suppression of the FWM components, better bandwidth is obtained.

Gurmeet Kaur [36] in this paper an algorithm for optimization of inter-channel separation has been discussed. Transmission distance depends on different parameters such as number of channels, distance, frequency spacing and amplifier spacing. By varying these parameters maximum transmission distance is achieved.

V. Sharma *et al.* [37] demonstrated a high speed dense WDM system at 80 Gbps and information is communicated over the link length of 100 km. It is evident that all the effects of FWM and other degrading factor are taken into account. Moreover, even and uneven channel spacing's are also investigated in the same system. Results revealed that as the frequency spacing between the adjacent WDM channels reduces, the performance also degrades due to more emergence of FWM. It is suggested from the conclusion that system that uses uneven frequency spacing between channels is better.

R.S. Kaler *et al.* [38] demonstrated and explained the optical communication system consisting of single mode fiber and data is transmitted at the rate of 10 Gbps. Modulation to provide pulse shape to data is considered RZ differential PSK. It is also concluded that the data transmission at 10 Gbps is less affected to the self-phase modulation and if the increase in the data speed takes place, it also distort the signals. At 40 GB/s the system tolerance is effectively disturbed by signal energy through pulse shapes.

B.Yao *et al.* [39] discussed the transmission characteristics in a WDM system using a wideband FWM suppression component called optical phase conjugation (OPC). It was reported that, at the slope 0.001ps/km/nm^{2}of dispersion flattened fiber, the modulation formats are disturbed noticeably by means of FWM, while modulation formats are exhibiting similar or superior output at 0.02ps/km/nm^2.

S. Pachnicke *et al.* [40] reported that the influence of the pulse width reduction in the inline arrangement on FWM. It was observed that FWM increases with the reduction of the pulse broadening and varies inversely. At the null point region of pulse width broadening of optical fiber emerged FWM is maximum.

P.L. Li *et al.* [41] presented a FWM based wavelength converter and it was reported that it can be tuned to desired frequency. To accomplish the goal, semiconductor ring laser was incorporated in the system. They considered the critical factors such as carrier density, variation of field, profile of gain as well as the wideband noise emission in the model. To comprehend and analyze the effects on wavelength conversion efficiency, the injection current and the lasing wavelength are investigated and performance is evaluated.

Iftikhar Rasheed *et al.* [42] present the nonlinear effects at various powers and number of channels on the performance of dense wavelength division reliant on fiber optic. The investigation of XPM, four wave mixing (FWM) and SRS effect in dense wavelength transmission system is done. Simulation tool is used to realize the system and optic system is widely used for communication design. It was concluded that, there is significant increase in the nonlinear effects when high power is passed through and more number of WDM channels incorporated. Furthermore, suppression methods for the degeneration of nonlinear effects are demonstrated and explained.

Borja Vidal *et al.* [43] described the improved four-wave mixing (FWM) in non-linear fiber. This was carried out by phase modulation of the pump carrier and product of microwave signals. The augmentation of FWM is investigated by phase modulation at dense channel gap. Results revealed that the amplitude modulation in C-band can be used to generate the microwave signals in the V-band. Multiplication harmonic factor of 13 is proposed with the incorporation of demonstrated method. The unconverted signal exhibits no extra deterioration because of the reason that there is presence of nonlinear photonic effect.

Qiang Hao *et al.* [44] proposed the emission of yellow and high power infrared by joining FWM in nonlinear ytterbium amplifier, generating average power of 2.0 W at 830 nm and 0.351W at1594 nm. Moreover, FWM processes which generates SC covering more than four octaves from 398 to 1700 nm was also investigated by seeding the Yb-doped fiber amplifier with Q-switched mode locked laser pulses.

Amarpal Singh *et al.* [45] demonstrated the techniques to combat the effects of FWM and suppression methods. In DWDM systems, FWM is a prominent degrading effect and has analyzed this work for different launched powers. Moreover, investigation has been done for the even and uneven frequency spacing along with the variable delays in the channels. Also, comparison has been established for the reported and proposed system by altering the pulse width broadening values of fiber optic. Results revealed that the proposed scheme decreases system complexity and performs better to reported schemes.

H.J. Abed *et al.* [46] explained the several methods in order to quell the effects of FWM as well as to enhance the system performance. Methods include combined technique of WDM and TDM, dispersion influence on the FWM, optical power booster etc. Comparative analysis and conclusion has been derived for various methods in the FWM suppression and also stated the limitations and advantages of each method.

M. Noshad *et al.* [47] proposed the method to quell the effects of FWM in WDM systems with the help of asymmetrical dispersion management optical fibers and derived the mathematical expression for FWM emerged power penalty. Different frequency spacing values are studied in the proposed system in terms of power penalty evaluation. From the derivation, it is concluded that the power penalty due to FWM is suppressed for the two fiber segments with uneven spacing, symmetrical dispersion.

Rajneesh Kaler *el al.* [48] investigated and evaluated the FWM effect in UDWDM systems and results were calculated for different link lengths in terms of Q factor, FWM component powers, and bit error rate (BER).Eye closer is also discussed and impact of FWM on eye opening factor is also described. It is observed that less FWM emerge for wide channel spacing in WDM systems and also with the increase of spacing, crosstalk also minimized. Maximum induced power of FWM components is reported for the frequency spacing of 6.25 THz.

Gurpreet Kaur *et al.* [49] investigated the performance of hybrid modules in WDM systems to minimize the effects of FWM. Optical phase conjugation is an effective module to combat the non-linear effects and also discusses about the incorporation of the pulse width reduction modules such as FBG (fiber bragg grating) and dispersion compensations fibers. Comparison of these join technique is compared with the reported FWM minimizing schemes with reported works. Compensation is mainly accentuated in this work for the midway dispersion compensation and FWM suppression by using the hybrid modules. It is seen that hybrid modules proposed in this work are more efficient than other FWM suppression techniques.

T. Sabapathi *et al.* [50] investigated the performance of maximum likelihood sequence detection in the suppression of FWM effects. Better results are realized with low complexity proper matrix likely MLSD. For high speed systems there occurs significant increase in calculations complexity with the length of the channel impulse response. For the long reach systems with MLSD, complexity reduced. However, in the linear regime other effects like PMD and dispersion can be completely compensated.

C. T. Politi *et al.* [51] proposed the system and studied the behavior of wavelength dependent wavelength converter as well as the need for tuning ability is also discussed. They also studied a configuration for extinction ratio improvement.

From literature review we came across various suggestions to reduce FWM like:

- Unequal channel Spacing- From the extensive literature works, it is found that the frequency spacing’s in WDM systems plays an important role and the allocations of channels be such that FWM components do not incident on the carrier frequencies. In other words, FWM overlapping should be avoided on carrier wavelengths grid. This may be constructive for less number of channels however, requires careful positioning of channels.
- Different modulation formats: Use of different advanced modulation formats reduces FWM.
- Reduction in Transmitted power.
- Using mid link spectrum inversion also called optical phase conjugation.
- Optimizing the placement of OPC in the transmission channel to suppress the FWM effects.
- Using Fiber Bragg Grating (FBG)

2.2 MOTIVATION

According to the literature survey, it has been reported that various research works has been done to suppress the FWM but are either limited to low launched power or have greater complexity issues. However, there are some advantages of FWM and extensively studied in wavelength conversion. It is observed that high capacity WDM systems investigation proposed till now are rare. Also ultra-low channels spacing in WDM is not investigated much in terms of Q factor, BER etc. The bit error rate decreases with increasing number of channels/users. Various approaches have been suggested for decreasing the fiber nonlinearity named as four wave mixing. According to international telecommunication-T standards, FWM has been evaluated above channel spacing of 6.25 GHz but no evaluation has been done for channel spacing below 12.50 GHz and channels not more than 96, yet. Till now advanced modulation formats has been evaluated for WDM systems having 64 channels at channel spacing of 100 GHz. However, more channels systems are required at reduced frequency spacing. Moreover, optical phase conjugation is well competent method to quell the FWM effects but used in transmission as mid link spectrum inversion. However, this is suffered from maintenance issues and performance limitation to suppress FWM issues. Placement of OPC should be explored and investigated to reduce induced FWM and maintenance related issue. The four wave mixing effect on BER, Q-factor, spectrums and eye opening for different frequency spacing; different number of channels, and varying each transmitting component in the circuit has not been studied yet.

2.3 OBJECTIVES OF THESIS

- To analyse the four wave mixing effects in ultra- high capacity WDM system for different physical parameters.
- To investigate the performance of different advanced modulation formats in ultra- high capacity WDM system.
- To design and compare the performance of WDM systems with different placements of optical phase conjugations and conventional WDM system.

2.4 ORGANIZATION OF THESIS

This thesis is divided into six chapters.

The first chapter presents the introduction about optical fiber technology and also different multiplexing techniques. Various non-linearities that exist in optical fiber such as self-phase modulation (SPM), cross phase modulation (XPM) and four wave mixing (FWM) etc. are also explained.

The second chapter explains the reported works which includes the literature survey of various applications of four wave mixing effect. The literature survey of investigating the FWM at different WDM channels, spacings, FWM suppression methods has been done.

In the third chapter, investigation of four wave mixing effects in ultra-high capacity WDM system at different channels spacing’s, optical windows, input powers, distances, fiber effective areas and optical fibers such as SMF and DCF has been done.

In the fourth chapter, performance analysis of FWM withdifferent advanced modulation formats such as (CSRZ, DRZ and MDRZ) in ultra-high capacity WDM system has been done in terms of induced FWM, Q-factor and BER.

The fifth chapter investigates the suppression method of four wave mixing incorporating optical phase conjugation at different positions in WDM system. Also comparison is established with and without OPC system in terms of efficiency to suppress FWM. Placement of OPC is suggested to reduce maintenance related issues and also quell FWM to greater extent.

Finally, the sixth chapter includes conclusion and future scope of the work done.

CHAPTER 3

TO ANALYZE THE FOUR WAVE MIXING EFFECTS IN ULTRA HIGH CAPACITY WDM SYSTEM FOR DIFFERENT PHYSICAL PARAMETERS

The major emphasis of this research article is to analyse four wave mixing in detail on an ultra-high capacity and ultra-dense WDM system. In this work. We accentuated on the emergence of four wave mixing in WDM system at different distances and to study behaviour of the system for different WDM channels, frequency spacing, optical windows, different optical fibers such as single mode fiber and dispersion compensation fiber, SMF effective areas. Performance of the proposed system is evaluated in terms of Q-factor, BER and FWM is analysed at different distances. Results revealed that maximum FWM emerged for 3.125 GHz WDM channel spacing and reduced as the spacing between channels increased. FWM power is also decreased with the link length enhancement. C-band is found out to be best optical window for operation due to less FWM induced at this frequency band. Moreover, small optical fiber effective areas exhibit more FWM and also more four wave mixing power induced in dispersion compensation fiber (DCF) as compared to single mode fiber (SMF).

3.1 INTRODUCTION

In fiber optic communication systems, a major deteriorating factor in WDM system is Four-wave mixing (FWM). This can also be stated as the four-photon mixing and is severe in the systems that use the dense frequency spacing and the minimum dispersion fiber. Basically in the multiple channel systems, number of channels interacts with each other, but in case of wide spacing they interfere less. However, the less interaction becomes prominent in the long reach optical fiber due to the fluctuation of refractive index in the core. Various effects introduced due to the high power in the system and in WDM, most significant factor is FWM in which three wavelengths interact to generate a fourth [16]. In expeditious development of optical fiber communication, the need for information capacity carrying systems is more because of augmentation in services reliant on internet, video on demand and cloud computing [17]. Wavelength division multiplexing is a promising technology to cater the demands of multi users by packing more dense channels. A potential and well competent alternative to fulfil the demands of user is the joint technique of WDM and low power with the unequal channel spacing

[18]. However, in recent times, several low power systems are also investigated to suppress the performance deteriorating issues in fiber optic such as FWM.

Modulation formats are bandwidth efficient, and also less vulnerable to noise induces due to phase. Consequently, it allows the accommodation of more channels and accumulation at dense spacing's in WDM system. These technologies are capable to support high data rate such as 40 Gbps and also can be spaced at frequency difference of <100 GHz. Modulation formats have numerous advantages such as high security, information carrying capacity and flexibility. Optical fiber non-linearities are the limiting factors in signal transmission and also restrict the data carrying capacity of the system. Major deteriorating Kerr's effect reliant nonlinearities are four wave mixing (FWM), Self-phase modulation (SPM), Cross phase modulation (XPM). Main cause of the emergence of nonlinear effects is the power dependence of refractive index of optical fiber. In order to accomplish long haul transmission, these factors need to be addressed. In multi-channel systems, FWM is a major performance deteriorating nonlinearity that arises due to power accumulation of WDM channels inside single optical fiber. FWM effect represents the fluctuation of refractive index when more than one frequency is simultaneously travelling through fiber optic and generates the new frequency signals that limit the overall performance of wavelength division multiplexing systems. Numerous researches has been reported till now to suppress the FWM effects in WDM systems such as unequal spacing [54], dispersion management [53] techniques. However, either these solution limits the transmission reach or support less data rate. Also, from reported works, it is seen that they are limited in total capacity of the WDM system and has more frequency spacing. But, as the demands of high speed internet increases, a high capacity WDM system is required and also investigation of FWM is needed before the realization of final system.

So far, FWM is investigated on WDM systems that have less number of channels and capacity as compared latest scenario of UDWDMs. In this research objective, effects of four wave mixing are extensively investigated for different WDM channels, channel spacing, single mode fiber, dispersion compensation fiber, SMF effective area in high speed and high capacity UDWDM system. Performance of proposed system is analysed for different link lengths, launched powers in terms of FWM power, Q-factor and BER.

In order to elaborate the proposed work, this chapter is separated in different sections. First and foremost, the section with explanation of recent trends, reported works and basic idea of four wave mixing effect is illustrated. In the second section, the proposed model is depicted and explained with all the necessity information. In the third section, various physical parameters are analysed and compared in the proposed model. Finally, in the fourth section, results after comparison and investigation are presented in terms of conclusion obtained.

3.2 SYSTEM SETUP

The simulation of proposed Wavelength division multiplex system is investigated in Optiwave's Optisystem. Figure 3.1 represents the proposed system setup. A continuous wave laser with 193.1 THz starting frequency is used to generate optical pulses of 0.1 ns and consists of 256, 128, 96, 64 and 32 WDM channels at 50 GHz, 25 GHz, 12.50 GHz, 6.25 GHz and 3.125 GHz frequency spacing. Launched power and laser line width of CW laser are -20 dBm and 10 MHz respectively. Pseudo random bit sequence generator of 2^7-1 sequence is generating bits in the form of 1's and 0's. Binary data is fed to pulse generator Non return to zero (NRZ) and drive is given to Mach-zhender (MZM) modulator for electrical to optical conversion. An ideal multiplexer of 128:1 is placed after transmitter and carriers are analysed with the help of optical spectrum analyzer (OSA). Multiplexed data is fed to single mode fiber (SMF-28) with attenuation 0.2 dB/km and dispersion 17 ps/nm/km in C-band (1530nm-1570nm). The WDM demultiplexer's work is to route particular frequencies to their respective output ports according to centre frequency and spacing between channels is provided to filter. Receiver consists of photo detector, Low pass filter (LPF), 3-R regenerator and BER analyser.

Parameters	**Values**
Data speed	10 Gbps
WDM channels	256,128, 96, 64 and 32
Frequency spacing	50 GHz, 25 GHz, 12.50 GHz, 6.25 GHz and 3.125 GHz
Distance	10 km- 50 km
Nonlinearity analysed	Four wave mixing
Photo-detector	p-i-n
Dark current	10 nA

Table 3.1 System specifications of proposed WDM architecture

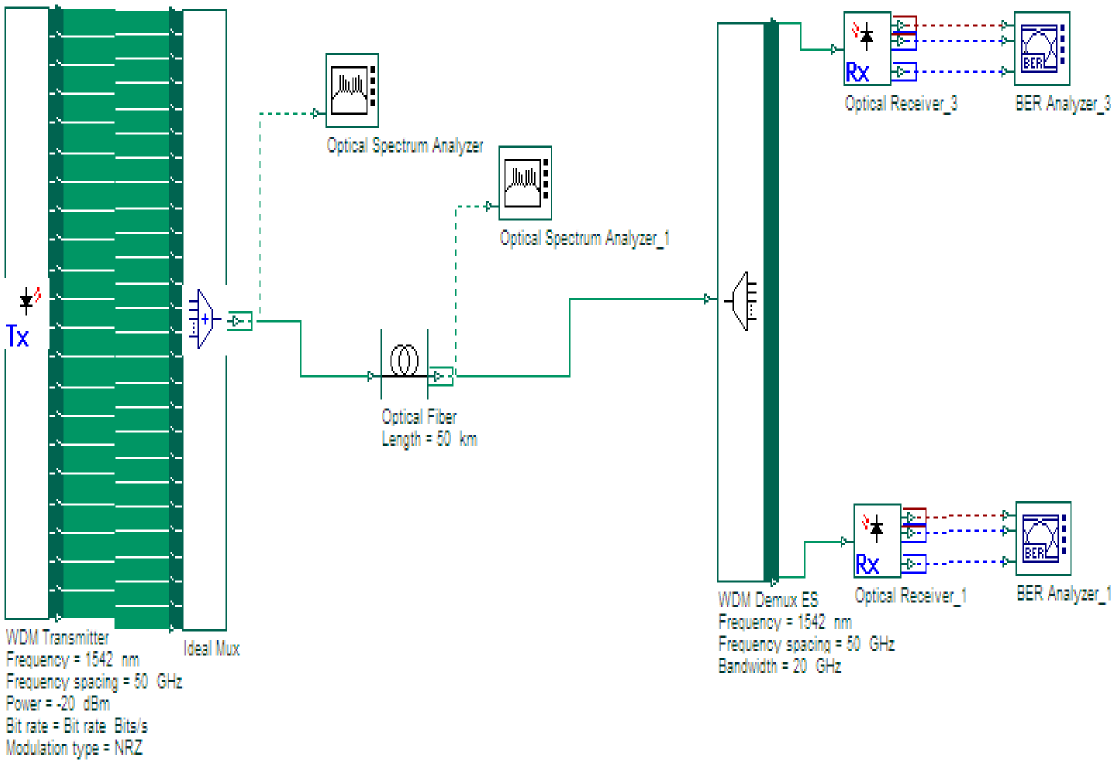


Figure 3.1 Simulation diagram of proposed WDM system

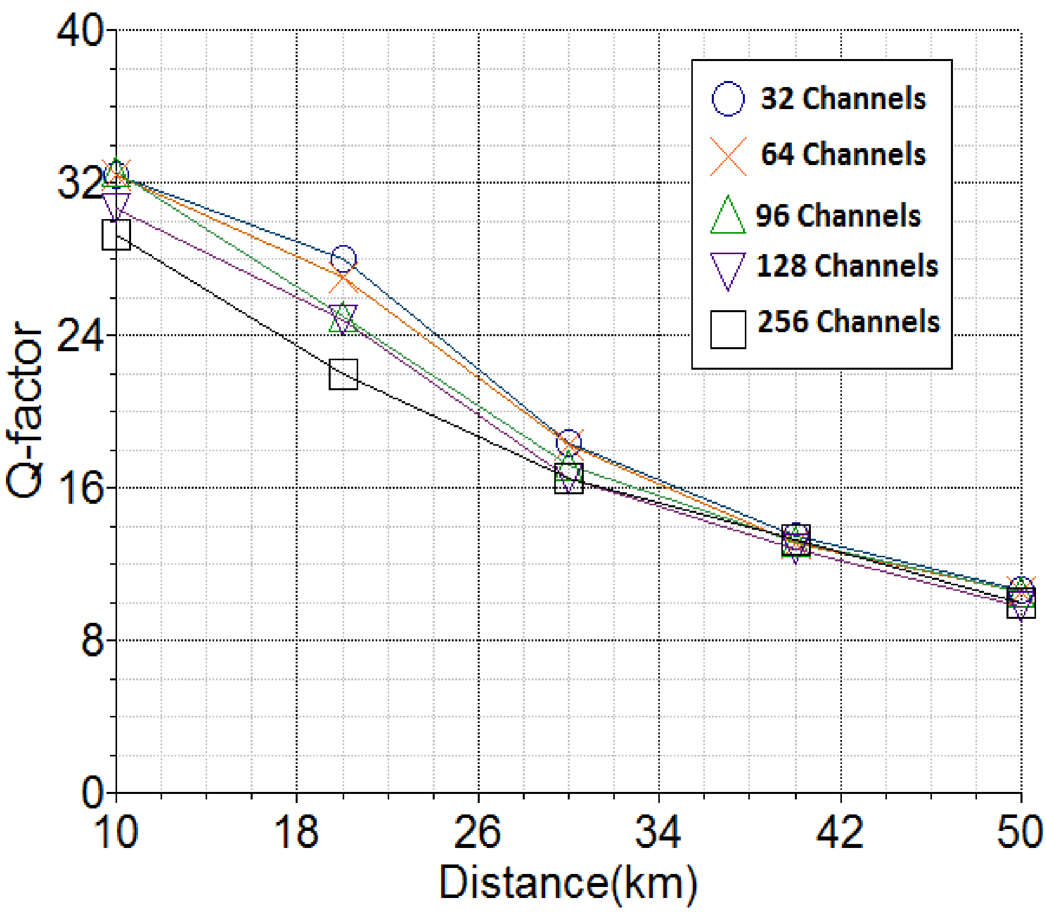
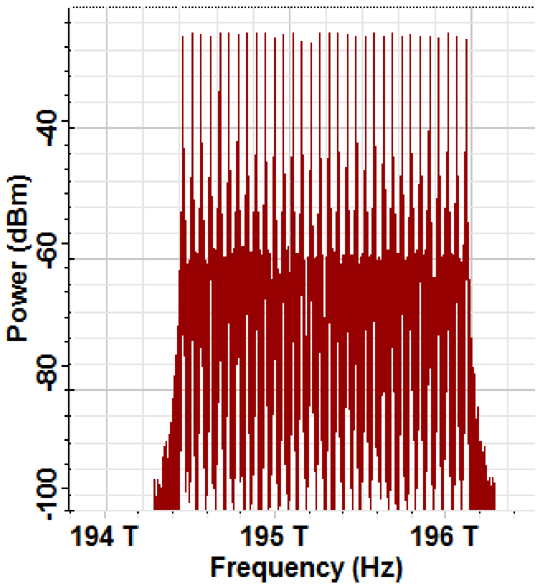


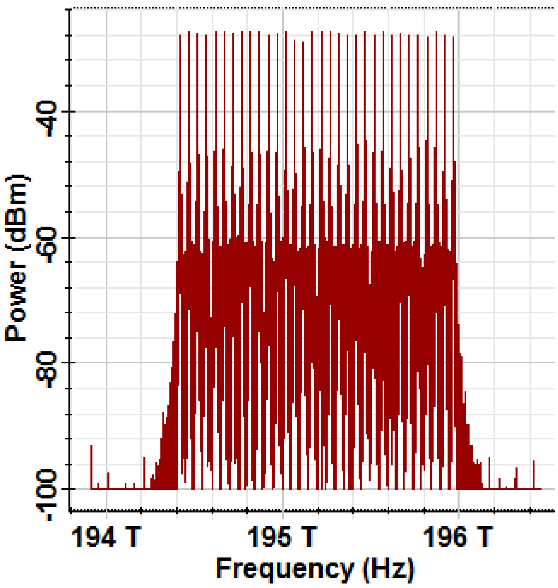
Figure 3.2 Q-factor versus distance for different WDM channels

3.3 OBSERVATIONS

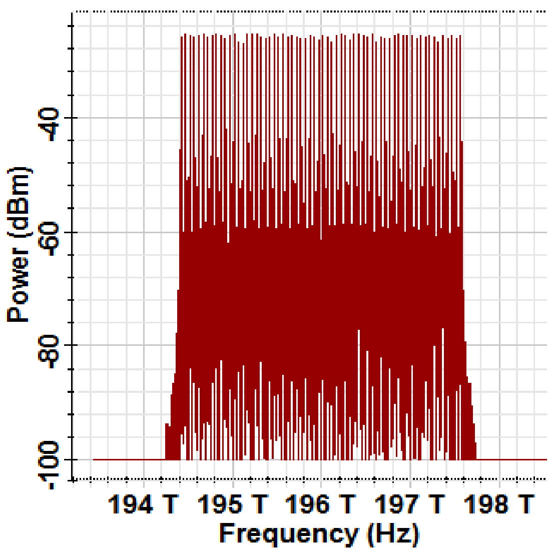
To investigate the FWM in high capacity WDM system, various parameters are considered such as number of channels, frequency spacings, different optical fibers and fiber effective areas. Figure 3.2 depicts the performance of WDM channels in terms of Q factor under the influence of four wave mixing. It is prominently observed that as the length of optical fiber prolonged, Q factor decreases due to attenuation and pulse broadening along with nonlinear effects. WDM channels are studied at different distances 256, 128, 96, 64 and 32 with 10 Gbps data rate at each channel. Maximum Q has been seen for the 32 channel WDM system and least of 256 WDM because of the reason the more channel cause more interference to adjacent channels. Optical spectrum for different channels before and after optical fiber is depicted in figures3.3(a) - 3.3(h).



(a)



(b)



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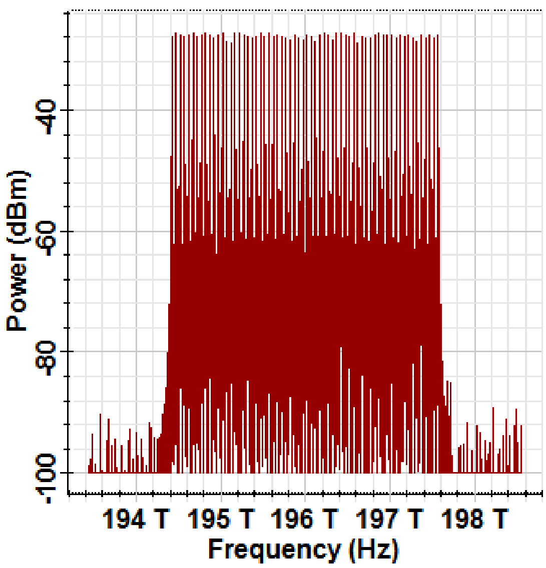

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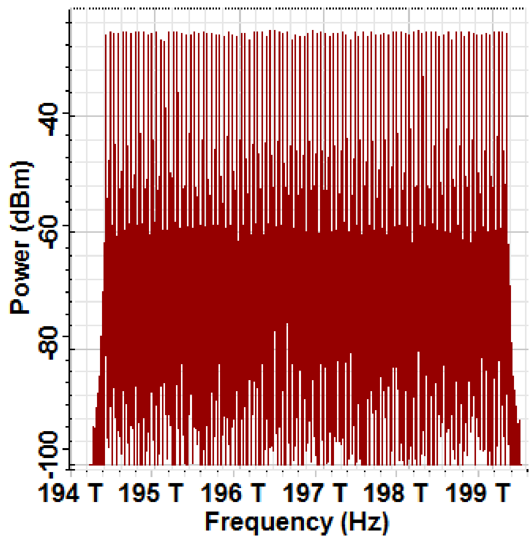

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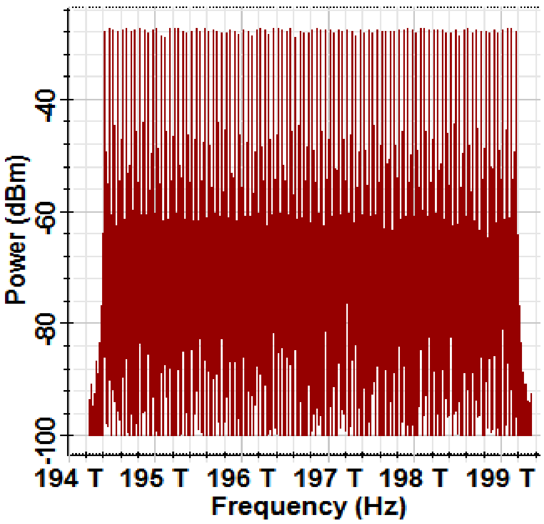
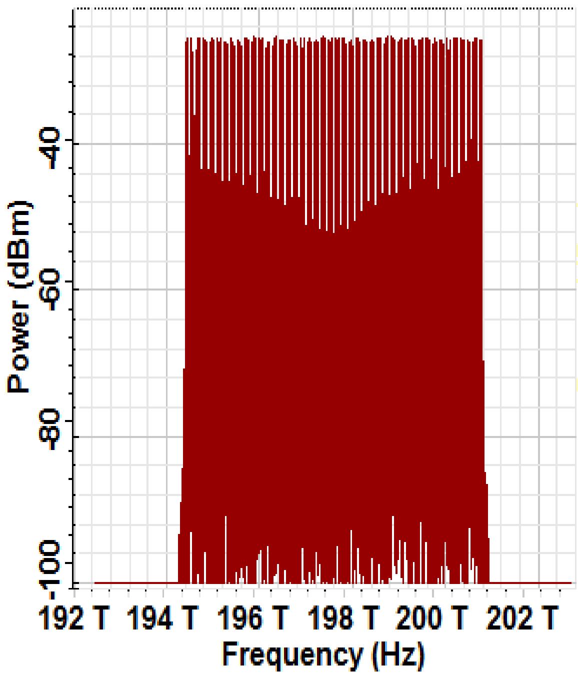
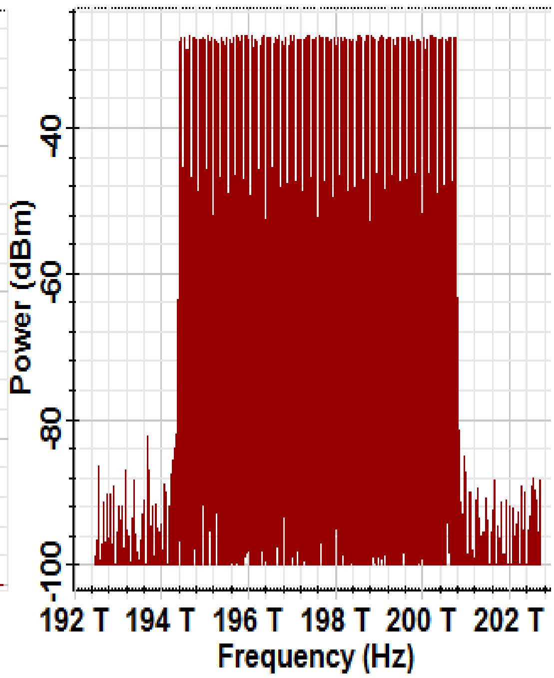


(f)



(g)



(h)

Figure3.3 Optical spectrum analyzer depictions before and after optical fiber respectively for (a) (b) 32 channels (c) (d) 64 channels (e) (f) 96 channels (g) (h) 128 channels

Figure 3.4 represents the illustration of four wave mixing with respect to the distance. FWM reduces at 50 km and maximum power of FWM is reported at less distance that is 10 km. Optical fiber has significant attenuation and as the fiber length is enhanced, attenuation becomes more degrading. As FWM is emerged due to high power in the SMF, so due to attenuation FWM observed less at higher distances. FWM is severe in case of 256 channels and reduces with the increase of distance and at less channels such as 32 WDM channels.

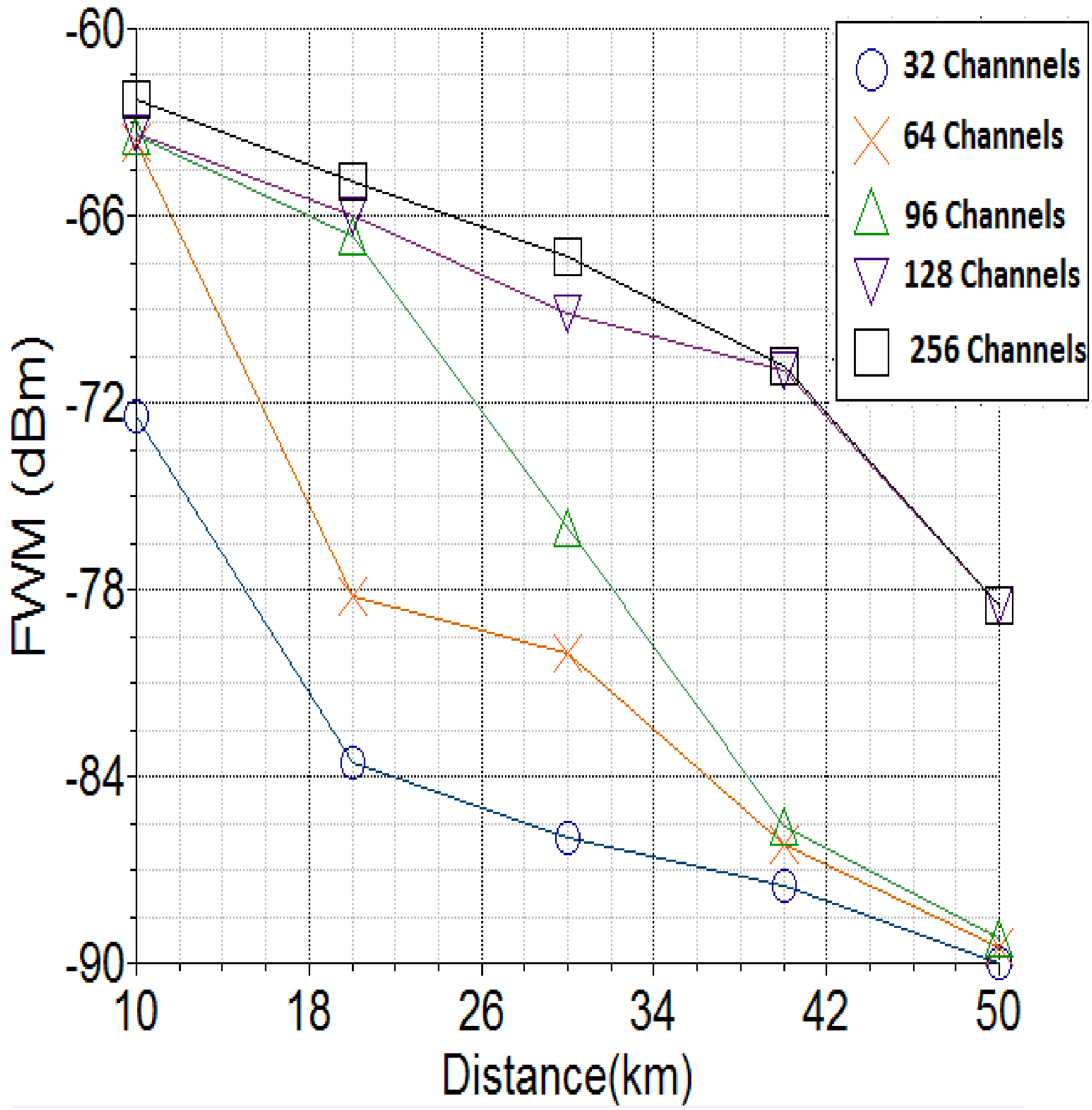


Figure 3.4 Representation of FWM power at different distances

Figure 3.5 depicts the variation of (BER) as a function of fiber length. At larger optical fiber length, more bit errors arises and tends to decrease when distance decreases. BER is inversely proportional to Q factor and it is noted that at maximum values of Q, BER is less and vice versa. 256 WDM exhibits maximum errors and 32 channels WDM system show minimum BER.

Further investigation has been carried out for diverse frequency spacing's among WDM 128 channels. Frequency spacing is altered from 50 GHz, 25 GHz, 12.50 GHz, 12.25 GHz and 6.125GHz. Figure 3.6(a) depicts the performance of WDM system for diverse frequency spacing at different loop lengths. Q factor for 50 GHz frequency spacing is maximum and for 3.125 GHz is minimum. Also as shown in fig 3.6 (b), FWM emerged for 3.125 GHz is high and less for 50 GHz

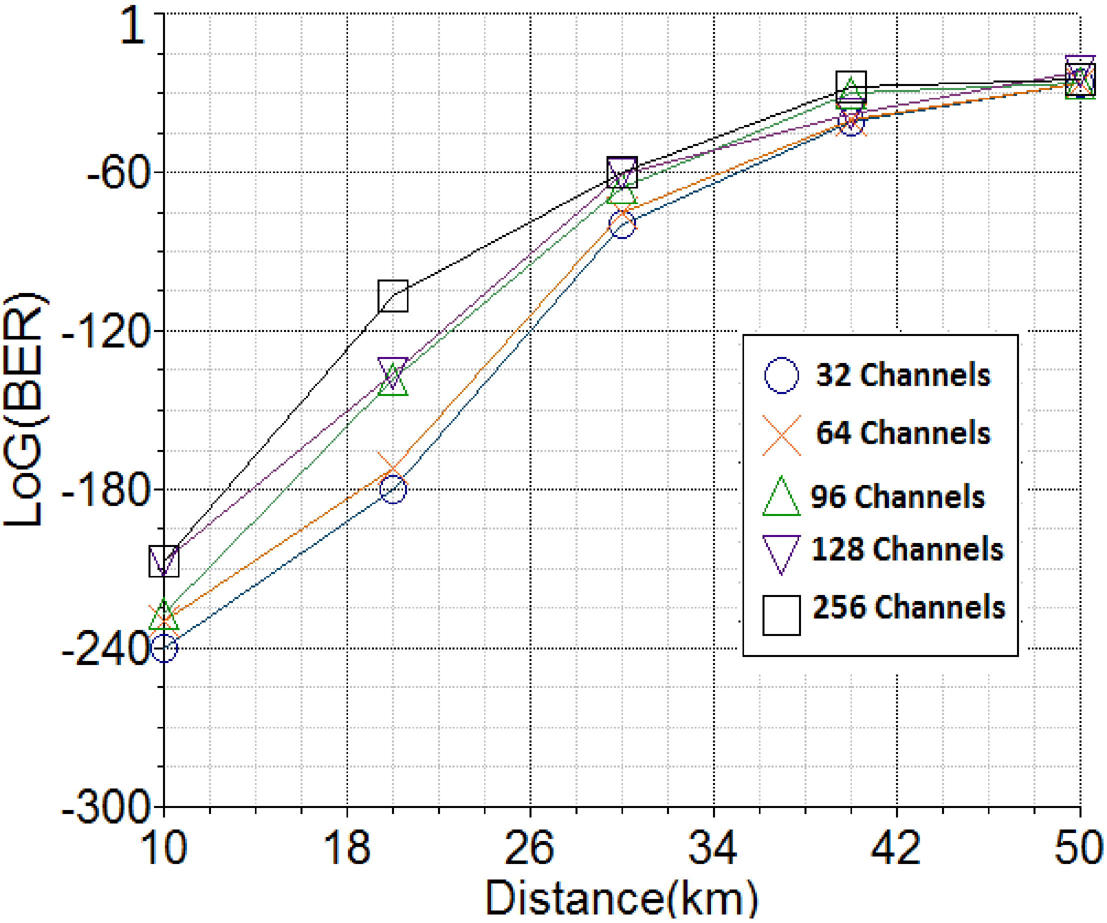
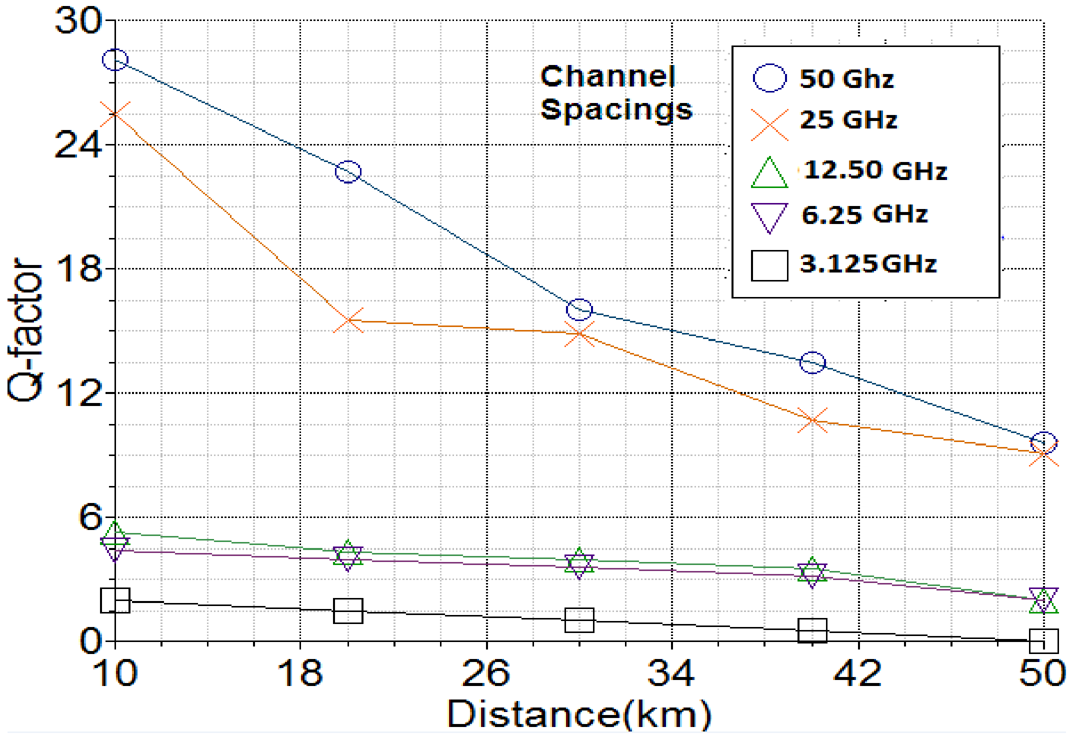
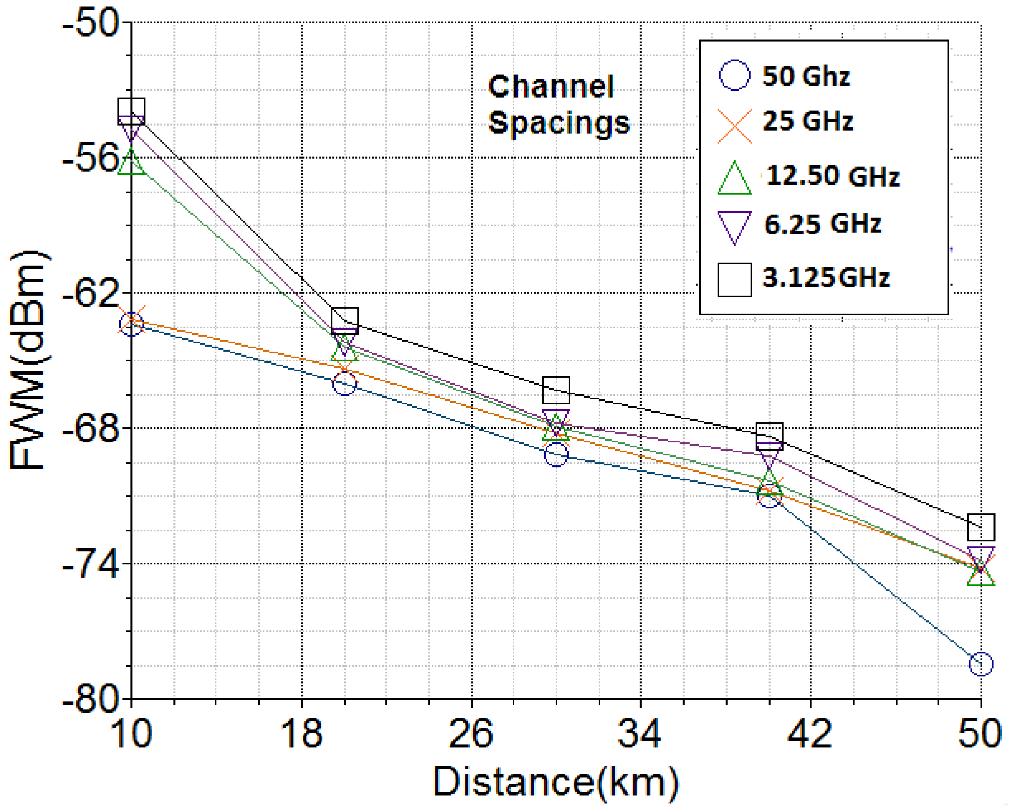


Figure 3.5 Graphical representation of BER versus distance for different WDM channels



(a)



(b)

Figure 3.6 Graphical representation of WDM system for (a) Q factor versus Distance (b) FWM versus Distance

Figure 3.7 expresses the graph and Table 3.2 shows values of FWM at different distances for different optical fibers such as single mode fiber and dispersion compensation fiber. Readings shows that FWM is more in DCF and less in SMF. But at higher distance due to more attenuation of DCF, FWM do not exceed SMF. Figure 3.8 and Table 3.3 shows the values of FWM at different effective areas of optical fiber. It is seen that at higher effective areas, FWM is less and vice versa.

Distance (km)	**SMF FWM**	**DCF FWM**
10	-86.51	-75.18
20	-87.1	-82.03
30	-86.4	-85.92
40	-90.2	-91.46
50	-91.92	-97.16

Table 3.2 FWM values for SMF and DCF

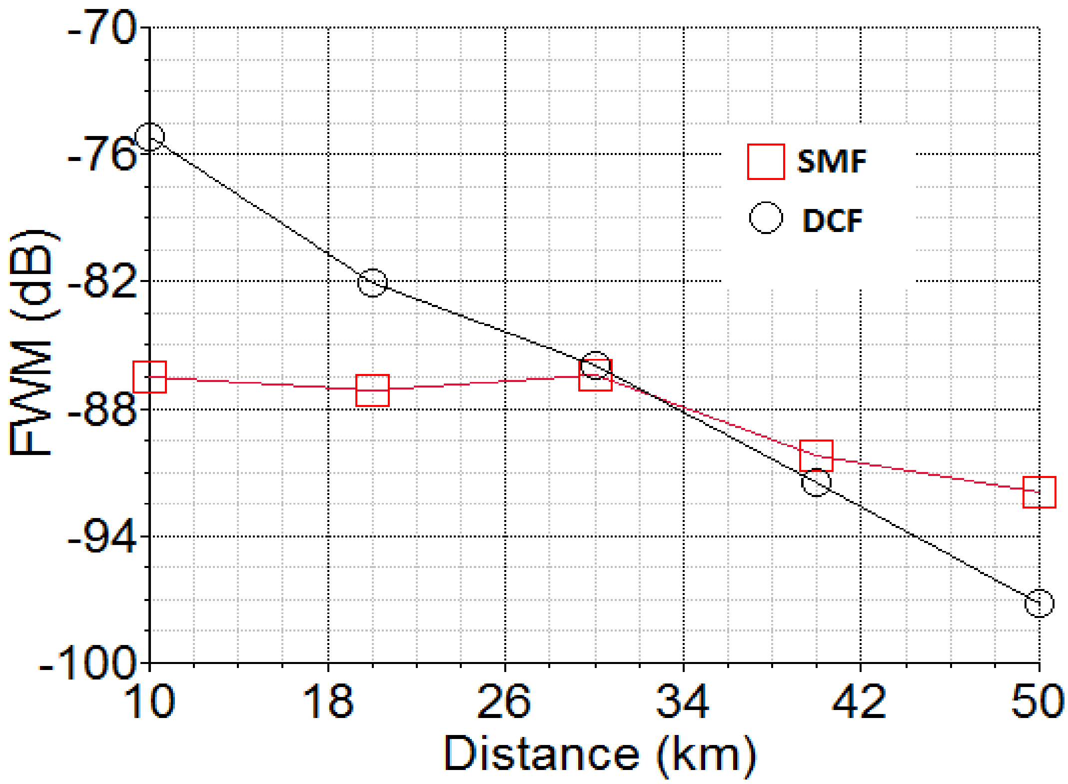


Figure 3.7 Graphical representation of WDM system for single mode fiber and dispersion compensation fiber

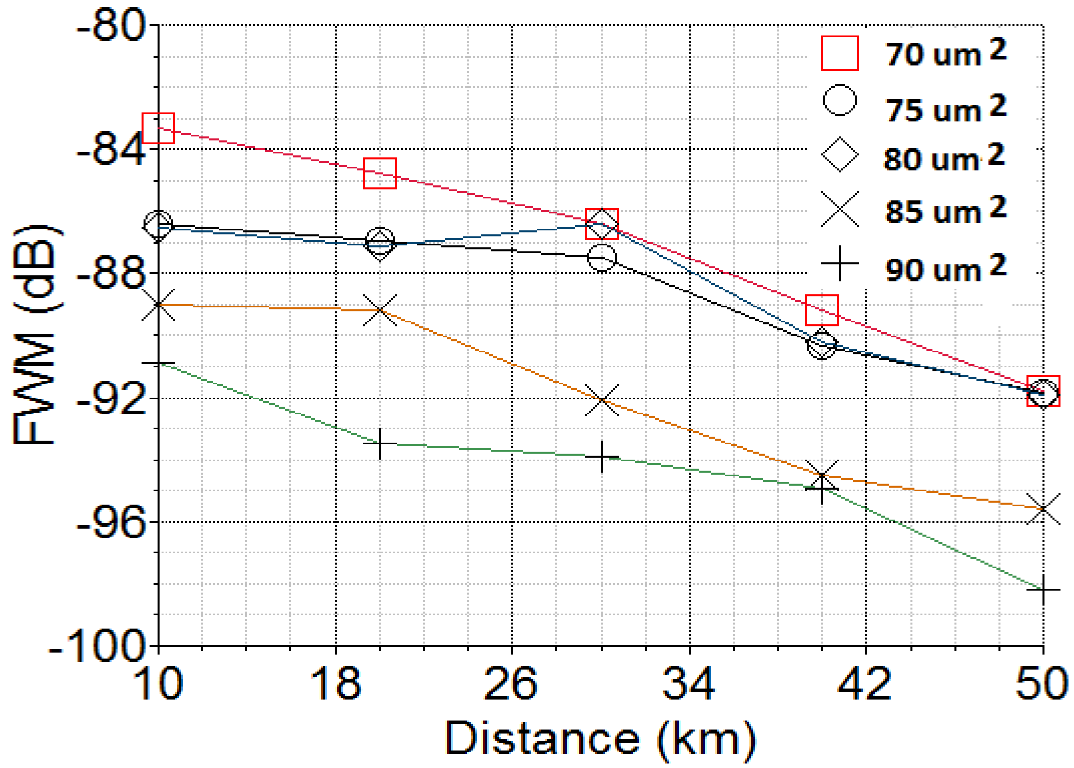


Figure 3.8 Graphical representation of WDM system for different single mode fiber effective areas

Distance(km)	70um^2	75 um^2	80 um^2	85 um^2	90 um^2
10	-83.32	-86.4	-86.51	-88.98	-90.87
20	-84.77	-86.97	-87.1	-89.2	-93.48
30	-86.42	-87.52	-86.4	-92.09	-93.91
40	-89.17	-90.35	-90.2	-94.5	-94.93
50	-91.79	-91.84	-91.92	-95.59	-98.19

Table 3.3 FWM values for different effective areas

Effect of power is also investigated and it is found that there is more FWM at higher launched powers due to power dependent refractive index of optical fiber. Figure 3.8 represents the Eye diagrams for WDM channels 256 and 32 channels. Eye opening is more in case of 32 channels and eye closer is more in 256 channels. Jitter is high for prolonged distances and due to FWM at 256 channels and less jitter is seen in the case of 32 WDM channels.

3.4 CONCLUSION

An ultra-dense and high capacity WDM system implementation has been investigated to analyse four wave mixing and also results are evaluated in terms of Q-factor and BER. Distances for FWM emergence is considered as 10 km – 50 km and it is observed that FWM show maximum degrading effects at 10 km and decreases as the distance increases due to attenuation. It is evident that with the decrease in the channel spacing to pack more information signals, under the effects of FWM, degraded results are observed. Results revealed that FWM is less for 32 WDM channels, 50 GHz frequency spacing, single mode fiber, large effective area of SMF (80 um^2). Launched power should be kept low to quell the effects of FWM and it is prominently observed that at high launched powers, FWM emerges more. However, in this work, no optical amplifier is incorporated in the system and FWM in optical amplifiers is beyond the scope of this work.

CHAPTER 4
TO INVESTIGATE THE PERFORMANCE OF DIFFERENT ADVANCED MODULATION FORMATS IN ULTRA HIGH CAPACITY WDM SYSTEM

In this work, performance analysis of high capacity and high speed WDM has been done by incorporating different linecoding and advanced modulation formats. A 96 channels WDM system is investigated for different distances and validated in terms of Q- factor, BER. Advanced modulation formats such as compressed spectrum return to zero (CSRZ), duo-binary return to zero (DRZ) and modified return to zero (MDRZ) are incorporated in the system to compare them in terms of induced FWM. Non return to zero (NRZ) and return to zero (RZ) are also used to check the FWM tolerance of modulation formats. Analysis is carried out at different input powers, laser line-widths and link lengths. Results revealed the DRZ is maximum tolerant to FWM effects and NRZ is maximum prone to FWM.

4.1 INTRODUCTION

With the development of the services reliant on internet augmented, there is peer pressure on the optical networks to exhibits enhanced data rate and make high speed system. There is a significant growth of the wideband application that introduces an extensive change in the triple play services [42]. Fiber optic communication has numerous advantages and considered as the only medium to support transmission of large number of channels as well as data rates in a easy and dynamic way [43]. System that uses fiber optic as a medium is very popular and attracted attention because of its ability to cater ever increasing demands in OFC. Major equipments or components to make speedy and flexible networks are optical switches and wavelength converters etc. [44]. To pack large number of channels and realize a high capacity system, a prominent and premier technique is used also referred as dense wavelength division multiplexing [45]. Also the aforementioned scheme is well competent and has a potential to use the available bandwidth efficiently. Principle of this method is to incorporate wavelengths to carry the several information signals on diverse wavelengths [46]. In order to accomplish better communication and to enhance the performance of the system, it is necessary to comprehend the degrading effect such as nonlinearity in the wavelength division systems. The degradation or deterioration in the fiber optic medium are nonlinearities and introduces the attenuation, crosstalk and also severely deteriorate the performance of the system. Basic principle of the emergence of non-linearities is the change of refractive index because of the accumulated power in the fiber optic. It is the major reason for the occurrence of these effects. Kerr's principle is a fundamental principle that explains the behaviour of these effects and stated as the further variants that introduces in the fiber such as self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM) [18]. FWM effect represents the fluctuation of refractive index when more than one frequency is simultaneously travelling through fiber optic and generates the new frequency signals that limit the overall performance of wavelength division multiplexing systems [19] as well as affects the extinction ratio [20]. In multi-channel systems, FWM is a major performance deteriorating non-linearity that arises due to power accumulation of WDM channels inside single optical fiber and also has effects of chromatic dispersion. Also the frequency spacings plays vital role and emergence of FWM is maximum in the WDM system with even spacing. It is because of the reason that the new waves generated by FWM will fall at channel frequencies in addition will give rise to crosstalk. Frequency components of new signals are generated due to the mixing of carrier signals in FWM process [10]. Amplitude of the new generated components relies on the frequency spacings, launched powers and fiber dispersion. It is also reported from previous researches that FWM has negligible effect on bit rate [15]. FWM in WDM systems should not be present; however, this limitation becomes the application in some cases. Major applications of FWM are such as the generation of multiple carriers from two carriers in semiconductor optical amplifier or fiber optic, wavelength converter, anti-jamming etc.

By studying the literature of the fiber optic and suppression of FWM, we came across following points such as low input power, wide frequency spacing, non- zero dispersion and change of polarization between adjacent channels. But these methods restrict system to support high data rates and to achieve longer distance. So, to overcome these issues, optical modulation formats are the key components. Modulation formats are bandwidth efficient, and also less vulnerable to noise induces due to phase. Consequently, it permits the accommodation of more number of channels as well as addition at dense spacing's in WDM system. These technologies are capable to support high data rate such as 40 Gbps and can allow implementing dense wavelength division multiplexed system. Moreover, advanced modulation formats have several advantages such as high security, information carrying capacity and flexibility.

4.2 SYSTEM SETUP

The simulation setup for studying the effect of four wave mixing (FWM) using different modulation formats is shown in figures 4.1. WDM system with 96 channels at bit rate of 10 Gbps in each channel is designed at frequency spacing 50 GHz. The transmitter consists of CW lasers used to create the signal of particular frequency. Starting frequency or the first user is operated at 193.1 THz. In order to generate tributaries of binary signals, a pseudo random sequence generator is used and operated at the data speed 10 Gbps. A continuous wave laser is placed in the system to modulate the data from NRZ into optical domain. For the conversion of data into optical domain, a MZM modulator is placed between laser and data format. Advanced modulation and line-codings used here are NRZ, RZ, CSRZ, DRZ and MDRZ. After data is modulated on the laser signal of different wavelengths, combined with the component called mux and fed into the optical fiber. Here, in this work, link length of SMF is considered 50 km. At the receiver, the signal is de-multiplexed by using a de-mux. At the receiver side the photo-diodes are used. After that signal is transmitted via a low pass Bessel. BER analyser is kept at receiver to scrutinize the eye diagram and Quality factor. Spectrum analysers are incorporated in the system to depict the FWM and carriers.

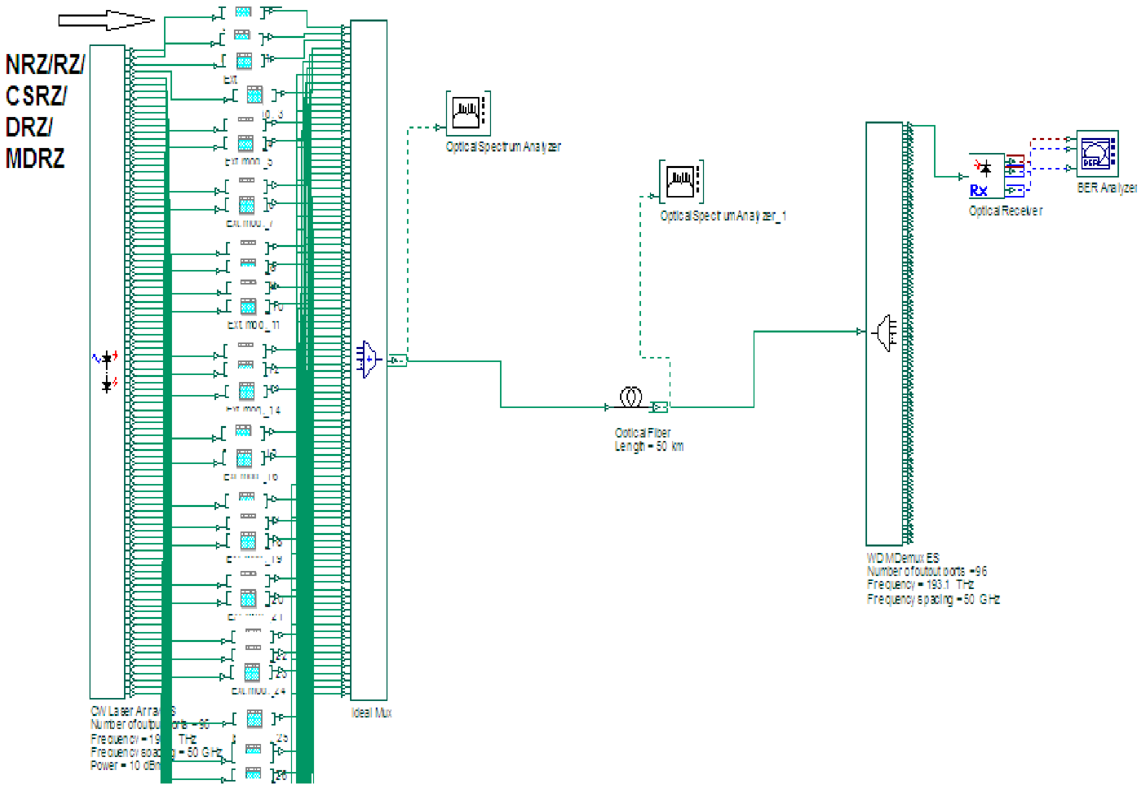


Figure 4.1 Proposed system setup for different advanced modulation formats

4.3 OBSERVATIONS

Proposed WDM system for different line-coding and advanced modulation formats are investigated for different distance, laser powers and laser line-widths. Figure 4.2 represents the performance of the system in terms of Q factor for different link lengths. It is prominently observed that there is significant deterioration in quality of the signal as distance prolongs. Major factor is attenuation that introduces due to signal transmission over single mode fiber. Return to zero line-coding performance is observed best out of all other formats due to better tolerance of RZ to nonlinear effects. However, till the distance of 40 km, RZ performs better but after this distance duo-binary return to zero exhibit better performance due to more spectral efficiency. In 96 channel and dense WDM system least performing modulation format is observed as modified return to zero modulation format.

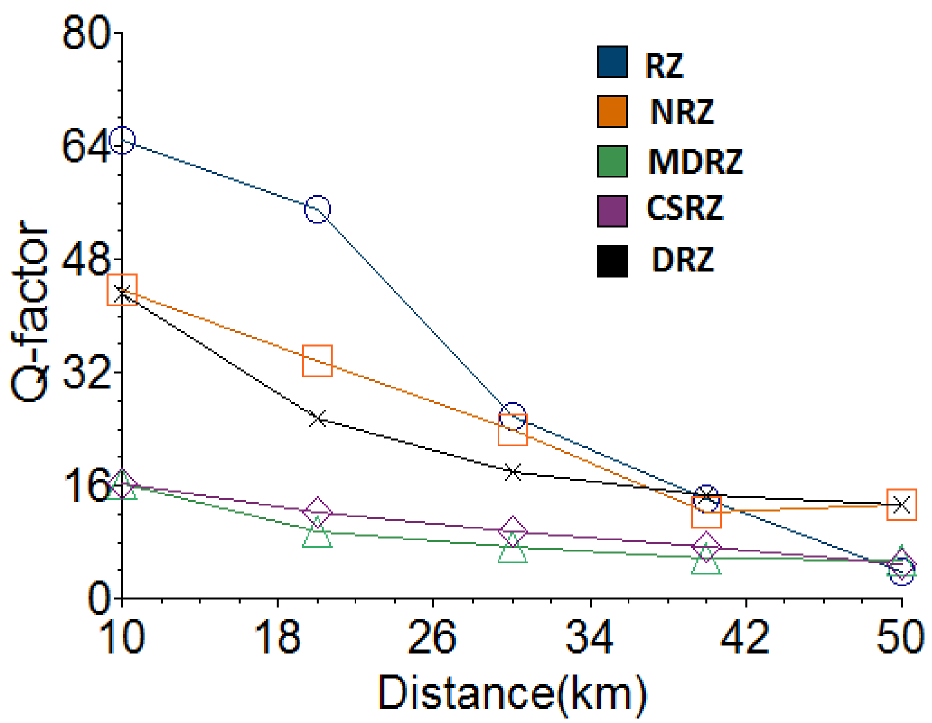


Figure 4.2 Graphical representation of Q-factor versus distance

Figure 4.3 depicts the four wave mixing emergence with the increase of distance and distance is increased from 10 km to 50 km. It is evident that FWM component power decreases as the distance prolongs and minimum FWM is reported for compressed spectrum return to zero modulation formats after 20 km. But from the results it is observed that duo-binary return to zero show better tolerance to FWM and very less fluctuation if FWM component is reported. Non return to zero is maximum prone to four wave mixing and thus not recommended for proposed system. Further the launched power is varied in the system to investigate effect of modulation formats in dense WDM system with Q factor as depicted in figure 4.4. It is evident that improvement in input power levels, improve the Q factor for all modulation formats.

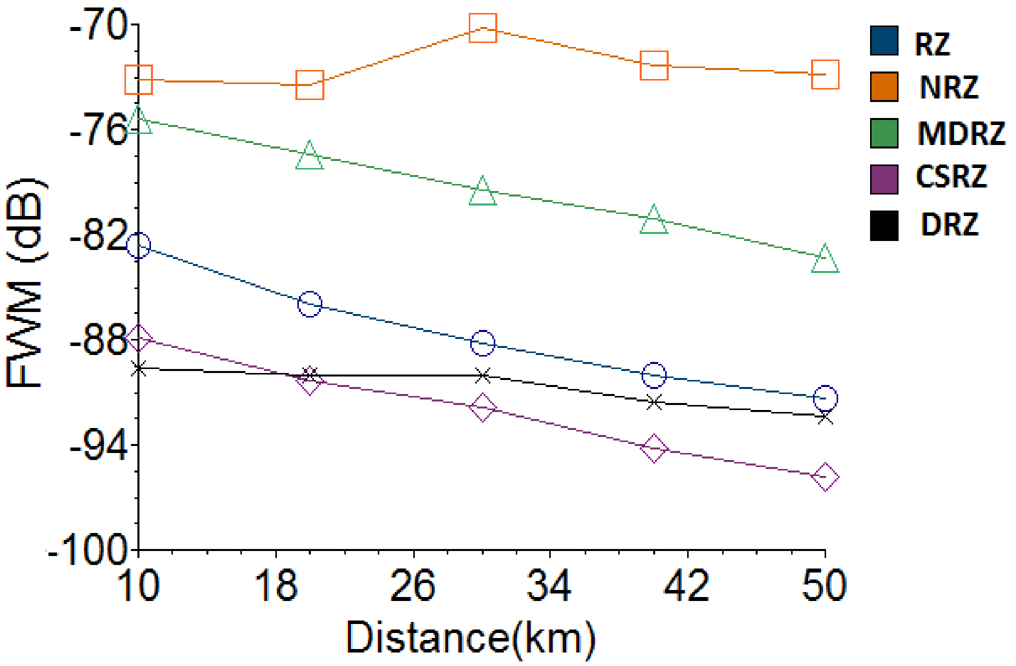


Figure 4.3 Four wave mixing powers at different distances for diverse modulation formats

Q of DRZ modulation format increases maximum due to the less dependence or fluctuation of FWM in this modulation and thus performs best in the 96 channel WDM system. Q factor of NRZ and RZ decreases at higher power levels because at high power there is less tolerance of these modulations to FWM.

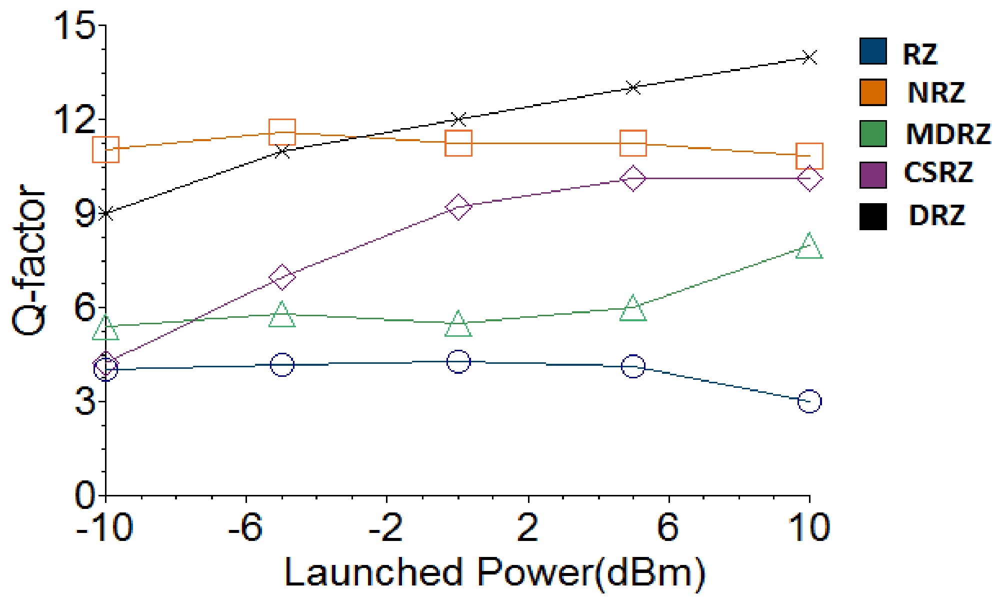


Figure 4.4 Q-factor versus launched powers

Also at diverse input powers, FWM components are also seen and it is evident that minimum four wave mixing emerged in case of modulation format DRZ and with power levels FWM components increased in DRZ along with all formats. Non return to zero is maximum prone to FWM and it is severe at high power levels. It is represented in figure 4.5 moreover, laser line-width of laser plays an important role in the optical communication systems and analyzed for proposed work.

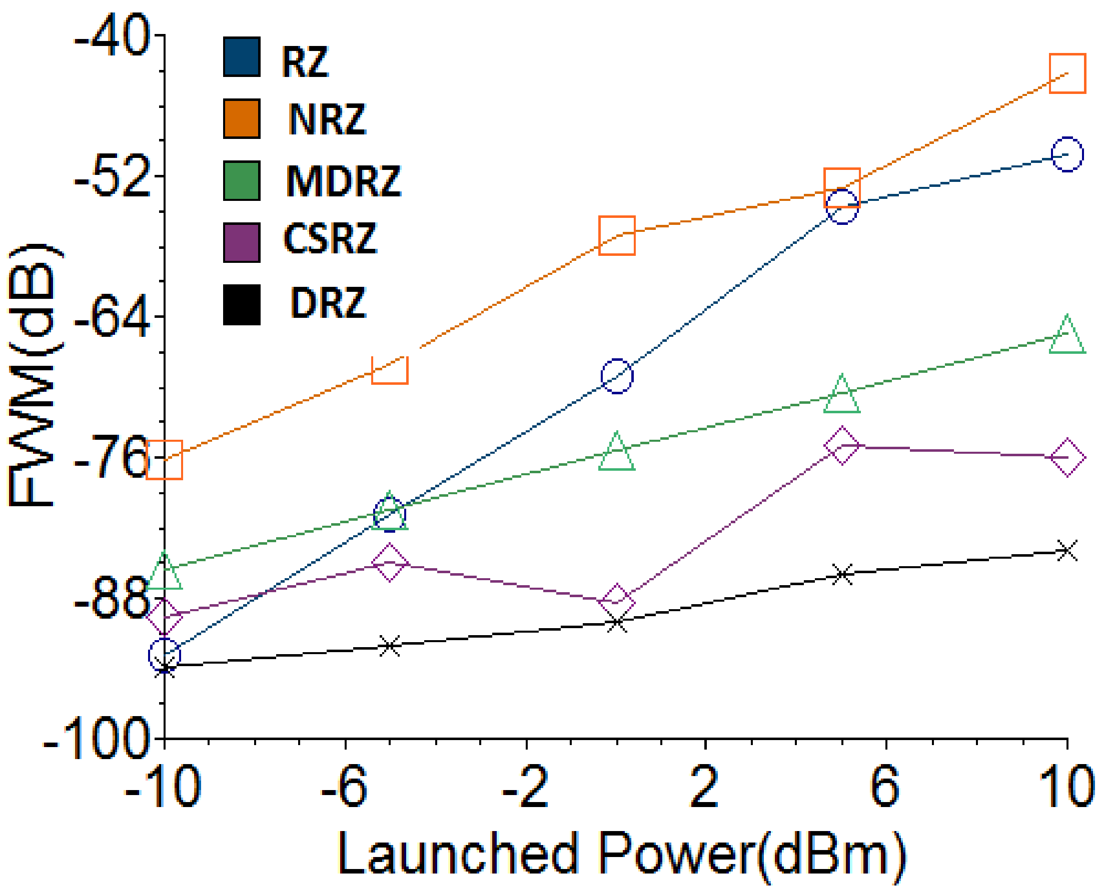


Figure 4.5 FWM components at different launched power levels

Laser line-width is varied from 0 MHz to 150 MHz and Q-factor is observed first as represented in figure 4.6. Q-factor values are maximum at 0 MHz for all formats and decrease as the line-width broadened. Non return to zero and DRZ performs and exhibits close results of Q factor and are best formats. Major degrading effects of line-width are seen on RZ and CSRZ. It is evident that low laser line-widths introduce more FWM due to the high power carrier effects of more SMF. Figure 4.7 depicts the FWM component with laser line-width as results revealed that DRZ tolerance to FWM is more and MDRZ is least for different line-widths.

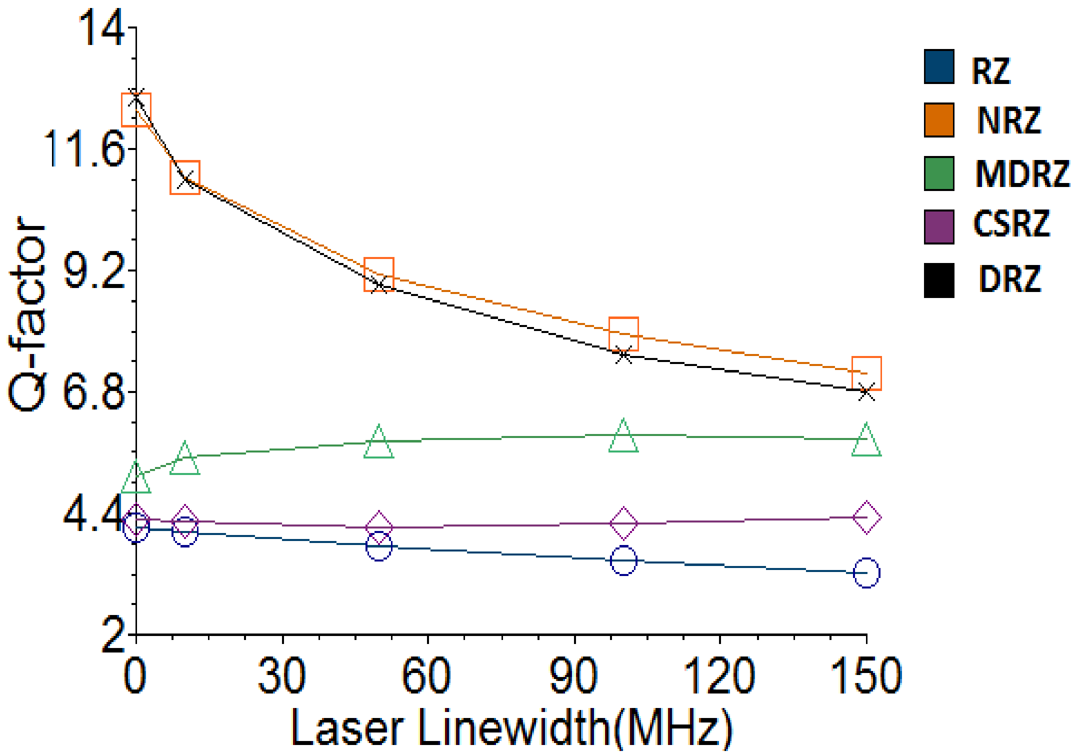


Figure 4.6 Graphical representation of Q factor at different laser line-widths incorporating diverse modulation formats

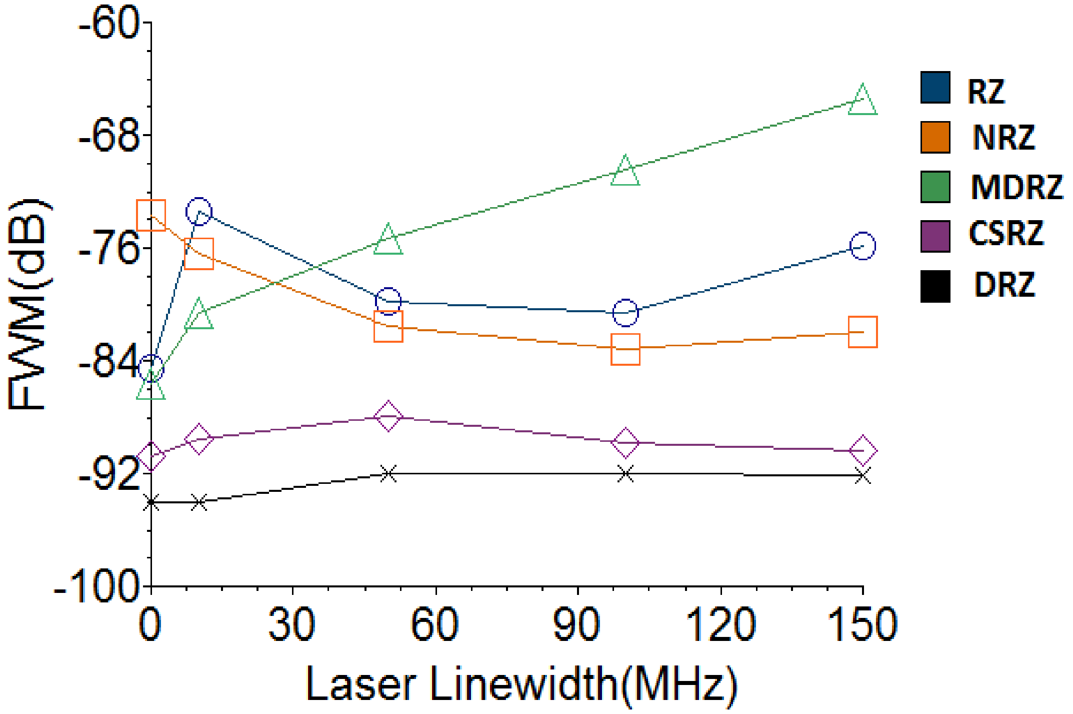


Figure 4.7 Graphical representation of FWM at different laser line-widths incorporating diverse modulation formats

4.4 CONCLUSION

In this chapter, the demonstration and investigation of FWM in wavelength division multiplexed system is carried out by using different line codings and advanced modulation formats in 96 channel system at 10 Gb/s. The level of components of FWM that emerged in the system is considered for each and every modulation separately. Performance evaluation of the FWM by incorporating advance modulation formats are shown by changing the link distance of optical fiber that effects the four wave mixing at the output and FWM decrease as the distance prolongs. Changing the line codings and advanced modulation formats effects the four wave mixing. DRZ gives the least four wave mixing on different distances, input powers and laser line widths. On changing the modulation formats, the FWM is largely affected in terms of components and power induced in the system. The DRZ found out to be best and NRZ is considered to be maximum affected by FWM. So, it is suggested to use the DRZ advanced modulation format to suppress the effects of FWM.

CHAPTER 5

TO DESIGN AND COMPARE THE PERFORMANCE OF WDM SYSTEMS WITH DIFFERENT PLACEMENTS OF OPTICAL PHASE CONJUGATIONS

In this work, a suppression method of FWM is proposed using optical phase conjugation (OPC) and different placements of OPCs are also investigated. Moreover, comparison of the placements of OPC in two different cases has been done and compared with conventional WDM system in terms of Q factor, BER and induced FWM. Analysis has been done at different link lengths, launched powers levels and laser line widths. It is observed that placement of OPC after laser source performs exceptionally well and suppresses FWM with ease of maintenance.

5.1 INTRODUCTION

In expeditious development of optical fiber communication, the need for information capacity carrying systems is more because of augmentation in services reliant on internet, video on demand and cloud computing. Proliferation of optical fiber technology is reported from last few years due to the numerous advantages such as tremendous transmission capacity, speed, immunity to electro-magnetic interferences (EMI) and security. Wavelength division multiplexing (WDM) is a promising technology to cater the demands of multi users by packing more dense channels. However, optical fiber communication suffers from linear (attenuation, dispersion) and nonlinear loses. Optical fiber nonlinearities are limiting factor in signal transmission and also restrict the data carrying capacity of the system. Major deteriorating Kerr's effect reliant non-linearities are four wave mixing (FWM), Self-phase modulation (SPM), Cross phase modulation (XPM). Main cause of the emergence of nonlinear effects is the power dependence of refractive index of optical fiber. In order to accomplish long haul transmission, these factors need to be addressed. In multi-channel systems, FWM is a major performance deteriorating nonlinearity that arises due to power accumulation of WDM channels inside single optical fiber. FWM effect represents the fluctuation of refractive index when more than one frequency is simultaneously travelling through fiber optic and generates the new frequency signals that limit the overall performance of wavelength division multiplexing systems. Numerous researches has been reported till now to suppress the FWM effects in WDM systems using unequal spacing [60], non-zero dispersion fiber (NZ DCF) [61], hybrid modulators [62], dispersion management [63], time delay lines in multiplexer and DE multiplexers [64], bit-phase arranged return-to-zero signals [65] techniques. The aforementioned all techniques are either increasing the complexity of the system or limit the channels efficiency. In several research works, optical phase conjugation was incorporated in the middle of the transmission line to combat with the nonlinear effects and pulse broadening (Dispersion) issues [66-67]. OPC becomes a right candidate to quell the four wave mixing in WDM systems by phase reversal properties and suppress the nonlinear effects. However, the maintenance of transmission modules consisting of OPC is hard and also increases the complexity of the system. So, a way out is required to place the OPC in order to reduce complexity and maintenance related concerns. In this work, an optimal placement of optical phase conjugation is proposed to suppress the FWM effects to greater extent and less maintenance related issues. Moreover, comparison of the placement of OPC in three different cases has been done in terms of Q factor, BER and induced FWM.

5.2 FOUR WAVE MIXING

FWM is a kind of optical parametric oscillations and based on principle of Kerr's effect. This is a major performance deteriorating issue in wavelength division multiplex systems. Four- Wave Mixing introduces crosstalk, performance degradation and is comprehended by nothing the side frequency peak that is emerged due to phase mismatch of travelling optical pulses as shown in (5.1). This condition arises when the three frequencies simultaneously propagate in the optical fiber as expressed in (5.2).

$$\omega_{ijk} = \omega_i + \omega_j - \omega_k \tag{5.1}$$

$$\omega_i, \omega_j, \omega_k \tag{5.2}$$

When the case of equal channel spacing of WDM is considered, a coherent in-band crosstalk occurs. Major reason of in-phase crosstalk is that the new generated frequency coincides with the already present frequencies. On contrary, in the case of unequal channels spacing, a non-coherent out of phase crosstalk induces due to the placement of FWM frequency in between the channels. Power loss and performance degradation of WDM system occurs in both cases. If total FWM products are denoted by M and N is the total number of channels, then equation is written as (5.3)

$$M = \frac{1}{2}(N^3 - N^2) \tag{5.3}$$

If we further consider three channels travelling inside optical fiber and contributing FWM remains un-depleted and the attenuation, dispersion effects are incorporated, then the amplitude is expressed as (5.4)

$$\frac{dA_F}{dz} = -\frac{\alpha}{2}A_F + d_F\gamma A_i A_j A_k \exp(-i\Delta kz) \tag{5.4}$$

where $A_m(z) = A_m(0)\, e^{(-\alpha z/2)}$ for m = i, j, k and $d_F = 2-\delta_{ij}$ is the degeneracy factor stated as the value approaches to 1, when i = j, however it becomes two times, when $i \neq j$. This expression can be incorporated to attain A_F (z). FWM component power experienced by link length of optical fiber is given as (5.5)

$$P_F = [A_F(L)]^2 = \eta_F (d_{F\gamma} L)^2 P_i P_j P_k \exp -\alpha L \tag{5.5}$$

Where the input power in the m_{th} channel and FWM is η_F are expressed in terms of power as (5.6)

$$P_m = |A_m(0)|^2 \tag{5.6}$$

The term η_F is represented as (5.7)

$$\eta_F = \{\frac{1-\exp(-(\alpha+i\Delta k)L}{(\alpha+i\Delta k)L}\}^2 \tag{5.7}$$

Channel spacing is a key factor to determine the FWM efficiency and mismatch of phase is as shown in (5.8)

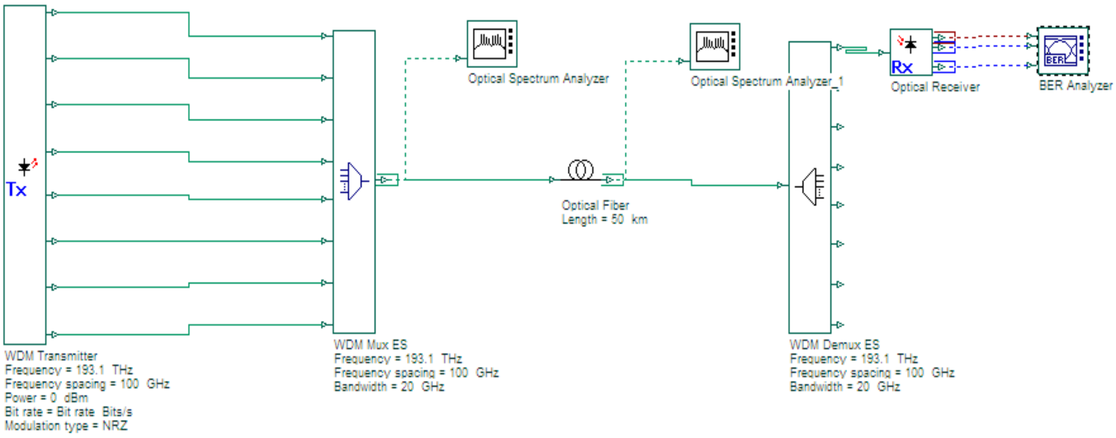
$$\Delta_k = \beta_F + \beta_k - \beta_i - \beta_j \approx \beta_2(\omega_i - \omega_j)(\omega_j - \omega_k) \tag{5.8}$$

Consequently, with the augmentation of more number of WDM channels, four-wave mixing will contribute its utmost indulgence. Therefore, it is essential to take care of four-wave mixing while designing the high capacity and ultra-dense WDM systems.

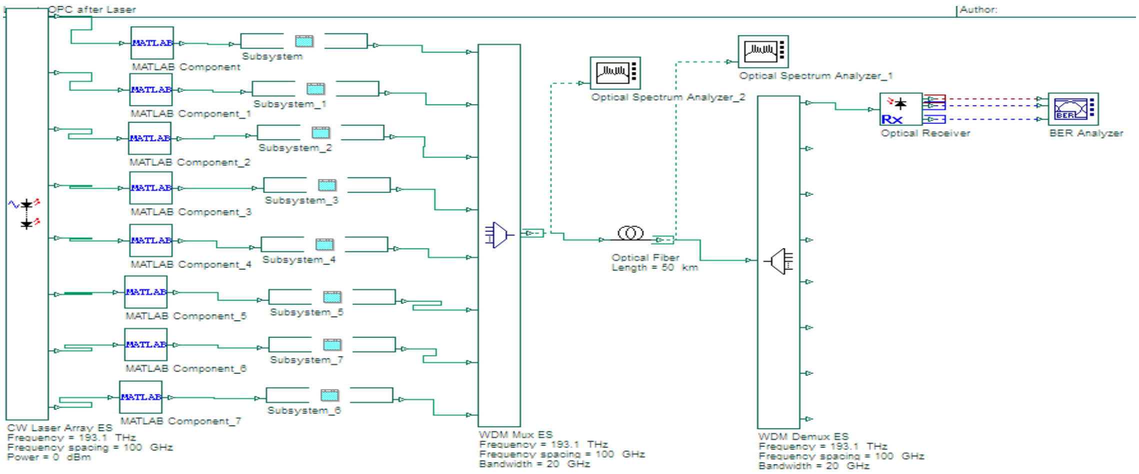
5.3 SYSTEM SETUP

The three proposed system architectures for wavelength division multiplexing (WDM) system and with or without placement of optical phase conjugation is depicted in Figure 5.1(a), 5.2 (b), 5.2(c). A WDM system that consists of 8 channels and 10 Gbps data operated in C-band due to less attenuation (0.2dB/km) and scattering. A continuous wave laser with starting frequency 193.1 THz is used with 10 MHz line width at 0 dBm launched power. Non-return to zero pulse formats is to provide pulse shape to the binary data sequence from pseudo random bit sequence generator. Mach-zhender modulator is incorporated for E/O of the data and output of each MZM is multiplexed through optical

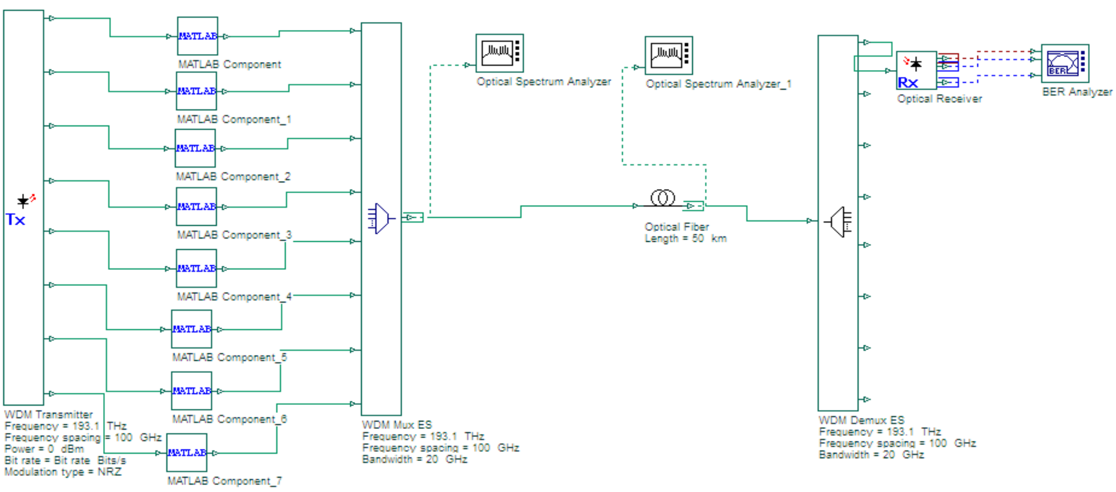
MUX of 8:1. Single mode fiber (SMF) of 50 km is placed after multiplexer followed by de-multiplexer to route particular wavelength to respective output port.



(a)



(b)



(c)

Figure5.1 System setup of proposed setups (a) conventional WDM (b) OPC after Laser (c) OPC after Transmitter

The receiver part consists of the photo-detector p-i-n and low pass Bessel filter. BER analyzer is the decision component and provides values for Q and bit error rate. Figure 5.1 (a) represents the conventional WDM system with no OPC across transmission line and Figure 5.1 (b) depicts the placements of OPC after continuous wave laser and Figure 5.1 (c) shows the OPC in the system after each transmitter.

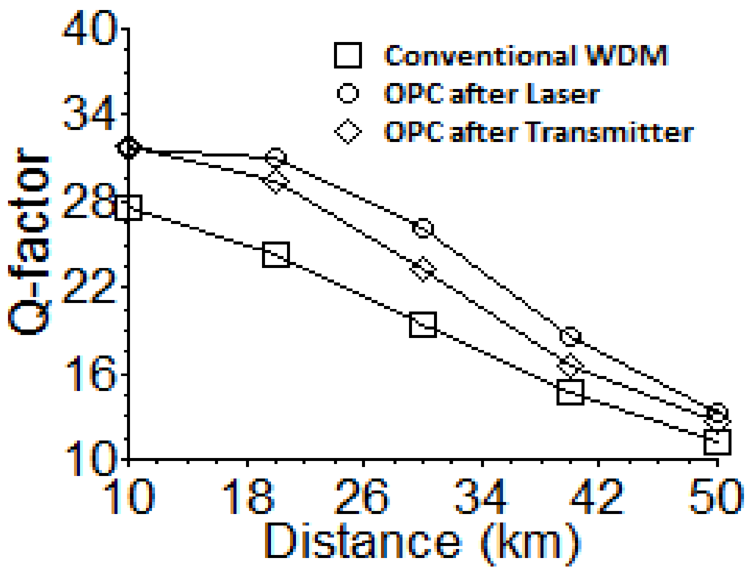
5.4 OBSERVATIONS

Investigation of an 8 x 10 Gbps WDM system is carried out with different placements of OPCs in the system and without OPC to evaluate the emergence of FWM. Also analysis has been done for different link lengths, input power levels and laser line widths in terms of Q-factor and BER. Table 5.1 describes the Q factor of three proposed arrangements at different link lengths. It is observed that as the link length prolongs, Q decreases due to attenuation, dispersion and nonlinear effects. In case of conventional WDM system, Q factor reported is least as compared to other two systems in which OPCs are used. Maximum Q has been seen for system which incorporates OPC after laser and performance of system after transmitter OPC is exhibiting medium Q factor. Figure 5.2 (a) depicts the graphical representation of proposed systems at varied link lengths. BER is also calculated for link lengths and increases as the distance increases. BER varies inversely to Q-factor, as at the points where Q maximum, BER reported minimum and vice versa. Enhanced bit error rate performance is obtained for system that has OPC after laser and maximum errors are observed for conventional WDM system as shown in Figure 5.2 (b).

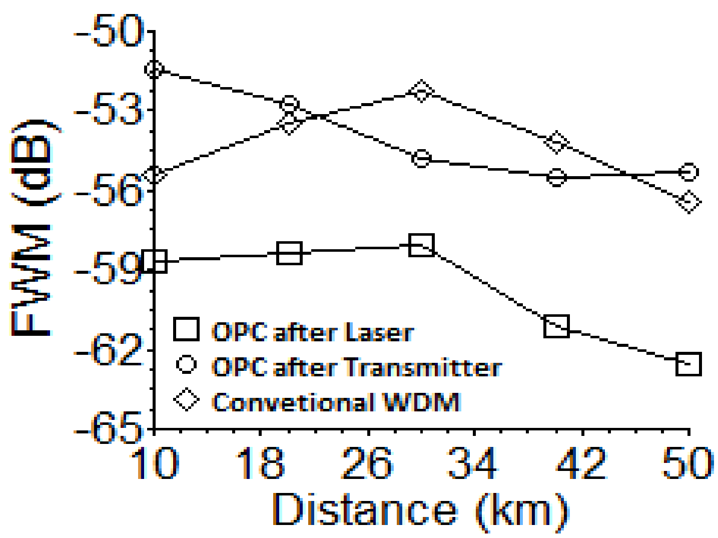
Distance (km)	**Conventional WDM**	**OPC after CW laser**	**OPC after Tx**
10	27.52	31.57	31.75
20	24.25	31.06	29.29
30	19.41	26.1	23.25
40	14.67	18.5	16.46
50	11.32	13.18	12.69

Table 5.1 Quality factor of three proposed systems at different distances

FWM power is emerged where minimum FWM component is seen in the OPC after laser setup and highest without OPC system. The property of OPC is that it reverses the phase of the incident signal and as signal travelled through SMF, phase starts to change again similar to transmitter. Moreover, FWM is investigated for different levels of launched powers for WDM with and without optical phase conjugation modules. Input power is varied from -10 dBm to 10 dBm. Figure 5.3 represents that the increase in launched power levels, generate more FWM components and also increase their power. Values of FWM are observed for conventional WDM system are -80.11 and -40.28 dB at -10 and 10 dBm input power levels.



(a)



(b)

Figure 5.2 Graphical representations of proposed WDM systems at different distances with (a) Q-factor (b) LoG (BER) (c) FWM

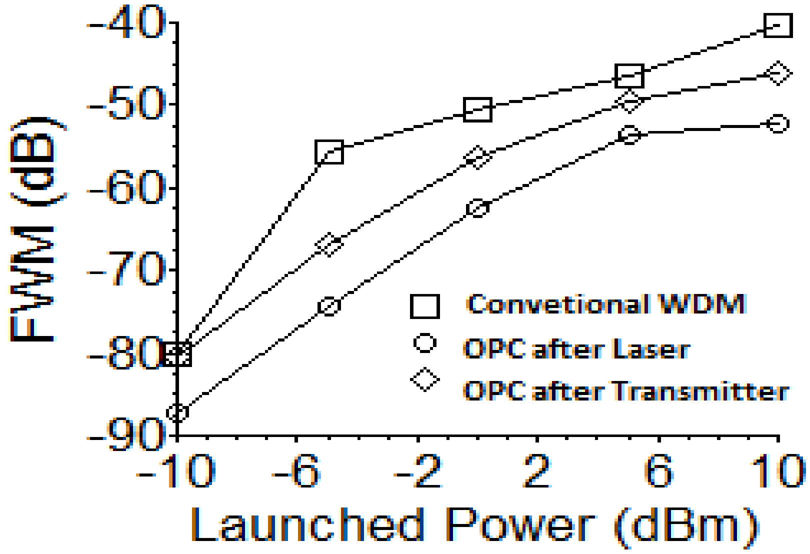


Figure 5.3 Representation of FWM for different launched power levels

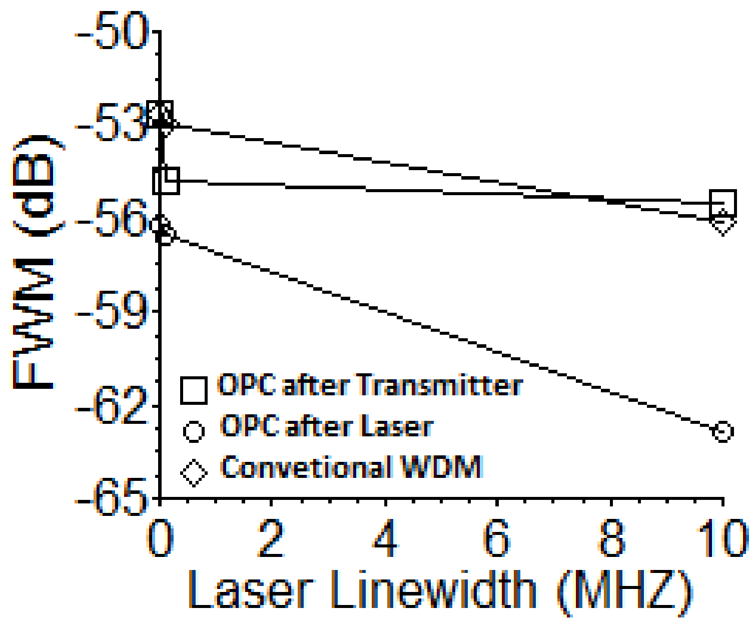
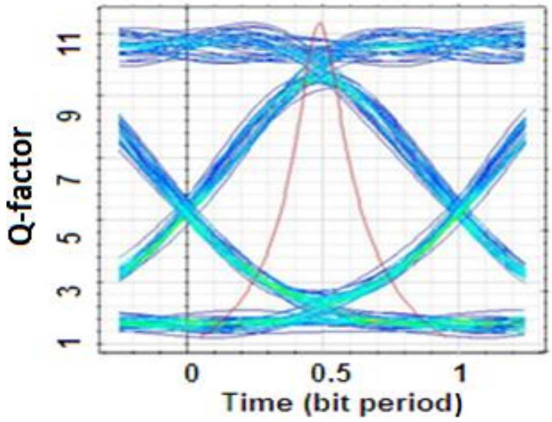


Figure 5.4 Laser line width versus FWM

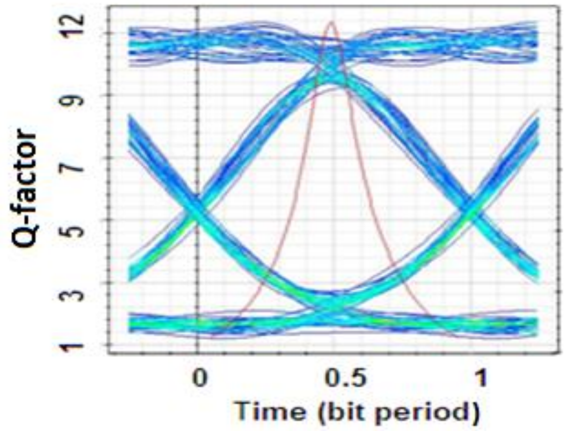
Laser Line width (MHz)	**Conventional WDM**	**OPC after CW laser**	**OPC after Tx**
0	-52.64	-56.23	-52.65
0.1	-54.78	-56.54	-52.97
10	-55.56	-62.9	-56.16

Table 5.2 FWM Values of three proposed setups at different laser line widths

Figure 5.5 (a), (b), (c) represents the Eye diagram of all the three setups at 50 km link distance and it is prominently observed that more eye opening is seen in case of the WDM system incorporated OPC after laser followed by system contains OPC after transmitter.



(a)



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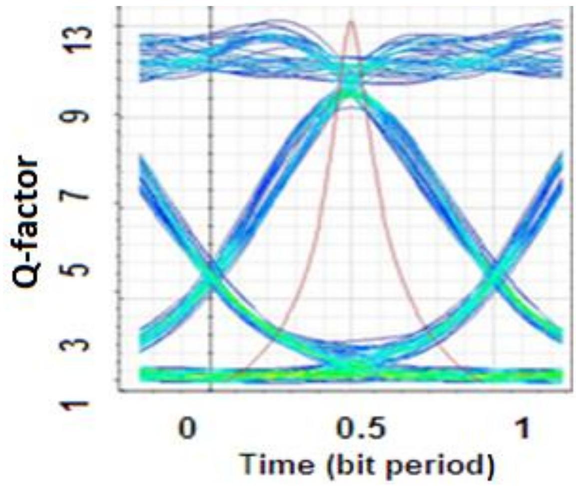

(c)

Figure 5.5 Eye diagrams at 50 km link distance for (a) Conventional WDM (b) OPC after transmitter in WDM (c) OPC after Laser in WDM system

Similarly for the system incorporating OPC after transmitter and after laser exhibit values such as -80.38 and -46.04 dB and -87.2 to -52.37 respectively. Consequently, WDM system with OPC after laser shows best performance in FWM suppression and system without OPC provide maximum FWM power components.

Figure 5.4 depicts the analysis of system for diverse laser line widths such as 0 MHz, 0.1 MHz and 10 MHz in terms of FWM induced. Table 5.2 shows the values of FWM at different laser line-widths and it is concluded from the observations that at 0 MHz laser line-width, FWM power is maximum for all the proposed system architectures. However, it is due to reason that laser having 0 MHz line-width effect the refractive index of optical fiber at greater extent and subsequently produces more FWM power. At 0.1 MHz line width, FWM reported least and the reason is more pulse broadening in this case which lead to less FWM as dispersion varies inversely to the nonlinear effects. In case of 10 MHZ, FWM again decreases due to more dispersion of the transmitted signals. WDM system with OPC after laser again suppresses the FWM more than other two cases.

Eye closure is more in the conventional WDM system. It is also suggested that maintenance of OPC in central office (after laser and transmitter) is far easy than transmission line as in the case of OPC in the middle.

5.5CONCLUSIONS

In this work, the suppression of FWM is investigated with and without optical phase conjugation in 8 channel WDM system. Placement of OPC is presented in two different architectures such as after laser and after NRZ transmitter. Investigation is done for different distances, power levels and laser line-widths and results are evaluated in terms Q-factor, BER and FWM power. It is observed that system consisting of OPC after laser exhibits best performance in terms of Q and BER, also suppressed FWM at maximum extent. OPC included after transmitter performs less than aforementioned system but better than system with no OPC.

CHAPTER 6
CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

This chapter provides a summary of the conclusions of the work which has been done so far. In this chapter, the future scope is also suggested. In first objective, an ultra-dense and high capacity WDM system implementation has been investigated to analyse and four-wave mixing and also results are evaluated in terms of Q-factor and BER. Distances for FWM emergence is considered as 10 km – 50 Km and it is observed that FWM show maximum degrading effects at 10 km and decreases as the distance increases due to attenuation. It is evident that with the decrease in the channel spacing to pack more information signals, under the effects of FWM, degraded results are observed. Results revealed that FWM is less for 32 WDM channels, 50 GHz frequency spacing, single mode fiber, large effective area of SMF (80 um^2). Launched power should be kept low to quell the effects of FWM and it is prominently observed that at high launched powers, FWM emerges more. However, in this work, no optical amplifier is incorporated in the system and FWM in optical amplifiers is beyond the scope of this work.

In second objective, the demonstration and investigation of FWM in wavelength division multiplexed system is carried out by using different line codings and advanced modulation formats in 96 channel system at 10 Gb/s. The level of components of FWM that emerged in the system is considered for each and every modulation separately. Performance evaluation of the FWM by incorporating advance modulation formats shows that changing the link distance of optical fiber effects the four wave mixing at the output and FWM decrease as the distance prolongs. Changing the line codings and advanced modulation formats effects the four wave mixing. DRZ gives the least four wave mixing on different distances, input powers and laser line widths. On changing the modulation formats, the FWM is largely affected in terms of components power induced in the system. The DRZ found out to be best and NRZ is considered to be most affected by FWM. So, it is suggested to use the DRZ advanced modulation format to suppress the effects of FWM.

In the third objective, the suppression of FWM is investigated with and without optical phase conjugation in 8 channel WDM system. Placement of OPC is presented in two different architectures such as after laser and after NRZ transmitter. Investigation is done for different distances, power levels and laser line widths and results are evaluated in terms of Q-factor, BER and FWM power. It is observed that system consisting of OPC after laser exhibits best performance in terms of Q and BER, also suppressed FWM at maximum extent. OPC included after transmitter performs less than aforementioned system but better than system with no OPC.

6.2 FUTURE SCOPE

For the realization of high capacity wavelength division multiplexed system, suppression and investigation of nonlinearities is required. In this dissertation, four wave mixing is analyzed and work is only limited to suppress the FWM effects in WDM. Investigation has been done at different channels of WDM, frequency spacing, line codings, advanced modulation formats, various distances, power levels and laser line widths in high capacity and high speed dense WDM system. Moreover suppression of FWM is presented using different placement of optical phase conjugation to ease the maintenance of the system. FWM is a performance degrading issue, but it can be used as application as wavelength converter. So, applications of FWM may also be studied. However, WDM system is not only prone to FWM effects, but also other nonlinearities such as self-phase modulation, cross phase modulation, cross gain modulation etc. Investigation and analysis that are proposed in this work, will also be studied in WDM systems under influence of SPM, XPM. Also, different approaches of reducing the FWM can be explored.

REFERENCES

[1] Ohtsuki Tomoaki and Sasase Iwao. *Optical Synchronous CDMA, Encyclopedia of Telecommunications* Editor: John Proakis, Wiley, 2002.

[2] Mendez A.J. *et al*. (2003). Design and Performance Analysis of Wavelength/Time (W/T) Matrix Codes For Optical CDMA, *IEEE Journal of Lightwave Technology,* 21 (11), 2524-2533.

[3] Kwong Wing C., Perrier Philippe and Prucnal Paul R (1991). Performance Comparison of Asynchronous and Synchronous Code-Division Multiple-Access Techniques for Fiber-Optic Local Area Networks, *IEEE Transactions on Communication*, 39 (11), 1625-1634.

[4] Dey Diptish. Theory towards an all optical WDM slotted ring MAN with support for optical multicasting. Ph.D. Thesis, University of Twente, Netherlands, 2003.

[5] Tsuritani T. *et al.* (2003). Study on optimum optical prefiltering condition for highly spectral-efficient ultra long haul transmission using 40 Gbit/s CS-RZ signal and all-Raman repeaters, *presented at the OFC2003*, paper FE4, Atlanta, GA.

[6] Warren Don and Moore Justin. Multiplexing in Fiber Optic Connections, *Summer Ventures in Science and Mathematics*,2001

[7] Hodžic Anes *et al.* (2003). Optimized Filtering for 40-Gb/s/Ch-Based DWDM Transmission systems Over Standard Single-Mode Fiber. *IEEE Photonics Technology Letters*, 15 (7), 1002-100.

[8] Miyamoto Yutaka *et al.* (2002). WDM Field Trials of 43- Gb/s/Channel Transport System for Optical Transport Network, *IEEE Journal Of Lightwave Technology*, 20 (12), 2115-2128.

[9] Tsuritani Takehiro *et al.* (2004). Ultra-Long-Haul 40-Gbit/s-Based DWDM Transmission Using Optically Prefiltered CS-RZ Signals, *IEEE Journal Of Selected Topics In Quantum Electronics*, 10 (2), 403-411.

[10] Cai Jin-Xing *et al.* (2006). Transmission of 40-Gb/s WDM Signals Over Transoceanic Distance Using Conventional NZ-DSF With Receiver Dispersion Slope Compensation, *IEEE Journal Of Lightwave Technology*, 24 (1), 191-200.

[11] Daikoku Masahiro *et al.* (2006). 8 X 160-Gb/s WDM Field Transmission Experiment With Single-Polarization RZ-DPSK Signals and PMD Compensator, *IEEE Photonics Technology Letters*, 18 (2), 391-393.

[12] Garrett Lara D. *et al.* (2003). Bidirectional ULH Transmission of 160-Gb/s Full-Duplex Capacity Over 5000 km in a Fully Bidirectional Recirculating Loop, *IEEE Journal Of Lightwave Technology*, 16 (7), 1757-1759.

[13] Spiekman L. H. *et al.* (2000). Transmission of 8 DWDM Channels at 20 Gb/s over 160 km of Standard Fiber Using a Cascade of Semiconductor Optical Amplifiers, *IEEE Journal Of Lightwave Technology*, 12 (6), 717- 719.

[14] Charlet G. *et al.* (2005). Comparison of system performance at 50, 62.5 and 100 GHz channel spacing over transoceanic distances at 40 Gbit/s channel rate using RZ-DPSK, *Electronics Letters 3rd* ,41 (3), 145-146 .

[15] Pincemin E. *et al.* (2004). Impact of the Fiber Type and Dispersion Management on the Performance of an NRZ 16 x 40 Gb/s DWDM Transmission System, *IEEE Photonics Technology Letters*, 16 (10), 2362-2364.

[16] Agrawal G. P. *Nonlinear Fiber Optics*. USA: Second Edition, Academic Press, San Diego, 1995.

[17] Yamamoto. *Optical Fiber Communications Technology*. Nikkan Kogyo Shimbun, 1995.

[18] Fonseca I. E., Ribeiro M. R. N., and Waldman H. (2005). Differentiated optical QoS under a Low Complexity FWM-aware Wavelength Assignment Algorithm. *Conference on Optical Network Design and Modeling*, Milan, 431-438.

[19] Li P. L. *et al.* (2005). Theoretical Analysis of Tunable Wavelength Conversion Based on FWM in a Semiconductor Fiber Ring Laser, *IEEE Journal of quantum electronics*, 41 (3), 581-588.

[20] Pachnicke S. *et al.* (2005). Impact of the In-Line Dispersion- Compensation Map on Four-Wave Mixing (FWM) – Impaired Optical Networks, *IEEE Photonics Technology Letters*, 17 (1), 235-237.

[21] Hwang B. and Tonguzc O.K. (1998). A generalized suboptimum unequally spaced channel allocation technique. *IEEE Commun.* 8 (46), 1027–1037.

[22] Song Shuxian *et al.* (1999). Intensity-Dependent Phase-Matching Effects on Four-Wave Mixing in Optical Fibers, *Journal of lightwave technology*, 17 (11), 2285-2290

[23] Tang Jau (2001). The Multi span Effects of Kerr Nonlinearity and Amplifier Noises on Shannon Channel Capacity of a Dispersion-Free Nonlinear Optical Fiber, *Journal of lightwave technology*, 19 (8), 1110-1115 .

[24] Hirano A., Miyamoto Y., Kuwahara S., (2003). Performances of CSRZ-DPSK and RZ-DPSK in 43-Gbit/s/ch DWDM G.652 single-mode-fiber transmission. *Proceedings of Optical Fiber Communications Conference,* Atlanta, 454–456.

[25] Jeffrey H. *et al.* (2004). RZ-DPSK Transmission Using a 42.7-Gb/s Integrated Balanced Optical Front End With Record Sensitivity, *Journal of light wave technology*, 22 (1), 180-185.

[26] Sun Junqiang *et al.* (2003). Suppression of four-wave mixing in erbium-doped fiber amplifiers by utilizing laser oscillation, *Optics Communications*, 1 (225), 39-45.

[27] Arumugam M. (2001). Optical fiber communication-An overview, *PRAMANA journal of physics*, 57 (5), 849-869.

[28] Monika, Wason Amit and Kaler R.S (2013). Investigation of four wave mixing effect with different number of input channels at various channel spacing, *Optik*, 124 (20), 4227–4230.

[29] Singh S.P. and Singh N. (2007). Nonlinear effects in optical fibers: origin, management and applications, *Progress in electromagnetic research*., 73, 249-275.

[30] Singh Surinder and Singh Sukhbir (2015). Investigation on four wave mixing effect in various optical Fibers for different spectral efficient orthogonal modulation Formats, *optics and laser technology*. 76, 64-69.

[31] Kaur Gurpreet and Singh ML. (2009). Effect of four wave mixing in WDM optical fiber systems, *Optik-International Journal for Light and Electron Optics*, 120 (6), 268-273.

[32] Yoo S.J.B. (1996). Wavelength conversion technologies for WDM network applications, *Journal of. Lightwave Technology*, 14 (6), 955–966.

[33] Yasin M and Ismail M., (2007). Effects of Four-wave Mixing Crosstalk in WDM Networks on the Transmitted Optical Frequencies and Wavelengths of Channels for Various Fiber Types *Asia pacific conference on applied electromagnetic proceedings*, Maleka, Malaysia.

[34] Sugumaran S, Aggarwal Manu and Arulmozhivarman P. (2014). Analysis of FWM power and efficiency in DWDM systems based on chromatic dispersion and channel spacing, *International Journal of Advances in Engineering Research*, 7 (11), 49-60.

[35] Senior John M. *Optical Fiber Communication*, second edition, principles and practice, 1999.

[36] Singh S.P. and Jain V.K. (2004). Novel strategies for reducing FWM using modified repeated unequally spaced channel allocation, *fiber and integrated optics*, 23 (6), 415- 437.

[37] Kaur Gurmeet. (2007). Optimization of inter channel Separation in WDM transmission system in the presence of Fiber Nonlinearities. *IFIP International Conference*, IEEE, 24, 1-6.

[38] Sharma Vishal and Kaur Ramandeep (2012). Implementation of DWDM system in the presence of four-wave mixing (FWM) under the impact of channel spacing, *int. j. light electron opt.*, 124 (17).

[39] Kaler R. S., Sheetal Anu and Sharma Ajay K. (2010). Impact of Optical Modulation Formats on SPM-limited Fiber Transmission in 10 and 40 Gb/s Optimum Dispersion-managed Lightwave Systems, *Optik*, 121 (3), 246-252.

[40] Yao Bing, Hanawa Masansor and Takahara Miko (1999). Wavelength division multiplexing transmission based on wide-band optical phase conjugator using dispersion flat fiber. *Fifth Asia-Pacific Conference on optoelectronics communications*, china, 313–316.

[41] Pachnicke S., ***et al.*** (2005). Impact of the In-Line Dispersion-Compensation Map on Four-Wave Mixing (FWM) – Impaired Optical Networks, *IEEE Photonics Technology Letters*, 17 (1), 235-237.

[42] LiP. L., *et al.* (2005). Theoretical Analysis of Tunable Wavelength Conversion Based on FWM in a Semiconductor Fiber Ring Laser, *IEEE Journal of quantum electronics*, 41 (4), 581-588.

[43] Rasheed I., Abdullah M., Mehmood Shahid., (2012). Analyzing the Non-linear Effects at various Power Levels and Channel Counts on the Performance of DWDM based Optical Fiber Communication System. *Conference on emerging technologies*, Islamabad, pakistan, 7-12.

[44] Vidal Borja and Bockelt Alexander (2013). Cascaded Four-Wave Mixing for Microwave Photonic Harmonic Multiplication, *IEEE photonic technology letters*, 25 (1), 100-103.

[45] Hao Qiang, and Zeng He ping (2014). Cascaded Four-Wave Mixing in Nonlinear Yb-Doped Fiber Amplifiers, *IEEE journal of quantum electronics*, 20 (5).

[46] Singh Amarpal and Sharma Ajay K. (2009). Investigation on modified FWM suppression methods in DWDM optical communication system, *optic communication*,

[47] Abed H.J., Din N.M. and Al-Mansoori M.H. (2013). Recent four-wave mixing suppression methods, *Optik*, 124 (15), 2214-2218.

[48] Noshad M. and Rostami A (2012). FWM minimization in WDM optical communication systems using the asymmetrical dispersion-managed fibers, *Optik*, 123 (9), 758-760.

[49] Kaler Rajneesh and Kaler R.S. (2012). Investigation of four wave mixing effect at different channel spacing, *Optik*, 123 (4), 352-356.

[50] Kaur Gurpreet and Patterh M.S (2014). Suppression of four wave mixing in wavelength division multiplexed system with hybrid modules, *Optik*, 125 (15), 3894-3896.

[51] Sabapathi T. and Brindha G. Jaya. (2014). Mitigation of Fiber Non Linear Effects by Maximum Likelihood Sequence Detection. *International Conference on communication and Network Technologies*, india, 154-157.

[52] Politi C.T., Klonidis D., and O'Mahony M. J. (2006). Dynamic Behavior of Wavelength Converters based on FWM in SOAs, *IEEE journal of quantum electronics*, 42 (2), 108-125.

[53] Pandey Neha et al. (2014). Performance Analysis of WDM Optical Communication System in the Presence of Four Wave Mixing (FWM) Under the Impact of Channel Spacing with Variable Dispersion, *IJETAE*, 4 (4), 874-879.

[54] Nitika Soni and Meenakshi (2016). Performance Analysis of Channel Spacing Variation in the presence of FWM for a DWDM System, *IJMECE*, 4 (4), 49-52 .

[55] Miyamoto Yutaka et al. (2002). WDM Field Trials of 43- Gb/s/Channel Transport System for Optical Transport Network, *IEEE Journal Of Lightwave Technology*, 20 (12), 2115-2128.

[56] Tsuritani Takehiro et al. (2004). Ultra-Long-Haul 40-Gbit/s-Based DWDM Transmission Using Optically Prefiltered CS-RZ Signals, *IEEE Journal Of Selected Topics In Quantum Electronics*, 10 (2), 403-411.

[57] Ibrahim M. and Moustafa H. Aly., (2008). FWM Suppression in WDM Systems Using Advanced Modulation Formats. *4th International Computer Engineering Conference, Information Society Applications*, cairo university, 1-6.

[58] Tiwari Ishita et al. (2015). Effect of different Modulation Formats on DWDM Optical Transmission Systems in the presence of Four Wave Mixing, *International Journal of Enhanced Research in Science Technology & Engineering*, 4 (3), 1-9 .

[59] Rouf A. and Islam M. S., (2012). A new approach of unequally spaced channel allocation for FWM crosstalk suppression in WDM transmission system. *Electrical & Computer Engineering (ICECE), International Conference*, Bangladesh, 2012.

[60] Kato Takatoshi *et al.* (2001). Design optimization of dispersion compensating fiber for NZ-DSF considering nonlinearity and packaging performance. *Optical Fiber Communication Conference and International Conference on Quantum Information technology*, USA.

[61] Sugumaran S. and Sharma Neeraj (2013). Effect of Four-wave Mixing on WDM System and its Suppression Using Optimum Algorithms, *International Journal of Engineering and Technology*, 5 (2), 143-1444.

[62] Matsuda T., Murakami M. and Imai T., (1998). Dispersion management scheme for suppressing FWM in DWDM transmission. *Lasers and Electro-Optics Society Annual Meeting*, USA.

[63] Inoue K. (1993). Suppression technique for fiber four-wave mixing using optical multi-/demultiplexers and a delay line, *J. Lightwave Technol.*, 11 (3), 455–461.

[64] Sekine K. et al. (1996). FWM crosstalk reduction using bit phase arranged RZ (BARZ) signals in WDM systems. *Proc. On Optoelectronics Communications Conf. (OECC)'96*, Paper 17B2-4, 114–115.

[65] Selvamani A. and Sabapathi T., (2011). Suppression of four wave mixing by optical phase conjugation in DWDM fiber optik link. *Recent Advancements in Electrical, Electronics and Control Engineering*, India.

[66] Pechenkin V. and Fair I.J (2010). Analysis of four wave mixing suppression in fiber optic OFDM transmission systems with an optical phase conjugation module, *J. Opt. Commun. Netw*. 2 (9), 704-710.

[67] Kaur G., Kaler R. S. and Singh S (2017). Performance investigation of suppression of four wave mixing using optical phase conjugation with different modulation format in DWDM soliton communication system, *Springer*, 105 (5), 279-282.

[68] Kaur Gurpreet, Patterh M.S. and Kaur Ramandeep (2015). Four wave mixing power suppression in hybrid network topology using optical phase conjugation module, *Optik*, 126 (3), 347-349.

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