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بسم الله الرحمن الرحيم

﴿اللَّهُ نُورُ السَّمَاوَاتِ وَالْأَرْضِ مَثَلُ نُورِهِ كَمِشْكَاةٍ فِيهَا مِصْبَاحٌ الْمِصْبَاحُ فِي زُجَاجَةٍ الزُّجَاجَةُ كَأَنَّهَا كَوْكَبٌ دُرِّيٌّ يُوقَدُ مِن شَجَرَةٍ مُّبَارَكَةٍ زَيْتُونَةٍ لَّا شَرْقِيَّةٍ وَلَا غَرْبِيَّةٍ يَكَادُ زَيْتُهَا يُضِيءُ وَلَوْ لَمْ تَمْسَسْهُ نَارٌ نُّورٌ عَلَى نُورٍ يَهْدِي اللَّهُ لِنُورِهِ مَن يَشَاءُ وَيَضْرِبُ اللَّهُ الْأَمْثَالَ لِلنَّاسِ وَاللَّهُ بِكُلِّ شَيْءٍ عَلِيمٌ﴾

صدق الله العلي العظيم

سورة النور الآية (35)

Dedication

First and foremost, I would like to dedicate this work Sincerely to Allah Almighty,

then,

To

The source of my strength and the secret of my success in life ……………
My father.

To

The foundation of love and tenderness, by her prayers miracles are achieved
My mother.

To

My dear husband and my two daughters, Maryam and Sarah, who supported me on my study trip and endured the difficult circumstances we went through together
I dedicate this work.

Nidhal Abd Mohammed
July
2021

Acknowledgment

In the name of God, praise be to God, prayer, and peace be upon the Messenger of Allah.

All praises and thanks be to Allah for easing my task to accomplish this work despite all the hardships.

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I would like to warmly thank and gratitude my father and mother who have devoted a large part of their lives to me. They were not just parents, but they were and still are mentors and teachers having always words of wisdom to share with me to help me understand my life and reach my goals.

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ABSTRACT

The optical communication system has become a major part of global infrastructure in the past years because of its variable benefits. The main objective of optical communication is to increase spectral efficiency and to utilize minimum bandwidth over long distances with minimum possible errors during transmission of signals. 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 starts to emerge at high launched powers in dense wavelength division multiplexing. FWM is the major deteriorating issue as it becomes severe at narrow frequency spacing and at minimum pulse broadening values. Spectral efficiency can be increased by using polarization multiplexing along with different modulation formats. Capacity can be increased by employing orthogonal polarization between adjacent WDM channels.

In the present work a new technique to suppress the FWM effect based on polarization combiner with modulation scheme technique is proposed. A comparison of placing a polarization combiner criteria in two different cases single and multichannel is performed and it is observed that placing polarization combiner with different modulation formats performs exceptionally well and suppresses FWM with ease of maintenance. The major emphasis of this thesis is to investigate the emergence of FWM in WDM system at different distances and to study the behavior of the system for different WDM channels. The performance of the proposed system is evaluated in terms of Q-factor, BER and FWM power. The results revealed that maximum Four Wave Mixing (FWM) emerges for (50,100 & 200) GHz Wavelength Division Multiplexing (WDM) channel spacing and reduced as the spacing between channels increased.

The performance analysis of high capacity (4×10, 8×10 & 16×10)Gb/s and high speed WDM is performed by incorporating different schemed modulation formats (NRZ, DBM-1, DBM-2 & CSRZ) with PC. The findings reveal that the proposed technique is able to reduce the FWM crosstalk and improve the system performance. At 12.5dBm input power and 300km fiber length the FWM power is reduced to 12.12%, 20.34% and 18.05% at NRZ, CSRZ & DBM-1, respectively, when compared with conventional WDM system Through the research, we noticed that (DBM-2) works only with high capabilities, and therefore it was excluded from the comparisons, and the focus remained on other types of modulation forms. The proposed system also provides improvement in Quality factor (Q) of 87.2%, 89.9% & 79.8% for the same sequence of modulation. The results conform the robustness of polarization technique with scheme modulation to reduce FWM crosstalk. The current work has been compared with

previous techniques, and the results have proven the superiority of the proposed technique over the previous ones. Opti-system version 17 is used for verifying various measurements, plots and all other graphical analysis.

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List of Abbreviations

Abbreviation	Definition
APD	Avalanche Photodiode
ASK	Amplitude shift keying
BER	Bit error rate
BER	Bit Error Rate
CD	Chromatic dispersion
CSRZ	Compressed Spectrum Return to Zero
CW	Continuous Wave Laser
CWDM	Coarse wavelength division multiplexing
DBM-1	Duo Binary mode-1
DBM-2	Duo Binary mode-2
DCF	Dispersion Compensation Fiber
DWDM	Dense wavelength division multiplexing
EDFA	Erbium-doped fiber amplifier
FDM	Frequency Division Multiplexing
FPG	Fiber Bragg Gratings
FSK	Frequency shift keying
FWM	Four wave mixing
LD	Laser diode
LED	Light emitting diode
MMF	Multi-Mode Fiber
MZM	Mach Zehnder Modulator
NRZ	Non return to zero
OFC	Optical Fiber Communication
OOK	On off keying
OSA	Optical Spectrum Analyzer
PC	Polarization combiner
PIN	Positive-Intrinsic-Negative
PM	pulse modulation
PSK	Phase shift keying
Q-factor	Quality factor
RI	Refractive index
RZ	Return to zero
SBS	Stimulated Brillion Scattering
SMF	Single-mode fiber
SNR	Signal to noise ratio
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
WDM	Wavelength division multiplexing
XPM	Cross Phase Modulation

List of symbols

Symbol	Description
$n1$	Core refractive index
l	Grating length
A_{eff}	Fiber effective area
B	Bit rate
$B.W$	Band width
c	Speed of light
V	Vacuum light speed
C	Capacity of the channel
d	Fiber core diameter
D	Dispersion parameter.
e	Electron charge.
f	Signal frequency
fc	Carrier Frequency
fd	Difference Frequency
$fijk$	Fourth intermodulation product
G	Amplifier gain.
I	Optical intensity
$I(t)$	Intensity of the signal
Ii	Optical power intensity of center channel
Ij	Optical power intensity of jth channel
L	Fiber length
LA	Span length.
L_{eff}	Effective Length of fiber core.
M	Number of new generated wavelength in FWM
N	Number of channels
n	Refractive index of the silica fiber
$n2$	Cladding refractive index
no	Linear part of the refractive index
P_{FWM}	Noise power due to FWM effects for
Pi	Optical input power
Po	Optical output power
X_{111}	Third order nonlinear susceptibility.
α	Fiber attenuation coefficient.
γ	Nonlinear parameter.
ΔBW	bandwidth of the receiver
ΔL	Length difference between two neighbor waveguides.
$\Delta\lambda$	Channels separation..
η	Quantum efficiency

λ	Carrier wavelength.
λi	Central wavelength
ΦNL	. Nonlinear phase shift.
Δn	Change in refractive-index
x	Fiber-optic longitudinal axis distance
ΔK	Detuning wave vector
V	Normalized frequency
$\Phi_1(t)$	Phase induced in the upper arm of MZM
$\Phi2(t)$	Phase induced in the lower arm of MZM
P_t	Transmitted power
Pr	Received power

1.1 **Motivation**

Optical communication is an advanced technology that is currently unchallenged for the transmission of huge amounts of data over long distances securely and short transmission time. The transmission capacity of optical network technology has increased significantly over the past decades since its emergence in the early 1970s. This increase has been achieved mainly through the deployment of additional fiber links, filling more wavelength channels per fiber link through Dense Wavelength- Division-Multiplexing (DWDM), and higher data rate per channel [1].

Nowadays, optical fiber is considered as the most important communication channel. These fibers are not only used in telecommunication systems but also in Local area networks (LAN) and internet so that to achieve high data rates. In addition, no crosstalk induced in optical fibers that are running along each side for long distances as in the case of electrical transmission lines. The demand and use of optical fiber are growing tremendously. Telecommunication applications i.e. data, video or voice transmission over long distances use a few standard designs of fiber [2]. The feasibility for using glass fibers was studied in the mid-1960 and Dr. Charles Kao proposed that it would be possible to reduce attenuation of fiber to less than 20 dB/km [3]. The initial step for this development was taken in 1970's using low pass fiber [4] with semiconductor laser which was considered to be important components in transmission systems [5]. With the use of erbium doped fiber amplifiers (EDFA) in 1986, it was possible to increase distance and speed of communication systems [6]. Figure (1.1) shows growth in fiber optic communication systems since 1840. Therefore, fiber communication can be considered as a savior that meets our huge bandwidth and capacity demands because of low distortion in signal, low cost, small amount of requirement of space and low usage of material [7]. With all these advantages, optical communication is considered as the medium of transmission for networks of future.
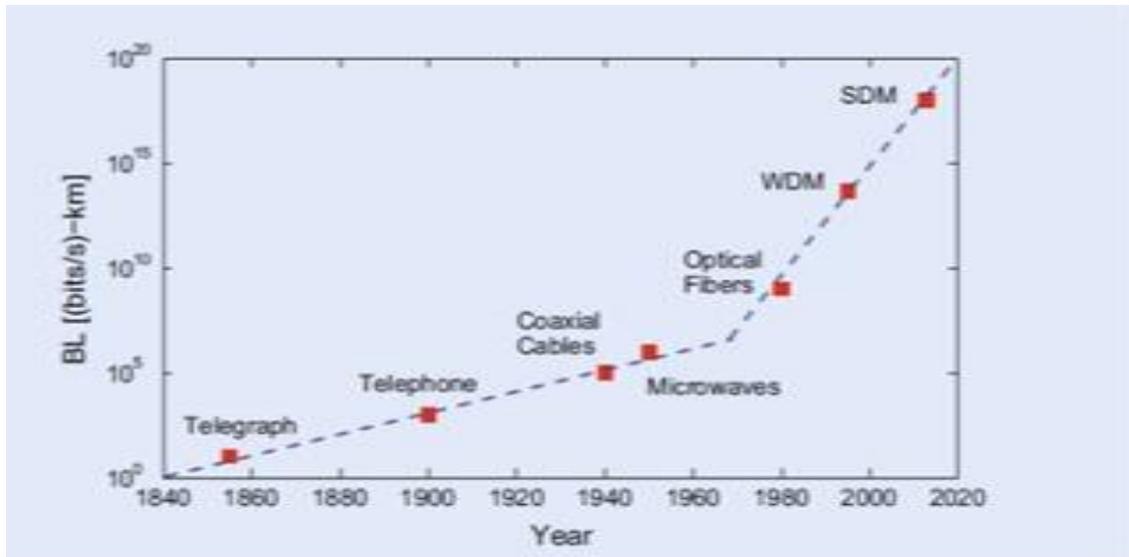
Figure 1.1**:** Growth in fiber optic communication system since 1840 [6]

Communication systems use optical fibers to transmit data due to their variable advantages such as: the immunity of interference, high speed, and high data rates. Optical fibers allow for high transmission distances with a low attenuation and improved signal integrity if compared to metal cables counterparts[8]. With the development in communication services, the need for large data capacity with high reliability transmission system is of high priority. Therefore, the dense wavelength division multiplexing WDM system was considered as an appropriate approach to meet such demands[9-11]. Each fiber can carry many independent channels, each one uses a different wavelength of light (wavelength division multiplexing (WDM)). Early Wavelength Division Multiplexing (WDM) began in the late 1980s using the two widely spaced wavelengths in the 1310 nm and 1550 nm (or 850 nm and 1310 nm) regions, sometimes called wideband WDM. Figure (1-2) shows an example of this simple form of WDM. Notice that one of the fiber pair is used to transmit and receive data . This is the most efficient arrangement and the most frequent one in Dense Wavelength Division Multiplexing (DWDM) systems[1].In WDM, each channel transmits high bit rate in a separate wavelength allowing for high bit rates transmission. However, chromatic dispersion and nonlinear effects are the main concerns within WDM which affect the system quality and the bit error rates (BER). The early 1990s witnessed a second generation of WDM, sometimes called narrowband WDM, in which two to eight channels were used. These channels are now spaced at an interval of about 400 GHz in the 1550-nm window[1]. By the mid-1990s [14], dense WDM (DWDM) systems were emerging with 16 to 40 channels and spacing from 100 to 200 GHz. By the

late 1990s DWDM systems had evolved to the point where they were capable of 64 to 160 parallel channels, densely packed at 50 or even 25 GHz intervals. Nowadays, development of technology showed that there is an increase in wavelengths number, it is go with a reduction in the spacing between the wavelengths. Along with increased density of wavelengths, systems also advanced in their flexibility of configuration, through add-drop functions, and management capabilities[1].
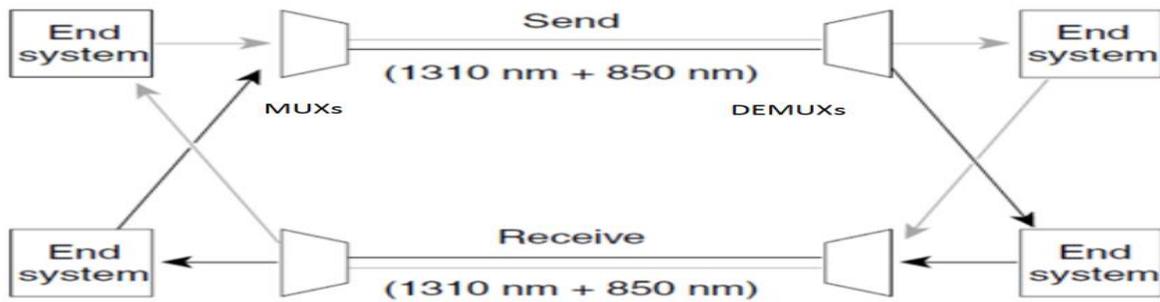
Figure 1-2: WDM with Two Channels [1]

DWDM system as an optical system contain Linear and Nonlinear Impairments, the terms linear and nonlinear in optics mean intensity independent and intensity-dependent phenomena respectively. Nonlinear effects in optical fibers occur due to [12]:

(1)   change in the refractive index of the medium with optical intensity.

(2)   inelastic scattering phenomenon.

The power dependence of the refractive index is responsible for the Kerr-effect. Depending on the type of input signal, the Kerr-nonlinearity manifests itself in three different effects such as Self-Phase Modulation (SPM), Cross-Phase Modulation (CPM) and Four-Wave Mixing (FWM). At high power level, the inelastic scattering phenomenon can induce stimulated effects such as Stimulated Brillouin-Scattering (SBS) and Stimulated Raman-Scattering (SRS). The intensity of scattered light grows exponentially if the incident power exceeds a certain threshold value. The difference between Brillouin and Raman scattering is that the Brillouin generated phonons (acoustic) are coherent and give rise to a macroscopic acoustic wave in the fiber, while in Raman scattering, the phonons (optical) are incoherent and no macroscopic wave is generated [14]. If the total light energy in the fiber increases, the nonlinear effect becomes uncontrolled, that affects the spectral efficiency of the signals and thus degrades the systems' functioning [13]. The density of the independent phenomena depends on the sequence of non-linear effects in the optical fibers which

occurred due to the optical density with a change in the refractive index for the medium inelastic proses phenomenon[14].

One of the major non -linear effects is the multiple channels of the optical communication systems is the crosstalk that results from the four waves mixing (FWM) [15]. FWM occurs when a number of users increase. Therefore, when the space between the channels is reduced, an increase in crosstalk and an increase in nonlinear effects takes place. The signal distortion occurs especially in long distances where the FWM is the most dangerous factor in signal destruction in dense wavelength division multiplexing systems (DWDM)[16]-[17].

1.2 Long- haul transmission systems

Communication has made a great progress after the improvements in optical fiber technology. It has reached a position that have never been reached before. The optical fiber has become a multi-channel video and audio transmission that links all over the world where it is possible to reach high traffic volumes for many optical signal amplification devices to provide the possible distance with more signal by combining the signals that are sent through optical fibers [18]. Thus, we find that the main goal of the remote optical system is to have a fiber-optic system to transmit data at the maximum capacity of throughput, given the specific bandwidth and amplifier, which is an optical application of optical fibers. It is important to reduce the Bit-Error-Rate (BER), but there are many restrictions imposed on the power of the analysis due to fiber effect, which is considered an important factor to reduce the signal-to-noise ratio (SNR). Maximizing the efficiency of the signal-to-noise ratio is also important in order to reduce the average of the transmitted power per bit or the amount of (SNR) required per bit [19]. Figure (1-3) shows the long-haul- fiber system, presented in a simplified form. The (Lroute) represents the total distance between the stations of two terminals that contains the transmitting signal, the wavelength multiplexers, and the receiver's equipment and (Lspan) represents the distance between each of the amplifier sites. In the unit gain (G) of the system, the gain of the amplifier is set to precisely compensate for the span losses is the total attenuation of the outside plant fiber, where the external losses are due to the binding and other components used to manage the signal properties and the integrity [20].
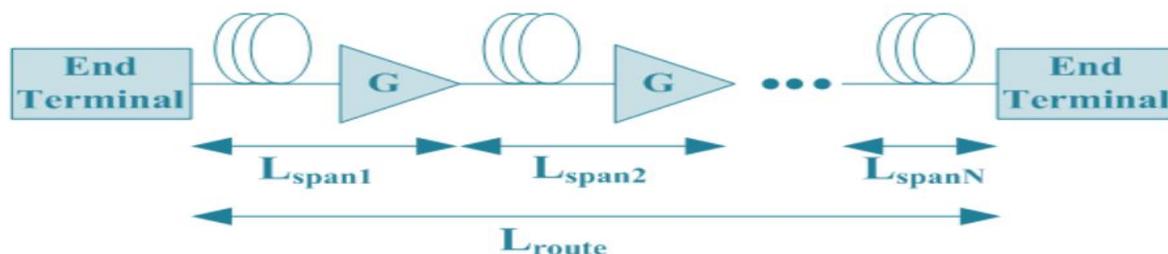
Figure 1-3: Simple optical transmission system comprised of N linked ranges of fiber and line amplifiers [20]

The optimum information-carrying performance of a long-haul saturated amplifier link is obtained when the SNR's is equalized over all channels. The positioning of the optical amplifiers in a long-haul system is a nontrivial problem because of fiber nonlinearities and the interplay between nonlinearities and dispersion. Amplifiers may be placed either before sections of dispersive Single-Mode Fiber (SMF), or before sections of Dispersion - Compensating Fiber (DCF), or both [21] for long-haul.

1.3 Literature Survey

The nonlinear effect is one of the most deleterious effects of an optical transmission system that can severely limit the bit rate and thus decrease the transmission performance . Four wave mixing is the significant harmful kind of this nonlinearity which should be addressed . Reviewing the most recent techniques that have been done for suppressing the nonlinearity which is highly important to predict the research direction in this work. The literature review can be summarized as follows:

In 2009 Singh, A., Sharma et al.[22] The focus of this paper is to investigate the methods for Four Wave Mixing (FWM) suppression. Modified techniques equal and unequal-channel spacing with polarization, equal channel spacing with alternate channel delay, optical coupling and varied laser power have been proposed to reduce the impact of FWM on Dense Wave Length Division Multiplexing (DWDM) optical communication system. Furthermore, a comparison of the reduction of FWM between existing and proposed techniques has been discussed by varying the dispersion of fiber from 0 to 16 ps/nm/km. It has been observed that the suggested techniques are simpler to design optical communication system and superior to the existing methods.

In 2011 Abd El Razak, B. K et al.[23] Presented a study on the effectiveness of the merging of asymmetric channel spacing and Duo-Binary modulation(DBM) form as a better alternative than the conventional non-return modulation (NRZ) to increase the suppression of four-wave mixing (FWM) in WDM system with 10Gb/s. The study showed that the form Duo-Binary modulation is better for suppressing (FWM) when compared to conventional (NRZ) in the WDM system.

In 2012 Singh et al.[24] Analyzed the performance of polarized interleaved with that of modified polarization interleaved systems using hybrid amplification in fiber in terms of OSNR, signal power and noise power for 8 channels with 50GHz and 100 GHz channel spacing. Hybrid fiber amplification was used to balance high OSNR requirements with non-linear impairments of channel consisting of distributed Raman amplifier along with EDFA. Reverse dispersion fiber was used instead of dispersion compensating fiber (DCF) to reduce non-linear impacts in the proposed system.

In 2013 Abd H.J et al.[25] Presented an approach for reducing four wave mixing (FWM) by using polarized interleaved system. The suggested system has been evaluated for input power value of -12dBm to 0dBm. It has been observed that FWM power increases for both cases with increasing input power. However, the proposed systems have more reduction of FWM power. At a particular input power of -12dBm , FWM have -88dBm power whereas simple WDM have -80dBm power. Also, at sixth channel BER of the proposed system is 4.86 10-21 whereas for WDM is 4.43 10-10 with the same value of input power which shows the suppressed FWM in the system.

In 2013 Sharma, V. et al.[26] Tell us the effect of (FWM) is inversely proportional to the space between the channels. FWM is reduced by holding all parameters constant and increasing channel spacing. It also lowers the power of the signal, OSNR, and Q- factor. Though other parameters are affected by the lower extent, the minimum BER stays constant. According to the analysis, the BER for 6.25 Gigahertz spacing, FWM is very large, while FWM for 80 Gigahertz spacing, BER is quite small.

In 2014 Taher et al.[27] Presented various modulation formats in optical fiber system in presence of PMD and nonlinearities. At various values of Different Group Delay (DGD) modulation schemes considered were Chirped- return to zero (CRZ), carrier- suppressed- return to zero (CSRZ), duobinary, return- to zero(RZ), non-return to zero (NRZ), DQPSK and CSRZ-DQPSK at data rate

of 40 Gbps. RZ DQPSK modulation showed the best performance among all schemes. Also, it was clear that PMD effect for some modulation schemes decreases within increase in non-linarites. From optical spectra's, it was observed that RZ-DQPSK have the maximum advantage. On the other hand, DGD diagrams indicated that RZ-DQPSK shows better performance with all PMD values.

In 2014 Abd, H., et al. [28] explores a method to suppress the (FWM) crosstalk by using the pairing combinations of differently linear polarized optical signals. The system was using four-channel with data rate of 10 Gb/s and varying the input power from 2dBm to14dBm. The robustness of the proposed technique was examined with two types of optical fibers, (SMF) and (DSF). The FWM power drastically was reduced to less than -68 and -25dBm at an input power of 14dBm, when the polarization technique was conducted for SMF and DSF, respectively. With the conventional method, the FWM powers were, respectively, -56 and -20dBm. The system performance greatly improved with the proposed polarization approach, where (BERs) at the first channel were $2.57 \times 10\text{-}40$ and $3.47 \times 10\text{-}29$ at received powers of -4.90 and -13.84dBm for SMF and DSF, respectively.

In 2015 Manzoor, H. U., et al. [29] Introduced a method in which alternative circular polarizers are used to change the polarization of input pulses into right and left handed polarized pulses before multiplexer to reduce four waves mixing. by increasing the demand and high use of input in (WDM) optical communication systems. So, the used lower channel spacing leads to the creation of non-linear effects, and it can be eliminated with the help of this technique. In this technique the system performance is improved, and completely eliminate FWM by optimizing optical network's parameters. system's performance has been calculated.

In 2016 Dehghani, F., et al. [30] In this paper, an approach for suppressing FWM crosstalk by using the pairing combinations of differently linear-polarized optical signals is investigated. The simulation is done by using an eight-channel system. The proposed technique uses different input powers. FWM can be strongly reduced when the polarization technique is conducted for SMF. Then, A comparison of the proposed method with a conventional one is done to demonstrate the effect of FWM as well. The comparison was conducted at an input power ranged as 2dBm. Decreasing the input power can decrease the FWM effects. In the absence of the polarization technique, the FWM power was –64dBm at an input power of 2dBm. The FWM power decreased to less than -82dBm at a 2dBm input power. The system performance has been improved greatly.

In 2017 Sabapathi, T., et al, [31] This paper introduces a method of reducing the non-linear effect known as four waves mixing in fiber optic communication system. A method was proposed for reducing the FWM effect using NRZ modulation and circular polarization. The system is designed, simulated and analyzed for a single mode optical fiber of length 50km, and analyzed for different number of channels with power level varied from -10dBm to 10dBm. The FWM effect was suppressed by introducing the Circular Polarizers (CP) alternatively in each channel before multiplexing. The SRS effect was reduced by using Super Gaussian Filter after the optical fiber

In 2018 Alipoor, A. H., et al, [32] A 64-channel optical system is proposed using single-mode fibers, and the performance of the optical network is evaluated on the basis of two methods of Duo-Binary modulation with bit rate limits (10,20,40)Gb/s and a distance of 1500 km. According to the formats, the results show that the two methods are effective, and that the two-way binary coordination method has better performance in the optical network with a capacity of (40Gb/s) and has also proven better performance in quality factor and bit error rate.

In 2019 Sabapathi, T.et al. [33] In this work, a method was proposed to eliminate FWM by analyzing optical fiber correlation by increasing the input power. The effect of FWM is reduced in the DWDM system by placing circular polarization in each transmitter before passing through the fiber link, where the FWM power level was reduced from -61dBm to -78.4151dBm. System analysis for 8-64 channels at a power level of -10 to 10dB.

In 2019 Atiya, Y.S et al.[34] Exhibited Two various compensation techniques, dispersion compensation fibers (DCF) and Duplicate. These techniques are suggested to reduce non-linear and Linear effects, particularly in the situation of asymmetric channel spacing, WDM system (wavelength division multiplexing). The results were revealed as Q -factor vs. Bit Error Rate (BER). Software of Optiwave V.7, 8- channels are used in two situations : Unequal & equal Channels spacing. Equal WDM system with DCF and signal power at 0dBm. The Q-factor is(45.5) While Q-factor is (35) and (59) are in the situation of asymmetric channel Spacing using repeater respectively as well as DCF respectively.

In 2020 Manzoor, H. U. et al.[35] In order to combat four wave mixing FWM, three optical transmission solutions have been proposed. High gain amplifier with Low input power, the hybrid Wavelength Division Multiplexing (WDM) with Optical Time Division Multiplexing (OTDM)

scheme. Another circular polarization. The first method entails lowering the power inputs to (-20) dBm, then before De-multiplexing it, amplify it by 20dB. Splitting the launching signal into four interval slots in the second method and then merging them using the power combiner. The third technique is the polarization. It is modified for input pulses previously Multiplexing inside right and left side of circular polarizer. A comprehensive collection of simulations is available. OPTISIM is used to run a comprehensive series of emulations. The performance investigation contains The Q-factor, eye diagram, received power and BER.

In 2020 Sharma et al.[36] In this study , optical filters and different modulation techniques are reflected to mitigate Four-Wave-Mixing (FWM) in Dense wavelength division multiplexing. DWDM, in the dense WDM system, a circular polarizer (PC) is practical to minimize the influence of FWM. Studies are performed by simulation in the OPTISEM 13 software designed for the DWDM system working on a data rate of (1 Gb/s). The output of the system have been measured depending on the power of FWM products and Q- factor

In 2021 Suresh, H. R. et al.[37] It discussed a proposed technique to reduce the effects of FWM, developing a principle of orthogonal polarization. Here, orthogonal polarization is combined with RZ-Mod, NRZ-Mod, GAUSSIAN-Mod, and RAISED COSINE-Mod. All these modulation techniques are used. The effects of FWM were found to be reduced more by orthogonal polarization than by circular polarization. For different degrees of power input, the PFWM is reduced to – 58dBm in NRZ with circular polarization at 5dBm input power. Q- factors and BER are used to evaluate the system performance.

After reviewing all these studies , it is observed that FWM has immense effect for decreasing the bit rate of the fiber. All the researchers are focusing on the channel spacing parameters for decreasing the FWM effect with a fixed model for the other system parameters. However, it is also found that some works have proposed some models for suppressing FWM by the modulation technique, still, there is no common or comprehensive model design for WDM which can be used for suppressing and analyzing FWM effect with all system parameters that may have great impact on FWM. In addition, all those researchers set their conclusions by considering a standard optical fiber parameters values but it is not yet explored that which kind of manufactured fibers has less effect of FWM for higher data transmission for long haul WDM communication.

From the previous studies above, our work is based on recent works about reducing the nonlinear effects in optical fibers, and from these literary surveys [29], [30], [33], [36] & [37]. However, we designed a new, better model that depends on a polarizer combined with different modulation forms and WDM where every design have linear polarization or circular polarization before the polarization combiner.

1.4 Statement of the Problem

Despite the various issues related to the long haul fiber transmission, the major bottleneck problem is the non-linear effects and impairments occurrence due to the variations of the refractive index and frequency overlaps, i.e. channel overlapping, dispersions, variations of refractive index in Single Mode Fiber(SMF) usages during high bit transmission for long distance fiber communication network.

Hence, the critical problem is pulse broadening due to refractive index variations during high power intensity pulse enters to the Long-Haul fiber transmission system. This critical problem causes Kerr-Effects. Therefore, various non-linear effects occur like SPM, XPM and FWM in the Long- Haul transmission system.

1.5 Thesis Objectives

The objectives of this research can be summarized as follows:

1- To investigate the fiber nonlinearity effect in the optical single system
2- To analyze the four wave mixing effects in high capacity WDM system for different fiber length, channel spacing, modulation forms.
3- To develop a new technique for FWM suppressions in optical links using polarization combiner with modulation scheme
4- To study and analyze the polarization combiner technique with different modulation form in the optical multichannel system to improve the performance and robustness against non- linear transmission impairments of FWM

5- To compare the conventional FWM suppression methods and the proposed techniques to suggest the optimum solution.

1.6 Thesis organization

This thesis is organized in five chapters as follow: -

- Chapter one presents an introduction to optical communication system and its related parameter background about the optical fiber Long- haul- transmission systems, and the main objectives. Also, this chapter includes the problem statement of the thesis and a recent literature survey of optical fiber WDM system and nonlinear FWM effect in optical telecommunication system in addition to the aims and organization of thesis.

- Chapter two describes the fundamental theory about fiber, modulation technique, study the different nonlinear effects that make polarization combiner an ideal device to use, applications of the optical networks. Also, different types of architecture for implementing different modulation forms are also discussed.

- Chapter three includes the research methodology employed to investigate the proposed technique to reduce FWM effect. It illustrates the schematic diagrams for conventional WDM technique and the proposed system simulation design and details for all parameters which are used for each technique.

- Chapter four discusses the results of the proposed polarization technique and its impact on WDM.

- Chapter five represents the conclusions and future work.

2.1 Overview of optical fibers communication system

The primary objective of optical fiber communication system is to transfer the signal information from a source to a destination. The basic components of the optical fiber are shown in Figure (2.1). The information source provides an electrical signal to a transmitter comprising an electrical stage. The transmitter is used to convert an electrical signal into optical signal and send it into an optical fiber. The optical source can be either semiconductor LASER or light emitting diode(LED). LED produces incoherent light with a spectral width of (30-60)nm, which is useful for low frequency applications. The laser produces coherent light with a spectral width less than (5nm) for the laser. There are drive circuits for laser such as bias control circuits, ECLs, and shunt drive circuits. Coupled emitter switches are used in LED circuits that need low impedance matching. The optical carrier is demodulated by driving an electrical stage in the receiver, which consists of an optical detector. Optical signals are detected using phototransistors, photoconductors, and photodiodes. The photoelectric effect can be used by photo-detectors to convert light into electricity. Avalanche diode and (p-i-n) are the two most combined photo detectors. Optical receivers should be capable of bit rate data compression, signal sensitivity, and independence from bit pattern, keeping time, and fixed range[38].

```
┌──────────────┐    ┌──────────────┐    ┌──────────────┐    ┌──────────────┐
│ Information   │───▶│ Electrical    │───▶│ Optical       │───▶│ Optical fiber │
│ source        │    │ transmit      │    │ source        │    │ cable         │
└──────────────┘    └──────────────┘    └──────────────┘    └──────────────┘

      ┌──────────────┐    ┌──────────────┐    ┌──────────────┐
      │ Optical       │───▶│ Electrical    │───▶│ Destination   │
      │ detector      │    │ receiver      │    │               │
      └──────────────┘    └──────────────┘    └──────────────┘
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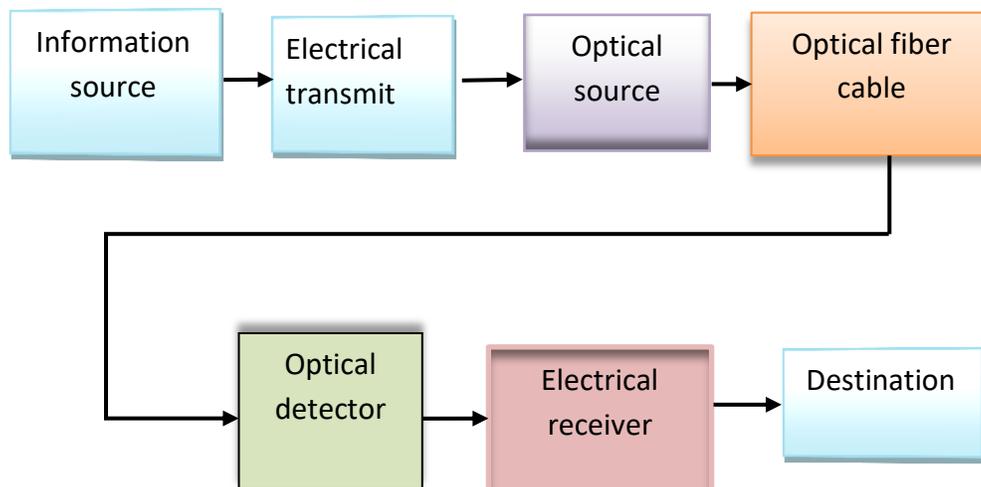
Figure 2.1: Block diagram of the optical fiber of the communication system[38]

2.2 Essential Components of Optical Fiber Communication OFC:

➢   Transmitter: Signal generation and conversion of E/O is carried out at transmitter. Lasers and light emitting diodes are the general components used to generate light and act as intensity source for communication .

➢   Channel: The channel is composed of a cable which consists of glass fibers that act as a waveguide through which optical signals (light) passes. Optical fiber provides special protection to the inside of optical fiber. 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 converts light into electric signal using the photoelectric effect. The most commonly used PD is the semiconductor reliant [39]. PIN and avalanche are the major two photo-detectors in optical communication.

Communication that uses fiber optic referred at as OFC which is a well-competent way for the signal transmission over longer distances. A 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 is 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 used mainly for large or prolonged distances but they are currently being deployed in almost all metro-networks [40]. Thus, the requirements for more number of channels in regional, and in networks called for the up gradation of the existing backbone communication networks to utilize higher transmission rates.

2.2.1 Transmitter (light sources)

i.   Light Emitting Diode (LED)

It is a semiconductor optical source that emits an optical ray when it is subjected to a forward-biased voltage. A p-n connector is the mechanism of the LED. The use of direct voltage on the LED causes a flow of (anode) n-side electrons to the (cathode) p-side. Each electron frees energy in a photon form when it reaches the p-side hole. The emitted photon's wavelength based on the gap of

energy between halfway materials. In short-distance used LED indoor implementations that required a degree of movement. Also, Circuits of LED are simple, and LED does not need constancy versus temperature changes. A LED schematic is presented in figure 2.2[41].
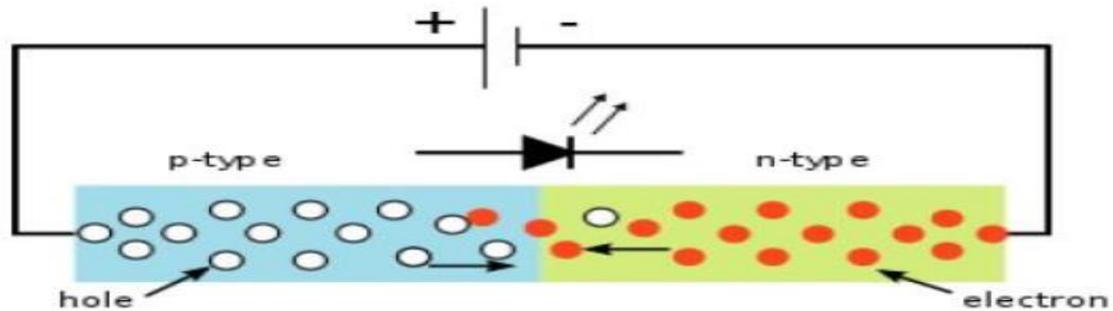
Figure 2.2 LED [41].

ii. Laser Diode (LD)

By the stimulated emission of radiation, laser is the acronym for Light Amplification[42]. Stimulated emissions represent an operation when the photon incident causes the stimulated electron to lie down and emits a neutral photon with a mimic frequency while phase of the current photon throughout this transition. The semiconductor optical amp principle diagram, the prime connotation implemented in the new laser technique is presented in figure(2.3) For a coherent photon beam, a straight bias voltage is theoretical to the diode. This causes the electrons to move into the type-p area and holes into the type-n area, therefore a pair of electrons holes has been created named pumping in new laser applications. For this situation, photon radiation leads to electron-hole pairs being recombined. As a result, an extra photon for the same frequency and phase as the initial photon is produced. These photons can be guided from the semiconductor, the input and the generated photon could be utilized to produce other photons. Two mirrors are used, the first mirror that shows the photons incidentally, and a partial mirror (second mirror) that shows just part of the photos and transmits the rest. This is one common way to achieve this objective. Trapped photons can be used to stimulate additional electrons and thus to produce more photons. The laser beam output is the photons passing through the partial mirror[42]. (LD) is so often preferred for highly speed guided LOS, links outdoor. As well as Light Diode (LD) is used at modulation average more than LED.
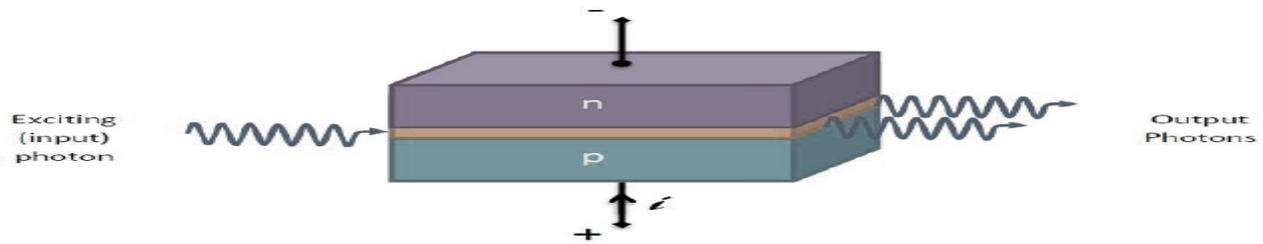
Figure 2.3: Laser Diode Diagram [42]

As the previous sections have shown, the choice between LEDs and Laser Diodes is difficult. Table (2-1) gives an overview of the comparison LED and LD.

Table 2-1. LED and LD Comparison[41] and [42].

Characters	LED	Laser diode (LD)
Output Power	Lower	Higher
Spectral width (nm)	25-100	0.1 to 5
Directionality	Broad (divergence $> 15\circ$)	Narrow ($< 10\circ$)
Temperature dependence	Little	Varying temperature dependence
Light Source	No self-interference, incoherent	self-interference, coherent
Cost	Cheap	High
Lifetime	Long life time	Medium life time
Safety of eye	Safe	should be render eye safe
E/O transmutation efficiency (%)	(10 – 20)	(30 – 70)

2.2.2 Transmission channel

Optical fiber is the transmission medium of the optical fiber communication system which bridges the distance between the optical transmitter and the optical receiver. To ensure the propagation of the transmitted signal up to the receiver with acceptable level of attenuation and distortion which is the main consideration in designing the fiber so that the same information can be received at the receiver with minimum error. With the development in the field of optical fiber communication, the attenuation of the signal could be reduced to 0.2 dB/km. Factors that contributed to this reduction in the loss parameter are improved fiber design technique, low loss fiber window, dispersion compensation, etc. [43]. Fiber loss, dispersion and nonlinear effects are main design considerations of optical fiber. Introduction of optical amplifiers and dispersion shifted fibers could successfully address the limitations imposed by fiber loss and dispersion. However,

many aspects of nonlinear characteristics of the fiber yet remained as the limitation of optical fiber. Optical fibers are classified into two main specifications : multimode fiber (MMF) and single-mode fiber (SMF). The fiber mode indicates the path number for the light rays within the cable. The geometrical fiber structure types are depicted in figure 2.4. single mode fiber is considered to work for long distances. [44]
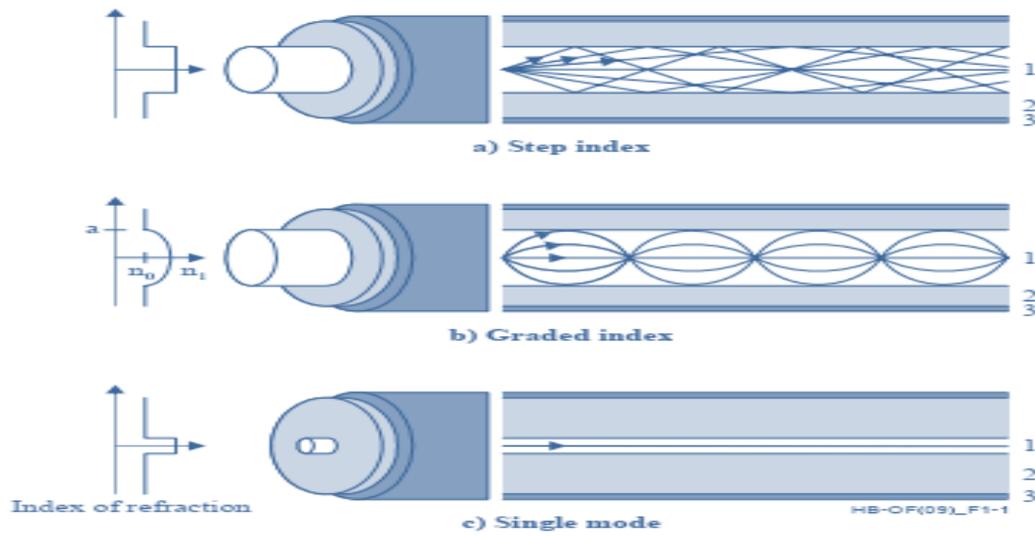
Figure 2.4: (a) MMF step index, (b) MMF graded index,(c) SMF single mode [44]

Single Mode Fiber (SMF) is prepared from glass (silica) which must have attenuation losses between 0.2 dB/km and 0.5 dB/km in the window (1550) and the window1300 nm, respectively [44].

2.2.3 MULTIPLEXING

2.2.3.1 Origin of Multiplexing

Since the origin of telegraphs backs to the 18th century, the steer has been to increase 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 motivated researchers 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 [45].

2.2.3.2 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. Therefore, 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 an assessment to the multi nodes in the network. When the bandwidth of a medium is more than the single channel which needs to be sent 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 [46].

2.2.3.3 Multiplexing and its concepts

Figure 2.6 represents a general operation of multiplexing. MUX is linked to de-multiplexer through one link. It accumulates the data from 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[46].
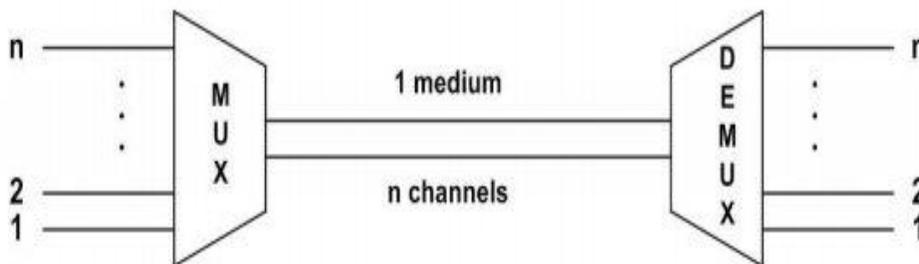
Figure 2.5*:* Block diagram of basic multiplexing [46]

2.2.3.4 Wavelength Division Multiplexing (WDM)

WDM technique is used to improve capacity and scalability of the communication system and send information simultaneously through optical links [47]. Two types of WDM are known: the first is (DWDM) dense wavelength division multiplexing with channel spacing (1.6, 0.8, 0.4) nm, and the second is (CWDM) coarse wavelength division multiplexing with spacing of channel (20) nm, both types are suitable for reliable communication [48] optical fiber -WDM transmission system is

supposed to be the major technique in the future of communication system[49]. WDM is a copy of (FDM) technique frequency division multiplexing but, the main variance the two methods is wavelengths or frequencies which are utilized in each method. With WDM, multiple data streams are transferred by various optical carriers which have distinguished wavelengths modified and crossed via an optical channel. WDM is used to share a great portion of data optimization usability of OFC. In WDM system, multiplexers merge a stream of data that are coming from many optical sources and then cross them during optical channel medium during visual channel. De-multiplexers, in the last edge of WDM communication system, recover the data using the technique of de-multiplexer. WDM communication systems permit independent information and access protocols to work in the same system [50]. This is the significant condition for the enhancement of communication system. It reduces cost of combining and changing between protocols that are used because every optical channel that is utilizing a determined protocol which can be treated (multiplexed / DE multiplexed) in the ends of the independent transmission system. Therefore, different formats of optical information utilizing various bitrates and can be sent in their original formats across the same channel. Mathematical model of WDM can be expressed in Eq. (2.1).

$$\lambda = \lambda 1 + \lambda 2 + \lambda 3 + \lambda 4 + \ldots \ldots \ldots \ldots + \lambda n \qquad (2.1)$$

Where, λ, is the total wavelength of channel. Figure 2.6 represents the WDM diagram.
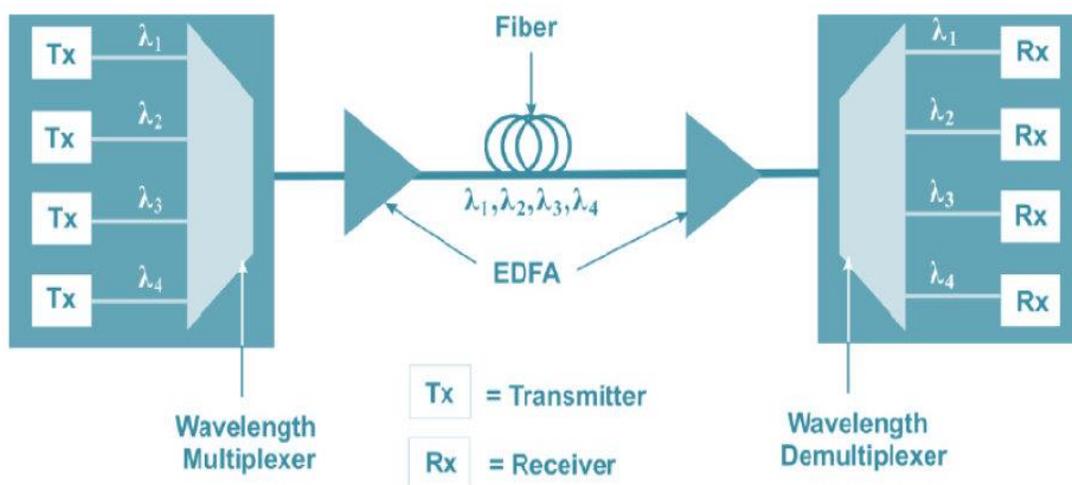
Figure 2.6: Block diagram of the WDM of the communication system[51]

2.2.4 Receiver (photo-detectors)

i. Positive-Intrinsic-Negative (PIN) Photodiode

The PIN photo-detector includes semiconductor materials p- and n-type isolated via a tiny intrinsic area of n-doped material [52]. The reverse biases voltage is generated on the device. The reverse bias guarantees that the intrinsic area is depleted by any charging carrier to transform an incident photon into an electron / electric current. The photon incident utilizes its energy to stimulate an electron from the valence band to the conductive band and create a free pair. The incident light usually focuses on the intricately depleted area. The high electric field in this disintegrated region separates and collects the created charging carriers through the opposite partition junction. This provides an increment to a current flow in an external circuit as presented in figure (2.7). There is one electron flowing for every carrier pair created. PIN photo-detector reactivity is always below the unit, and PIN photo-detectors can work at very high rates over 100Gbit [53].
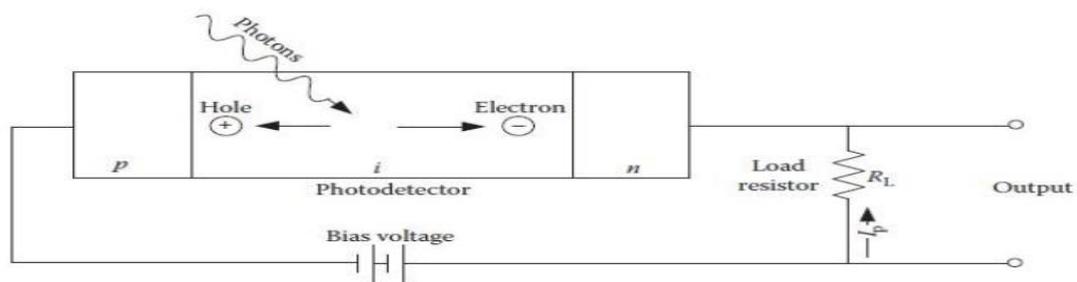
Figure 2.7: PIN detector [53].

ii. Avalanche Photodiode (APD)

The APD varies from a PIN photo-detector where it presents an inherent current gain through an operation named a repeated electron ionization. This process increases the sensitivity since the photocurrent is multiplied before encountering the thermal noise related to the receiver circuit. The typical value for gain lies between 50 and 300. Therefore, an APD's response value can be higher as a unit. The APD is higher than the PIN, but the ionization/avalanche process statistical nature means that the APD is associated with the APD always in multiplication noise. The process of avalanche is also much more sensitive to temperature. These parameters are essential and should usually be considered when an APD is being utilized in an optical system [54]

2.3 Channel Impairments

2.3.1 Linear Channel Impairments

I.   Optical Fiber Losses

An important fiber parameter is the measure of power loss during transmission of optical signals inside the fiber [55]. Attenuation is the loss of optical power as light travels along the fiber. This loss or attenuation in fiber depends on the wavelength of the light propagating within it [56].

If P0 is the power launched at the input of a fiber of length L, the transmitted power PT is given by:

$$P_T = P_O e^{-\alpha L} \qquad (2.2)$$

where the attenuation constant α is a measure of total fiber losses from all sources. It is customary to express α in units of dB/km:

$$\alpha_{dB} = -\frac{10}{L} \log \frac{P_T}{P_O} \qquad (2.3)$$

Figure 2.8:Measures loss spectrum of a single-mode silica fiber [55].
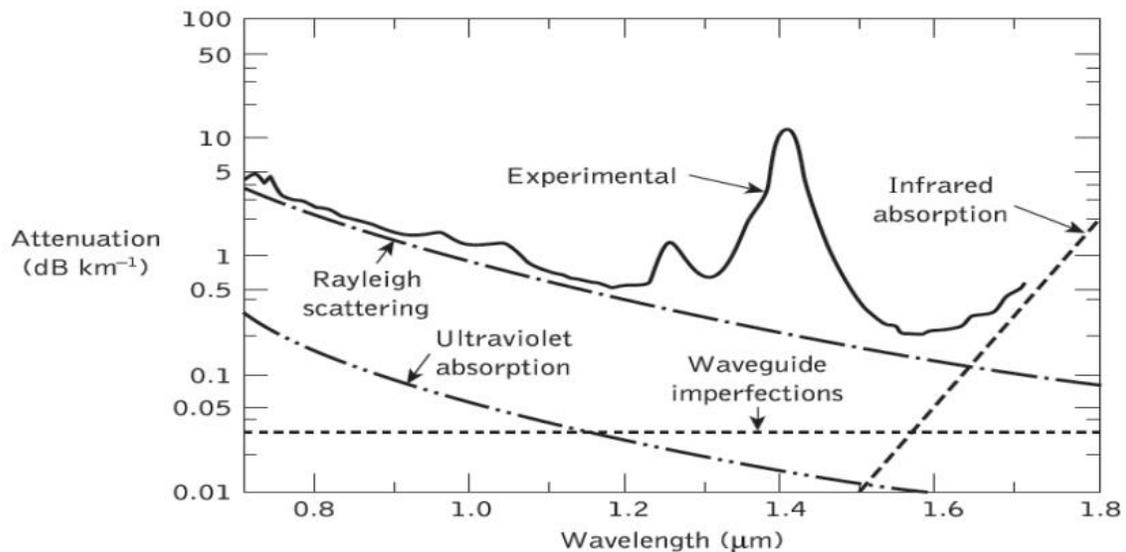
Figure 2.8 The loss spectrum of a silica fiber [55]

Most optical communication systems operate in the 1.55μm window which provides the lowest attenuation. However, for long distance transmission, the fiber attenuation can degrade the signal considerably and thus sets a limit as to how far one can transmit without errors. In order to overcome limitations imposed by fiber losses, regenerator stations are placed periodically along the

fiber link. The regenerator station's main purpose is to recondition the signal before any further transmission. It is performed adequately well for low bit-rate. However, as the operating bit rate increases, electronic regeneration is no longer feasible because of the speed limitation of electronic equipment, hence equipment modification is required. Furthermore, for multiple channel systems, such as DWDM, each individual channel requires its own regenerator. The cost for adopting the system to higher operating bit-rates proves to be too costly given the vast magnitude of the already deployed equipment . This constraint can be easily overcome by employing the use of an all optical repeater station. In an all optical station, an optical amplifier is used to boost the signal power.

II Optical Channel: Chromatic Dispersion

Chromatic dispersion (CD) happens to belong in the category of distortion due to the designing in some optical fiber. It results from frequency dependence on the proportion by which the phase of the wave transmits in an area (optical phase velocity) and its effectiveness on the conveyed optical signal mostly scales through the information rate. The frequency dependence of the phase pointed out could be simply known by a pulse that transmits over a single mode fiber into the frequency domain [57].

$$X_{out}(\omega) = X_{in}(\omega)e^{-j\beta(\omega)z} \qquad\qquad (2.4)$$

where $X_{in}(\omega)$ resembles   the Fourier Transform of the signal transmitted and at the receiver $X_{out}(\omega)$ corresponds to the Fourier Transform of the signal recovered and $\beta(\omega)$ represents the phase constant of propagating mode. Because of frequency dependence of phase on β, the major obstructive effect measured in equation (2.4) is due to the C.D. Other phenomenon as nonlinearities or attenuation will not be measured, although their properties are going to be considered later. The phase constant $e^{-j\beta(\omega)z}$ is linearly dependent with frequency, in an ideal case. This means that each spectral component propagates with the identical velocity and thus experiences the identical phase delay. The signal is going to be received with a constant delay but deprived of any distortion. Nevertheless, the phase constant $e^{-j\beta(\omega)z}$ which is nonlinearly reliant on frequency, in a dispersive channel. This results in separate arrival time of these frequency components; its significance is that at the reception end, the recovered signal would not be the same with respect to the transmitted signal.

2.3.2 Polarization Mode Dispersion

Polarization related impairments represent a major obstacle in increasing data rate for WDM systems. These impairments include polarization mode dispersion (PMD) in fibers, components polarization loss of passive networks and polarization gain of optical amplifiers.
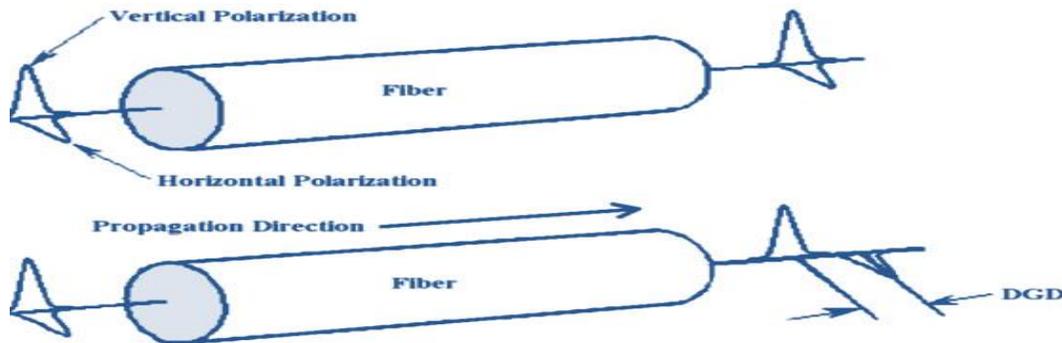
Figure 2.9 Polarization mode dispersion [58].

PMD is linear phenomenon occurring inside single mode fiber as each fiber has two propagation modes which differ from each other by their polarizations. However, due to presence of birefringence, the two modes have different group velocities while travelling through fiber resulting in propagation time difference which is known as Differential group delay (DGD) and randomly changing birefringence with fiber length leads to random coupling of these modes which causes receiver to be unable to interpret received signal correctly. Problems manifest themselves in 5Gb/s and have major dislocation at 10Gb/s. It leads to signal distortion, render bits accuracy and leads to distortion of integrity of network. The PMD value of older fibers was 100 times greater as compared to fibers of the present day. Still, in new fibers , PMD is a major problem due to the following factors:

 a) Residual asymmetry in core of fiber

b) Slight PMD in inline discrete components for example couplers, isolators, multiplexers and modulators. Also, external forces due to environment in cabling, handling leads to bend and twist the fibers and internal forces due to thermal expansion which leads to asymmetries in fiber [58].

2.3.3 Non-linear effects

In the optical fiber, the non-linearity can be classified into two main types: -

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> ➢ stimulated scattering effects are the result of the scattering leading to an intensity dependent attenuation constant.
>
> ➢ Optical Kerr effects are the result of intensity dependent of refractive index of an optical fiber leading to a phase constant.

The non-linear effects can be classified as shown in figure 2.10[59].
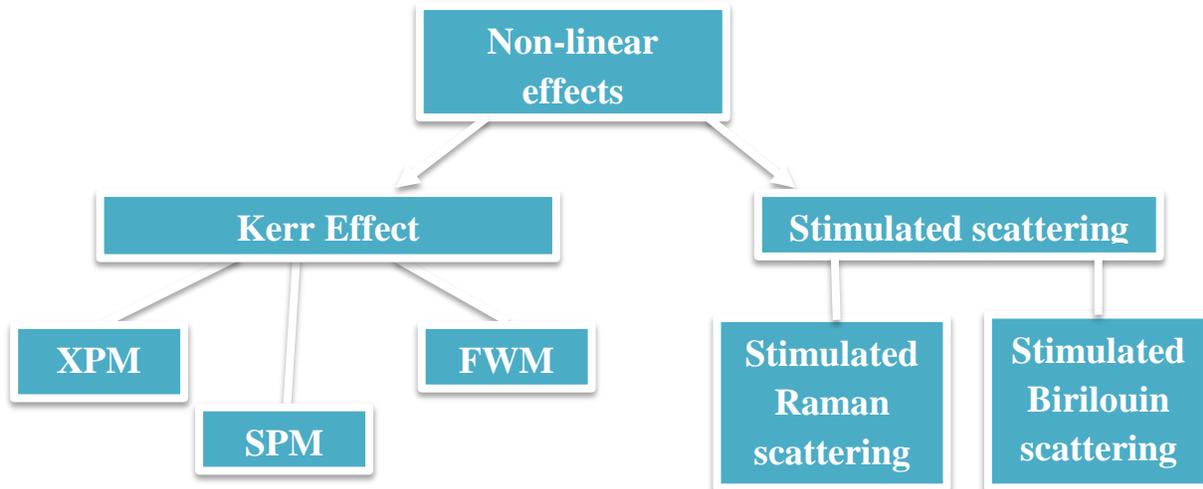
Figure 2.10: classification of nonlinear effects[59]

2.3.3.1 Scattering Effects

Inelastic-scattering phenomenon: This phenomenon induces stimulated effects at high power level which stimulated Raman scattering (SRS) and Brillion scattering (SBS). Exponential increase in the scattered light intensity occurs when incident power crosses a certain critical value. Raman and Brillion scattering differ in the way that in SRS, the generated phonons (optical) are incoherent and there is no generation of macroscopic wave while in SBS, the phonons (acoustic) are coherent leading to the generation of a macroscopic acoustic wave in optical fiber [60]. Stimulated scattering effects can be divided into Stimulated Raman Scattering (SRS) Brillion Scattering (SBS).

Both phenomena describe nonlinear light scattering where new light of a different frequency is generated. Newly generated photons are referred to Stokes particles, if part of energy is lost and their frequency is lower than the original light. In case that the new photons were supplied with a part of energy and thus their frequency is higher, they are called Anti-Stokes particles. In both of these variations, the generation and performance of the scattered light increases strongly when a certain threshold level is exceeded. In general, the broader the spectrum of the optical source signal,

the higher the threshold power. In case of Stimulated Brillion Scattering, which is spreading backward, a powerful light wave travels through a fiber and interacts with acoustical vibration modes in the glass. The newly generated light wavelength differs only in the order of several GHz from the original one. The bandwidth in which the light is located is only units of tens of MHz . The Brillion scattering power threshold for classical SM fibers is in the order of tens of mW and is strongly dependent on the fiber composition, the width of the source spectrum, the transfer rate, and the modulation used. Raman's scattering, unlike Brillouin's scattering, is omnidirectional. When the threshold is exceeded, some of the scattered light is scattered in the same direction as the working optical signal, but a portion of the scattered energy is exported out of the fiber outward and a portion advancing back to the beginning of the fiber. Moreover, it leads to some changes in its wavelength, which can be qualified as a loss of energy at the working wavelength. Therefore, Raman scattering may cause problems with the broadband DWDM system, where the optical power from higher frequency channels is transferred to lower frequency channels (Stokes). On the other hand, this effect can be used to intensify all channels through the SRS phenomenon. This is why Raman's phenomenon is being used to construct an optical amplifier[61].

2.3.3.2   Optical Kerr effect

In the optical fiber the non-linearity Kerr effect can be classified into three main types

I.   Self-phase modulation (SPM).
II.   Cross phase modulation (XPM).
III.   Four-wave mixing (FWM).

The most significant non-linear effect is the Kerr effects. It rises from the dependence of the refractive index on the power of the signal P(t), and is denoted as follows by the Equation. (2.5): [61]

$$n(\omega, \text{P}(t)) = n_0(\omega) + n_2 \frac{P(t)}{A_{eff}} \qquad (2.5)$$

So that the linear portion of the refractive index is n_0, the nonlinear portion of the refractive index is n_2, and the effective area of the optical fiber is A_{eff}.

The non-linearity coefficient is (γ) in $[w^{-1} \, km^{-1}]$ combination the nonlinear refractive index and the effective core area for the fiber in the term seen in Eq. (2.6)

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}} \qquad\qquad (2.6)$$

Despite the fact that the refractive index is a weak function of signal power, the increased power of optical amplifiers as well as long transmission lengths make it no longer a minor factor in current optical networks. Self-Phase Mod. (SPM), Cross-Phase Mod. (XPM), and Four-Wave Mixing are all nonlinear phenomena caused by phase modulation caused by a power dependent refractive index (FWM)[62].

I. Self-phase modulation (SPM).

The nonlinear change in the refractive index causes a power dependent nonlinear phase shift, which is given by Eq. (2.7)

$$\emptyset_{NL} = \gamma P(t)L_{eff} \qquad\qquad (2.7)$$

where L_{eff} represents the effective length ,that given by

$$L_{eff} = \frac{1-e^{-\alpha L}}{\alpha} \qquad\qquad (2.8)$$

This effect appears due to the dependence of refractive index on light intensity: in those parts of pulse where the intensity is going higher, the refractive index is increasing, along with the wavelength. Self-Phase Modulation is a modulation of the optical signal phase and occurs in mono wavelength systems with large bit rates as this mod tends to cancel the dispersion due to the increase in high signal energy levels and for the purpose of avoiding losses such as (linear attenuation and description in a factory fibers) [63]. Following the previous definition, the immediate carrier frequency is decreasing with ascending part of pulse (shift to IR frequencies), and on the contrary, the immediate carrier frequency is increasing in descending part of pulse (shift to UV). This frequency change in combination with chromatic dispersion (CD) leads to the change of pulse shape over time. The temporary frequency change is known as "chirp"[64].
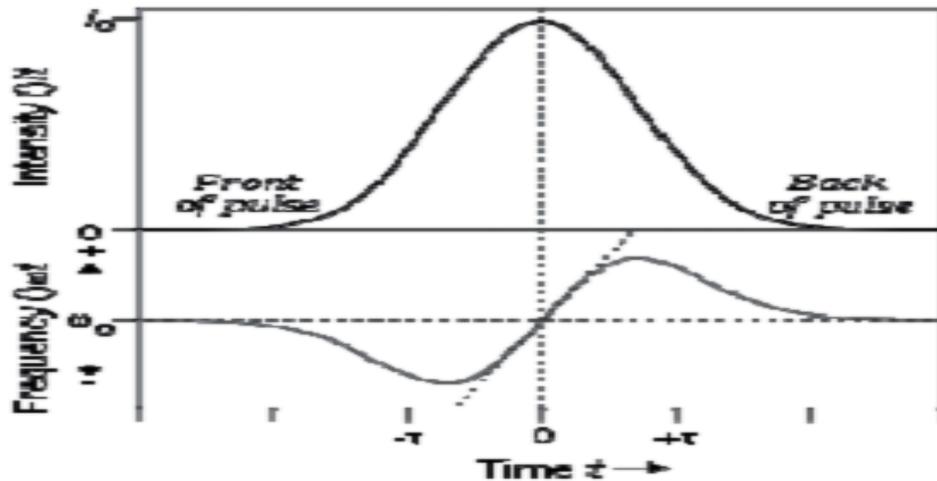
Figure 2.11: Phenomenological description of spectral broadening of pulse due to SPM [64]

II. Cross-phase modulation (XPM).

It is a special case of SPM, where the refractive index is not only affected by the pulse itself, but also by other pulses transmitted by the fiber at the same time on different wavelengths. XPM happens only in multi -channels systems. In the multi-channels system, the non-linear phase shift of the indication at the focus wavelength(λ_i) describes by [65]

$$\emptyset_{NL} = \left(\frac{2\pi}{\lambda_i}\right) n_2 z \left[I_i(t) + 2 \sum_{i \neq j}^{N} I_j(t)\right] \qquad (2.9)$$

The same as SPM, XPM leads to a change in the frequency spectrum that is in combination with the CD which leads to a change in pulse shape over time. The refractive index changes can be characterized as[66]:

$$\Delta n^{(2)} = 2n_2 I^{(1)}, \qquad (2.10)$$

That n_2 represents non-linear index , and the intensity $I^{(1)}$ of beam A produces a change in the refractive index of beam(B), at the same polarization , the factor 2 is accurate through the beams, in isotropic medium accurate the cross-polarized beams, this value has been substituted by ($\frac{2}{3}$).

In long-haul WDM systems, SPM and XPM are the most nonlinear effects. It can be reduced by:

✓ Lowering the optical power at the expense of decreasing the optical signal-to-noise ratio.

✓ Dispersion management, because dispersion can partly mitigate the SPM effect.

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III. Four-Wave Mixing (FWM)

FWM is one of the major limiting factors in DWDM optical communication systems that use narrow channel spacing and low or almost zero dispersion fibers. If two or more channels in a fiber interact with one another through FWM, this causes additional noise on the system and degrades the signal quality. The newly generated frequencies appear at the cost of reduction of power at the original optical wavelengths. Power is lost from desired signals due to unwanted ones. When this fourth wavelength acts as an interfering signal to the original one, the retrieval of the original signal is di-cult. This is why it is very important to take steps to prevent from FWM or suppress FWM effect in multichannel optical communication systems.

In addition, FWM yields inter-channel crosstalk if the generated signal falls into other co-propagating channels. This results in significant system performance degradation due to crosstalk among channels. FWM depends on the fiber dispersion and channel spacing [67]. Thus, increasing the fiber dispersion limits the interactions between signals and reduces the power transfer to the newly generated signals. Increasing the channel spacing decreases the FWM effect as well. The dependence of the refractive index on the light intensity results in the propagation constant, β, varying as the light intensity due to: $\beta = 2\pi n/\lambda$, and the propagation constant can be written as:

$$\beta(\omega, P) = \beta_0(\omega) + \frac{2\pi n_2 P}{\lambda A_{eff}} \qquad (2.11)$$

Where $\beta_0(\omega)$ is the propagation constant in the absence of nonlinear effects, fiber nonlinear coefficient becomes:

$$\gamma = \frac{2\pi n_2 P}{\lambda A_{eff}} \qquad (2.12)$$

The total nonlinear phase shift due to the Kerr effect after the distance L is given by:

$$\phi_{NL} = \int_0^L (\beta - \beta_0) dz \qquad (2.13)$$

Substituting (2.11) and (2.12) using (2.13)

$$P(z) = P_0 \exp(-\alpha z) \qquad (2.14)$$

Where P_0 is the launch power, and α is the loss coefficient, we obtain

$$\phi_{NL} = \gamma P_0 \int_0^L \exp(-\alpha z) dz = \gamma P_0 \frac{1 - \exp(-\alpha z)}{\alpha} = \frac{L_{eff}}{L_{NL}} \qquad (2.15)$$

Where $L_{eff} = \frac{1 - \exp(-\alpha z)}{\alpha}$ is the effective length, and $L_{NL} = \frac{1}{\gamma P_0}$ (2.16)

is the nonlinear length. Physically, the nonlinear length, L_{NL} , indicates the distance at which the nonlinear phase shift reaches 1 radian, and it provides a length scale over which the nonlinear effects become relevant for optical fibers. It can be seen from Eq. (2.16) that the fiber nonlinear effect enhances when L_{NL} decreases, or equivalently power P_0 increases.

Table 2.1: Comparison of fiber nonlinearities.

Nonlinear phenomenon	SPM	XPM	FWM
1-Bit Rate	Dependent	Dependent	Independent
2-Origin	Nonlinear susceptibility	Nonlinear susceptibility	Nonlinear susceptibility
3-Effect of X	Phase shift due pulse itself only	Phase shift is due to co-propagating signal	New waves are generated
4-Shape of Broadening	Symmetrical	May be symmetrical	-
5-Energy transfer between medium And optical pulse	No	No	No
6-Channel Spacing	No effect	Increases on decreasing the spacing	Increases on decreasing the spacing

2.4 Theoretical model of FWM

This phenomenon occurs in DWDM system because of non-linear susceptibility in optical fiber when three wavelengths of near frequencies propagate together giving rise to the new fourth wavelength. For three continuous- wave channels of input powers P_i , P_j , P_k at frequencies f_i . f_j . f_k the intermodulation products will appear at frequencies[68]:

$$f_4 = \pm f_i \pm f_j \pm f_k \qquad (2.17)$$

We do not pay attention to all the frequency combinations of equation 1, for example $f_i + f_j + f_k$, because these frequencies lay out of the telecommunication band that is of particular importance since such waves may easily be eliminated by filtering process. The amount of intermodulation products which are really important from the point of view of encumbering noise is [68]:

$$M = \tfrac{1}{2}.N^2 \cdot (N - 1) \qquad\qquad (2.18)$$

The number of generated FWM products grows exponentially with the number of channels, as demonstrated in figure 2.12 For example, optical systems with 40 channels have around 30000 FWM products while for such systems with 80 channels, this number reaches over 250000. New frequencies laying inside the readable band and generated by three continuous wave channels are:

$$f_i + f_j - f_k$$
$$f_i + f_k - f_j$$
$$f_j + f_k - f_i$$
$$2f_i - f_j, \ 2f_i - f_k \qquad\qquad (2.19)$$
$$2f_j - f_i, \ 2f_j - f_k$$
$$2f_k - f_i, \ 2f_k - f_j$$
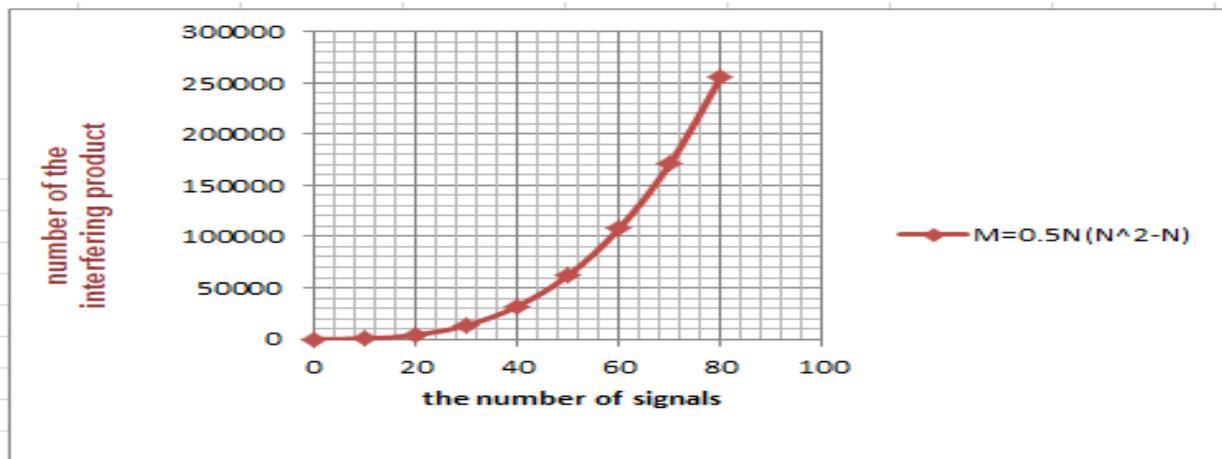
Figure 2.12: Number of FWM products depending on number of channels system [69].

The nonlinear Schrodinger equation (NLSE) is used to explain the envelope of the optical field when the nonlinear effects are in the form that is given by the following equation[70].

$$\frac{\partial A(z,t)}{\partial z} + \frac{\alpha}{2} A(z,t) + B_1 \frac{\partial A(z,t)}{\partial t} + \frac{j}{2} \frac{\partial^2 A}{\partial t^2} - \frac{1}{6} B_3 \frac{\partial^3 A(z,t)}{\partial t^3} = -j \Big) A(z,t)|^2 A(z,t) \qquad (2.20)$$

Where A is the complex electric-field envelope of the wave, α is the fiber loss coefficient, B_1, B_2 and B_3 are the dispersion coefficients and γ is the nonlinear coefficient. In a WDM system, the power

transfer due to the FWM to new frequencies after light has been propagated within a distance L in the fiber can be estimated from the (2.23)

where precious FWM wavelength was calculated and compared with real arose FWM products from the mensuration on the required spectrum band.

Then the power of the light-wave resulting from FWM at the frequency is [70]:

$$P_{ijk} = d_{ijk}{}^2 \, \gamma^2 L_{eff}{}^2 P_i P_j \, P_k \eta_{ijk} \, e^{-\alpha z} \qquad\qquad (2.21)$$

where d_{ijk} is the degeneracy factor, which takes value 1 and 2 for degenerate $(i = j)$ and non-degenerate $(i \neq j)$ terms respectively, L_{eff} is the effective length, η_{ijk} is FWM efficiency, α is an optical attenuation in dB/km, z is the length of fiber in km, γ is the nonlinear coefficient, which is given by the below equation [70]:

$$\gamma = \frac{(2\pi n_2)^2}{A_{eff}{}^2} \cdot \frac{1}{\lambda^2} \qquad\qquad (2.22)$$

where n_2 is the fiber nonlinearity coefficient, A_{eff} is the core effective cross-sectional area, λ is the central wavelength[71].

Consider a WDM where a system of equations (Maxwell equations) is employed to represent this low-order nonlinearity, with the nonlinear susceptibilities acting as coupling coefficients between the waves of electromagnetism. As an example, consider the following electric field:[73]

$$P_{FWM} = \frac{1024\pi^6}{n^4 \, \lambda^2 C^2} \left[\frac{D x_{111} L_{eff}}{A_{eff}} \right]^2 (P_i P_j P_k) e^{-\alpha L} \frac{\alpha^2}{c\alpha^2 + 2\pi D_e (\Delta f j k)} \qquad\qquad (2.23)$$

Under the effect of polarization, FWM efficiency becomes:

$$\eta_{FWM(pol)} = \frac{1}{N} \times \eta_n \times X_{111r}^{\,2} \qquad\qquad (2.24)$$

$\eta_{FWM\,(pol)}$ is FWM efficiency attained by polarization technique.

X_{1111r} is a factor that presents a polarization dependency of the nonlinear effect and varied from 0 to 1 according to SOP between channels

η_n is the normal FWM efficiency in WDM system.

FWM efficiency (η_n) can be rewritten as follows:

$$\eta_n = \frac{\alpha^2}{c\alpha^2 + 2\pi D_c (\Delta f i k)(\Delta f j k)} \qquad\qquad (2.25)$$

By substituting Eq. (2.25) into Eq. (2.24), we can derive Eq. (2.26) as the following:

$$\eta_{FWM(Pol)} = \frac{1}{N} \times \frac{X_{111r}^2 \times \alpha^2}{c\alpha^2 + 2\pi D_c (\Delta fik)(\Delta fjk)} \quad\quad (2.26)$$

With the OEC effect, FWM power in Eq.(2.23) will be changed as follows:

$$P_{FWM(Pol)} = \frac{1024 \ \pi^6}{n^4 \lambda^2 C^2} \left(\frac{DX_{111}L_{eff}}{A_{eff}} \right)^2 \left(P_i P_j P_k\right)^N e^{-\alpha L} \times \frac{X_{111r}^2 \times \alpha^2}{N \times (c\alpha^2 + 2\pi D_c (\Delta fik)(\Delta fjk))}$$

FWM noise power N_{FWM} is [72]: -

$$N_{FWM} = 2b^2 Ps \left(\frac{P_{FWM}}{8} \right) \quad\quad (2.27)$$

Where b is the responsive of the detector, b= (ηe/hf) , where h is the Planck's constant, η is the quantum efficiency of the detector, e is the elementary electric charge, and Ps is the signal light power at the receiver that may be assumed. The system performance can be evaluated using Q factor as [73]

$$Q = \frac{bP_S}{\sqrt{N_{th} + N_{sh}} + N_{FWM} + \sqrt{N_{th}}} \qu\quad (2.28)$$

and the BER has been designed from the Q factor: -

$$BER = 0.5 \times erfc \left[\frac{\varrho}{\sqrt{2}} \right] \qu\quad (2.29)$$

These combinations $\left(f_i \mp f_j \mp f_k\right)$ are the new frequencies created by new waves, with a focus on those that occur inside the telecommunication band, such as $\left(f_i \mp f_j \mp f_k\right)$ with i, j$\neq$ k), when $i = j$ are identical, the FWM is regarded degraded**.** If the channels are equally spaced, some of the generated waves will have the same frequencies as the injected waves. Clearly, the appearance of the additional waves as well as the depletion of the initial waves will degrade multichannel systems by crosstalk or excessive attenuation [71]. The FWM power is proportional to the interacting signal powers, and can be expressed as in :Fig.2.13 , a schematic diagram that shows four-wave mixing in the frequency domain. As can be seen, the light that was there from before launching the two pumping waves in the frequency domain, is called the probe light (or signal light). The idler frequency idler may then be determined by: f idler $= f$p$_1$ $+ f$p$_2$ $-f$ probe

where $f\mathrm{p}_1$ and $f\mathrm{p}_2$ are the pumping light frequencies, and $f$probe is the frequency of the probe light [73],[74]. This condition is called the frequency phase-matching condition. When the frequencies of the two pumping waves are identical, the more specific term "degenerated four-wave mixing" (DFWM) is used, and the equation for this case may be written as $f$idler $= 2f\mathrm{p} - f$probe; where: $f\mathrm{p}$ is the frequency of the degenerated pumping wave.
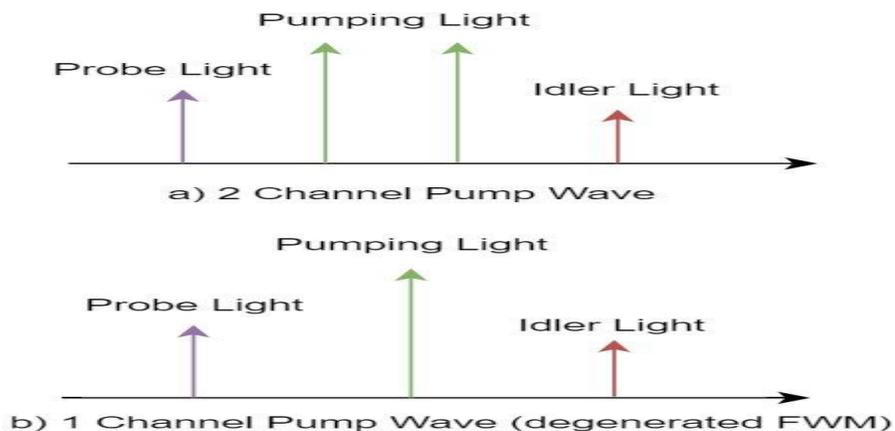
Figure 2.13: FWM in the Freq. Province [70]

For both cases of Fig. (2.13), the two frequencies i, j generate sidebands, the idler component will be the newly generated component f_{ijk}, and the probe light will be the frequency of the probe light f_k. If the number of wavelengths launched to the fiber is increased from 2 to 3, the number of FWM products will grow exponentially from 2 to 9, as shown by the foregoing equation (2.18)[70].

2.5   Methods to avoid FWM product creation

2.5. 1Using of Non-Zero Dispersion Shifted Fibers (NZDSF)

It is a generally accepted view that chromatic dispersion causes pulse spreading in time, which is a substantial problem for pulses travelling over long distances. Because of that reason do exist optical fibers which compensate for dispersion. What we just call dispersion is a sum of two factors: material dispersion, which is determined by material of the fiber and therefore is nonadjustable, and waveguide dispersion, which can be modified by changing of refractive index profiles in fibers. This waveguide dispersion is used to compensate material dispersion. ITU-TG.652 is a specified characteristic of the single-mode cable of optical fiber [75] which has zero dispersion at wavelength $\lambda = 1310$ nm. Sometime, after this specification long-distance telecommunication networks began to use wavelengths mainly around $\lambda = 1550$ nm, which leads to the development of Dispersion Shifted

Fibers (DSF) specified at ITU-T G.653 [76]. Such fibers have zero dispersion at wavelength $\lambda =$ 1550 nm. DWDM systems though are incompatible with such fibers because multiple channels and zero chromatic dispersion are added up to create serious FWM cross talks. Having this problem in mind, Non-Zero Dispersion Shifted Fibers (NZDSF) were specified in ITU-T G.655 [77] in order to let DWDM achieve its maximum efficiency by setting low, but non-zero dispersion value at 1550 nm, so that the signal could travel long distances without causing crosstalk.

2.5.2 Spacing channels unequally

It is a more damaging variant, when FWM generates new wavelengths at frequencies that coincide with channels that carry a useful signal. In this case, FWM noise interferes the most. An investigation was conducted about the influence of channel spacing on FWM product spectral position[78].

2.5.3 Using of the dual-phase amplifier model

Usually high power of amplifiers causes FWM effect in DWDM systems. To avoid FWM, instead of one amplifier or a cascade of amplifiers one by one, the first amplifier should be inserted before the optical fiber and the other one behind the fiber. The power of these amplifiers should not be high. Such model is called dual-phase amplifier, which does not cause FWM effect, and power at the output of the cascade is not reduced[79].

2.5.4 Using the correct channel spacing

DWDM has a channel spacing less than 1 nm. According to the ITU-T G.694.1 recommendation, describing safe usage of channel frequencies over the total frequency band, the channel spacing can be set as follows:

- channel spacing 100 GHz (0.8 nm),
- channel spacing 50 GHz (0.4 nm),
- channel spacing 25 GHz (0.2 nm),
- channel spacing 12.5GHz (0.1 nm).

About 40 channels with 100 GHz spacing can occupy the complete C-band of 1530-1565 nm. Indeed , the number of channels can be doubled when using a channel spacing of 50 GHz[80].

2.5.5 Fiber based method (using DCF):

This employs dispersion compensation through a small section of fiber length. It consists of an optical fiber that has a special design such as providing a large negative dispersion coefficient while the dispersion of transport fiber is positive. Proper length of DCF allows the compensation of chromatic dispersion accumulated over a given length of transport fiber. Conventional DCF (DCF) has a high negative dispersion –70 to –90 ps/nm-km and can be used to compensate the positive dispersion of transmission fiber in C and L bands. Trough further reduction in the core effective area of new type DCF, some slope correction has been made possible for SMF[81].

2.6 Polarization

In space, representation of light is given as a wave of transverse nature in which wave motion is perpendicular along propagation direction. Continuous wave (CW) in which propagation direction is chosen as z is represented by E (z , t)e$^{j(wot-\beta z)}$, β here refers to the propagation constant, ω_o refers to the angular frequency of carrier, x, y denotes transverse coordinates. Polarization is a property that represents electric field orientation E (z,t) of electromagnetic waves in plane of x, y coordinates at t time with propagation distance of z. Light is linearly polarized when the phase difference between E_x and E_y is 0 or multiple of π with constant oscillation plane. When x and y components have equal amplitudes with multiples of $\pi/2$ phase difference, then have elliptical polarization. Jones formalism provided representation of light polarization with electric field using ket 2D vector [82]

$$\langle s \rangle = \begin{pmatrix} s_x \\ s_y \end{pmatrix} \tag{2.30}$$

Here s_x and s_y are complex quantities and bra-ket notation is used to distinguish jones vector from Stokes vectors. Jones vector basically has unity magnitude i.e.

$$\langle s|s \rangle = s_x^* s_x + s_y^* s_y = 1 \tag{2.31}$$

polarization can also be described by stokes formalism which have four stokes parameter . Stokes parameters for coherent light are given by [82]:

$$s_o = s_x s_x^* + s_y s_y^* \tag{2.32}$$

$$s_1 = s_x s_x^* - s_y s_y^* \tag{2.33}$$

$$s_2 = s_x s_y^* - s_x^* s_y \tag{2.34}$$

$$s_3 = j(s_x s_y^* - s_x^* s_y) \tag{2.35}$$

Stokes vector is defined as s$^\wedge$=(s_1,s_2,s_3) having unit length indicating polarization of filed. For s_1=1, light is known to be linearly polarized along x axis, s_2=1 in linear polarization of 45^o and s_3=1 in right circular polarization of light. The stokes vector locus which represents possible states of

coherent light polarization form a sphere known as Poincare sphere providing three dimensional representation of light polarization of 45^0 and =1 in right circular polarization of light. The stokes vector locus which represents possible states of coherent light polarization form a sphere known as Poincare sphere providing three dimensional representations of light.

2.6.1. Polarization technique

The FWM power strongly depends on the polarization states of the mixing channels. Orthogonal polarization has recently been found to reduce the FWM crosstalk. The researcher has reduced the FWM by randomly adjusting the polarization state of the adjacent channels to be orthogonal to one another [83-84]. The researcher in [83] suggested an effective solution to suppress the FWM crosstalk by the arrangement of signal polarization states in multichannel systems, i.e. alternate polarizations by assuming that half of all channels have a state of polarization (SOP) orthogonal to the other half, because FWM signals are generated when the SOPS are identical, for example for 8-channels (four channels have an identical SOP and four channels have the other SOP). Based on the experimental results for three signals, the FWM power reduction was estimated under different arrangements of SOP and various numbers of channels with polarization sensitive receivers and using standard parameters in[83]

2.6.2 Polarization Combiner

In this model, the two input signals are combined into one output port. The polarization combiner chooses the input ports with the appropriate polarization component of each signal and adds the selected polarization components. How this model is applied is shown in figure 2.14. At each input terminal, there is a linear polarizer. The angle of each polarizer is given according to the angle of the unit. The device is applied to an angle of 90°[85]
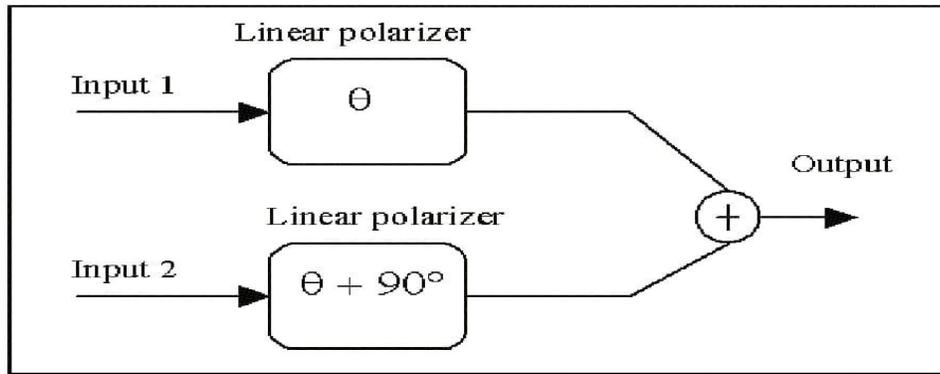
Figure 2.14 Optical spectrum of the polarization combiner[85]

2.6.3 Polarization Multiplexing

An approach towards multilevel modulation forms that uses polarization dimension of the signal that passes through optical fiber. In comparison with phase shift keying (PSK) and amplitude modulations, modulations using polarization multiplexing (POLMUX) has attracted simply limited attention. This is unpaid of the reason where these modulations require the use of receivers that are sensitive to polarization. POLMUX also refers to as Polarization division multiplexing (PDM) or dual polarization. (DP) modulation is the most commonly used polarization sensitive formats for modulation. these two independent signals are transmitted in each of the two orthogonal polarizations and used to increase SE as compared to single polarization modulation. This modulation also leads to reduce the symbol rate by half in comparison with binary modulations having same bit rate [86] and leads to reduce linear and nonlinear channel impairments. However, due to birefringence of optical fiber, they require polarizations sensitive receiver for DE multiplexing of two polarizations at receiver.

This DE multiplexing can either be done in electrical or optical domain and is more sensitive to polarization related impairments. This modulation has been used in number of laboratory experiments for recording capacity and in field trials [87].

2.6.4 Polarization Interleaving

In WDM systems , capacity can be increased either by increasing data rate or the number of channels in the system. However, to increase the number of channels, spacing between channels

have to be reduced. This reduction in spacing leads to increase PMD and nonlinear effects in the transmission system. Different techniques have been generated for the reduction of this nonlinear and PMD effects. The most commonly used technique is polarization interleaving. In WDM systems, amplitude of signal at nth detector after de-multiplexing is given by [88]

$$E_n = S_n + \sqrt{\gamma}[S_{n+1} + S_{n-1} + S_{n+2} + S_{n-2} \dots \dots \dots] \qquad (2.36)$$

Here S_n denotes signal amplitude of nth channel and γ is a fraction of leakage of optical power in WDM due to adjacent channel interference into nth channel.

Electrical current is directly proportional with $|E_n|^2$

$$i_n(t) \propto |E_n|^2 = |S_n|^2 + \sqrt{\gamma}[S_n S_{n+1} + S_n S_{n-1} + S_{n+1} S_{n-1} S_{n+2} + \cdots \dots \dots]$$

$$+\sqrt{\gamma}|S_{n+1}|^2 + |S_{n-1}|^2 + |S_{n-2}|^2 + |S_{n+2}|^2 \dots \dots \dots] \qquad (2.37)$$
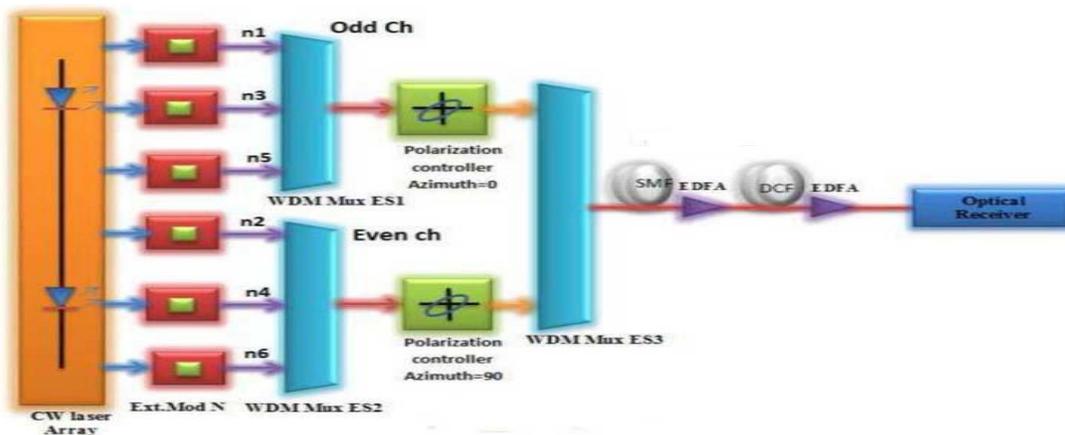
Figure 2.15**:** Polarization interleaving scheme in WDM system [88].

Here, in this equation, the second term indicates interference which can be eliminated by using the method of polarization interleaving. The third term in the equation represents power leakage. In this scheme, the total number of channels of WDM Systems is divided into even and odd channels, and are then multiplexed together. Then, both multiplexed channels pass through linear polarizers before interleaving. For examples, consider six WDM channels denoted as m1,m2,m3,m4 ,m5 and m6.Odd Channels m1,m3 m5 pass through one multiplexer and even channels m2,m4 and m6 pass through another multiplexer. Then, the output of both multiplexers pass through PC which changes polarization state by changing azimuth as well as elliptical angle of signal. The

polarization state of odd channels is Θ^o where the even channel is $\Theta^o + 90^0$ so that adjacent channels are orthogonally polarized to each other. Then, both of these outputs pass through the final multiplexer. Whereas in simple WDM all channels have 0^0 polarization state [14]

2.7 Mach-Zehnder Modulator (MZM)

For external optical modulation, the MZM is the most extensively used modulator. It was Ernst Mach and Ludwig Zehnder suggested in 1891. The Mach-Zehnder Interferometer (MZDI) is made up of two 3 dB couplers and two connecting waveguides with equal length waves, as illustrated in Figure 2.16 .The MZM's two waveguides are commonly made of an electro-optic material like lithium niobate (LiNbO3). In addition, Gallium Arsenide (GaAs) and Indium Phosphide (InP) are employed in the MZM production. The refractive index of an electro-optical material is determined by the applied electric field. As a result, an electrical signal can alter the crystal's refractive index, altering the velocity of light traveling through the waveguide. The combination of signals from the two waveguides through the second 3 dB coupler can be constructive or destructive depending on the proper degree of electrical power. The voltage of the modulator (V) is the difference in voltage that permits traveling from the lowest (destructive interference) to the highest (constructive interference)[89].
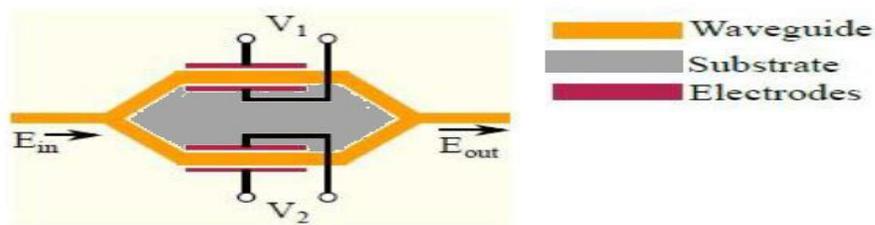
Figure 2.16:MZM modulator [89]

The output optical field of the MZM is given by [89]:

$$E_{out} = \frac{E_{in}(t)}{2}\left(e^{i\phi_1(t)} + e^{i\phi_2(t)}\right) \qquad (2.38)$$

Where $\phi 1\ (t)$ and $\phi 2\ (t)$ represent the phase induced in the lower and the upper arm of the MZM that are calculated as:

$$\emptyset_1(t) = \frac{V_1(t)}{V_{\pi 1}}\pi \qquad\qquad (2.39a)$$

$$\emptyset_2(t) = \frac{V_2(t)}{V_{\pi 2}}\pi \qquad\qquad (2.39\ b)$$

Where $V\pi 1$ and $V\pi 2$ represent the voltages required to achieve a phase shift of π compared to the input for both arms, respectively. The MZM can be operated both in push-push mode and in push-pull mode. Considering $V\pi 1 = V\pi 2 = V\pi$ and $V1(t) = V2(t) = V(t)$, both arms of the MZM induce the same phase shift on the propagating light wave which after combining gives a phase-modulated output. Hence, an MZM acts as a phase-modulated when used in push-push mode and the output, in this case, is given by:

$$E_{\text{out}}(t) = \frac{E_{\text{in}}(t)}{2}\left(e^{i\frac{V(t)}{2V_\pi}\pi} + e^{-\frac{V(t)}{2V_\pi}\pi}\right) \qquad\qquad (2.40)$$

By squaring the Eq. (2.40), the relation between input and output power that can be obtained as:

$$P_{\text{out}}(t) = P_{\text{in}}(t)\left(\frac{1}{2} + \frac{1}{2}\cos\left(\frac{V(t)}{V_\pi}\pi\right)\right) \qquad\qquad (2.41)$$

The extensively used external modulator in optical communication is Mach-Zehnder modulator (MZM) that modulates the light produced with the help of a laser source which is operating in continuous wave (C.W) mode. The MZM generally has a DC bias input and an RF input, as shown in Fig 2.15. The optical power at the MZM output depends on the difference because of the phase of the two supports of the modulator (MZM) that ought to be altered by fluctuating the bias of the modulator (MZM) [90]

2.8 Modulation Techniques

The optical communication system used the optical signal that can be generated with various modulation techniques. There are four requisite physical attributes, which could be modulate to transmit optically information: frequency ,intensity, polarization , and phase. The carrier signal modulates the electrical signal. Modulation techniques are classified as amplitude shift keying (ASK), frequency shift keying (FSK), phase shift keying (PSK), plus polarization shift keying based on which signal parameter is modified (PolSK)[91].
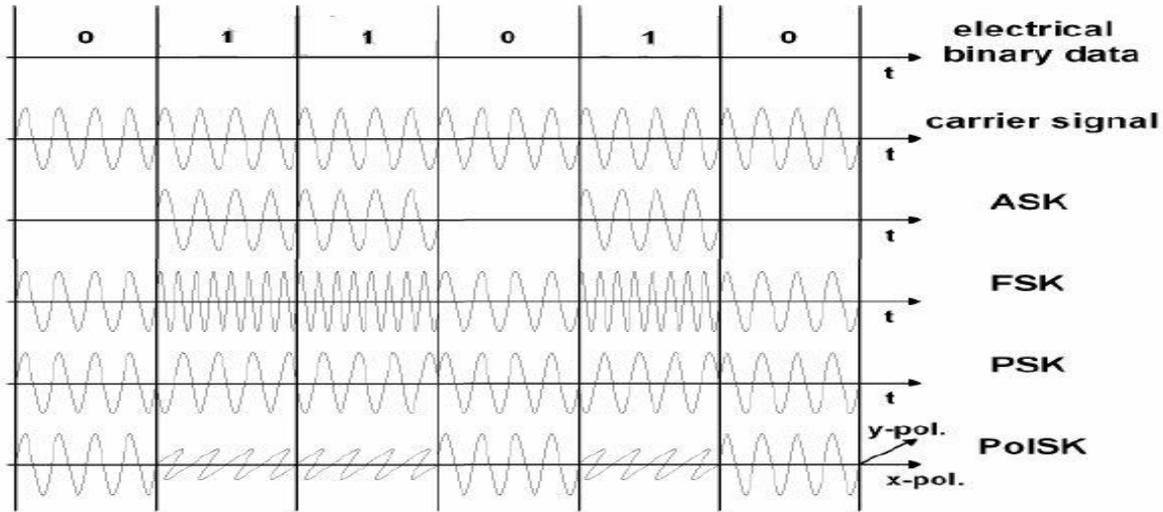
Figure 2.17: Optical signal of typical modulation[91]

In optical communications systems   as well as other digital communications systems, the modulation of a transmitted signal, which modulates information on optical carriers, plays a key role in optical communications systems and other digital communication systems. The formats of modulation employed in optical communications systems are similar to those used in communications systems for radio frequencies (RFs), with the amplitude, the phase and the frequency of information transmitted by an optical carrier corresponding [91]. Intensity modulated direct detections is the most system used in optical wireless communication systems, where the optical source intensity is modulated to transmit data [92]. The information could be modulated in optical carriers and transmitted in optical systems through analog modulation schemes technology, such as amplitude shift-keying (ASK) and phase shift-keying (PSK) and frequency shift key (FSK).On the other hand, several types can present binary modulation types like pulse modulation (PM) and on off keying (OOK). The popular modulation in optical modulation is (OOK). Binary bits in OOK are represented in a corresponding symbol interval by the existence or lack of the light pulse. There are two symbols of OOK signaling which can be classified as non-return to zero (NRZ) signaling and back to zero (RZ). In NRZ-OOK, the symbol (S1) represents a binary "1" and the symbol (S0) represents a binary "0" where the waveforms of S1 and S0 can be represented as [93]:

$$S1(t) = A(2\pi f°t) \tag{2.42}$$

$$S0(t) = 0 \tag{2.43}$$

2.8.1. Non- return-to-zero (NRZ) Modulation format
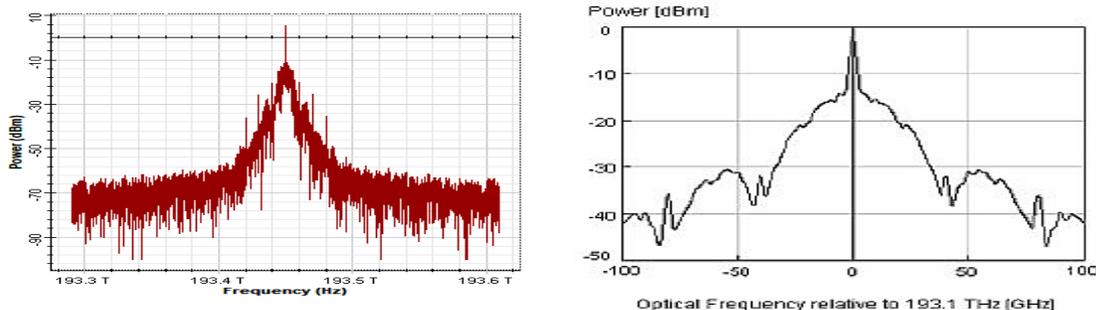
Figure 2.18**:** Optical spectrum of NRZ modulation format[94]

A non-return-to-zero (NRZ) modulation technique is the most basic, with the pulse on throughout the whole bit period. The NRZ modulation format is used by the majority of commercial systems [94]. For the past several years, the non-return-to-zero (NRZ) modulation format has dominated intensity modulated-direct detection fiber-optical communication systems. The reasons for employing NRZ in the early days of fiber-optical communication were that it is not susceptible to laser phase noise, which has a relatively modest electrical bandwidth for transmitters and receivers when compared to RZ, and has the simplest transmitter and receiver design. The optical spectrum of NRZ pulses is narrow, as seen in figure 2.18. Although the smaller spectrum width increases dispersion tolerance, it also causes inter symbol interference between the pulses, making this modulation scheme unsuitable for high data rates and long distances. In DWDM systems, the narrow spectrum of NRZ pulses allows for better implementation of dense channel spacing.

2.8.2 Carrier suppressed return-to-zero (CSRZ) modulation format
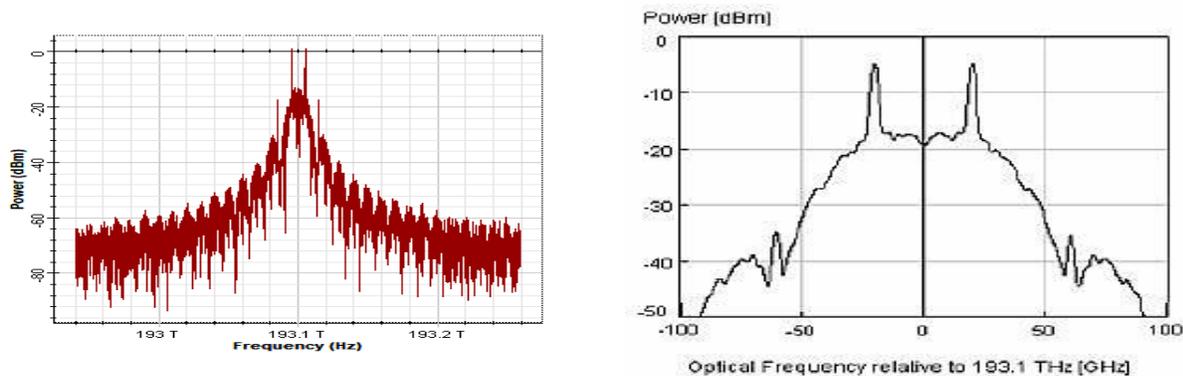
Figure 2.19 Optical spectrum of CSRZ Modulation format[95]

CSRZ modulation (carrier-suppressed RZ modulation) is a recently suggested modulation form for high data rate transmission systems that has been thoroughly examined in computational and experimental investigations [95]. The primary goal of this modulation style is to reduce nonlinear effects in transmission lines while also increasing spectral efficiency in high-bit-rate WDM systems. Because of its smaller spectral width in comparison with standard RZ modulation, CSRZ modulation is predicted to increase transmission dispersion tolerance. In CSRZ, a factor of two spectrum decrease occurs when compared to the RZ scenario, as illustrated in figure 2.19. The RZ signal form of the CSRZ pulses has an optical phase difference between consecutive bits. This condition of inter-pulse phase can help to boost nonlinear tolerance. A carrier suppressed RZ pulse is a kind of RZ pulse in which the carrier is turned off. The CSRZ signal differs from normal RZ in that consecutive bits in the CSRZ signal that have a phase shift. In the optical domain, this phase change yields no DC component, hence there is no carrier component for CSRZ. Return to zero modulation is used in CSRZ modulation. It also changes the optical signal's phase. The CSRZ signal is less susceptible to fiber nonlinear effects and is more resistant to transmission failures. CSRZ modulation's resilience to narrow-band filtering may be enhanced, which is advantageous for DWDM systems. In 40 GB/s CSRZ-based DWDM transmission systems, spectral efficiency exceeding 0.4 bit/s/Hz may be achieved by using efficient narrow-band filtering.

2.8.3 Doubinary modulation format
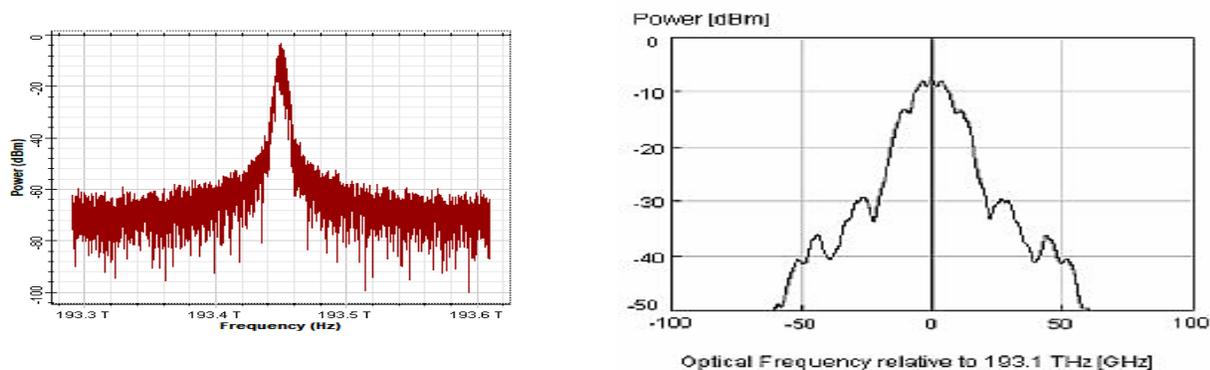
Figure 2.20: Optical spectrum of Dou-binary Modulation format[96]

A very interesting modulation format is optical duobinary, which offers high spectral efficiency and chromatic dispersion tolerance. Duobinary modulation can be described as a combination of a conventional ASK-based modulation and phase shift keying (PSK). Depending on the realization, optical duobinary transmission can be understood as a multilevel transmission with phase encoded

bits and a reduced spectral width. Duobinary transmission technology was introduced for the first time by A. Lender in the 1960s as a mean of transmitting binary data over an electrical cable with high-frequency cut-off characteristics. Recently, duobinary modulation has become popular. [96] it has been used to increase the dispersion tolerance of high-speed optical transmission systems with a channel data throughput of 10 GB/s. The optical phases of "1" bits separated by an odd number of "0s" vary by radians in the duobinary format. In comparison to many other binary formats, the optical spectrum of the duobinary signal is considerably compact. The optical duobinary format is often implemented using one of two methods: electrical low pass filtering (ELPF) or optical filtering of a DPSK signal in a delay interferometer (DI). The LPF duobinary has recently gotten a lot of attention. One explanation for this is because duobinary may be easily produced utilizing low-cost methods. As seen in figure 2.20, the signal's spectral breadth is cut in half when compared to a traditional NRZ transmission. The optical duobinary signal's lower spectral width accounts for its superior dispersion tolerance as compared to NRZ signals, as well as higher spectral efficiency in WDM systems. Another benefit of duobinary modulation is the suppression of the SBS effect, because the carrier is well-muted in the optical duobinary spectrum [96]. The fundamental drawback of duobinary signals, like NRZ signals, is the relatively large influence of fiber nonlinearities, which is the primary determining factor for the high propagation length and transmission quality. The use of RZ-based signals in combination with novel duobinary-based modulation algorithms enables the construction of WDM systems with compact channel spacing and increased transmission performance. Due to its high dispersion tolerance, duobinary modulation is well-suited to optical metro area networks (MANs) [97], where component prices and signal production in the electrical domain are critical.

2.9 Dispersion Compensating Fiber (DCF)

In today's transmission networks, DCFs seem to be the most extensively utilized in-line dispersion compensation approach. A wide negative dispersion and a tiny core diameter define DCFs. Large negative dispersion values can be produced by changing the fiber design and doping of fiber cladding (for example, with fluorine) to enhance the refractive index is to show the difference between fiber core and the cladding. The demands on DCFs are a large negative dispersion (-70-300 ps/nm), low insertion losses, low polarization dependent (PDL) losses, a low polarization mode dispersion (< 0.05 ps/km), a large effective area (A_{eff}) and a negative dispersion slope. The DCFs may be used to compensate many channels at the same time. However, owing

slope compensation flaws a small portion of residual dispersion persists, notably in the outer channels[98].

2.9.1 Dispersion Compensating Patterns

Several alternative dispersion correction methods can be achieved depending on the positioning and mixing of the compensation devices within transmission line (Fig. 2.21). The compensation of an accumulated dispersion mostly in transmission fiber must be done according to the following rule, which is common to all dispersion compensation systems that provide full dispersion compensation:

$$D_{SMF}.L_{SMF} + D_{DCF}.L_{DCF} = 0 \qquad (2.44)$$

Where D_{SMF}, D_{DCF} are the chromatic dispersion values of transmission and compensating fibers, respectively, and , the lengths of fibers are L_{SMF}, L_{DCF}

DCFs can be placed at various points inside a transmission line to satisfy this criterion. A transmission line is usually made up of numerous cascaded spans. Three fundamental dispersion compensation systems may be identified depending on the reality of the span infrastructure: pre, hybrid, and post-compensation figures 2.21. DCFs are put before or after the SMF fiber in pre- and post-compensation. In hybrid-compensation, half of the SMF dispersion compensated fiber before the SMF, while the other half is adjusted after the SMF. Because of the impact of dispersion compensation on linear and nonlinear influences, the system behavior for different schemes might be considerably different[98].
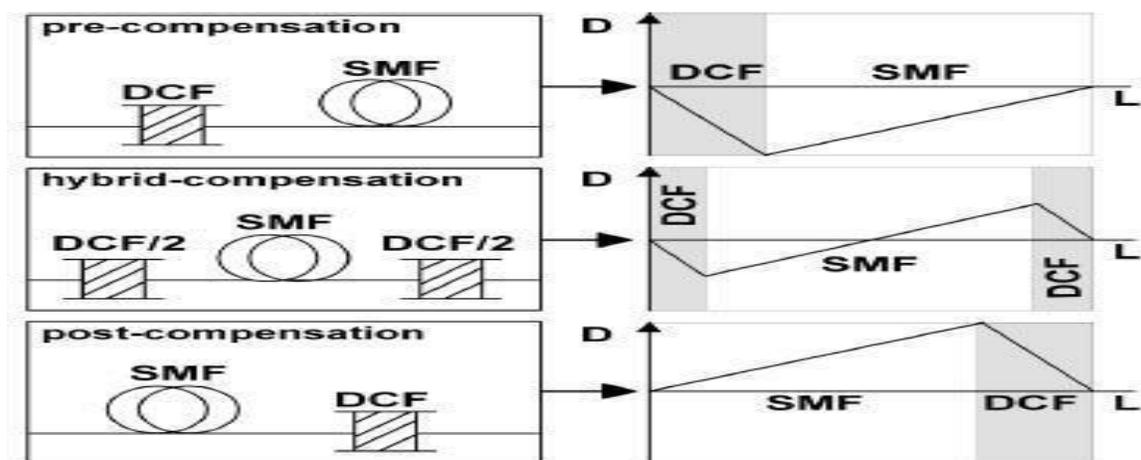
Figure 2.21: Various dispersion compensating techniques [98]

2.10 Optisystem Software

Optisystem^{TM} From Optiwave cooperation is a comprehensive software design which permits utilizers for planning and examining optical links within a new networks transmission layer. This tool provides a wide variety of optical components to plan and implement a complete optical network with low cost, time-saving and efficient approach for the researcher. Optisystem enables users to simulate and design the following:

- Systems with Multimode

- Access Networks

- Co-Simulation with MATLAB program

- Analysis and Design of Fiber

- optical code division multiple access for Passive networks

- Advanced Modulation

- Receivers, transmitters and Amplifiers

- OptSim: This software consists of the most commonly used components required for engineering of the electro-optical systems and particular emphasis is laid on digital CATV and WDM systems. Innovative optical approaches such as dispersion managed soliton and quasi-return-to-zero systems are also supported by the software. OptSim exchanges signals by utilizing documented OptSim signal format during simulation. It is a stand-alone product which comes with an on-line HTML help and Windows-like user interface. The users do not require expensive frameworks or additional tools for realizing full power of OptSim. This software is extremely easy to use and allows even the non-experts to carry out complex simulations in minutes.

2.10.1 Monitors

The monitor is a useful tool for qualitative signal analysis, which provides a view of the evaluation of the transmission system characteristics and allows to diagnose channel errors. It is related to terms such as Q-factor, Optical-Signal to Noise Ratio (OSNR), and Bit Error Rate (BER). Unlike these parameters, eye diagram lets us find the specific problem that brings additional noise to the system. For example, it is easy to determine such signal distortions as ASE (Amplified Spontaneous Emission) noise, which induces stronger signal level fluctuations in marks than in spaces, or chromatic dispersion resulting in variations of the signal levels, or interaction between

linear and nonlinear effects resulting in fluctuations of the signal power at the rising and trailing edges of the signal [99]

2.10.2 Eye diagram

The more the eye is open, the less degraded the system . The place of the largest eye opening is considered to be the moment of signal sampling. The eye diagram can be also described by the Q-factor parameter as shown in figure 2.22[100].
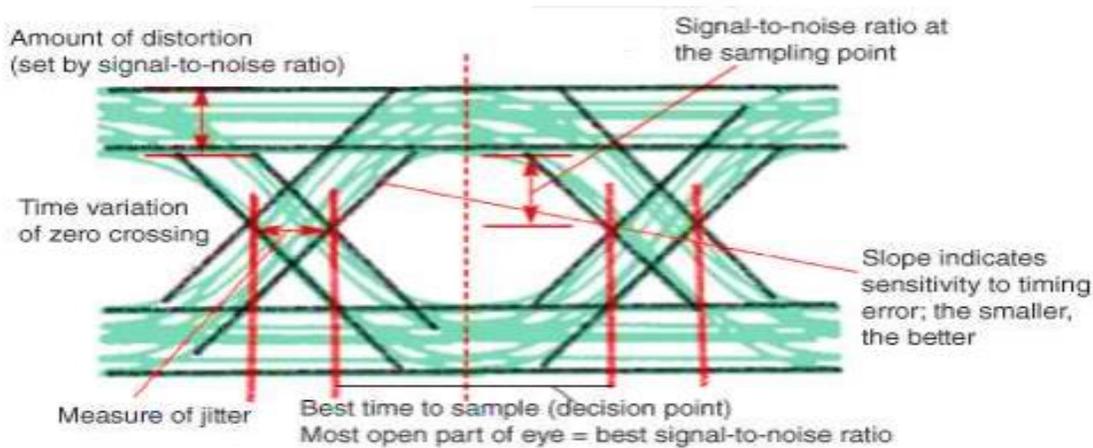
Figure 2.22: The eye diagram description[100]

2.10.3 Q-factor and OSNR

The OSNR parameter represents the ratio of the optical power of the signal Ps to the noise level P_n in mW [101]:

$$\text{OSNR} = 10 \log \left(\frac{P_S}{P_n} \right) \tag{2.45}$$

The Q-factor expresses eye quality. It indicates the effect of interference at the measurement place and means the minimum decision level. It can be calculated as [100]:

$$Q = \frac{|\mu_1 - \mu_0|}{\sigma_1 + \sigma_0} \tag{2.46}$$

where μ_0; μ_1 stands for mean log.0, log.1 level values respectively, and σ_0; σ_1 are the corresponding standard deviations, as shown in figure 2.22 Only Q-Factor but not OSNR will be monitored further in this work because FWM is not measurable in the optical domain.

2.10.4 BER

BER is specified by the proportion of received error bits to the total number of received bits. BER and Q-factor are in an inverse relationship: the BER decreases as the Q-factor increases. The mathematical relation between Q-factor and BER can be expressed as[101]:

$$BER = \frac{1}{2}\ erfc\left(\frac{Q}{\sqrt{2}}\right) \qquad (2.45)$$

Acceptable BER of optical systems which its transmission capacity is up to 10 Gbit/s is minimum BER = 10^{-12} [104], but systems over 100 Gbit/s demands at least BER = 10^{-14} [101]

3.1 Introduction

In this chapter, a new approach to overcome the FWM by using polarization technique with different modulation forms and WDM system is suggested. The WDM technique is unable to suppress the FWM crosstalk for long distance where the nonlinearity especially FWM will be increased in all active signals. Therefore, to solve this problem, by the orthogonality for the entire channel interaction by combining every two channel together and then linearly polarized them with a specific rotation angle using a polarization beam combiner. In the first part, have investigated the single channel under nonlinearity with and without polarization technique. In the second part, the same study was performed for multichannel with and without polarization. The polarization combiner scheme with different distance, input power and channel spacing are simulated and tested on different number of channels . In addition to that, the effects of four wave mixing are extensively investigated for different bit rates, channel spacing, single mode fiber (SMF) and dispersion compensation fiber (DCF). Performance of proposed system is analyzed for different link lengths, launched powers in terms of FWM power, Q-factor and BER.

The schematic diagram of our proposed model can be explained in figure (3.1)
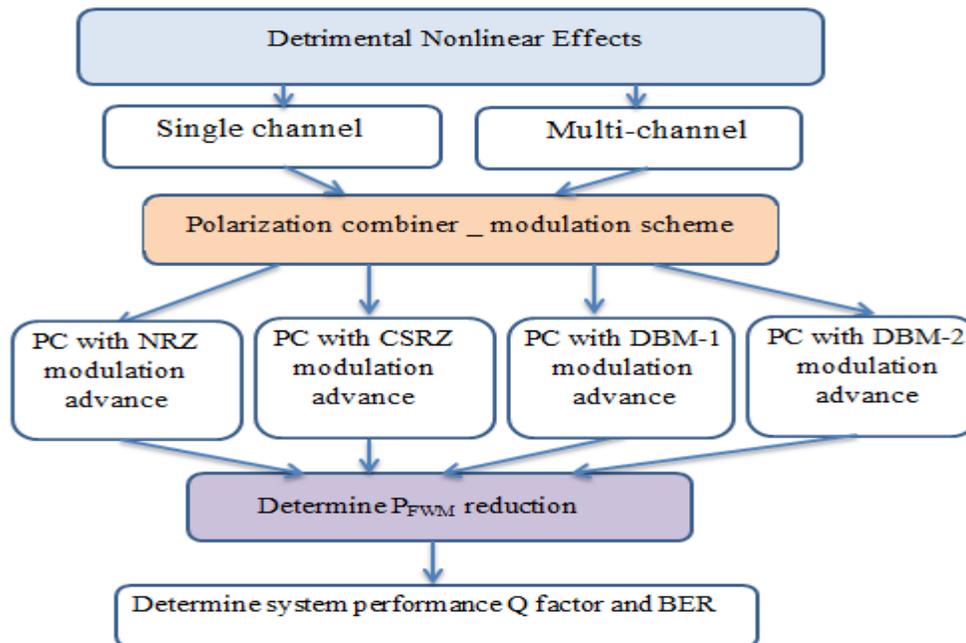
Figure 3.1: Methodology of the thesis

3.2 Proposed transmission system

In order to evaluate the influence of polarization combiner in mitigating the fiber nonlinearity, this chapter presents the design and simulation of:

i.   Single channel CSRZ, DBM-Mod1,DBM-Mod2 and NRZ modulation
        scheme with & without PC.

ii.   Multi-channel CSRZ, DBM-Mod1,DBM-Mod2 and NRZ modulation
        scheme with & without PC.

In the following sections, the proposed system is simulated and analyzed using Optisystem[17] commercial software. A brief description of the Optisystem program is provided in chapter two.

3.2.1. Single channel transmission fiber system

This section presents the design and simulation of the 10 Gb/s single channel systems for four modulation formats CSRZ, DBM-Mod1,DBM-Mod2 and NRZ. figure(3.2) shows the general construction of single channel system.
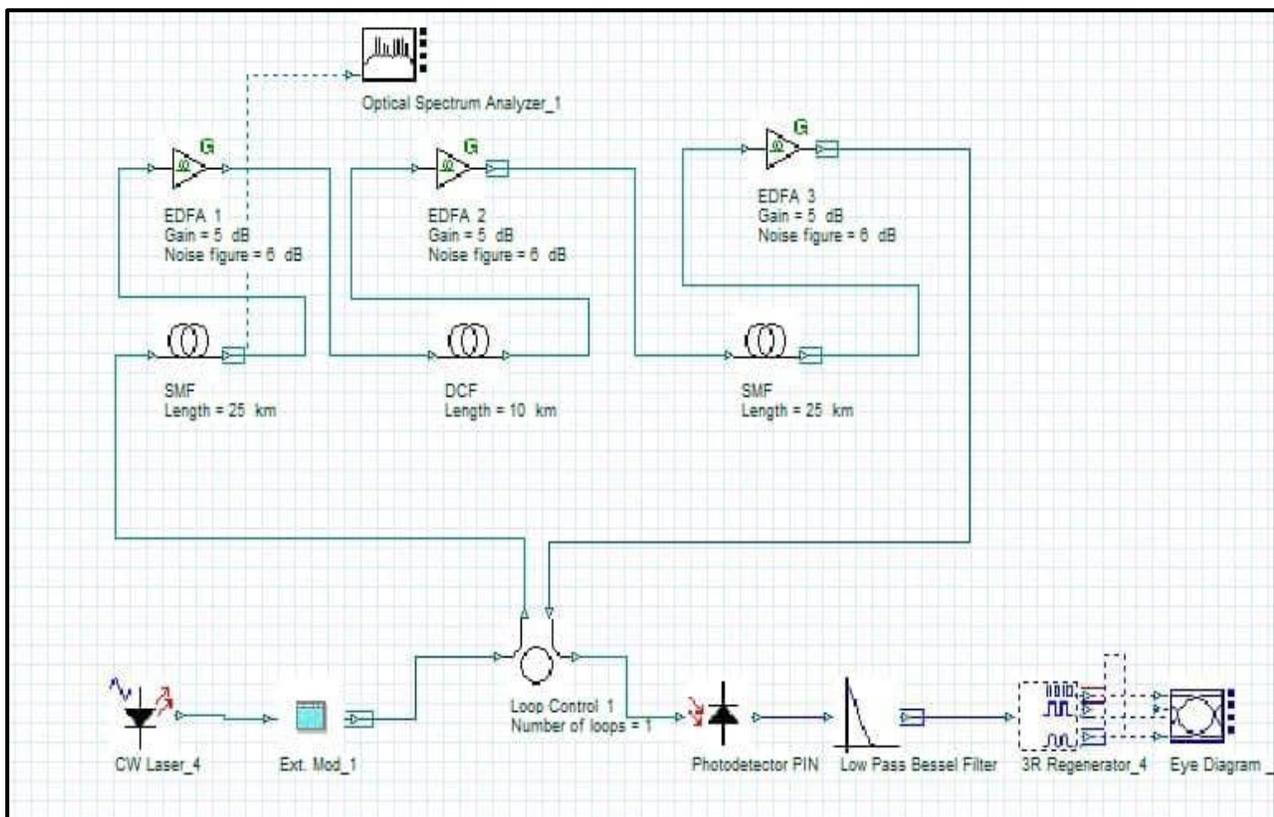
Figure 3.2: The general construction of single channel system.

3.2.1.1 Single channel transmitter

Generally, the four types of the modulation formats (NRZ, DBM-Mod1,DBM-Mod2 and CSRZ) are common in their construction with several blocks.

A-Pseudorandom Binary Sequence Generator (PRBS)

Pseudorandom binary sequences are provided in the package. A pseudorandom binary sequence (PRBS) is commonly wanted in simulations of communication system when representing an information source. A random digit generator can be utilized to create the concatenation binary. The Pseudorandom binary sequences PRBS- Module creates N bit sequences with a previous and successive bit sequence of integers m and n of zero bit (spaces).

B- NRZ Pulse Generator

At its input, a sampled NRZ coded signal represented by such a stream of bits is created by the module. By using the PRBS generator, the input bit sequence is usually generated. The NRZ pulse generator's parameter is presented in Table (3-1).

Table (3-1) NRZ pulse Generator parameters.

Parameter	Value	Units
Rectangle shape	Exponential	
Amplitude	(1)	a. u.
Maximum	(1)	a. u.
Minimum	(-1)	a. u.
Rise- time	0.05	bit
Fall- time	0.05	bit

C-Mach Zehnder Modulator (MZM)

An intensity modulator based on interferometry basis is the Mach - Zehnder modulator. In order to decrease the chirp induced in the optical signal to increase the transmission distance, a chirp free MZM structure is used in the modulation process. The two modulator arms are driven by the same amount but in opposite directions. Lithium Niobate Mach-Zehnder modulator (LiNb) performs this function to decrease the chirp in the optical signal. The value of the switching bias

voltage is taken as 4 volt for all the modulation formats as shown in Table (3-2) . The value of the bias voltage of the two-modulator arms differs from modulation format to another.

Table (3-2) the parameters of Mach Zehnder Mod.

Parameter	Value	Units
Extinction ratio	30	dB
Switching bias voltage	4	V
Switching RF voltage	4	V
Bias voltage1	0	V
Bias voltage2	2	V
Modulation voltage1	2	V
Modulation voltage2	-2	V

D- Modulation scheme

i.   **CSRZ transmitter,** as shown in figure (3.3), the simulated CW laser source produces a beam of a continued wave laser indication, that is used accordingly as a carrier to modify the electrical data indication in the modulator with a frequency of about 193.1THz, linewidth of 10MHz and an initial phase of 0 deg. The PRBS signals are coupled with the Non-Return to Zero Pulse Generator, which provides a coded NRZ signal, that is coded. This encoded electrical signal is then used to drive (LiNb) a MZM, which modifies phase of the CW laser source signal to form a CSRZ optical signal. The output pulses of CSRZ are applied to a second MZM modulator that is powered by a sinusoidal electrical signal with frequency value Bit rate/2 ,then to Fork component is used to provide multiple beams of the laser from single source to modulator to form a CSRZ optical signal. Finally, using two MZ modulators concatenated can generate the CSRZ.
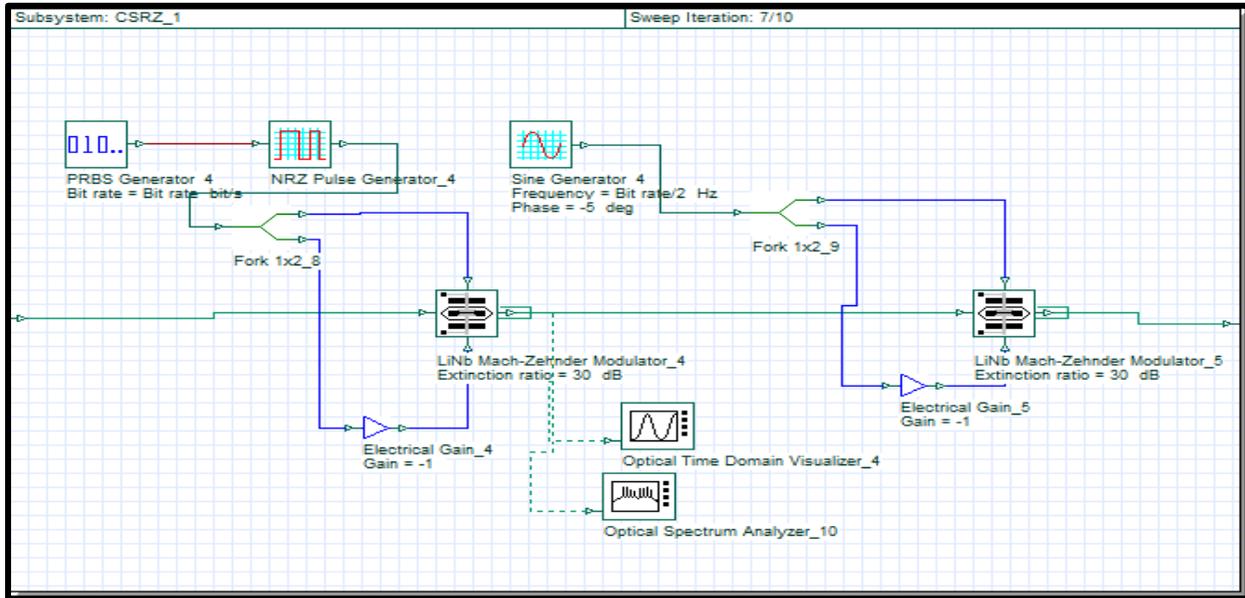
Figure 3.3 CSRZ-Mod. transmitter.

ii. **DBM-1 transmitter**, as shown in figure (3.4) the CW laser has the same specification as that used in CSRZ, also the PRPS generator output is entered to NOT gate. To create Duo-binary mode-1 by creating a double signal NRZ, it is first done using a pre-encoder and a dual pulse generator, where this modulator is connected to a low pass Bessel filter which has cutoff frequency 0.28*Bit rate. Then, Fork component is used to provide multiple beams of the laser from single source to modulator where it is powered by the electrical frequency sinusoidal signal.
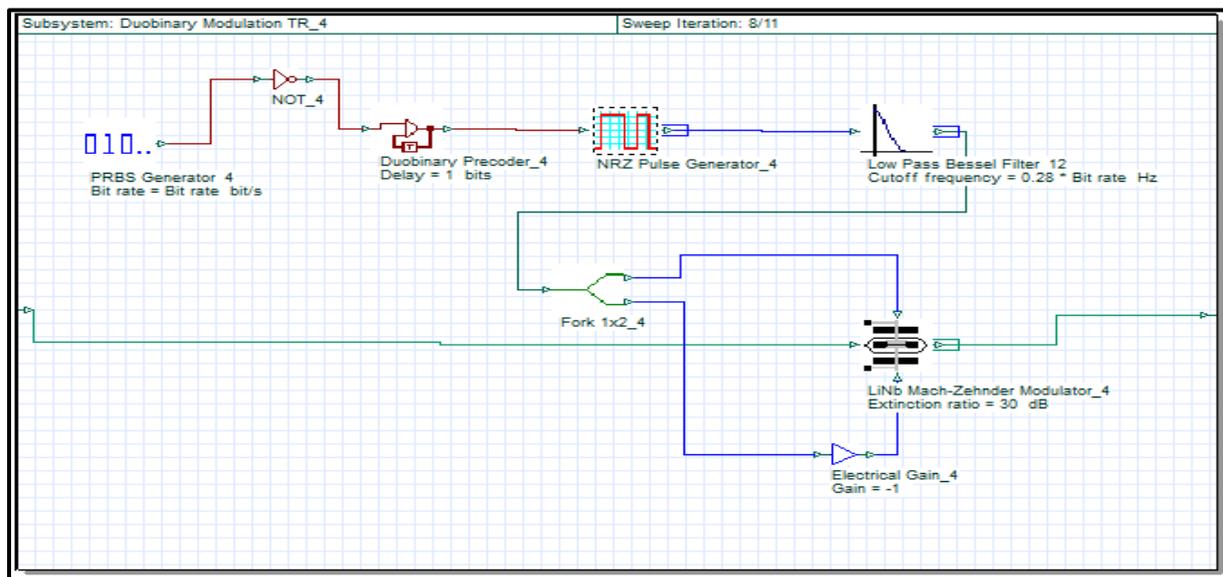
Figure 3.4: Duo-Binary Mod-1 transmitter.

iii. **DBM-2 transmitter** as shown in figure (3.5) the PRBS signals are combined together with its one-bit retard version by an XOR-gate at the Duo binary Precoder. Then, Fork component is used to provide multiple beams of the laser from single source to modulator, then NRZ Pulse Generator generates the non-return to zero (NRZ) coded signal, this one encoded electrical signal is then used Duobinary pulse generator to drive an MZM and modulates the phase of the CW laser source signal to generate a NRZ-DPSK optical signal. RZ-DPSK optical signal is generated by applying the output pulses of DBM-2
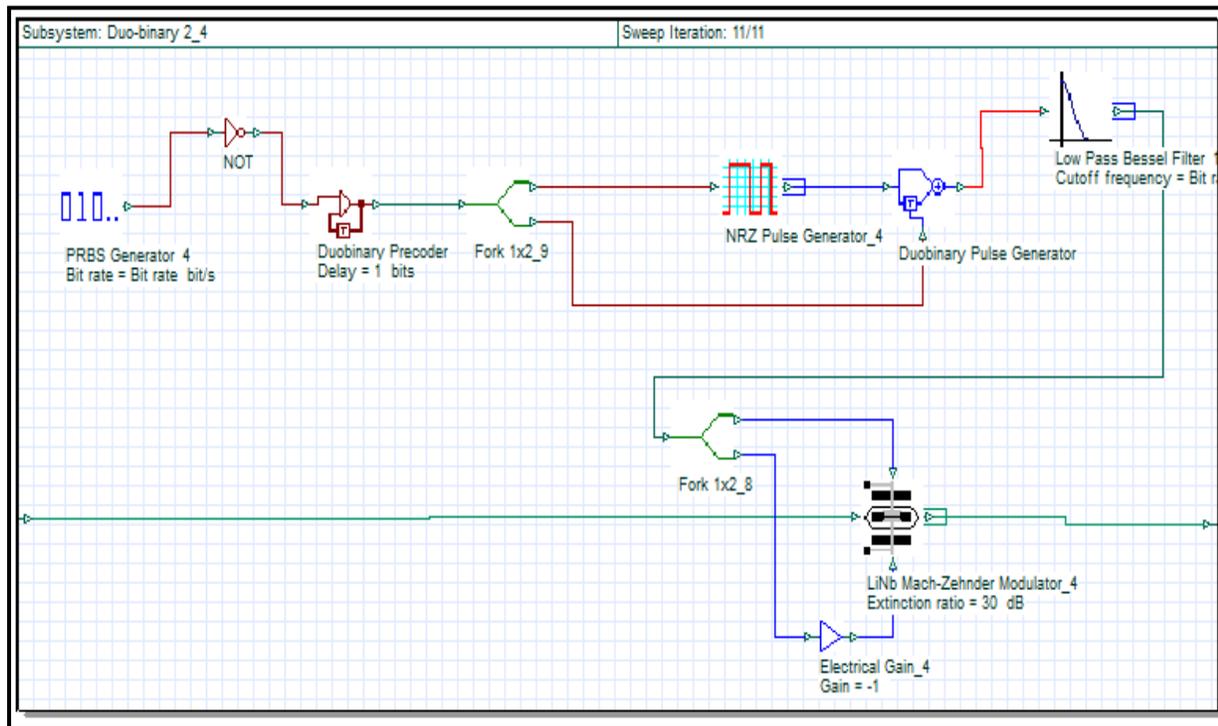
Figure 3.5: Duo-Binary Mod-2 transmitter.

iv. **NRZ transmitter,** its construction is shown in figure (3.6). The parameter of CW laser has the same specifications as that used in CSRZ. Also, the PRPS of bits at a rate of 10 G bit/s generator. The output is entered to Fork component which is used to provide multiple beams of the laser from single source to modulator fork component which is used to provide multiple beams of the laser from single source to NRZ pulse Generator.
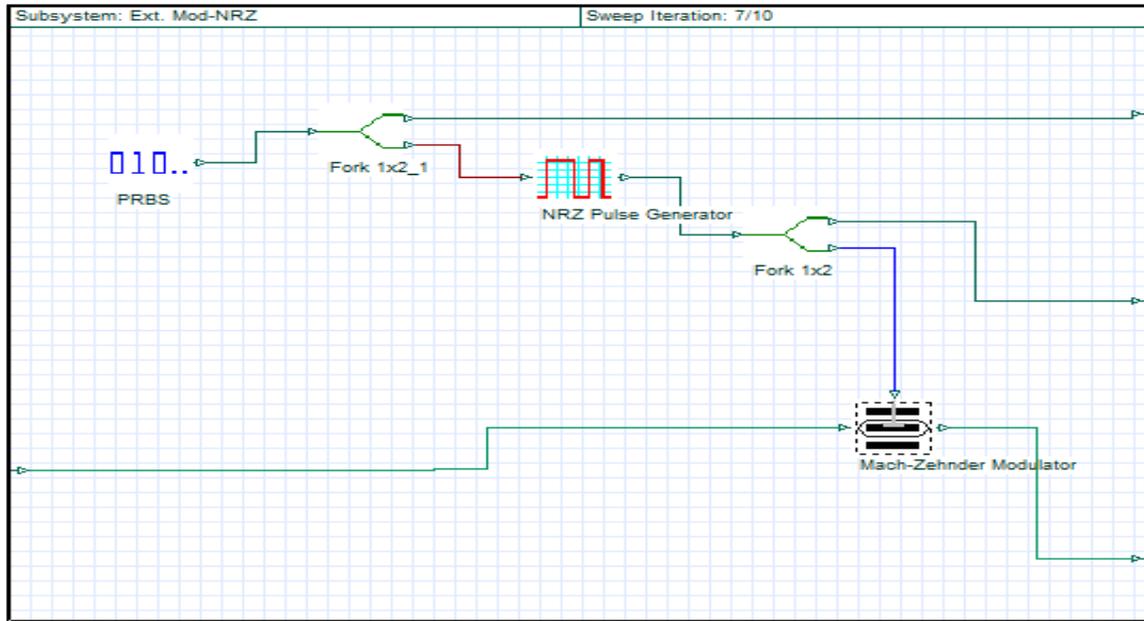
Figure 3.6: NRZ Mod transmitter.

3.2.2 Optical Fiber Link

ITU-T G.652 is the optimum fiber channel type against fiber nonlinearities in our simulation. The fiber channel's configuration is depicted in Figure (3-7). It includes four spans and a single mode fiber (SMF) followed by Erbium-Doped Fiber Amplifier (EDFA) optical amplifier which has noise figure value of 6dB and gains 5 dB followed by Desperation Compensation Fiber (DCF) where a symmetrical dispersion compensation scheme is used. It is possible to use DCF to mitigate the desperation in the fiber which has negative dispersion and a native dispersion slop that leads to reduce the broadening of the pulse resulting from the products of chromatic dispersion (CD), a dispersion compensating fiber (DCF) is used in the simulation to reduce pulse expansion caused by chromatic dispersion of the fiber optic channel. DCF is one of the most often used devices for compensating chromatic dispersion across a wide wavelength range. It is infectious to achieve great negative wave-guide dispersion more than -85ps/nm/km, allowing the quantity of CD in the fiber to be balanced. The dispersion compensation schema is formed by this combination. For all fiber types in the simulation, the Differential Group Delay (DGD) value is 0.2 ps/km. The transmission is performed through a recirculation loop, which consists of four spans of (two (25Km) SMF and 10Km DCF) (1st', 2nd', 5nd' and 7nd' spans). Table (3-3) summarizes the parameters of SMF and DCF parameters in simulation. It is possible to use fiber DCF to mitigate the desperation in the fiber

which has negative dispersion and a native dispersion slop accumulated that leads to reduce the broadening of the pulse caused by the products of the chromatic dispersion (CD).
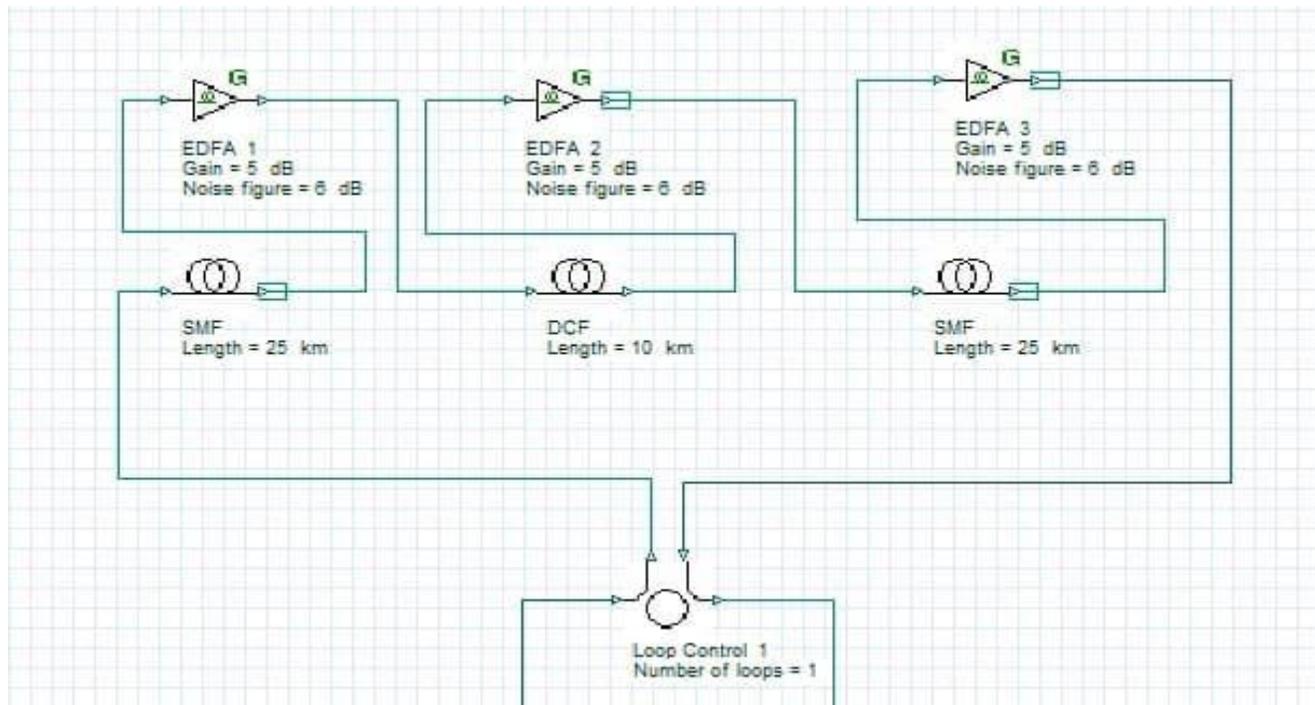
Figure 3.7: optical link channel.

Table (3-3) simulation Properties of the SMF and DCF

SMF parameters	Values	Units
Length	25	km
attenuation (α)	0.2	ps/km
dispersion slope (S)	0.075	$ps/nm^2/km$
dispersion parameter (D)	17	$ps/nm/km$
effective area	70	
Differential Group Delay (DGD)	0.2	ps/km
DCF parameters		
Length	10	km
attenuation (α)	0.5	d B/km
dispersion slope (S)	-0.3	P s/nm^2.km
dispersion parameter (D)	-85	P s/nm.km
effective area	22	μm^2
Differential Group Delay(DGD)	0.2	ps/km

3.2.3 Single channel receiver

The receiver detects the signal that is fed from transmission in the recirculating loop. It is converted into an electrical signal. The receiver is composed of the following components as shown in Figure (3.8). The last edge of the WDM-DMUX is the De-multiplexers for communication system. It retrieves the data utilizing the technique of (de multiplexing). In a communication system, WDM-DMUX is the last edge where, the work of WDM-MUX is the opposite of the work of WDM-MUX. Independent information in addition to access protocols where the communication networks allow it to operate in a single system

1- After the operation of DEMUX, the photo indication enters the optical receiver. The received signal is fed to PIN photo-detector that has parameters as listed in Table (3-4) , the photo signals are converted into an electrical signals and detected by PIN . The detected signal is applied to the second part which is named a low pass Bessel filter.

2- The low pass Bessel filter is used in the receiver to divide the modulated informative to rising carrier frequencies. The utilized low pass Bessel filer at cutoff frequency $0.75 \times$ data rate ,also reduces the noise that is resulted in the detection process.

3- The received signal is fed to 3R Regenerator which has three outputs, namely bit sequence, reference (modulated NRZ signal) and a copy of input signal which fed to Eye diagram .

4-Eye diagram is used to show Quality factor and Bit Error Rate. It is directly connected to the 3R regenerator which is utilized to produce the diagram.

A balanced detector is used to correlate each bit with a delayed version of it, to properly decode the signal. The simulation layout of the receiver is shown in figure (3.8).
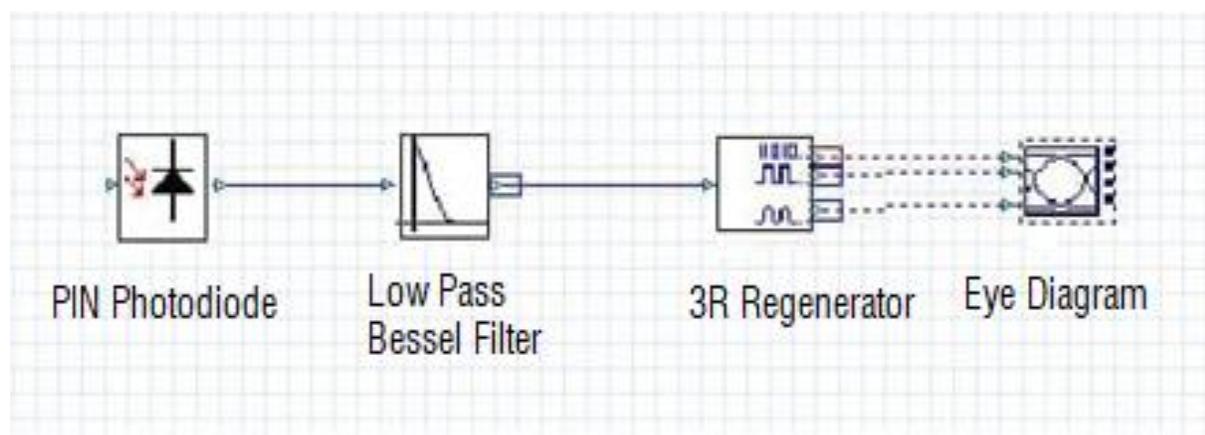
Figure 3.8. Scheme of optical receiver

Table (3-4) the receiver simulation parameters.

Parameter	Value	Unit
Type of Photodetector	PIN	------
Responsivity	1	A/W
Dark current	10	nA
Type of filter	Bessel filter	------
Order of filter	4	------
Cutoff frequency	0.75*Bit rate	HZ

3.3 Multichannel system

In wavelength division multiplexer WDM, different data channels modulated with various optical carriers are transmitted along the same fiber. The concepts of Inter-channel effects are similar to XPM and FWM . The simulation of the modulation formats in DWDM system is divided into three parts:

1.   Simulation of 4-channels within channel spacing 50,100 and 200 GHz with data rate 10 Gbps for NRZ, DBM-mode 1, DBM-Mode2 and CSRZ modulation formats.

2.   Simulation of 8-channels within channel spacing 50,100 and 200 GHz with data rate 10 Gbps for NRZ, DBM-mode 1, DBM-Mode2 and CSRZ

3.   Simulation of 16-channels within channel spacing 50,100 and 200 GHz with data rate 10 Gbps for NRZ, DBM-mode 1, DBM-Mode2 and CSRZ

The purpose of modeling the system at various channel spacing is to see how well it works. The number of channels is used to evaluate the modulation's performance. Configurations with a tighter channel spacing and a smaller system FWM Crosstalk between nearby channels, as shown in the block diagram 3.9
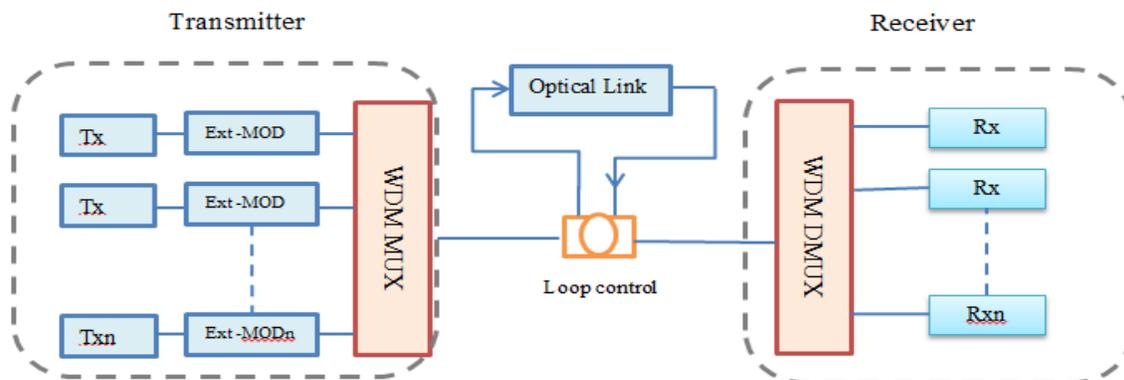
Figure 3.9. Scheme of multichannel WDM system

3.3.1. WDM System without polarization combiner

As shown in figure (3.10) ,the transmitter section consists of 4x10 Gb/s WDM channel system. In this case, the transmitters are of four cases CSRZ, DBM-mode 1, DBM-Mode2 and NRZ. In the case of the spacing between channels 100GHZ, a comparison has been made between the four modulation formats to show which has the best performance, then it is found that the CSRZ modulation format gives the best performance. Another comparison has been made for CSRZ modulation format for various channel spacing 50,100 and 200 GHZ and the score has been found. The optical link is the same for the case of single channel, the span length is 60 km and there are 4 spans. That means that the optical fiber length is (60,120,300 and 420) km. The receiver also has the construction of the receiver which was described in the first part of the chapter. The simulation parameters of WDM Multiplexer and DE multiplexer are listed in Table (3-5)

Table (3-5) the simulation parameters of the Mux, De-Mux.

Parameter	Value	Units
WDM Multiplexer& De-multiplexer		
Frequency spacing	200,100 and 50	GHz
Bandwidth	20	GHz
Insertion loss	4	dB
Filter type	Bessel	
Filter order	2	

As a result of comparison, it has been concluded that the performance of the 4×10 Gb/s WDM system, a 8×10 Gb/s WDM system and a 16×10 Gb/s in the case of CSRZ is the best one. So, WDM system has been proposed by CSRZ modulation scheme and 200, 100 and 50 GHZ channel

spacing to view the results in case of increasing the number of channels and reducing the channel spacing from 200 to 100 to 50 GHZ. The configuration of the systems are shown in figures (3.10), (3.11), and (3.112). The simulation parameters of MUX & DEMUX are listed in Table (3-5), also the fiber parameter is the same as it is described in single channel.

It can be seen that the channel fiber system generally consists of several parts, such as transmitter, and Optical Spectrum Analyzer (OSA). A continues wave (CW) laser diode emits a modulated optical carrier with a wavelength of 193.1THz and a strength of 0 dBm. This part is connected to OSA (or dual OSA to compare different signals) to monitor the signals of FWM after each different input power.
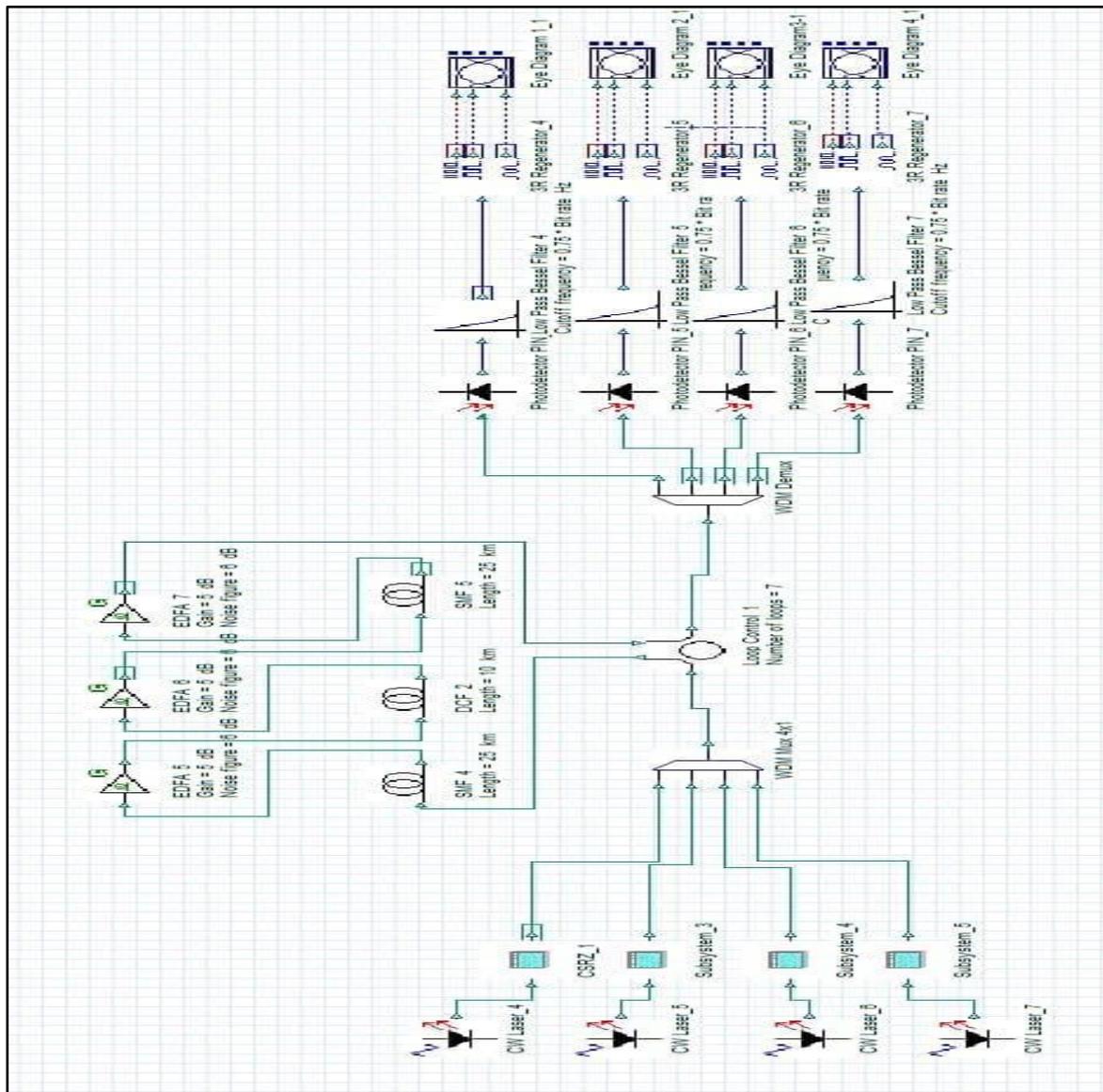
Figure 3.10: 4×10Gb/s WDM system.
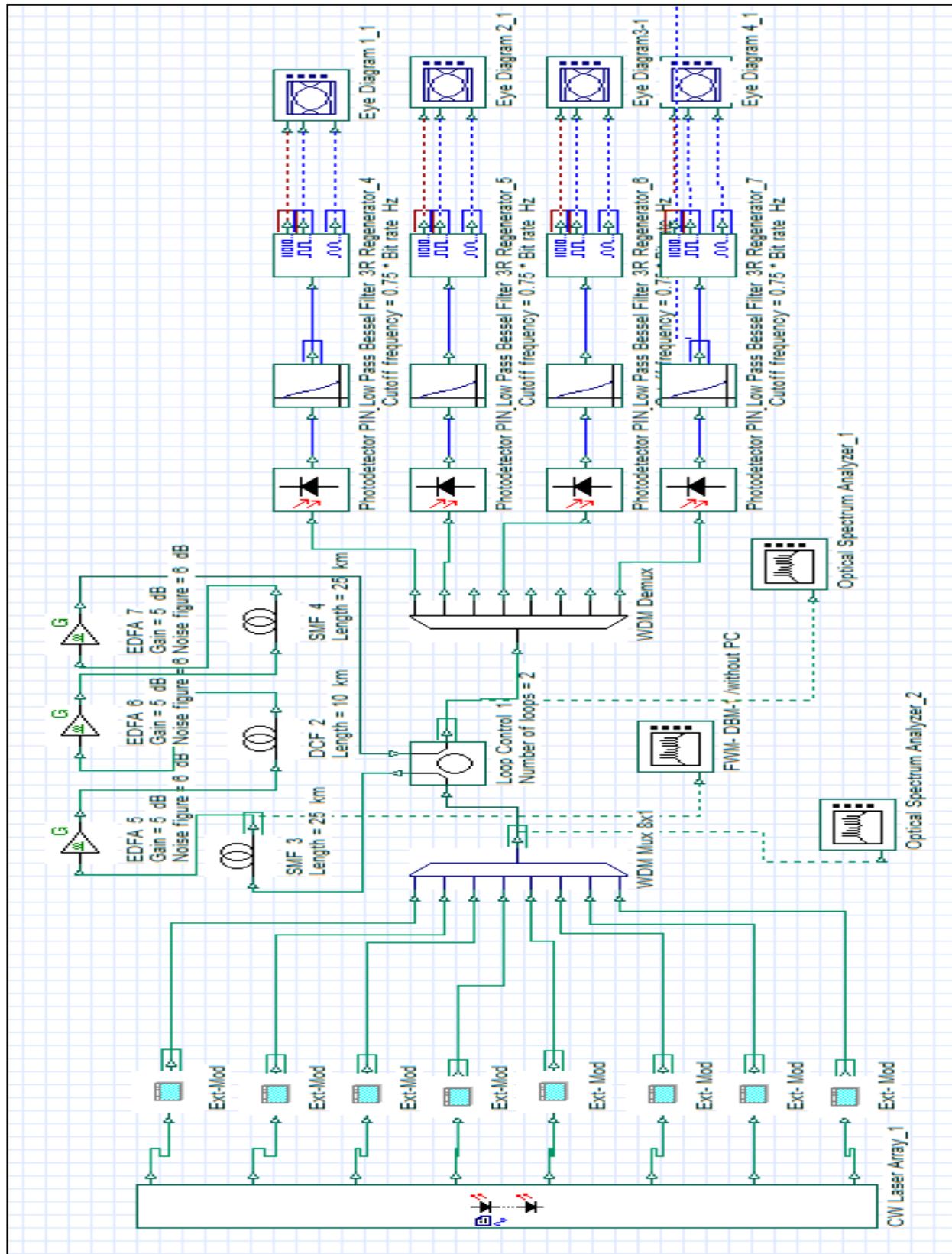
Figure 3.11: 8×10Gb/s WDM system.
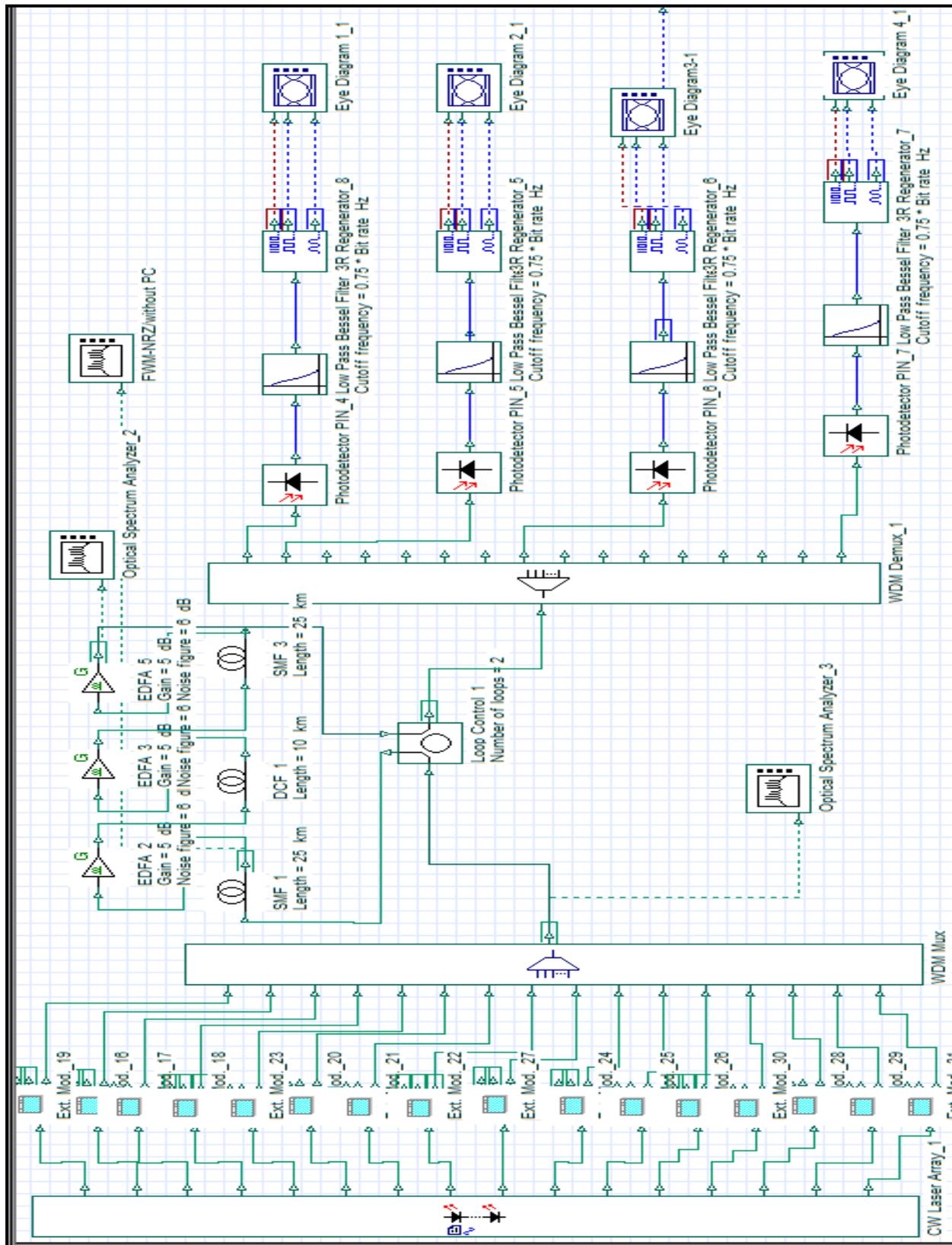
Figure 3.12: 16×10Gb/s WDM system.

3.3.2 Implementation of Polarization Combiner PC

Polarization combiner is a new powerful method which is used to mitigate the optical fiber nonlinearities specially in Wavelength Division Multiplexing system (WDM).The combiner combines the two linear polarizations to one output port directly. The polarization combiner has a device angle (Θ) which can be changed manually. The Polarized is using a linear polarization of (Θ +90°)as shown in figure(3.13.a). In pairing polarization technique, the polarization combiner has a device angle (Θ) which can be changed manually. The first two polarizer combiners with 45^o polarized angle while the third one is a polarizer combiner with a 0° polarization angle to combine all the signals adding the selected polarization components as seen in figure (3.13.b)
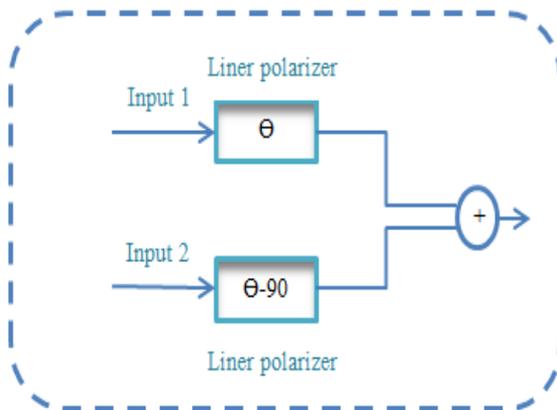
Figure 3.13.a: polarization combiner   Figure 3.13.b: polarization combiner connection in the Layout.
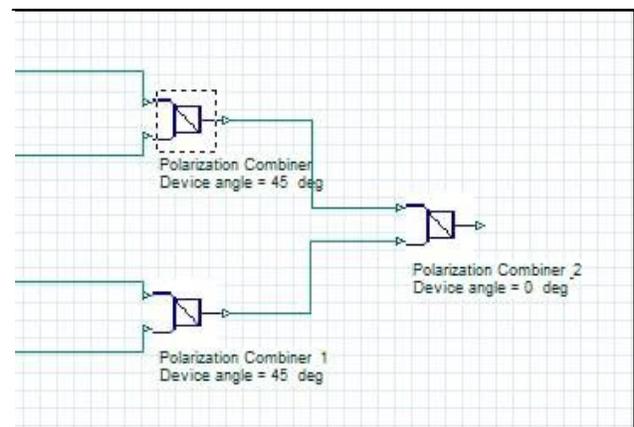
3.4. Design of the proposed system

Figure 3.14 shows the system block diagram and model for performance of optical system for with four, eight and sixteen channel WDM system with polarization combiner. And its performance has been measured with Q-factor and BER, by varying the bit rate, input power, length of the fiber and modulation scheme.

The above diagram consists of:

✓ **Optical Transmitter Section**: CW Laser diode, difference modulation forms and WDM system with polarization combiner

✓ **Optical Fiber/ channel:** Here, single mode fiber SMF, desperation compensation fiber DCF and Erbium-Doped Fiber Amplifier (EDFA) are used in optical loop. Optical Fiber is desired for

the study of FWM. The fiber model in the Optisystem considers the Non-linearity coefficient, Effective aperture, length and Dispersion which introduces non linearity in the fiber.

✓ **Optical Receiver section:** It consists of PIN Photo, a Low Pass Bessel Filter detector that generates the electrical signal which is then given to the Eye Diagram Analyzer for the measurement of Q factor, BER and Eye Opening.

-A-

-B-
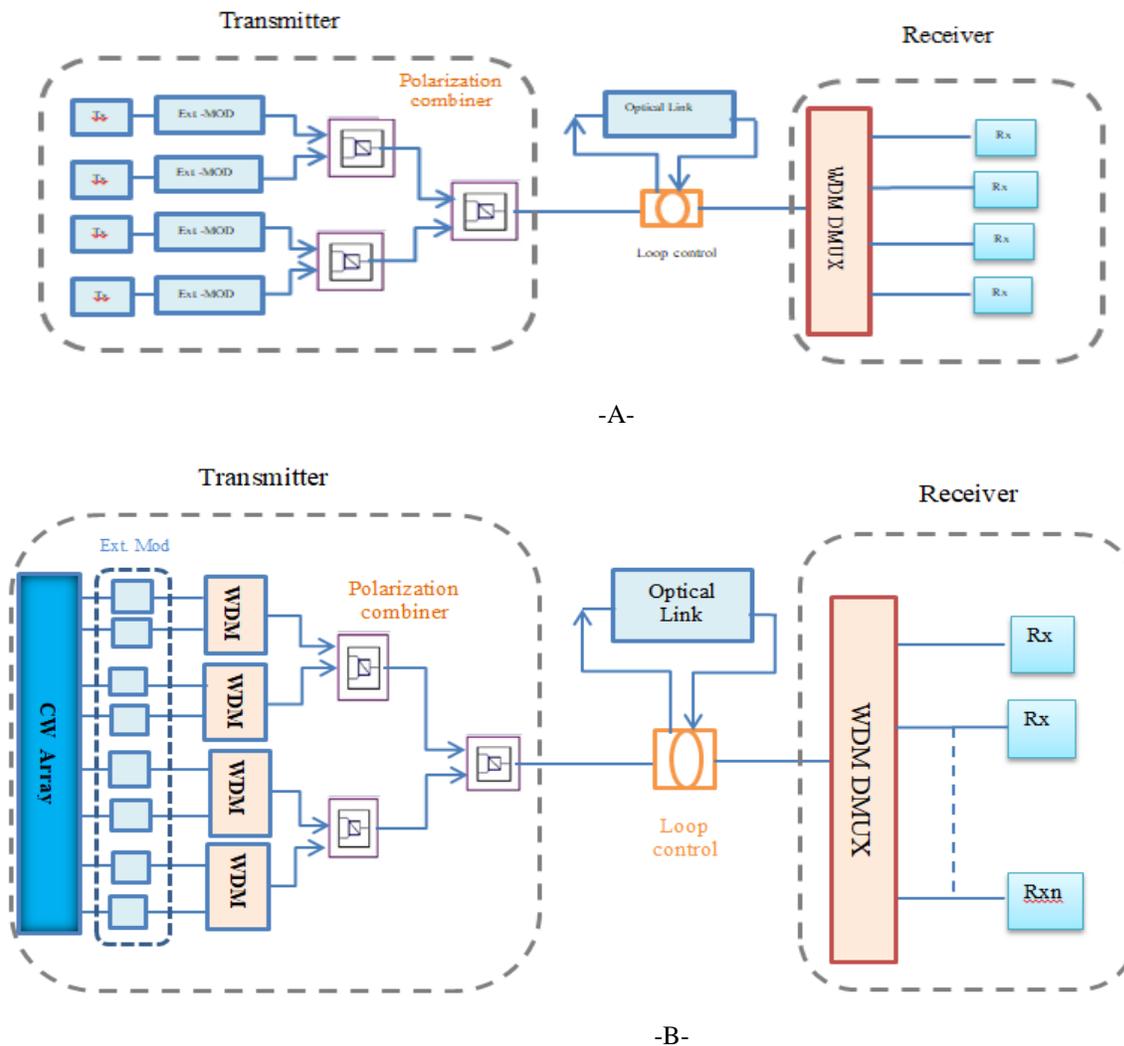
Figure 3.14: Block diagram of the proposed system (A) 4 channel (B) 8 channel

3.4.1.Analysis of 4×10Gb/s multichannel WDM system with combiner polarizers

Fig 3.15 depicts the block diagram of the proposed system. The system is divided into different parts, the transmitter consists of 4 channels .A continuous wave laser is used to generate optical signal, with different spaces of channel, which is connected to different modulators CSRZ,DBM-

1,DBM-2 and NRZ transmitter followed by polarization combiner. Both the first and second channels are connected to the polarization combiner with an angle (45^o) and the same case is applied for the third and fourth channels. The polarization combiner chooses at the input ports the appropriate polarization component of each signal and adds the polarization components selected. The polarization combiners outputs for each paired channel are connected to a third polarizer combiner with an angle of (0^o) and then the signal is sent through the transmitter optical link fiber that was indicated in Fig.3.6 The optical link consists of (1, 2, 5,7) loop span. Each loop has (60, 120, 300, 420)Km Fiber length respectively. The transmission link has the same parameters that are used in a single channel. Its specifications are described in details in section 3.2.2, then the signal passes through WDM -DMUX to the receiver where the signal is detected by PIN photo-detector then to low pass Bessel filter. The signal is sent to 3R regenerator, then the signal is connected to the eye diagram tester to configure the graph and system performance which is evaluated in terms of Q-factor and BER. The effect of the polarization technique on WDM performance with regard to FWM is simulated using an optical systems simulator OptiSim^{TM} 17. The parameter of the layout in the proposed system edited in Table(3-6).

Table (3-6) simulation parameters of the layout editor and CW laser

Parameter	Value	units
Layout Editor		
Rate of the Bit	10	Gb/s
Rate of the Sample	320	GHz
The Sequence length	128	bits
The Samples per bit	32	bits
The Number of samples	4096	
CW laser		
Frequency λ	193.1-193.4	THz
Power p_i	(-0.5─20)	dBm
Line width	10	MHz
Initialphase	0	deg
Channel spacing ,Δf	50,100 and 200	GHz

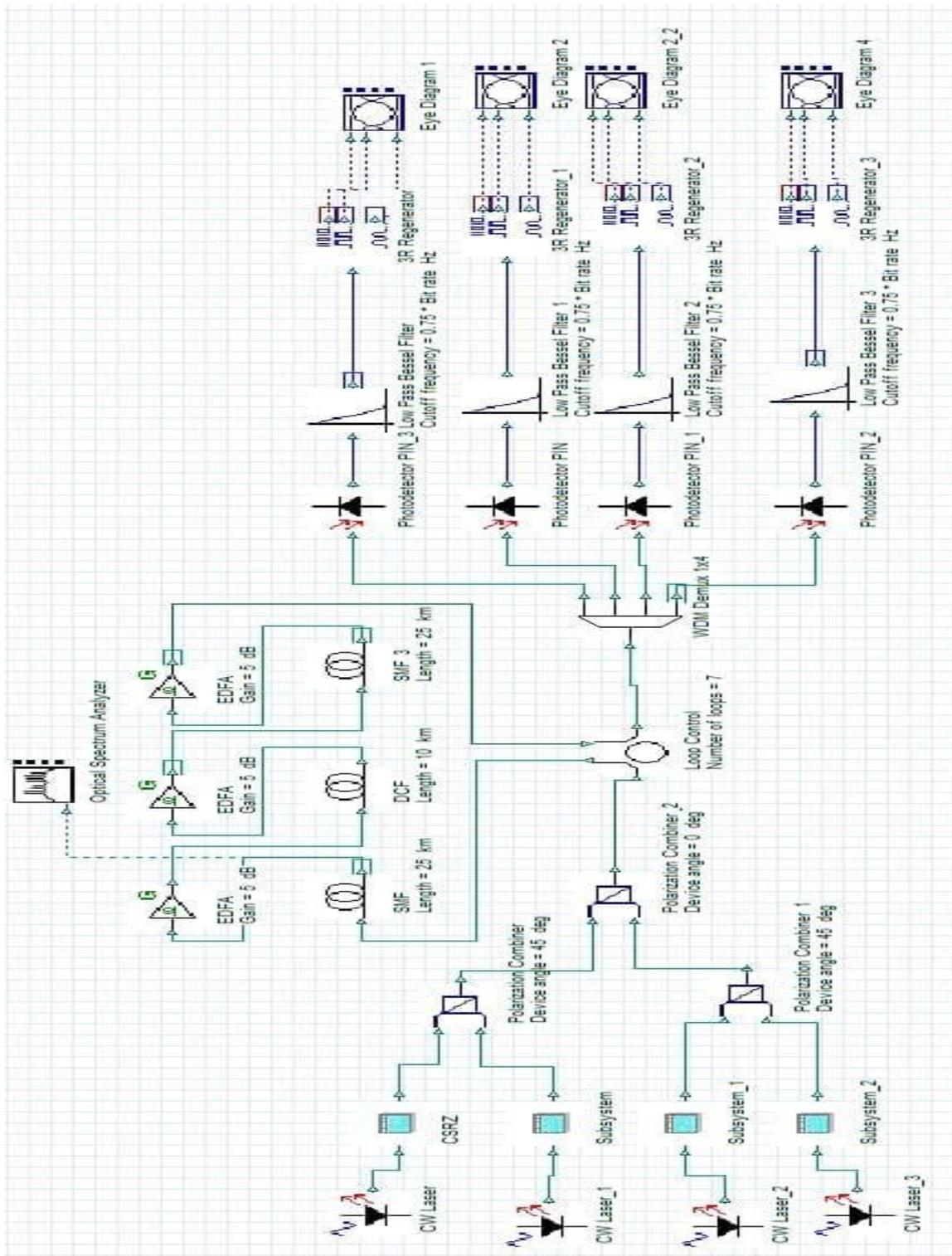Figure 3-15: 4×10Gb/s proposed system.

3.4.2. Analysis of 8×10Gb/s multichannel WDM system with combiner polarizers

The simulation of proposed system is investigated in Optisystem[17]. Figure (3.16)described the proposed system setup. The specifications of proposed WDM-PC system are illustrated in Table 3.7. Generally, the system consists of several parts, transmitter, CW laser Array that its parameter of simulation presented in Table(3-8). The frequency of the optical source is CW laser Array fed to various modulations   (CSRZ, DBM-1, DBM-2 and NRZ). Each two channels are connected to the WDM-MUX and then they reach to the polarization combiner with an angle of (45 ^{o}). The polarization combiner chooses at the input ports the appropriate polarization component of each signal and adds the polarization components selected. A third polarizer combiner with an angle of (0 ^{o}) combined outputs for each paired polarizer combiner and then the signal is sent through the transmitter optical link that is indicated in figure 3.6. The optical link has (60, 120, 300 & 420)Km fibre length. Its specifications are described in details in Section 3.2.2. This part is connected to OSA(optical spectrum analyser). It compares different signals then the signal passes through WDM -DMUX to the receiver. An optical receiver is used to change the optical signal back into electrical form and recover the original data that are transmitted by a CW laser. Optical Receiver Consists: Photo Detector, Filter and 3R (Re-Amplify + Regenerator + Reshaping) sensitivity, fast response, and low noise, the main component in the receiver is a photo detector that converts the signal of light into electricity signal over the photoelectric effect of the requirements photo detector are the same to that for an optical source. It should have a low cost and high reliability. Optical receiver subsystem is built using a PIN photo detector, a Bessel filter and a 3R re generator that is used to produce original sequence of bit and to modulate electrical signal to be ready to compute the BER of the received signal at the eye diagram tester. The system performance was evaluated in terms of Q-factor and BER. The purpose of that is to show the effect of the proposed technique on the spectrum of the transmitted signal especially when the modulation is CSRZ. The effect of the polarization technique on WDM performance with regard to FWM. Table (3-4) shows the parameters of the receiver.

Table (3.7) system specifications of proposed WDM with PC

Parameters	Values
Data speed	10 Gbps
WDM channels	8
Frequency spacing	50 GHz, 100GHz, 200 GHz,
Distance	60 km,120km,300km,420km
Nonlinearity analyzed	Four wave mixing
Input power Pi	(-0.5-20) dBm
Frequency	193.1
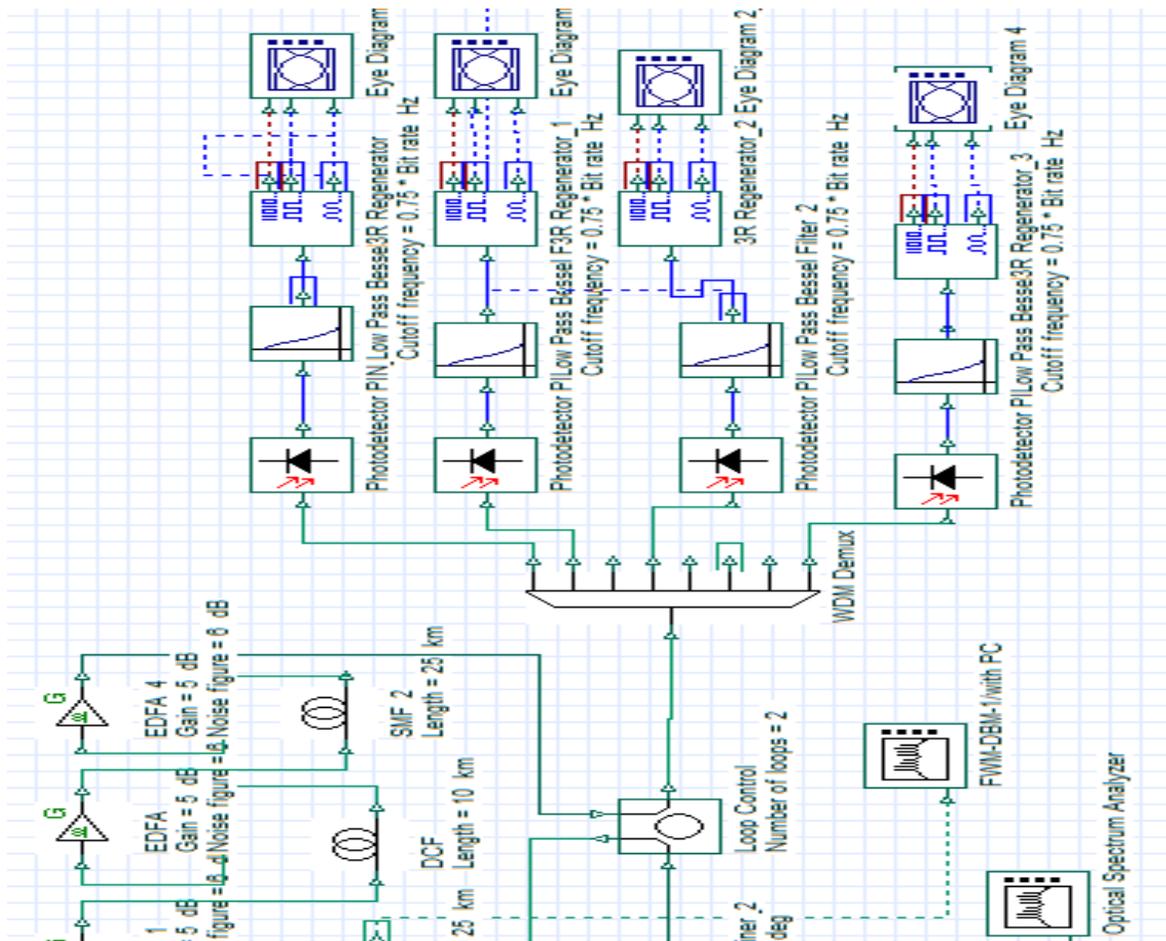
Figure 3-9: 8×10Gb/s proposed system.
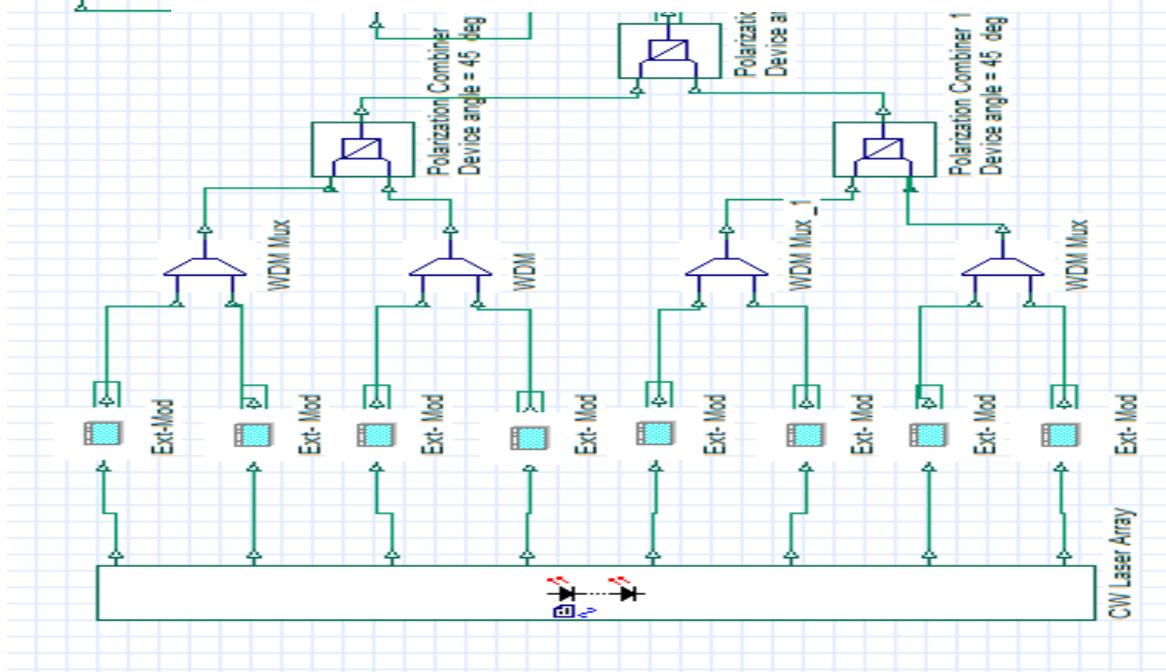
Figure 3.16: 8×10Gb/s proposed system.

3.4.3. Analysis of 16×10Gb/s multichannel WDM system base combiner polarizer

Figure (3.17)describes the proposed system setup.WDM transmitter consists of 16 subsystems each four sub-system fed to 4x1WDM-MUX and then they reach to the polarization combiner. its design is at the same setup of 8- WDM channels with PC. The first frequency is considered as 193.1THz, and to determine the final channel for a given total number of channels in WDM system , the final channel frequency depends on the channel spacing; e.g. for sixteen channels WDM system, the frequency of the last channel is

$FC = 193.1THz + 100GHz \times (N - 1)=193.1THz +100 GHz\times(16-1)=194.6THz$

The simulation parameters of the WDM multiplexer which are used in the system are shown in Table (3-8). Table (3-9) shows the parameters of WDM DE multiplexer.

Table (3-8) the parameters of simulation of CW laser Array

Parameter	Value	Unit
Output ports number	8 ,16	…….
Frequency	193.1	
Channel spacing	50 & 100	GHZ
Linewidth	10	MHZ
Type of Filter	Bessel	-------
Order of Filter	2^{nd}	-------
Signal Power	-0.5_ 20	dBm

Table (3-9) WDM transmitter parameters

Name and description	Default Value	Default Unit
Output ports number	4 for 4- Mux	16 channel
Frequency	193.1-194.6	THz
Iseration loss	0	dB
Depth	100	dB
Bandwidth	20	GHZ
Filter type	Bessel 2^{nd} order	-------

Simulation and validation of the normal WDM-without PC and proposed WDM-with PC system include the following:

- The simulation of traditional system (WDM-without PC) to compute the quality factor of the received signal under different conditions of (length, input power, different modulation) by changing this conditions . Also , the simulation shows the degradation of the system in terms of quality factor and bit error rate when compared to the proposed system.

- The simulation of the proposed system is utilized to compute the quality factor of the received signal under different conditions by changing the transmission distance, input power and modulation type . Also, it is used to show the impact of the FWM that is mitigated in the proposed system on the implementation of the optical communication system. The system is also improved.

Figure 3.17: 16×10Gb/s proposed system.

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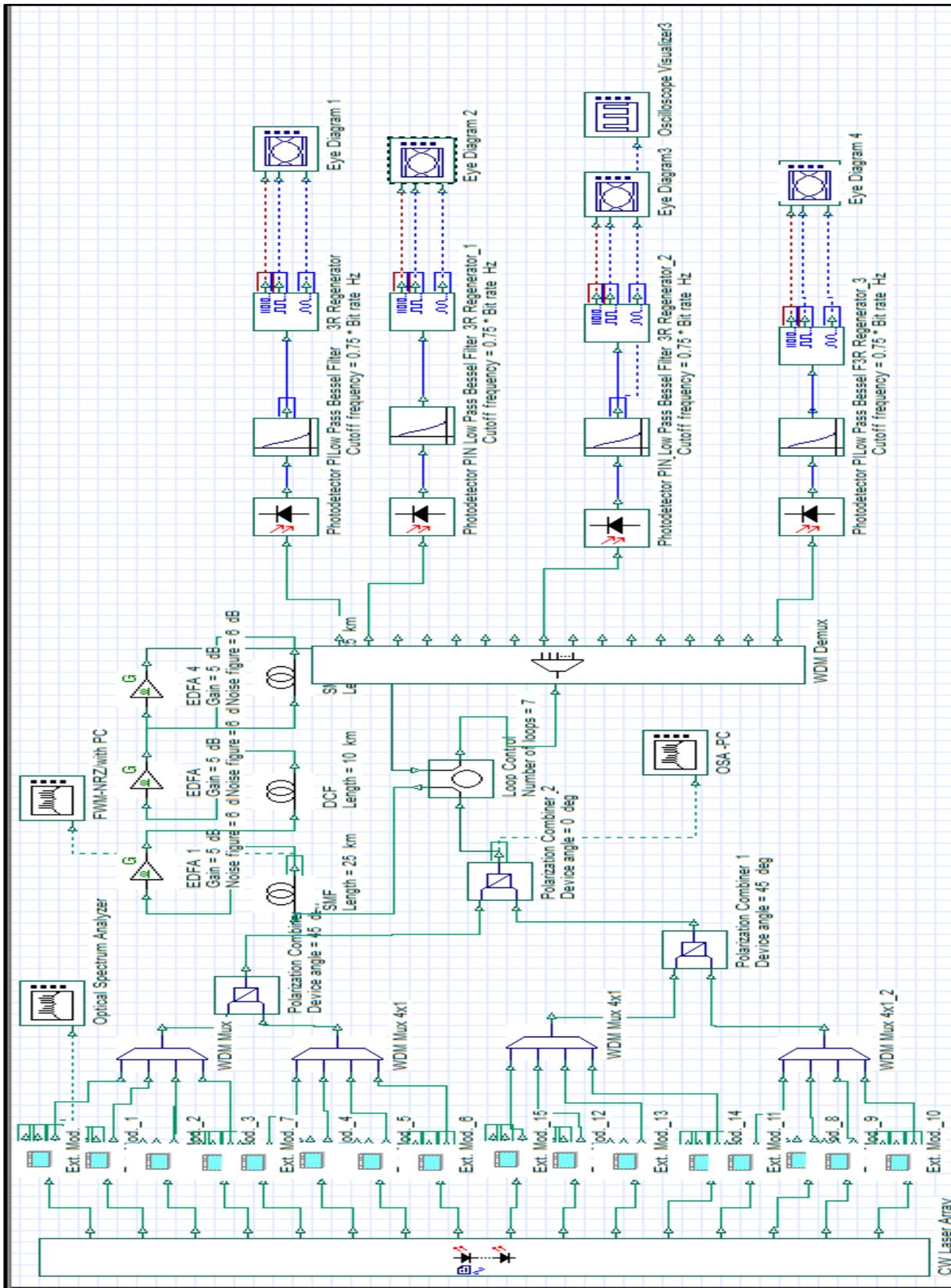
4.1 Introduction

In this chapter, the simulation results of the proposed FWM reduction approach by polarization combiner with different modulation scheme are investigated. This approach includes the effect of both modulation frames and combined polarizer parameters optimization like different channel spacing, fiber length and lunched power. FWM power is calculated in each case. In addition to that, the comparison between the system performance in term of BER and Q factor of WDM system without and with polarization combiner has been made . The findings show that all the modulation schemed with polarization combiner can reduce the FWM power at different rates. Moreover, the findings indicate that increasing the input power, fiber length, and decreasing the channel spacing lead to an increase in FWM effect. This work is able to suppress the FWM and offers a great improvement in BER and Q factor. The results were analyzed in Optisystem software based on the eye diagrams and optical spectra for the measurement of the BER value, the Q-factor.

4.2 Single channel system

Figure (4.1) explains the results of a single channel transmission system with four modulation schemes which are NRZ, DBM-1, DBM-2 and CSRZ. This simulation completes four spans for each with 60 Km length and 10Gb/s a bit rate. It shows Q factor versus input power. The simulated results show that the CSRZ modulation scheme has the best performance in the case of single channels at 6.5dBm. Figure (4.2) illustrates the performance of the single channel system at the proposed system in terms of input power versus Q-Factor. From the comparison between the two below figures (4.1)& (4.2) it can be realized that in each case CSRZ is the best, but CSRZ with PC gives the best performance in the system.
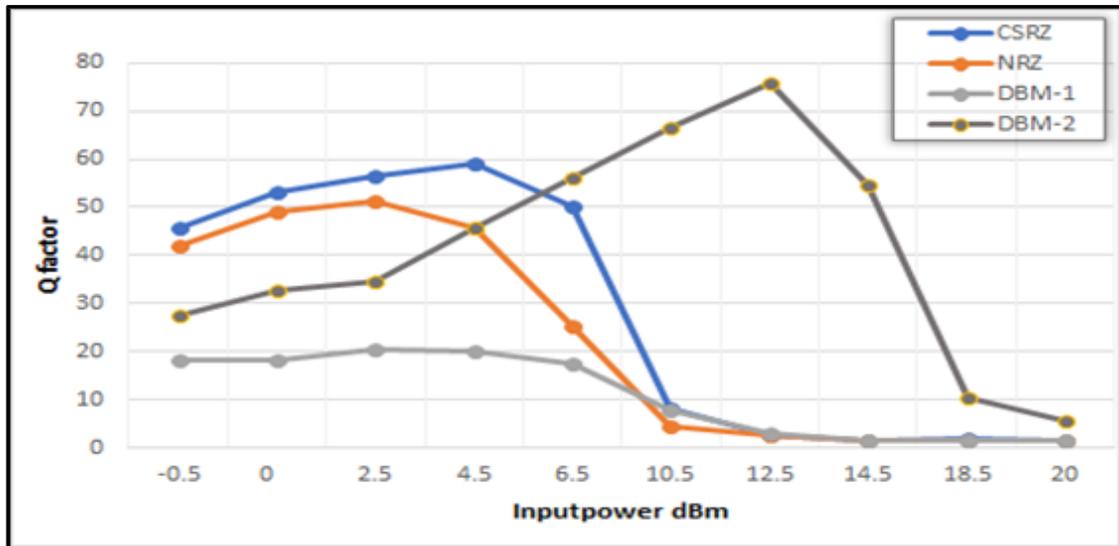
Figure 4.1: Q factor versus input power for single channel -four types of modulation schemes without PC at 60km fiber length and 100Ghz channel spacing.
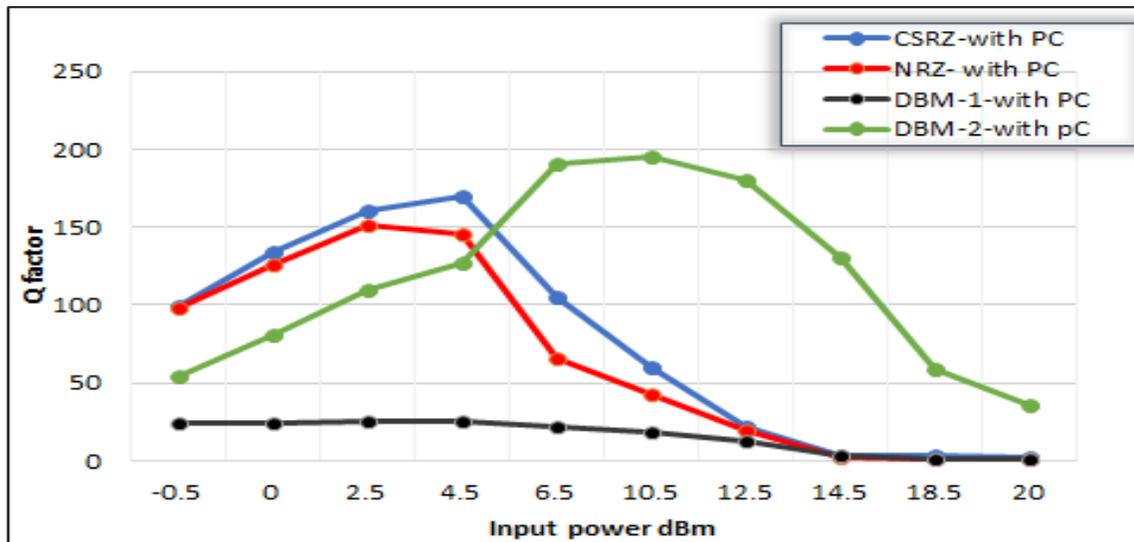
Figure 4.2: Q factor versus input power for single channel -four types of modulation schemes with PC at 60km fiber length and 100Ghz channel spacing

Figure (4.3) represents the eye diagram for single channel-four types of modulation schemes at input power of 4.5dBm ,60km and 100GHz channel spacing. This figure exhibits the best opening eye in case of CSRZ modulation frame with PC.

NRZ

CSRZ

DBM-2

DBM-1
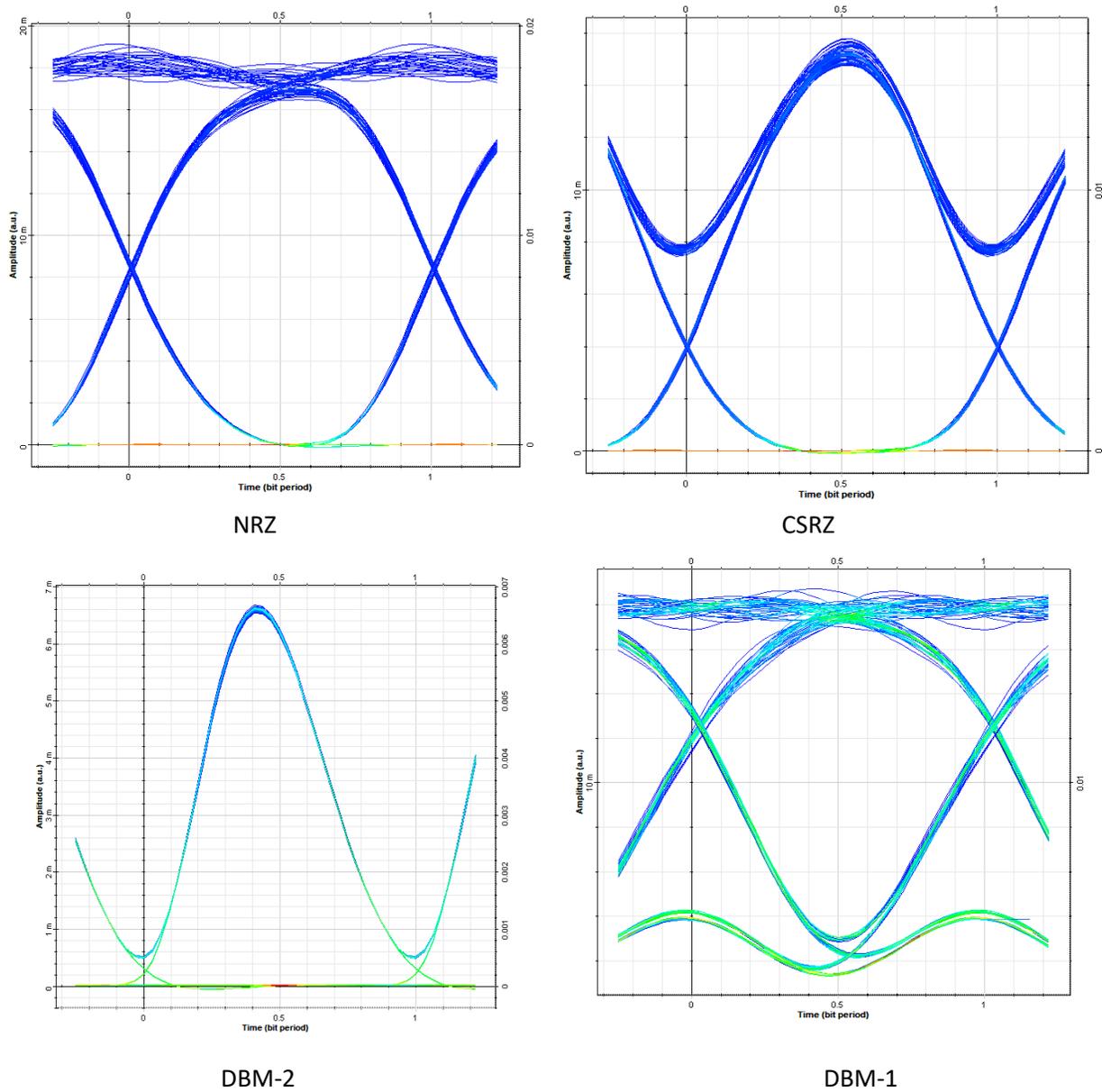
Figure 4.3: Eye diagram of single channel for the four modulation schemes with PC at 4.5dBm input power.

Table (4-1) shows the Q-factors of the four modulation schemes with and without PC at input power of 4.5dBm for single channel system at 100GHz channel spacing and 60km fiber length. Figure (4.4) Represents a comparison between different modulation forms with & without PC ,where it can be seen that CSRZ modulation with &without PC is the best one.

Table (4-1) the Q-Factors of the four modulation schemes at 4.5dBm input power.

Modulation Format	Max Q-Factor	
	Without PC	**With PC**
CSRZ	59.2213	161.038
NRZ	45.7055	145.133
DBM-1	20.0366	25.9024
DBM-2	45.227	109.648
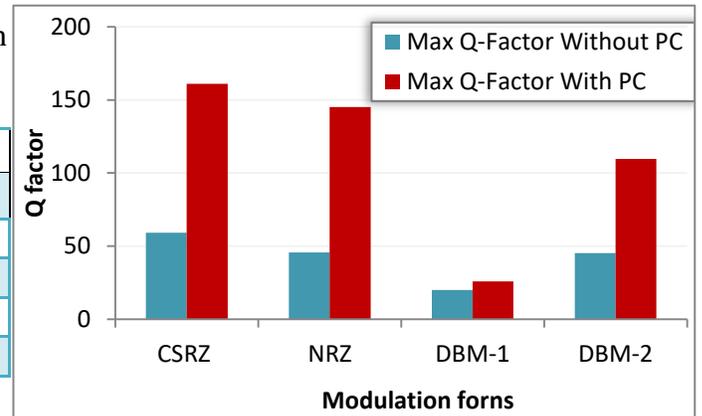
Figure 4.4: Statistical presentation for Q-factor under various four modulation after 60km distance

From the obtained results of the values of Q-Factors for single channel system at 10Gb/s, four spans, the CSRZ modulation scheme represents the best performance.

4.3 Multichannel system

Multichannel system has been simulated to investigate the FWM in high capacity WDM system with and without PC. Also various parameters that effect FWM are considered such as the number of channels, frequency spacing, different optical fibers length and different input power.

4.3.1 The effect of number of channel variation

The number of channels is the first parameter that effects the FWM power. Figure(4.5) represents the performance of WDM channels without PC in terms of Q factor under the influence of four wave mixing. It is prominently observed that the increasing number of channels leads to decrease the Q factor and increase the nonlinear effects. WDM channels without PC are studied at different channels number 4, 8, and 16 with 10 Gb/s data rate at each channel and the fiber length is 300km. The Q factor performance is inversely proportional with the number of channels, where maximum Q factor at 4 channel and least on 16 channel because of the more channels cause more interference to adjacent channels. Figure (4.6)shows Q factor at the proposed system CSRZ modulation scheme with PC at various numbers of channel.
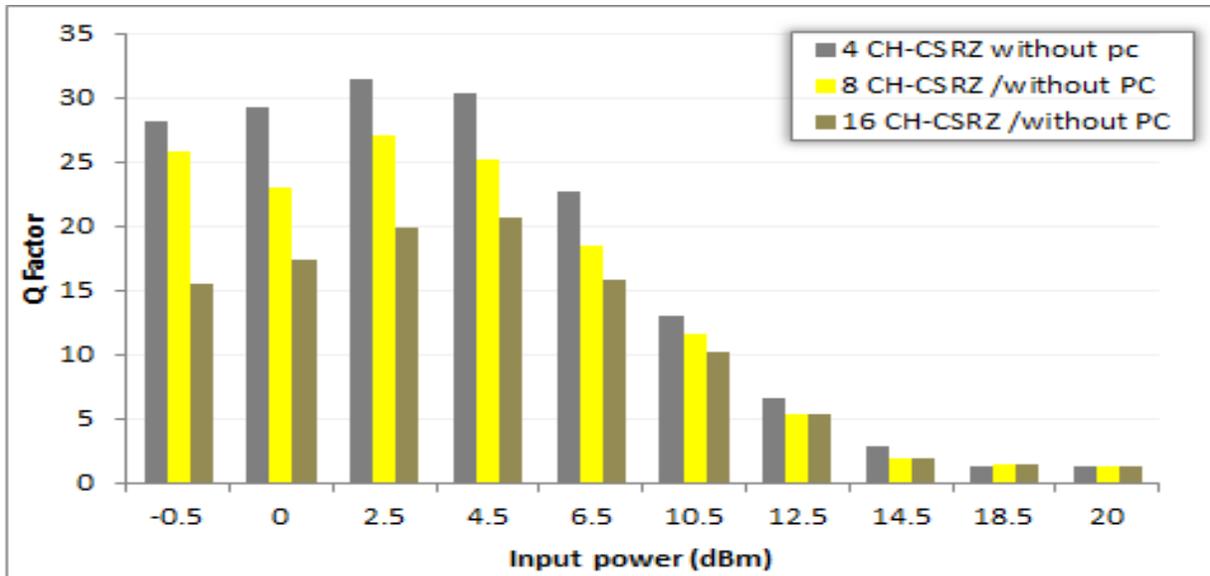
Figure 4.5: : Q-factor versus input power at various no. of channels at CSRZ modulation without PC
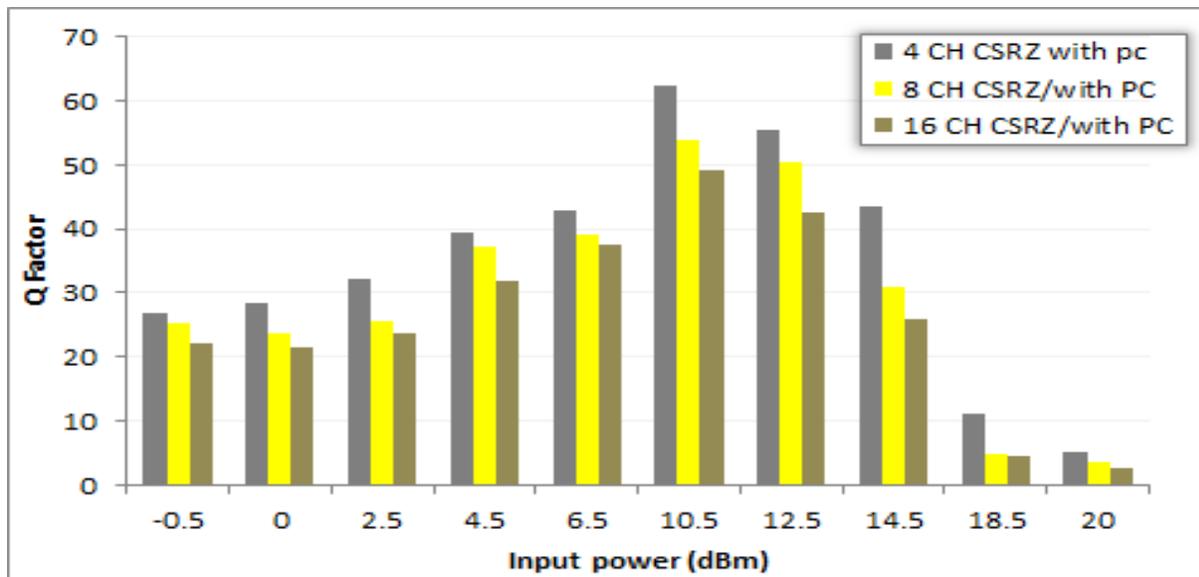
Figure 4.6: : Q-factor versus input power at various no. of channels at CSRZ modulation with PC

Figures (4.7) (a, c & e) show the optical spectrum of conventional WDM system without PC after multiplexing and figures (4.7) (b, d &h) after propagation distance of 300km. at input power 12.5dBm in CSRZ modulation form. It is observed that the spectrum is distorted and broadened after propagation through fiber representing induced nonlinearities and FWM effects that are increased when the number of channel is increased.
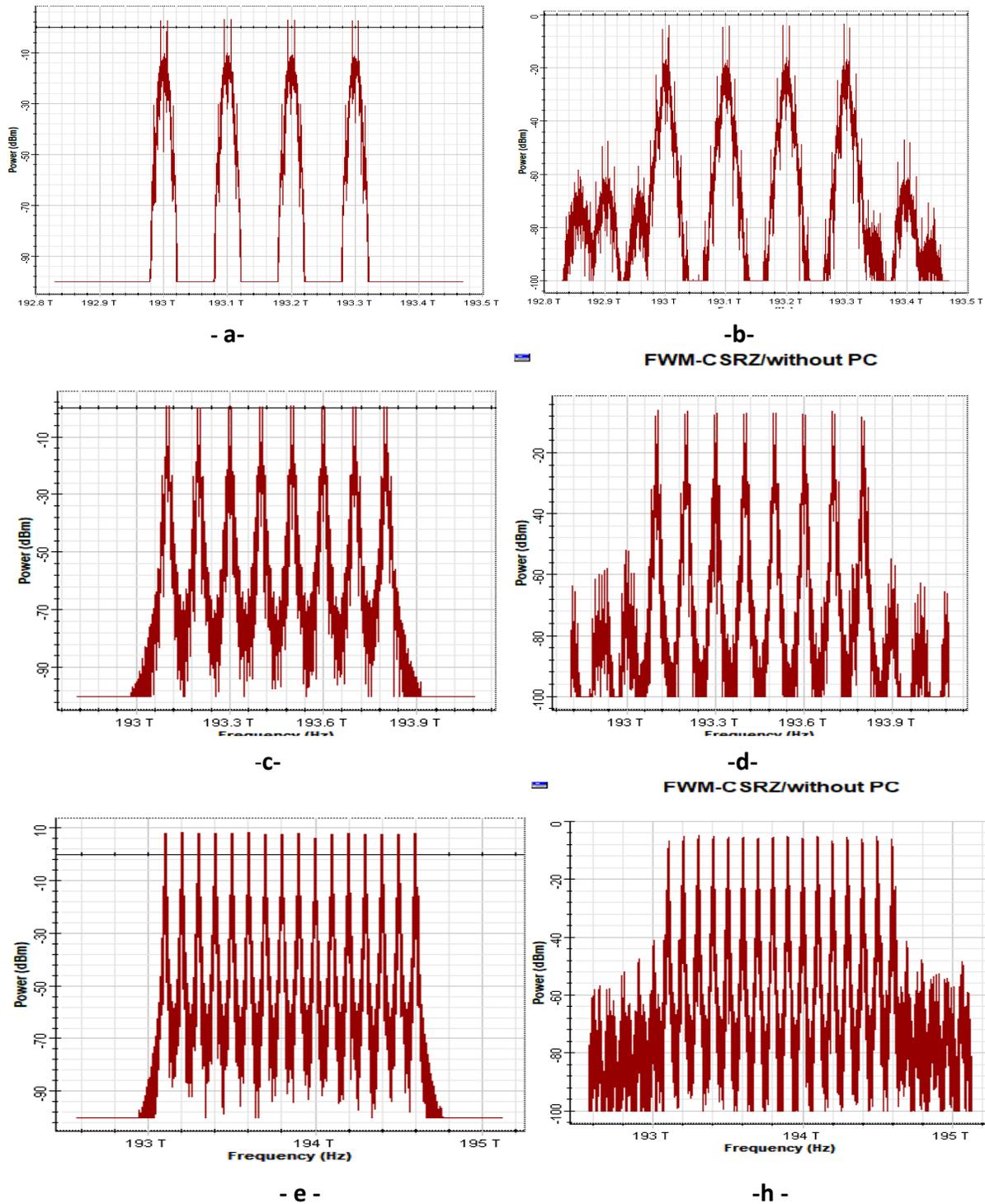
Figure 4.7: Optical spectrum analyzer depictions after multiplexing and after optical fiber respectively for (a , b) 4 channels (c, d) 8 channels (e, h) 16 channels at distance 300Km

From figure(4.7) the effect of FWM it is clear that after optical fiber in (b-4channel, d-8channels , h-16 channel) and it is increased when the number of channels is increased.

4.3.2 The effect of channel spacing

The second parameter that increases FWM power is the channel spacing. Further investigation is performed for different channel spacing in WDM system 8 and16 channels with CSRZ modulation form. Channel spacing is tuned for 50 GHz to 100GHz. Figure (4.8) illustrates the relationship between FWM power and channel spacing for multichannel system without PC. It can be seen that increasing channel spacing at different loop lengths at input power of 12.5dBm leads to improve the system performance. The results showed Q factor for 100 GHz frequency spacing is maximum and for 50 GHz is minimum.
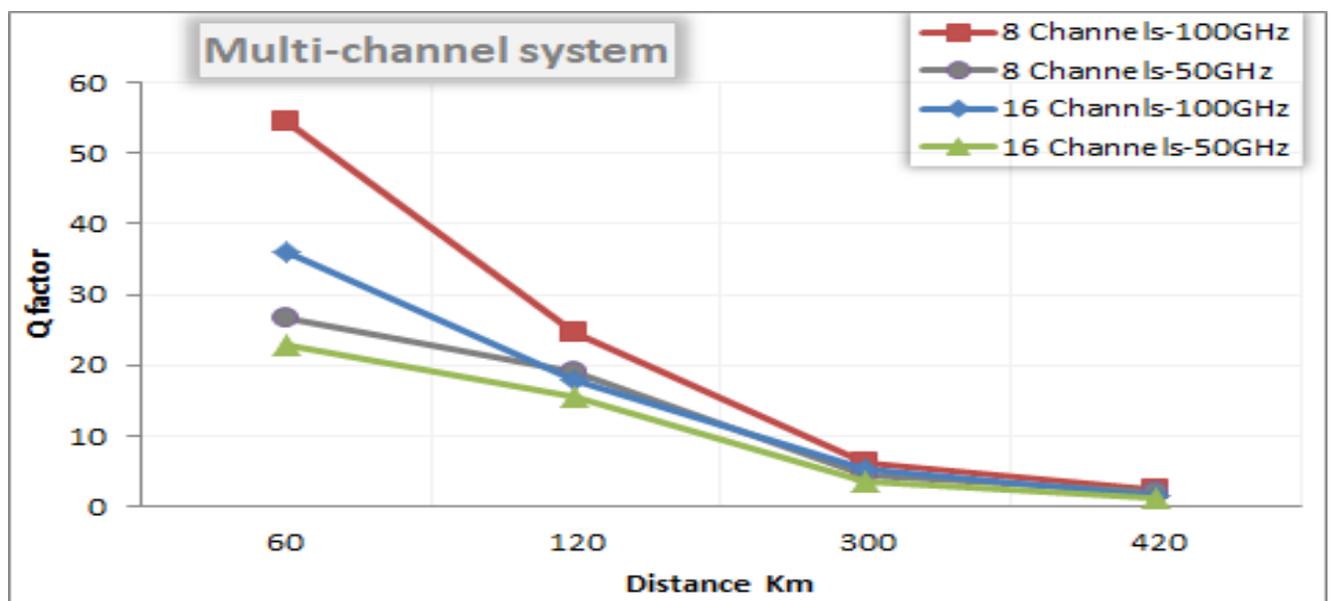
Figure 4.8: Q factor at different channel spacing of WDM system-CSRZ Mod. without PC

Figure (4.9) shows the values of FWM power with various space of channel at WDM system - CSRZ modulation without PC.

The values showed that the FWM power is increased when channel spacing has been decreased. Thus , decreasing the channel spacing frequency can make the time period of FWM shorter, which shortened the waves and made them closer to each other.
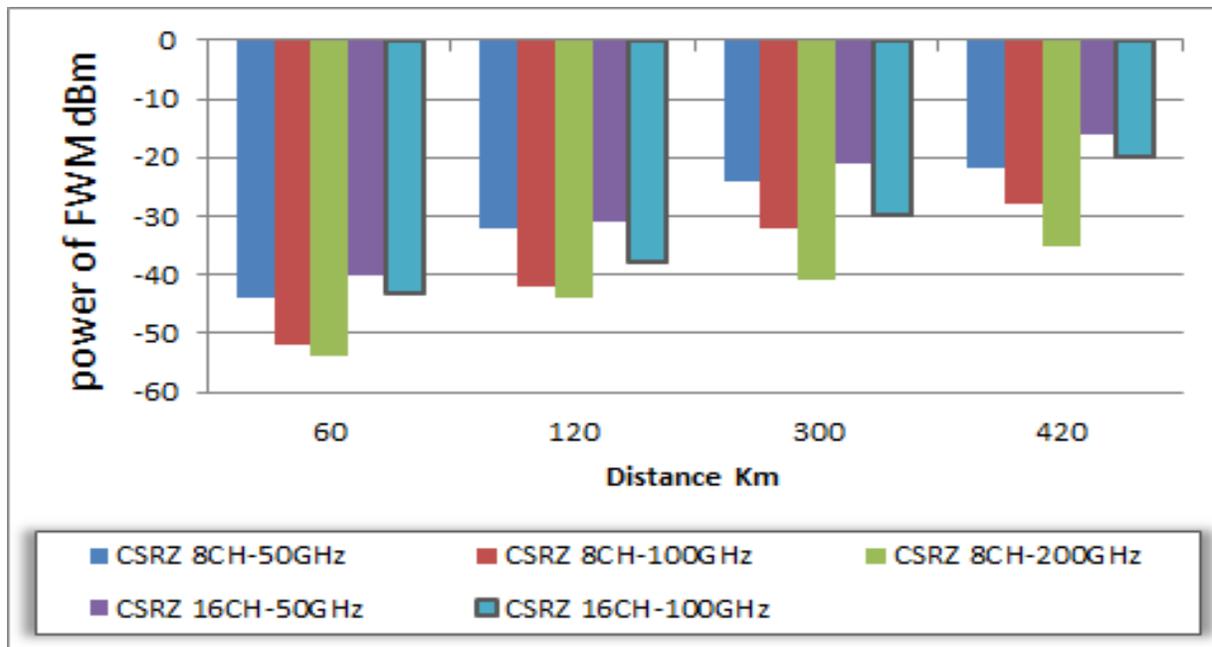
Figure 4.9: FWM power for WDM system- CSRZ Mod without PC. for varies channel spacing
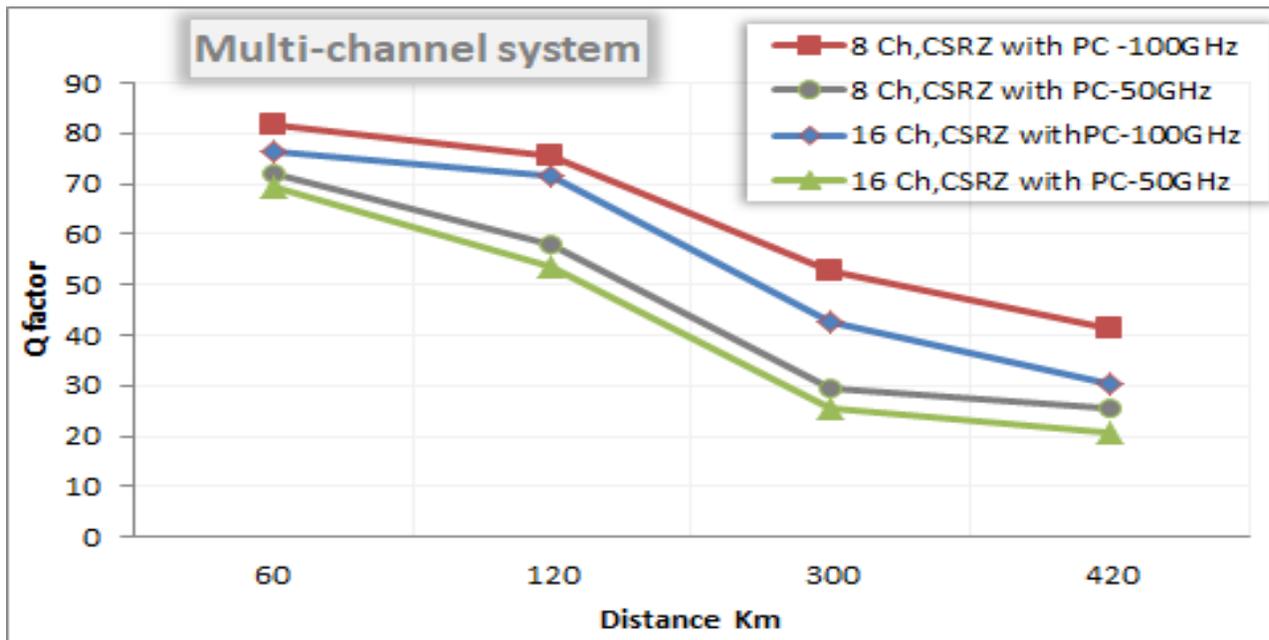
Figure 4.10: Q factor at different channel spacing of WDM system-CSRZ Mod. With PC at 12.5 input power

By observing the Figures (4.8) and (4.10), it is noticed that adding PC with modulation form improves the system performance.

4.3.3 The effect of fiber length

The third parameter that effects the FWM power is the length of the fiber. Figure (4.11)(a, b, c, and d) show the performance of a 4×10 Gb/s WDM without polarization combiner, at 100GHz channel spacing optical system, with the mentioned modulations schemes to evaluate the performance of the simulated systems. Under variable lengths (60,120,300 & 420) km , these parameters are used by Optisystem simulation toolbox, the Quality factor at various conditions of distance is calculated by changing the loop span of transmission fiber length between the transmitter and receiver. The simulations are based on different transmission powers and 100GHz (channel spacing) at 2^{nd} channel. By varying the length of the fiber with four loop span (60, 120, 300 and 420) km, to observe the Q-factor for different optical fibers with different input powers. As the Figures (4.11)(a, b, c& d) show, Q-factor is decreased as the optical fiber length is increased.
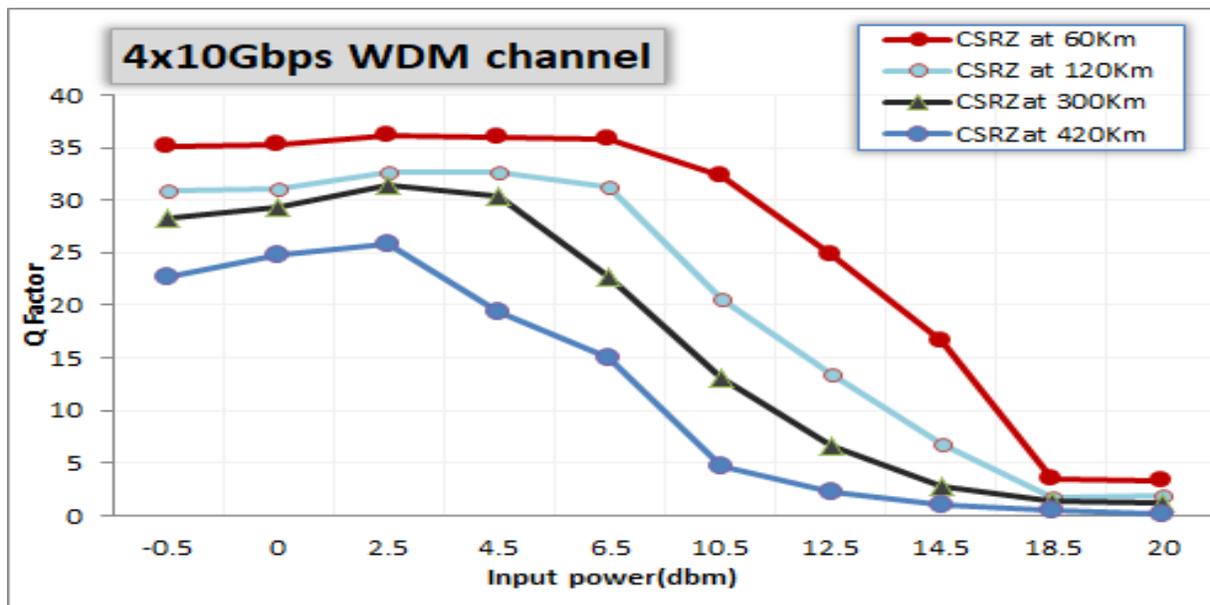
Figure 4.11 (a) Q-factor versus input power of 4x10 Gb/s WDM system in CSRZ Mod. without PC in the 2^{nd} channel. at channel spacing 100GHz and different fiber length
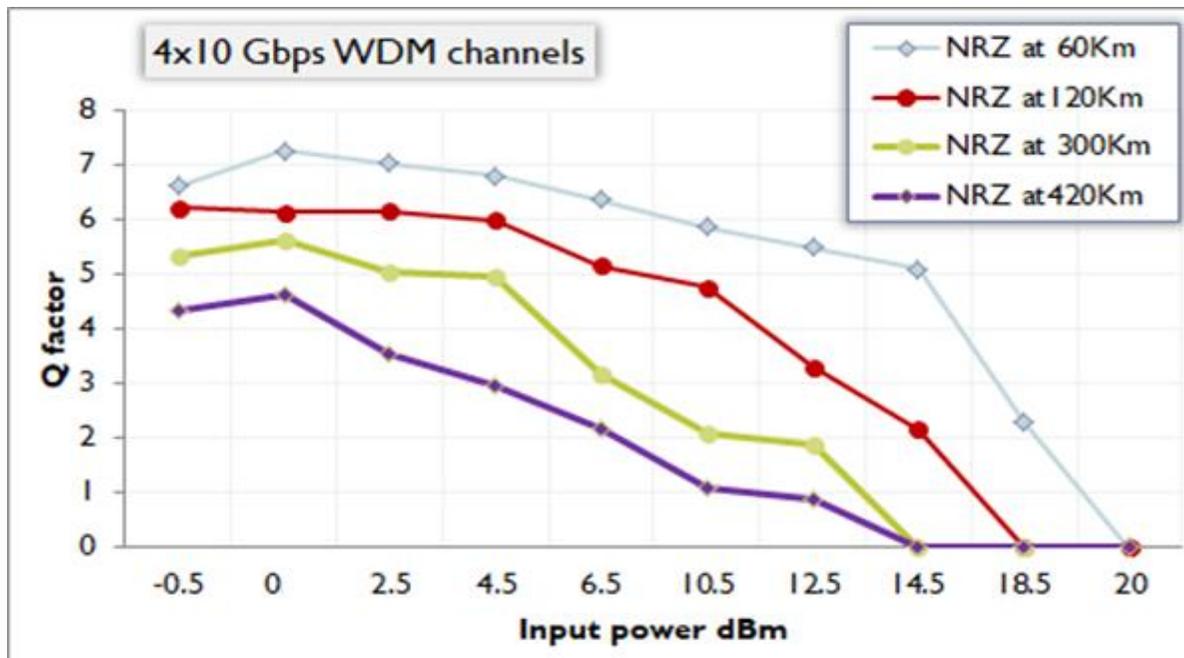
Figure 4.11(b) Q-factor versus input power of 4x10 Gb/s WDM system in NRZ Mod. without PC in the 2[nd] channel. at channel spacing 100GHz and different fiber length
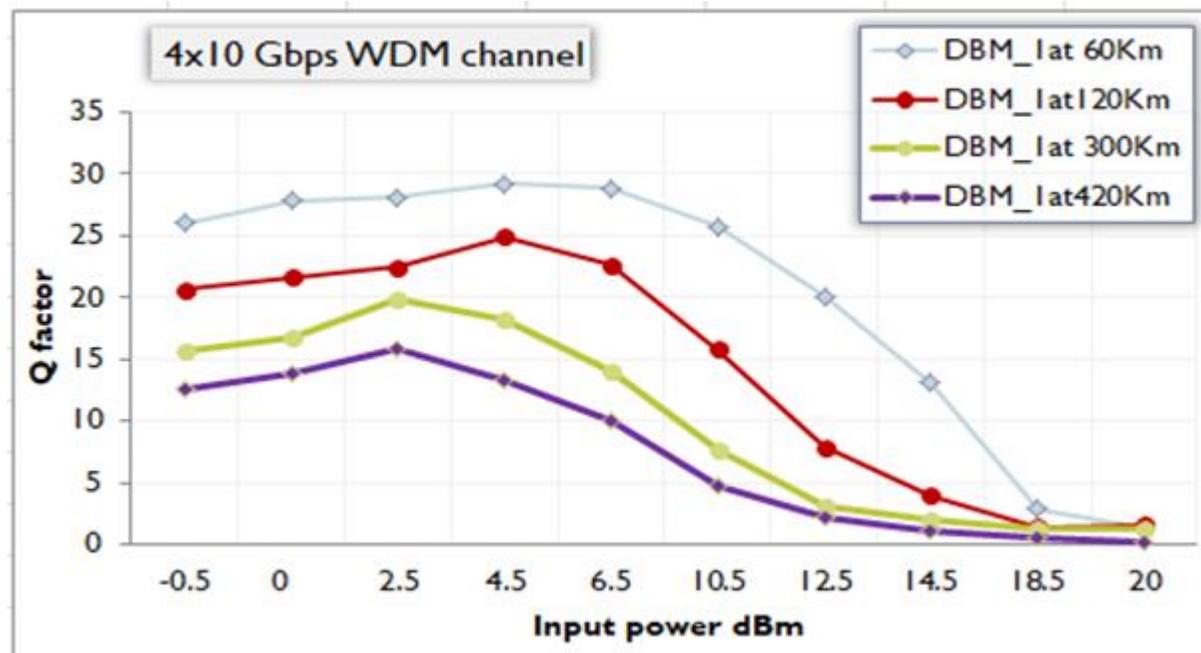
Figure 4.11 (c) Q-factor versus input power of 4x10 Gb/s WDM system in DBM-1 Mod without PC in the 2[nd] channel. at channel spacing 100GHz and different fiber length
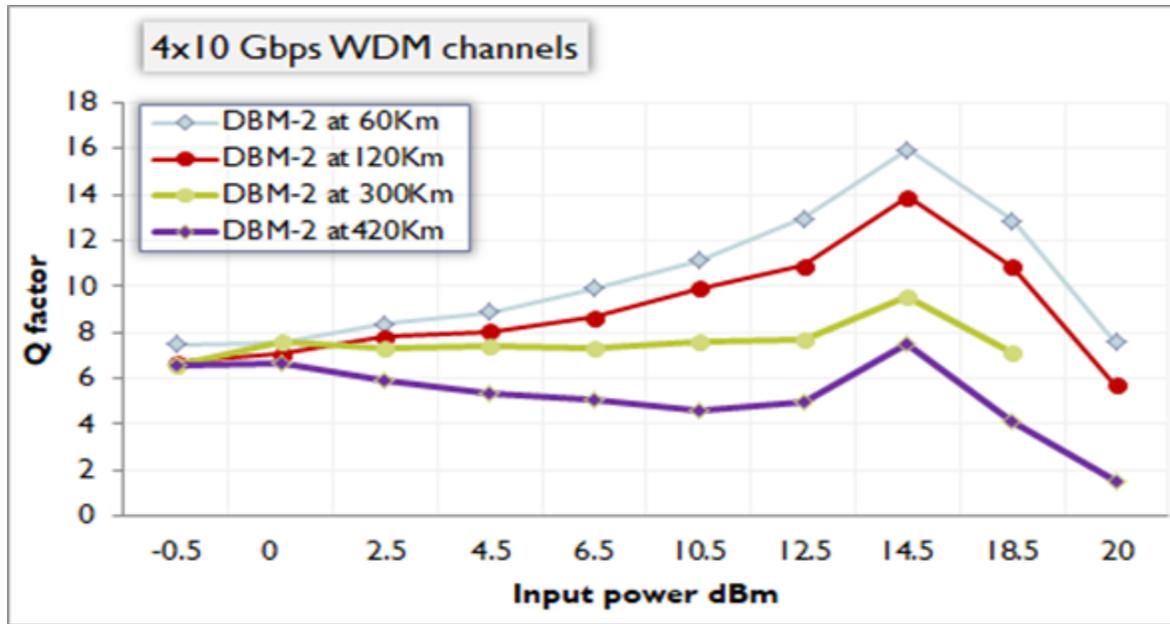
Figure 4.11(d): Q-factor versus input power of 4x10 Gb/s WDM system in DBM-2 Mod without PC in the 2nd channel. at channel spacing 100GHz and different fiber length

From the above figures, we can observe the effect of fiber length, so that Q factor performance is inversely proportional with the fiber length, where the maximum values of Q factor at length 60km. Table (4-2) Summarizes the Q-factors of the four modulation formats at input power of 12.5dBm for 4×10 Gb/s optical system without PC, at100GHz channel spacing and different distance.

Table 4-2: Q-Factors in case WDM system with different modulation form without PC.

Modulation Format	Q-Factor			
	At length 60km	At length120km	At length 300km	At length420km
DBM-1	20.12	8.212	3.71	2.611
DBM-2	9.91563	8.66153	7.32519	5.02519
NRZ	5.603	3.33	2.101	0.92
CSRZ	25.03	13.52	6.350	2.211

The proposed system has modulation formats (NRZ, DBM-1, DBM-2 and CSRZ) with PC, which is a new method for making a reduction in fiber nonlinearity, especially FWM effects at different input power.

Figure (4.12) shows a comparison of the performance of the Q-Factor versus input power at 4×10 Gb/s system with the use of PC with CSRZ modulation scheme and without it for different fiber length in 100GHz channel spacing.
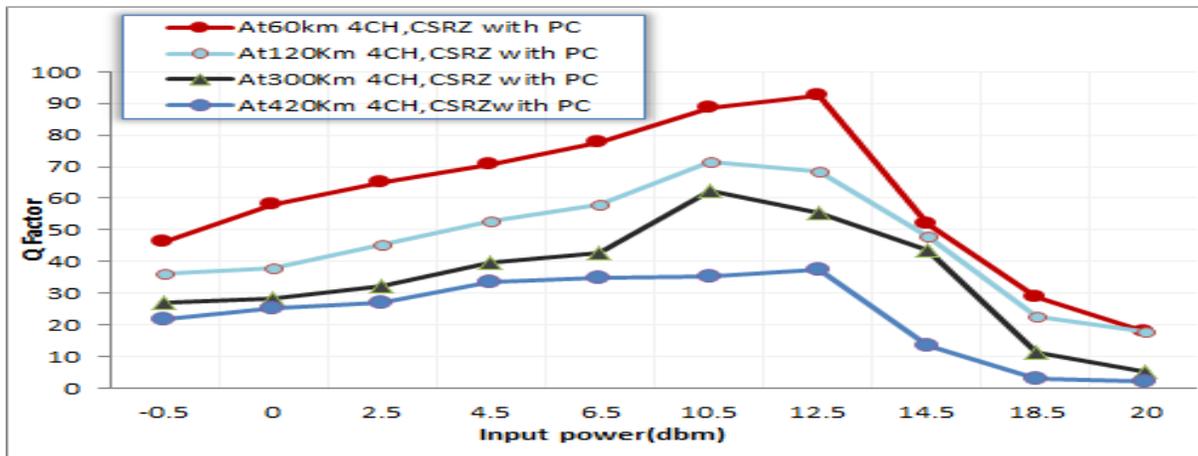
Figure 4.12: A comparison of the Q-Factor versus input power for 4×10 Gb/s system with the use of PC and CSRZ modulation scheme for different fiber length at channel spacing 100GHz

Table (4-3) Represents Q-factors for 4x10Gbps channel system four modulation form schemed with polarization combiner at input power of (12.5dBm) ,100GHz channel spacing , at different fiber lengths

Table (4-3) the Q factor for different modulation schemes with PC at different fiber length

Modulation Format	Q-Factor			
	At length 60km	At length 120km	At length 300km	At length 420km
DBM-1	28.7988	22.6797	14.0272	10.032
DBM-2	26.372	25.9018	20.4156	12.356
NRZ	45.2982	36.6276	14.6276	12.365
CSRZ	92.4519	68.4519	43.0196	37.3892
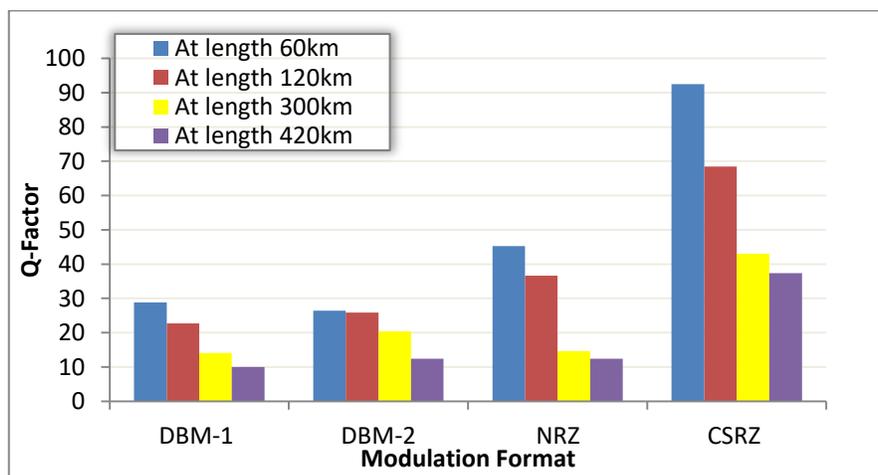
Figure 4.13:Statistical presentation for Q-factor under various four modulation at different distance

When we compare figures (4.11) and (4.12), we notice that adding PC with modulation form improves the system performance.

Figure (4.14) displays the eye diagrams of 8×10Gb/s for fourth channel after 300km fiber length for input power of 12.5dBm , with different modulation forms and 100GHz channel spacing scheme without PC. We can observe the distortion in eye diagram when fiber length becomes longer. That means the nonlinear effects of the fiber optic degrades the system.

CSRZ

NRZ

DBM-1

DBM-2
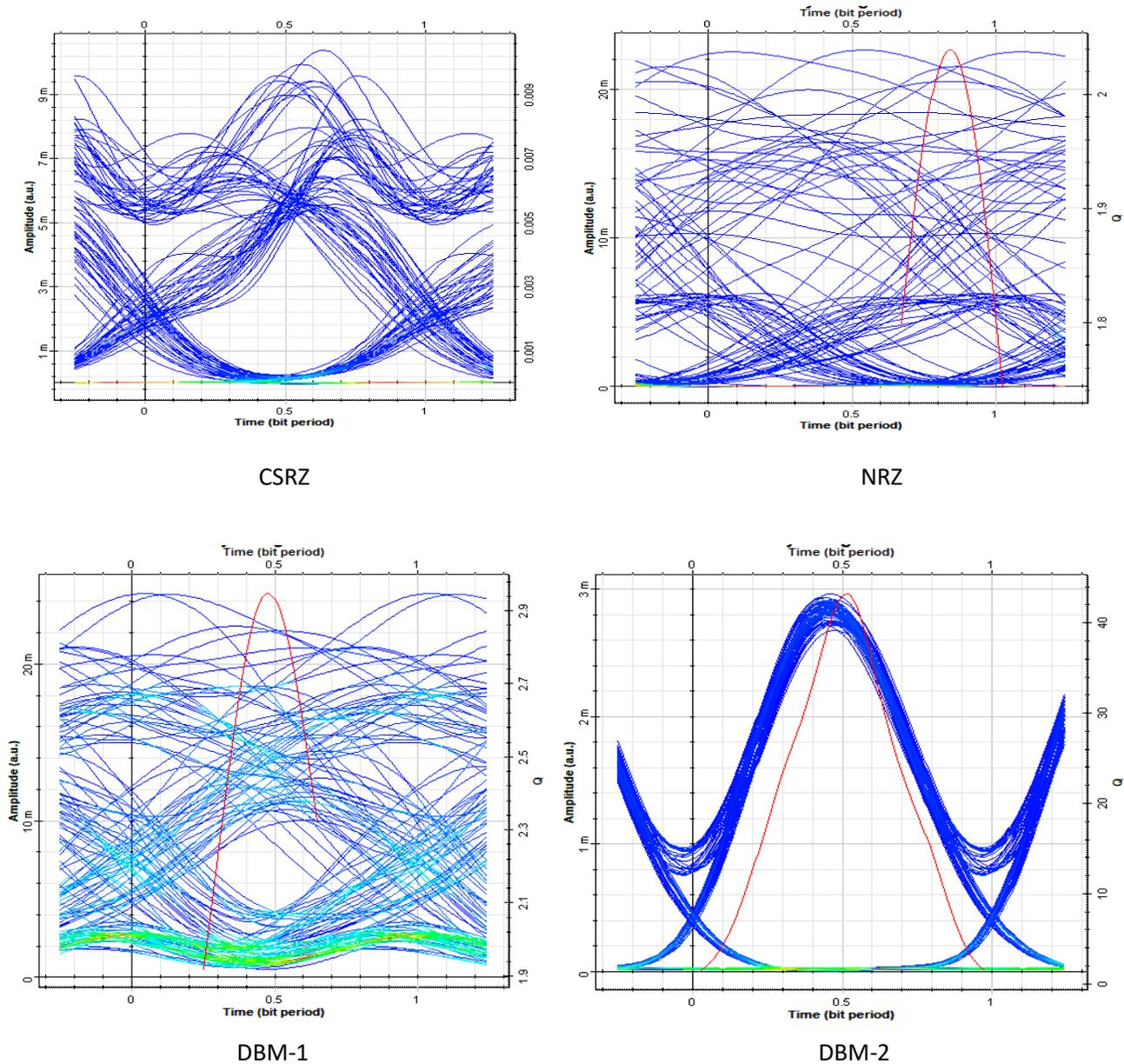
Figure 4.14.: Eye diagrams of 8×10 Gb/s, WDM channels without PC of the four modulation schemes, at 12.5dBm input power. and 100GHz channel spacing

So, the obtained results from simulation the values of Q-Factors for the proposed system at different modulations schemed with PC for four spans, the CSRZ modulation scheme represents the best performance.

Figure (4.15) shows the optical power spectrum of 4- channels proposed system (a, c, g) at different modulation schemed with polarized combiner to the mitigation of FWM, nonlinearities in the received signal, figures 4.15(b, d, h) represent the system without polarized combiner technique after propagation distance 300 km, at 100GHz, with varied modulation formats.

CSRZ-PC

- a -

- b -

-c-

- d -
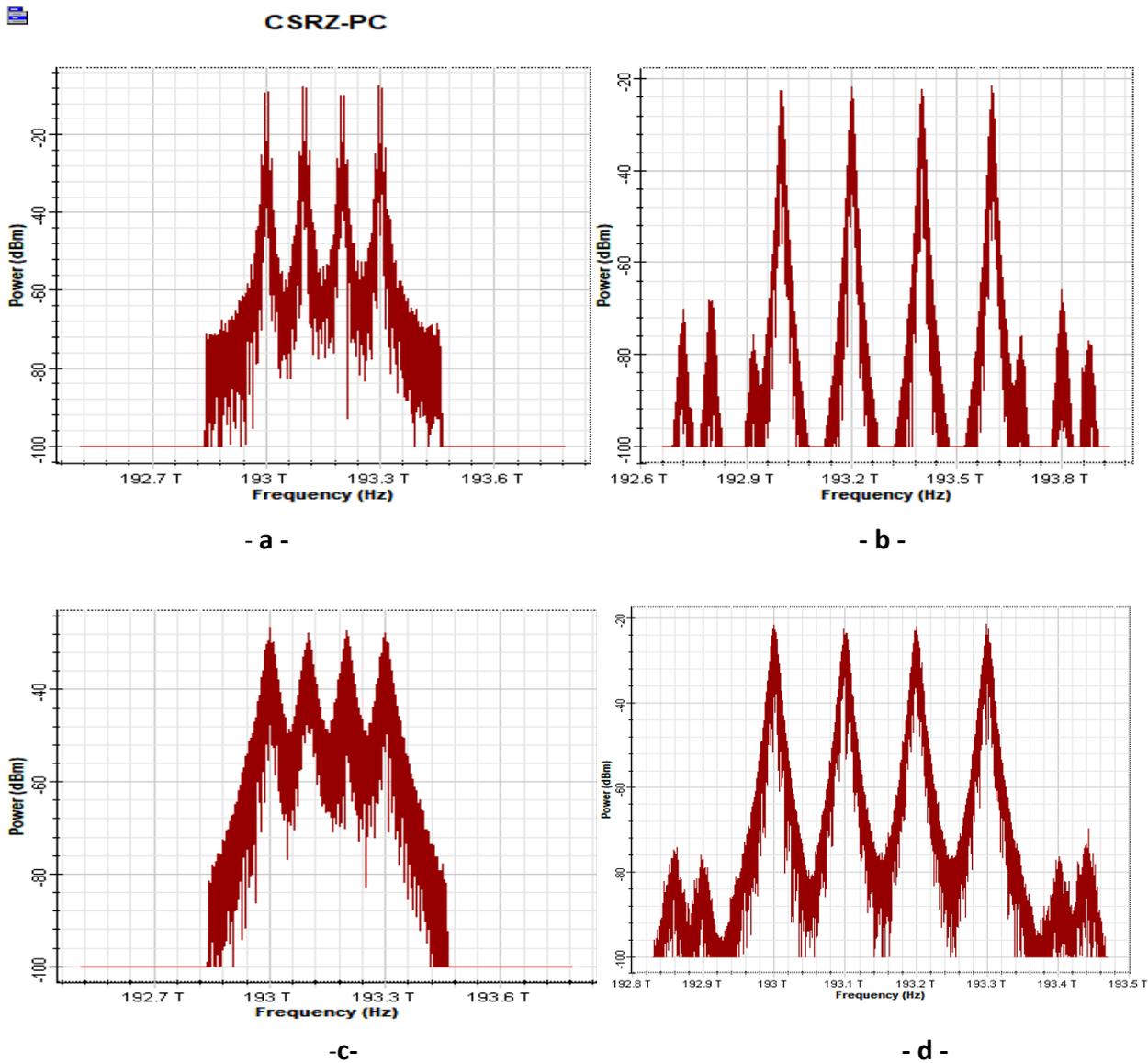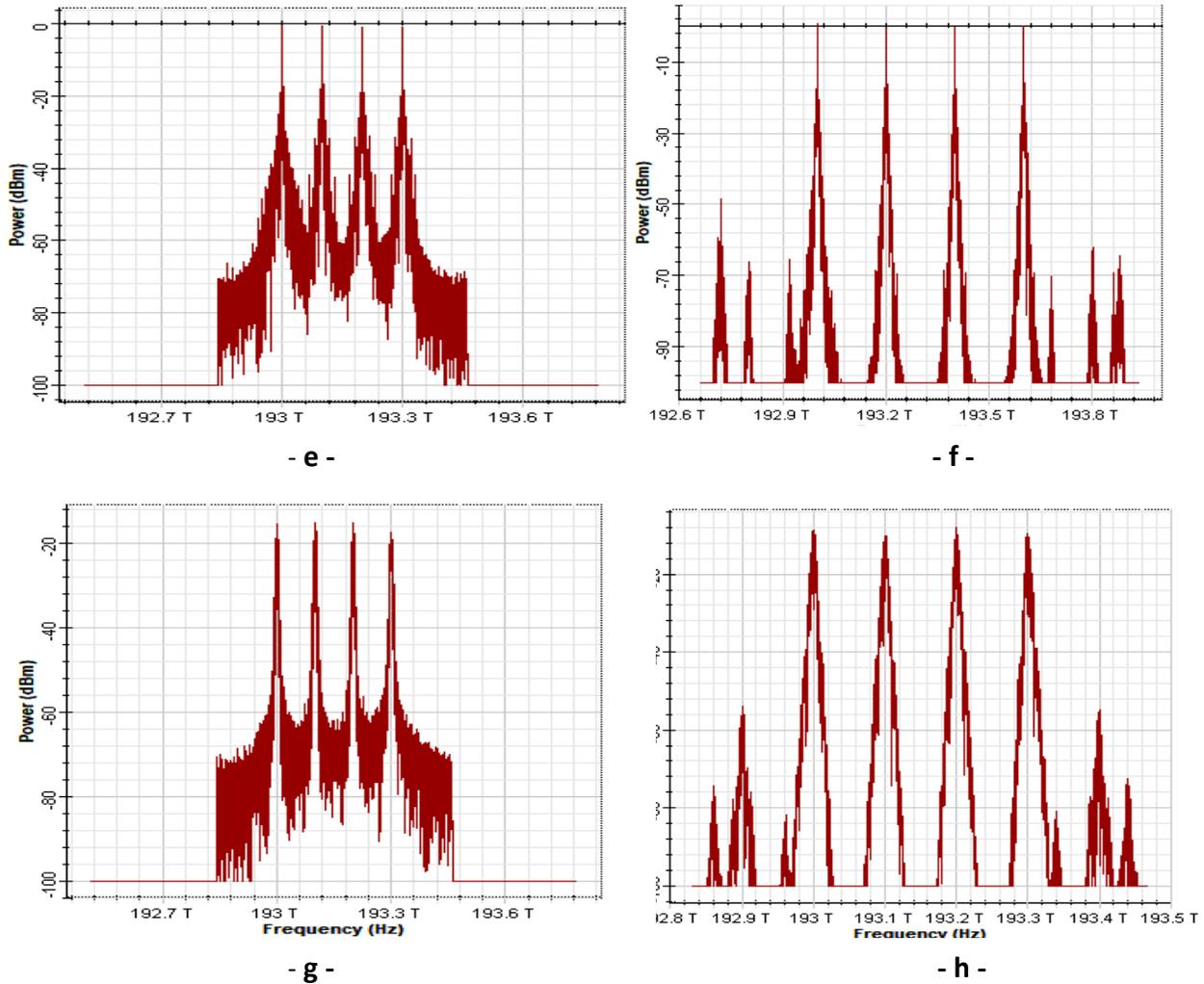
Figure 4.15: Optical spectrum analyzer depictions after optical fiber (a,c ,e ,g) represent mitigation of FWM in the proposed system and (b, d, f, h) represent traditional system without PC ,at 4-ch   respectively for (a,b)CSRZ (c,d) DBM-2 (e,f) NRZ (g,h) DBM-1 at 300km

4.3.4 The effect of input power

The effect of input power is also investigated and it is found that there is more FWM effects at higher launched power of the laser. Figure(4.16) explains the values of FWM power with &without PC with CSRZ modulation scheme versus different input powers in, at 300km and 100GHz channel spacing, and the eye diagrams of this system is shown in figure (4.17). From figures (4.16) and (4.17), we can observe that the proposed system provides high FWM suppression on the polarization combiner with the schemed modulation. For further clarity, the eye diagrams over the system have been observed with and without polarization. An eye diagram shows the signal quality aimed faster schemed signal transmission. The closure of eye diagram represents distortion in the signal due to

noise and inters-symbol- interference. In this way, an open eye diagram corresponds to the minimum signal distortion.
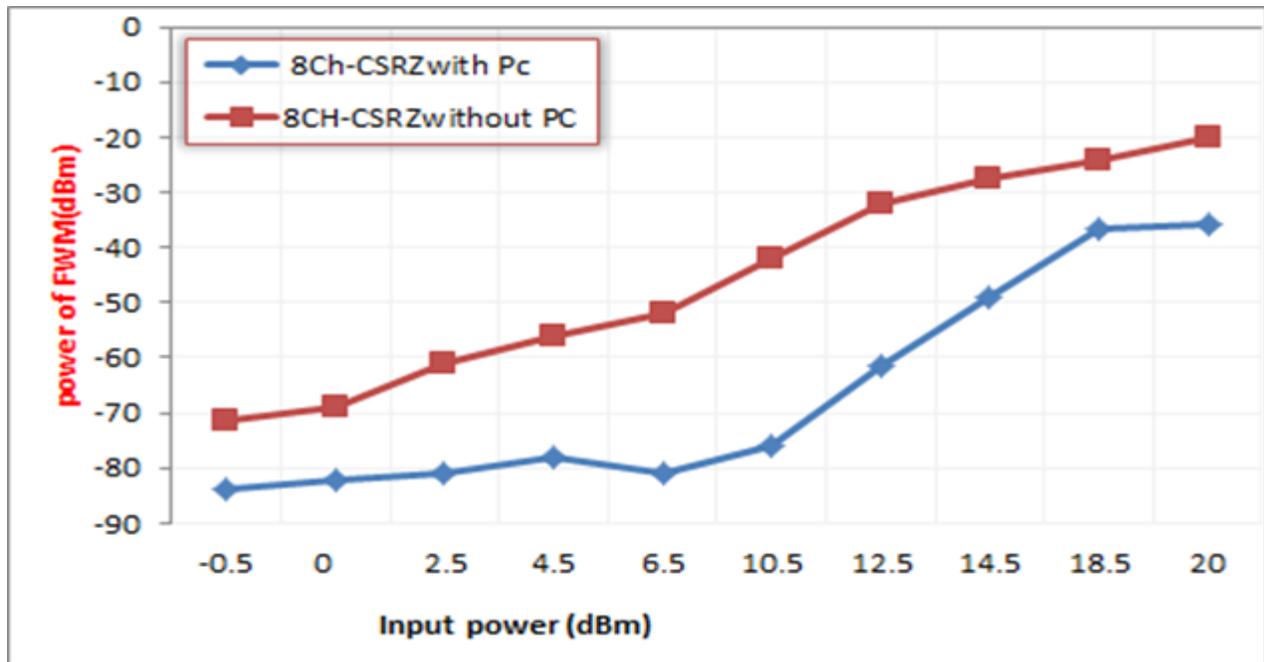
Figure 4.16: Power of FWM versus input power for 8×10 Gb/s system ,100 GHz channel spacing with and without PC with CSRZ modulation scheme at 300 km fiber length

CSRZ with PC   CSRZ without PC
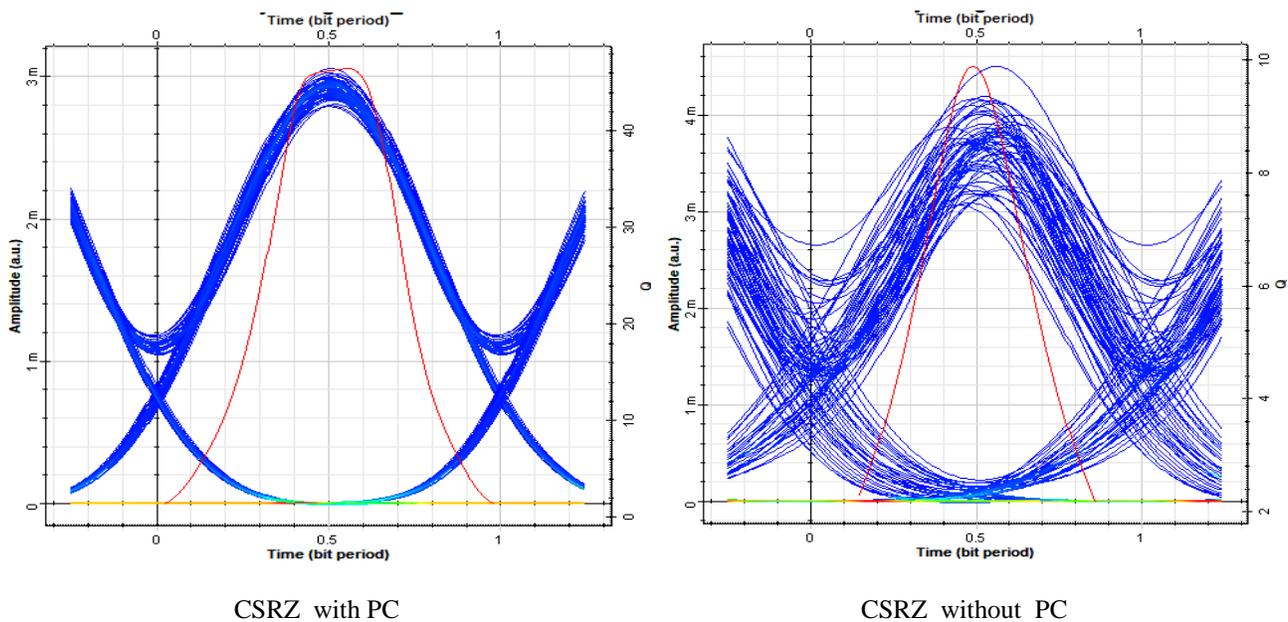
Figure 4.17: Eye diagrams of 8×10Gb/s, 100GHz channel spacing , 4[th] channel CSRZ modulation format with and without PC

4.4 Effect of the FWM on Bit-Error-Rate in the proposed system and traditional system

It illustrates the relationship between log BER and input power under the effect of different optical fiber lengths, as noted in figure (4.18). It can be seen that the increase in the fiber length leads to increase the log BER, where minimum log BER is found at 60km fiber length. The simulation done for an8×10 Gb/s, 50GHz channel spacing optical system CSRZ modulation scheme without PC at variable input power at the fourth channel.
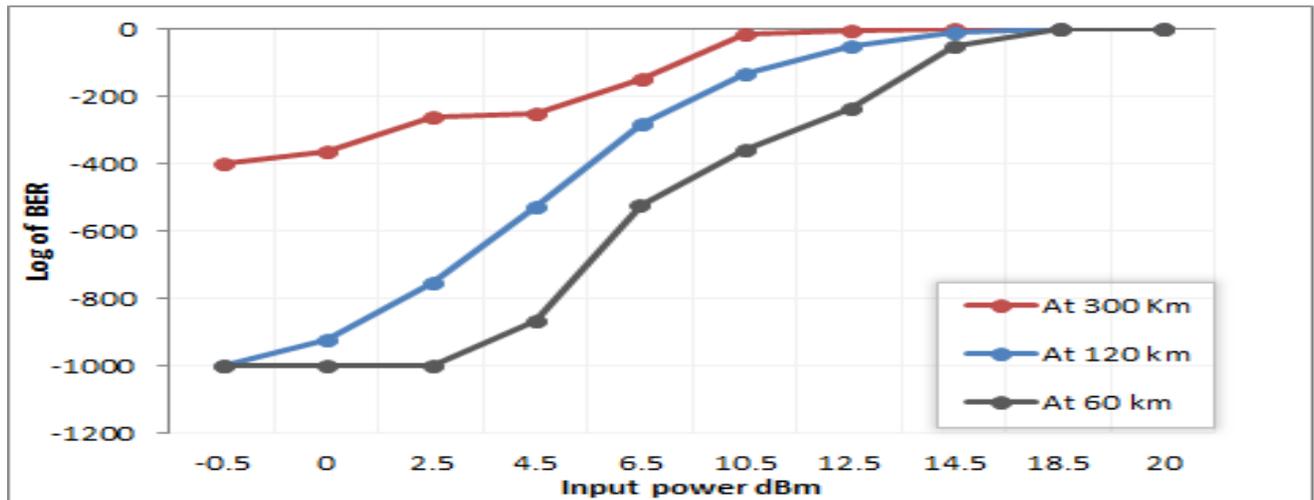
Figure 4.18: Log BER against input power for different fiber length in 8x10 Gb/s WDM system -CSRZ Mod. without PC at 50GHz channel spacing .
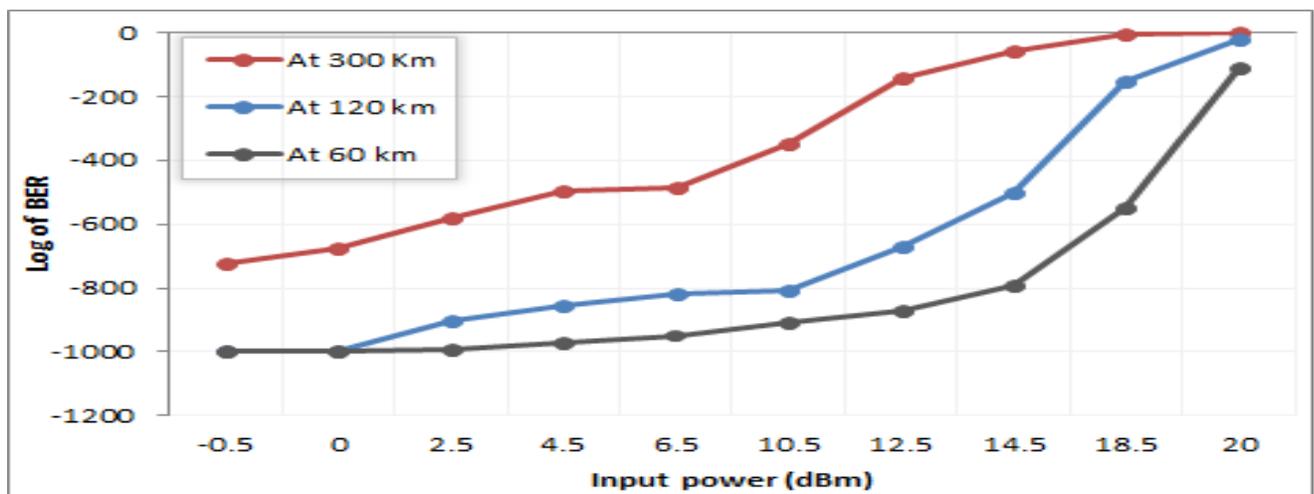
Figure 4.19: Log BER against input power for different fiber length in 8x10 Gb/s WDM system -CSRZ Mod. with PC at 50GHz channel spacing .

When we compare Figures (4.19) & (4.18), we notice that adding PC with modulation form improves the system performance and BER values.

Table (4-4) Represents a comparison of the BER of the 8x10Gbps WDM channels four modulation schemes with and without PC at 12.5dBm input power,100 channel spacing,300km fiber length.

Table (4-4) a comparison the BER in different modulation schemes

Modulation Format	Min Bit Error Rate	
	With PC	Without PC
CSRZ	0	2.14417e-23
NRZ	3.7234 e-18	0.01138
DBM-1	5.8369 e-45	0.0015618
DBM-2	0	0

Figure (4.20) shows the BER versus input power for 16 channels WDM system with date rate 10Gb/s, channel spacing 50 GHz for channel No.8 with and without PC with CSRZ modulation scheme at distance 300km.
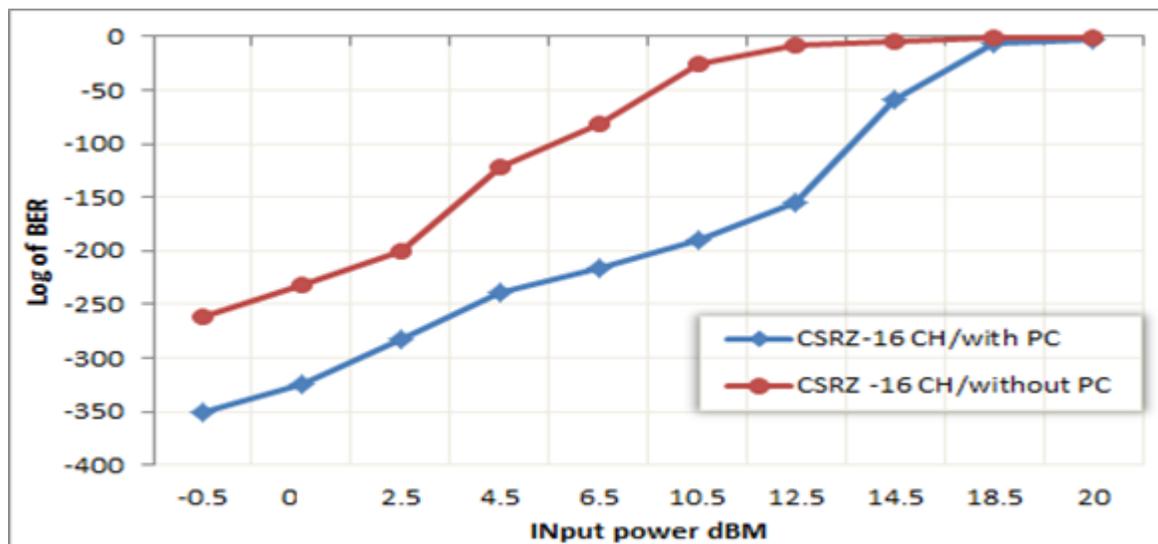
Figure 4.20: BER versus input power for channel No.8 , 16×10 Gb/s system , 50 GHz channel spacing with and without PC using CSRZ modulation format.

4.5 Effect of the FWM on different modulation form in the proposed system and traditional system

In this case, we study the effects of the type of modulation scheme in the proposed system (modulation form with PC) and the traditional system (modulation form without PC) to reduce the FWM. From figures (4.21) to (4.24) we can see the Q factor at 8×10 Gb/s system 4^{th} channel, 100 channel spacing with and without PC using different modulation formats. These figures indicate the following:

1- In CSRZ modulation –without PC when increasing transmission input power and fiber length to (420 km) lead to increase the FWM effect. So the proposed system at CSRZ modulation with PC suppresses the FWM effects and the quality factor is improved which is increased to read the max value of Q factor which is 35.635 in input power 10.5dBm.

2- In DBM-1 modulation – without PC when increasing transmission input power and fiber length to (420 km) that leads to increase the FWM effect. So, the proposed system at DBM-1 modulation with PC suppresses the FWM effects and the quality factor is improved which is increased to read the max value of Q factor which is 16.44 in input power 4.5dBm.

3- In NRZ modulation – without PC when increasing transmission input power and fiber length to (420 km) that leads to increase the FWM effect. So, the proposed system at NRZ modulation with PC suppresses FWM effects and the quality factor is improved which is increased to read the max value of Q factor which is 13.63 in input power 6.5dBm.

4- In DBM-2 modulation – without PC when increasing transmission input power and fiber length to (420 km) that leads to increase the FWM effect. So, the proposed system at DBM-2 modulation with PC suppresses the FWM effects and the quality factor is improved which is increased to read the max value of Q factor which is 47.91,but in this case, we can see its work in high input power where the high value of Q factor at input power is more than 18.5dBm.
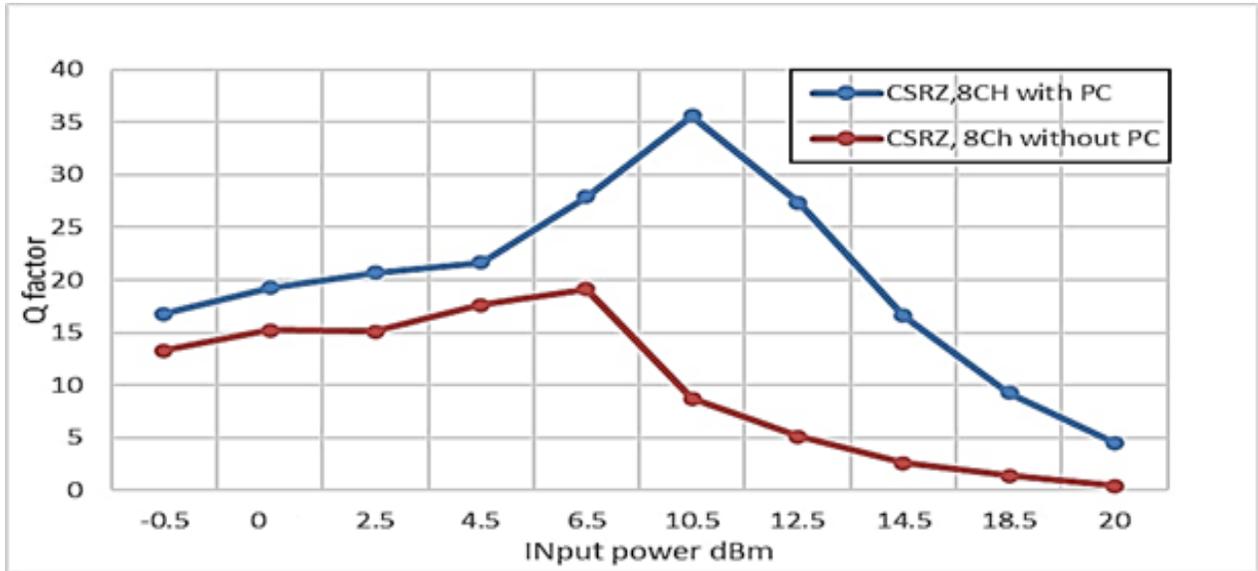
Figure 4.21: Q factor ver input power for 4[th] channel , 8×10 Gbps system ,100 GHz spacing of the channel with and without PC using CSRZ modulation format.420 km fiber length
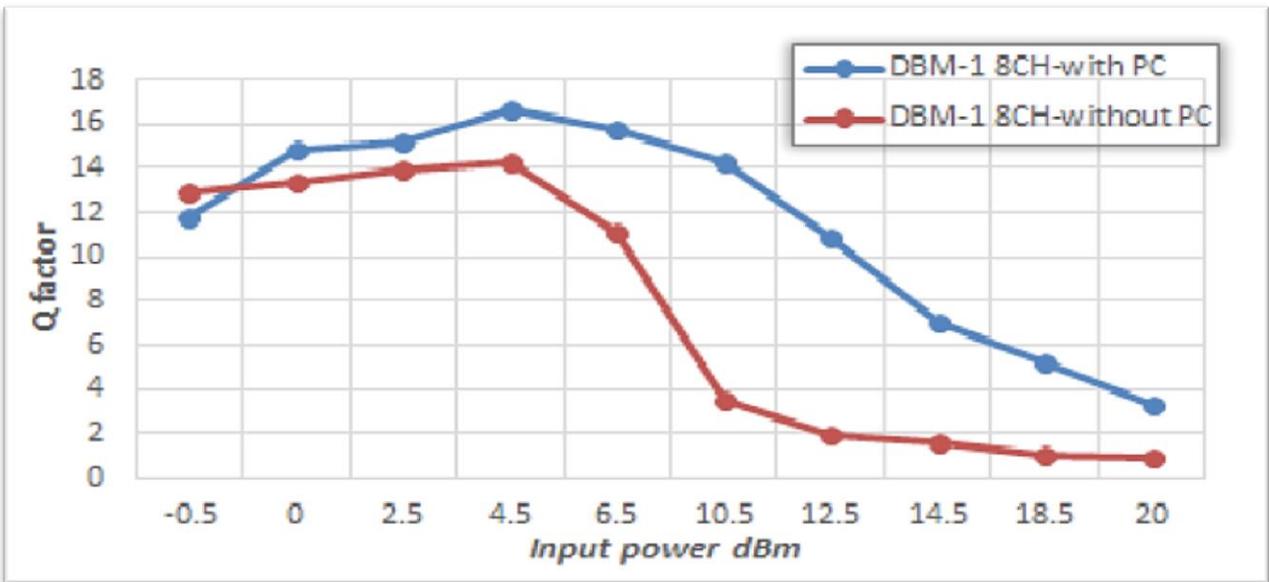
Figure 4.22: Q factor ver input power for 4[th] channel, 8×10 Gbps system ,100 GHz spacing of the channel with and without PC using DBM-1 modulation format.420 km fiber length
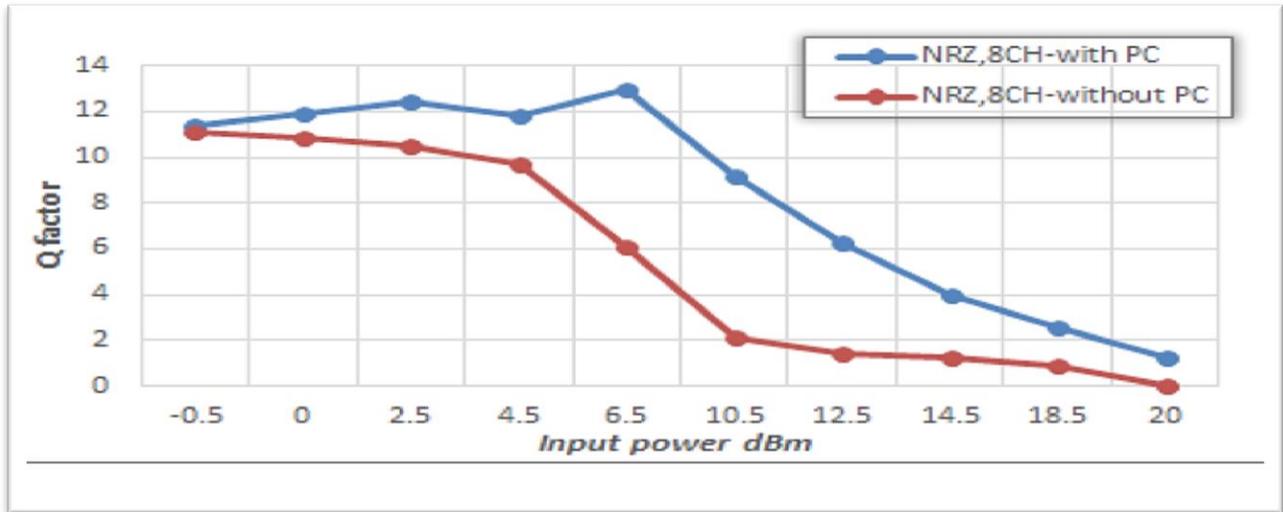
Figure 4.23: Q factor ver input power for 4th channel, 8×10 Gbps system ,100 GHz spacing of the channel with and without PC using NRZ modulation format.420 km fiber length
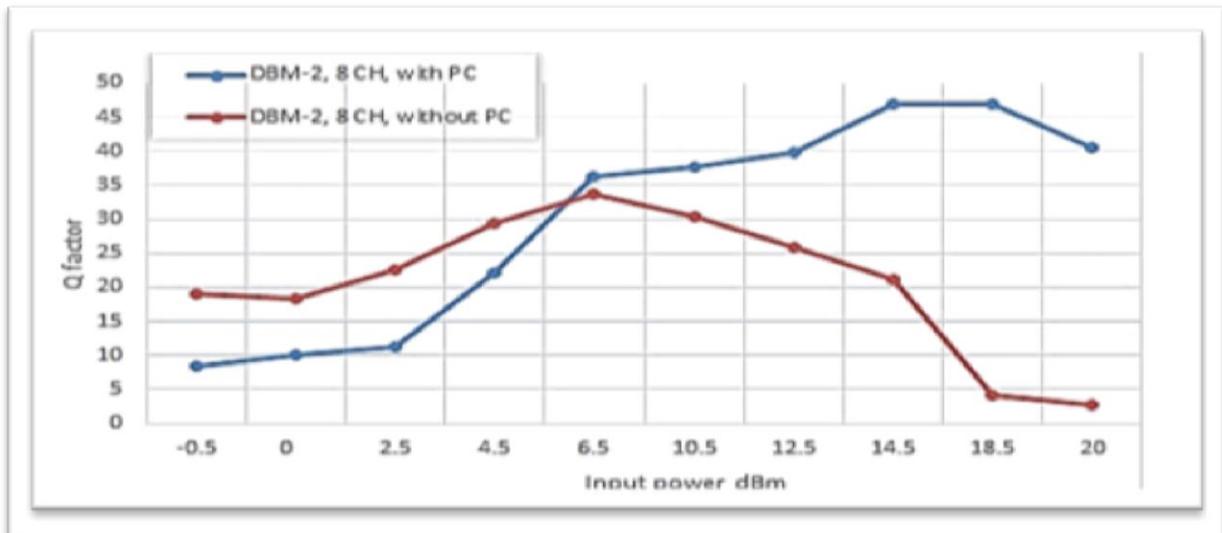
Figure 4.24: The Q factor ver input power for 4th channel, 8×10 Gbps system ,100 GHz spacing of the channel with and without PC using DBM-2 modulation format.420 km fiber length

Table (4-5) Represents a comparison of the Q-Factors of the 8x10Gbps WDM channels four schemes modulation with and without PC at 12.5dBm input power,100GHz channel spacing,420km fiber length.

Table (4-5) a comparison the Q-Factors in different modulation form

Modulation Format	Max Q-Factor	
	With PC	Without PC
CSRZ	27.635	5.135
NRZ	8.32	1.62
DBM-1	10.663	2.11
DBM-2	40.156	25.864

The spectrums of the eight channels system at 4[th] channel with CSRZ-without and with PC at 50GHz channel spacing, at 12.5dBm input power are shown in figure (4.25). from this figure when the channel spacing is decreased the effect of the FWM is increased. So adding PC decreases the effect of the FWM.
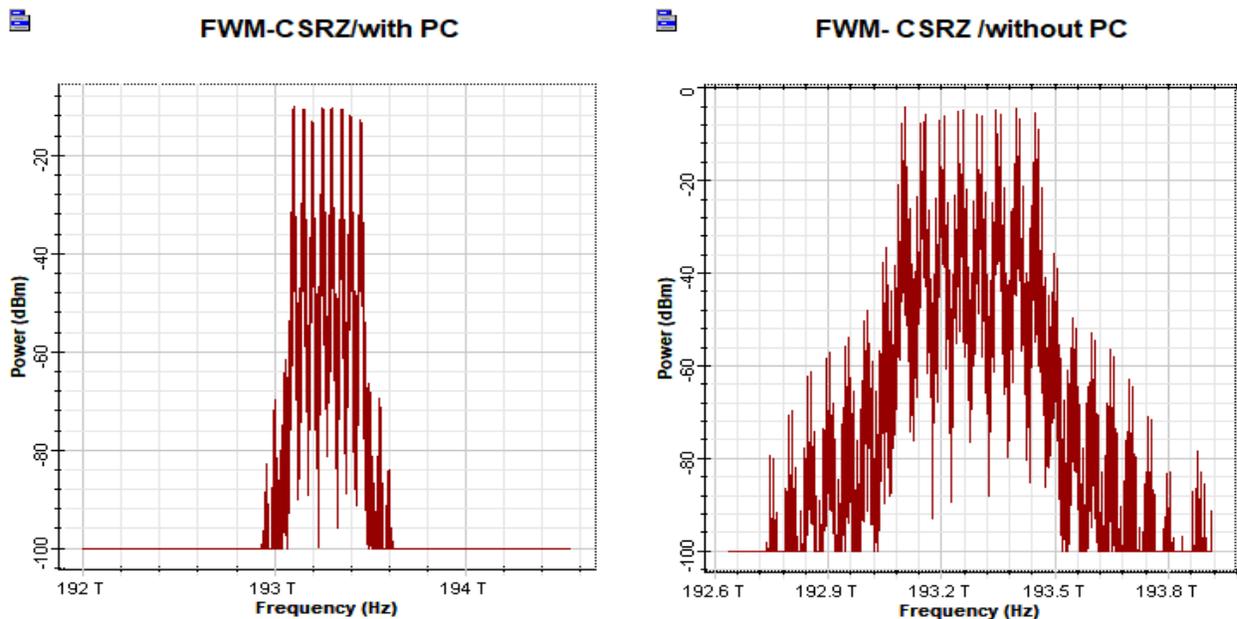
Figure 4.25: Spectrum of eight channel CSRZ modulation format with & without PC, 50GHz channel spacing after fiber.

The spectrum of the SMF output signals in figure (4.25) (CSRZ-PC) and (CSRZ-without PC) show the presence of some undesirable frequencies, which were produced due to the effect of FWM. It is observed that when the value of the channel spacing parameter decreases, the power levels of the FWM products is increased. From the above figures, when adding PC with modulation forms, the

effect of FWM suppress ion   is increased and   the FWM power is reduced about 54% in the proposed system.

Figure (4.26) shows a comparison of the performance of the Q-Factor versus input power for 8×10 Gb/s system with the use of PC-CSRZ modulation scheme and without it for different fiber lengths in 100GHz channel spacing.

Figure 4.26: A comparison of the Q-Factor versus input power for 8×10 Gb/s system with the use of PC and CSRZ modulation ,and without it for different fiber length at channel spacing 100GHz

Figure (4.27) represents two eye diagrams for 16 channels WDM system with date rate 10 Gb/s, channel spacing 50 GHz for channel No.8 with and without PC with CSRZ modulation scheme at distance 300km, with input power 12.5dBm, the obtained quality factor and a bit error rate are 25.5367and 2.48x10^{-161} respectively, to the CSRZ-with PC. For CSRZ-without PC, the obtained quality factor is 3.45177 and the bit error rate is 0.000704 . In this case, CSRZ with PC, the opening of the eye is increased. However, with the increase in the fiber length of SMF, the effects of FWM were reduced. In spite of decreasing channel spacing, the non-linearity is decreased and this depends inversely on the length of the optical fiber. The nonlinear effects in general can be reduced considerably with the modulation form with PC in WDM system.

The spectrum of the SMF is shown in figure (4.28) at CSRZ-with PC, with power of 12.5dBm, for the fiber length 300km and channel spacing 50GHz had maximum amplitudes of FWM power -60dBm and a minimum of -84dBm. The spectrum of the SMF is shown in figure 4.28 at CSRZ-without PC, with power of 12.5dBm, for the fiber length 300km had maximum amplitudes of FWM power -28dBm and a minimum of -52dBm, this showed the increased power of FWM products depended on the increase in fiber length and channel spacing.

CSRZ with PC   CSRZ without PC
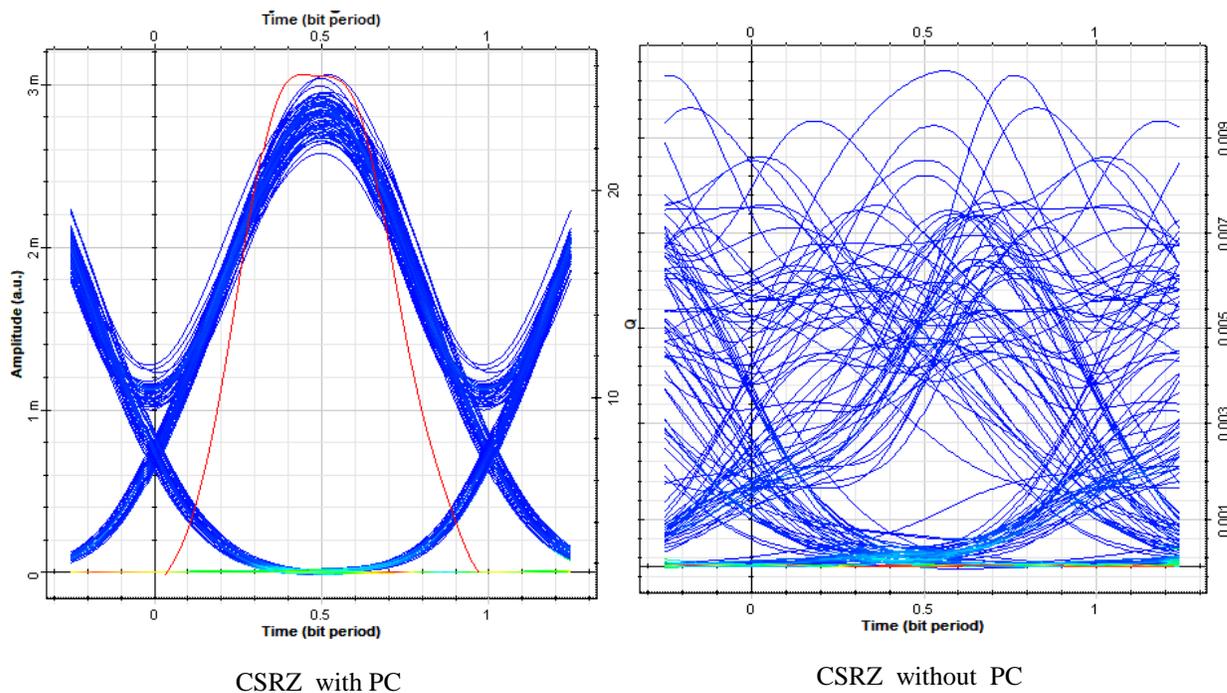
Figure 4.27: Eye diagrams of 16×10Gb/s, 50GHz channel spacing ,8[th] channel CSRZ modulation form without and with PC at 300km

Figure 4.28: The spectrums of 16×10Gb/s, 50GHz channel spacing , 300km,channel No.8CSRZ modulation format, without and with PC

The Oscilloscope Visualizer displays electrical signals for sixteen channels of this system without and with PC as shown in the figure(4.29). We can see the distortion in the electrical signal, where the nonlinear effect degrades the system performance at case CSRZ-without PC.

CSRZ without PC   CSRZ with PC
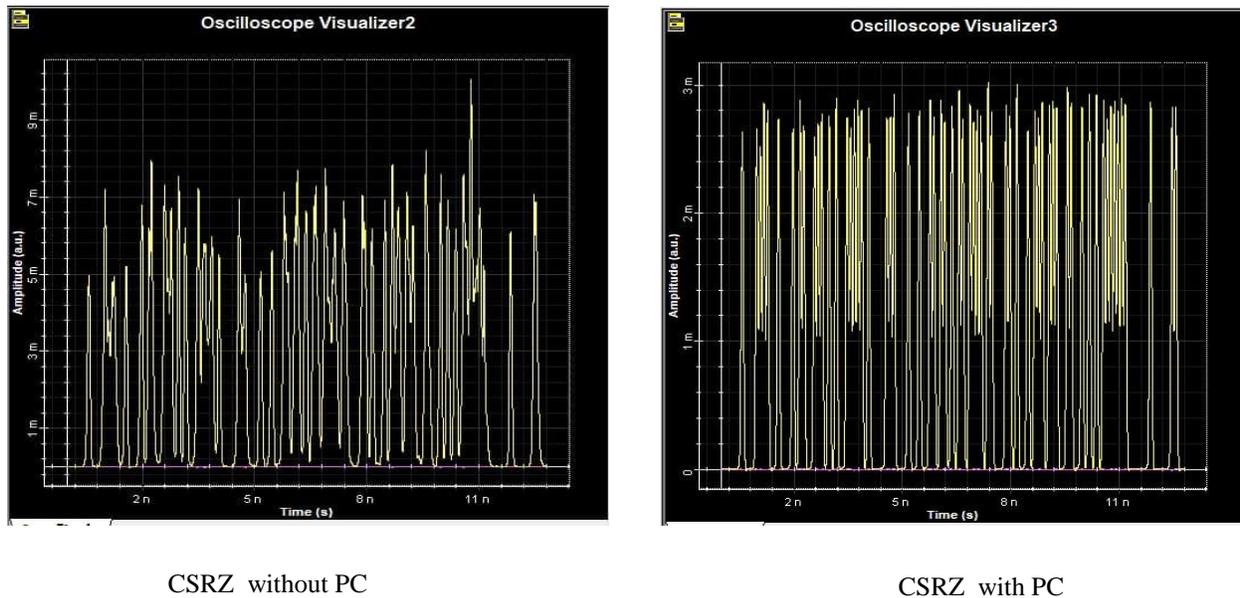
Figure 4-29: The Oscilloscope Visualizer of 16×10Gb/s, 50GHz channel spacing , 300km,channel No.8CSRZ modulation format, without and with PC

Figure (4.30) shows a comparison of the performance of the Q-Factor versus input power to16×10 Gb/s system with CSRZ modulation form with and without PC for different channel spacing at 420km fiber length. The non-linear effect increased when the channel spacing decreased, where the effect appears on the BER and Q factor values, so, the system performance improved through the addition of modulation form with Pc.
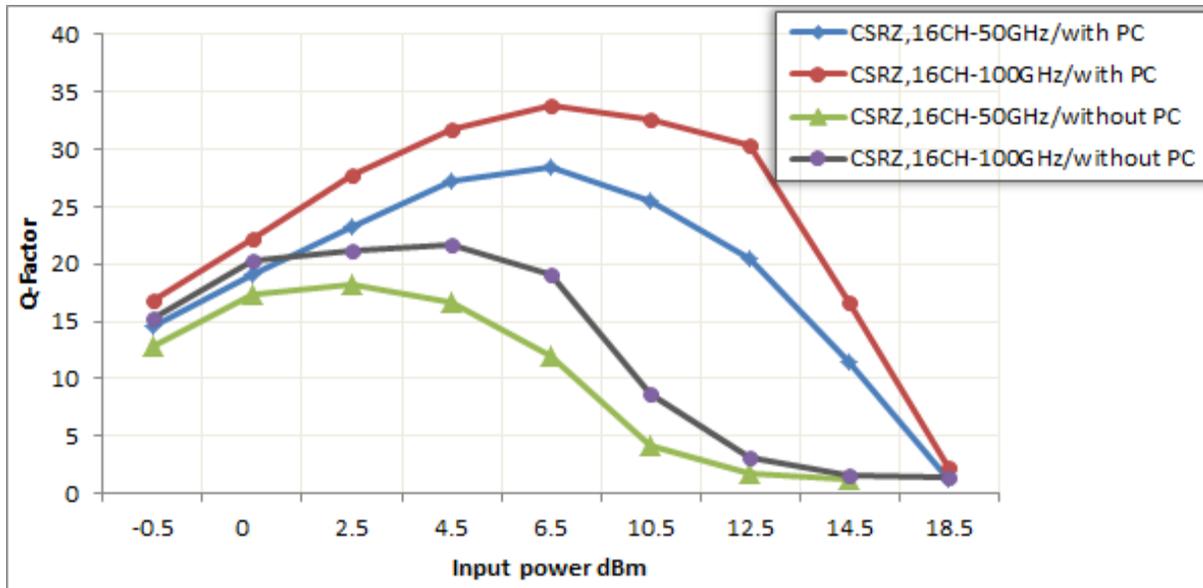
Figure 4.30: A comparison of the Q-Factor versus input power for 16×10 Gb/s system with the use of PC and CSRZ modulation ,and without it for different channel spacing.

Table (4-6) exhibites a comparison of the Q-Factor at the 16x10Gbps WDM channels CSRZ modulation schemed with and without PC at 12.5dBm input power, with different channel spacing,420km fiber length. We noticed the effect of channel spacing where the Q factor is inversely proportional with channel spacing.

Table (4-6) a comparison of the Q-Factors in CSRZ modulation from with and without PC.

Channel spacing	Q-Factor	
	With PC	Without PC
50GHz	20.4631	1.74902
100GHz	30.3758	3.13607

The effect of fiber length is shown in figure (4.31), where a comparison of the performance the Q-Factor versus input power for 16×10 Gb/s system with the use of CSRZ modulation scheme with and without PC at different fiber lengths, at 100GHz channel spacing.
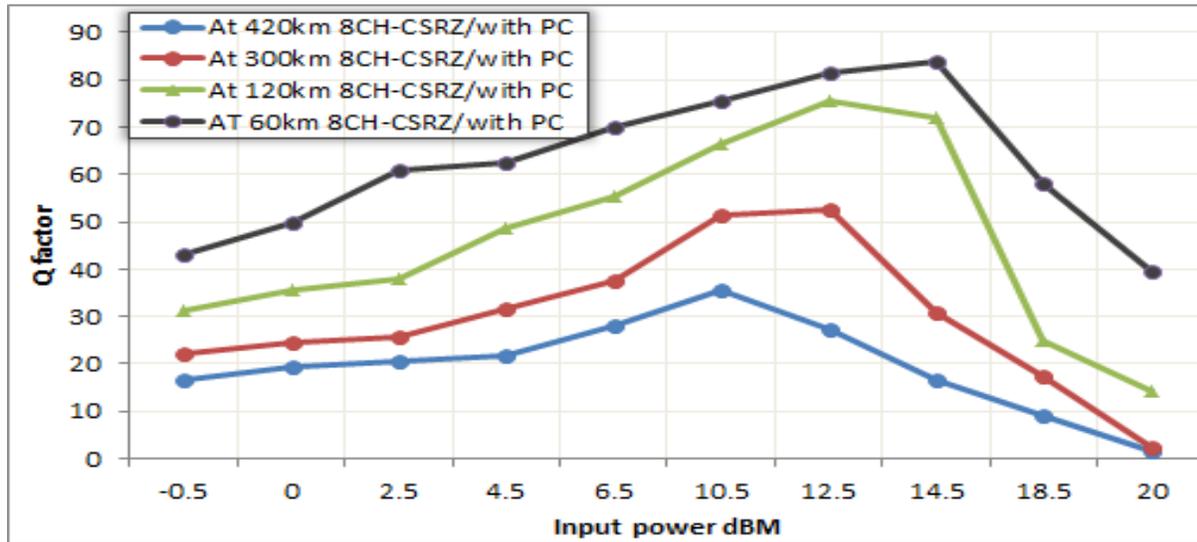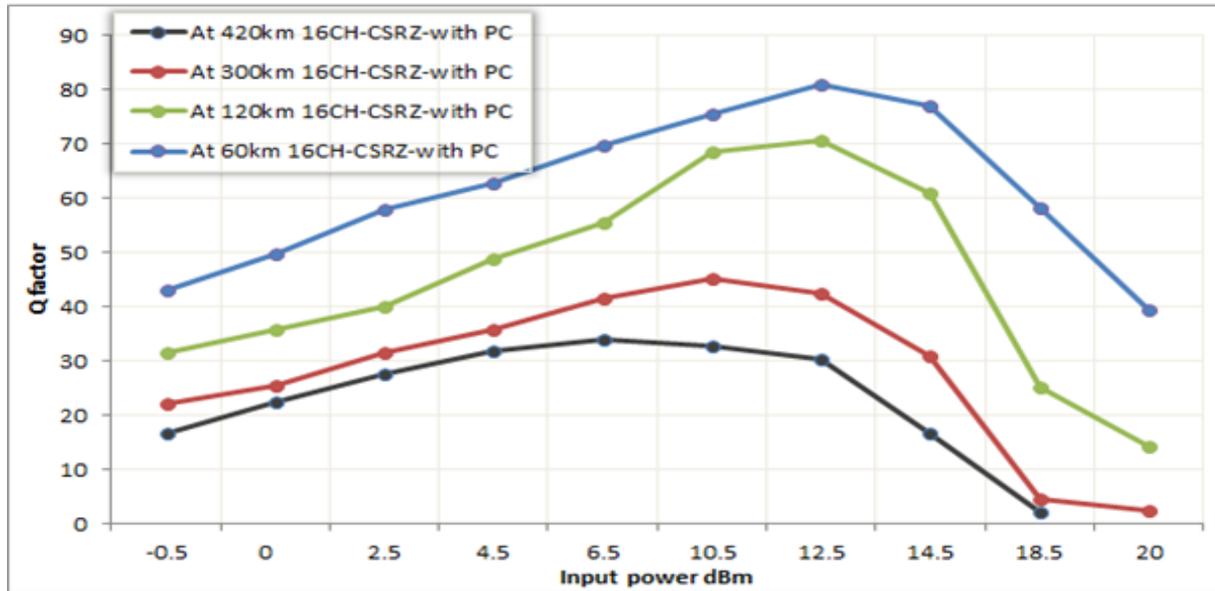
Figure 4.31: A comparison of the Q-Factor versus input power for 16×10 Gb/s system with the use of PC and CSRZ modulation ,and without it for different fiber length at channel spacing 100GHz

Table (4-7) Represents a comparison of the Q-Factor of the 16x10Gbps WDM channels CSRZ modulation schemed with and without PC at 12.5dBm input power, with different fiber lengths, at 100GHz channel spacing.

Table (4-7) a comparison the Q-Factors in CSRZ modulation scheme with and without PC.

Fiber Length	Q-Factor	
	With PC	**Without PC**
60Km	80.7854	20.5514
120Km	70.5152	12.7394
300Km	42.4706	4.31266
420Km	30.3758	3.13607
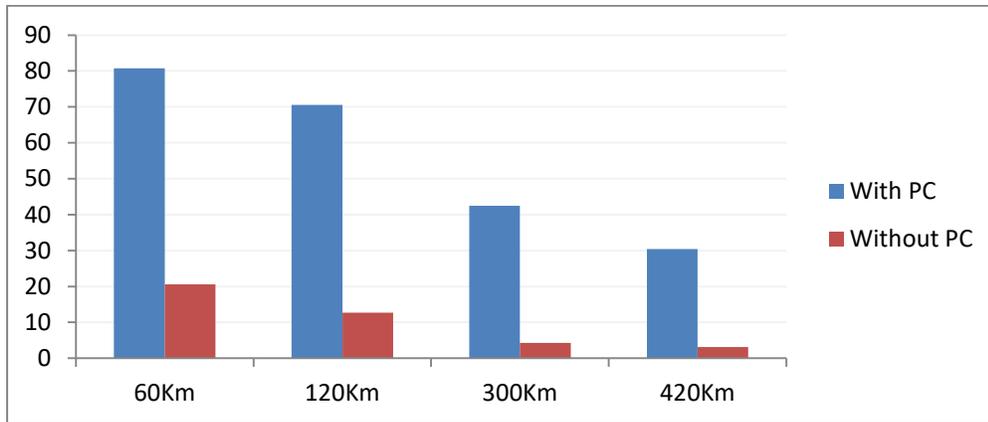
Figure 4.32:Statistical presentation for Q-factor under various different distance at CSRZ modulation form

Figure (4.32) shows eye diagrams for 16×10 Gb/s system with the use of CRSZ modulation scheme with PC and without it, 300Km fiber length at 200GHz channel spacing. where the FWM effect degrades the system performance and closure of eye diagram at case CSRZ-without PC

CSRZ with PC   CSRZ without PC
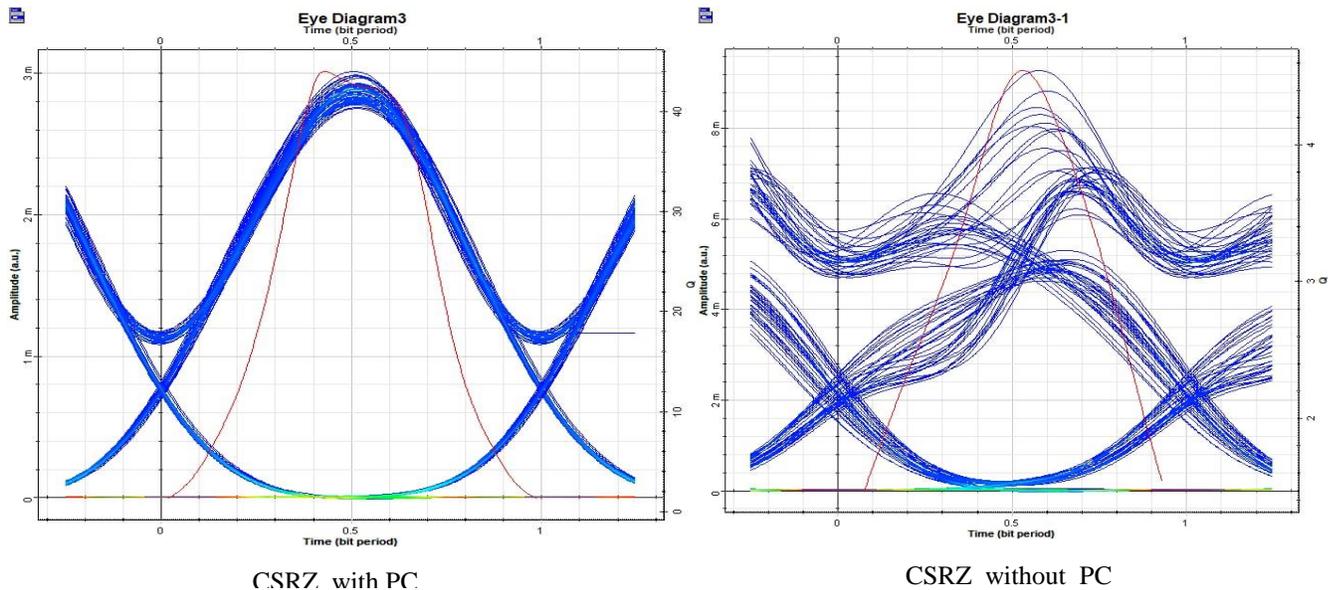
Figure 4.33: Eye diagrams of 16×10Gb/s, 200GHz channel spacing ,8[th] channel CSRZ modulation format, without and with PC at 300km

From figures (4.31) and (4.33) , we can observe that the proposed system provides a high quality factor on polarization combiner with modulation forms. For further clarity, the eye diagrams over the system has been observed with and without polarization. An eye diagram shows the signal quality amid schemed signal transmission. The closure of eye diagram represents distortion in the

signal due to noise and inters-symbol- interference. In this way, the opened eye diagram corresponds to minimum signal distortion.

The spectrums of the sixteen channels of this system without and with PC at 200GHz channel spacing, 12.5dBm input power are shown in figure (4.34).
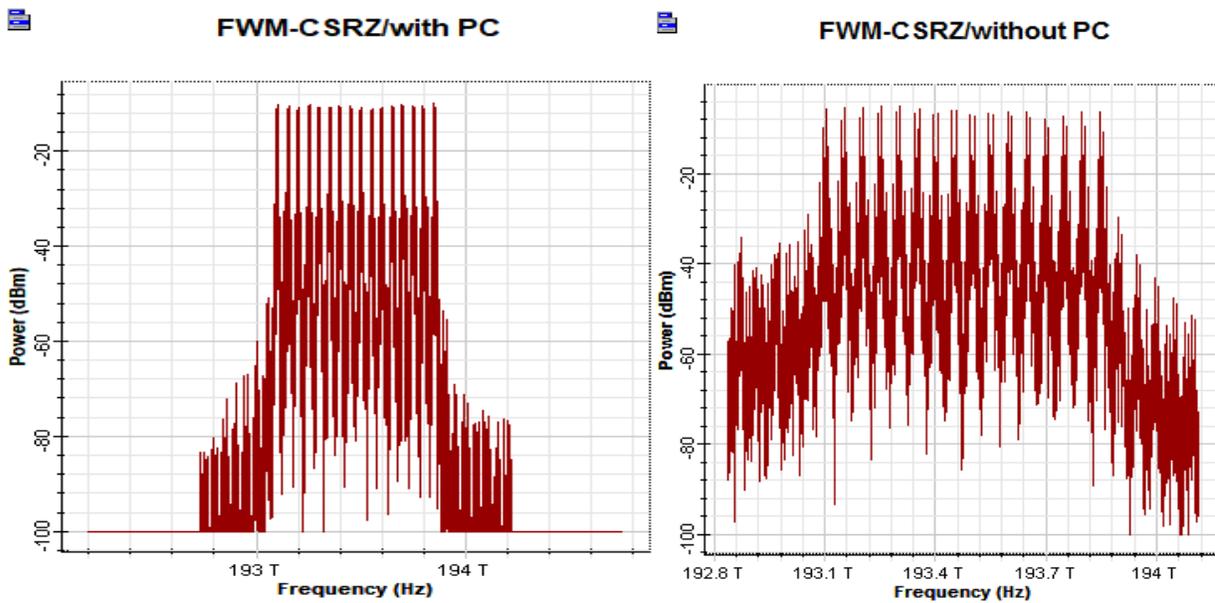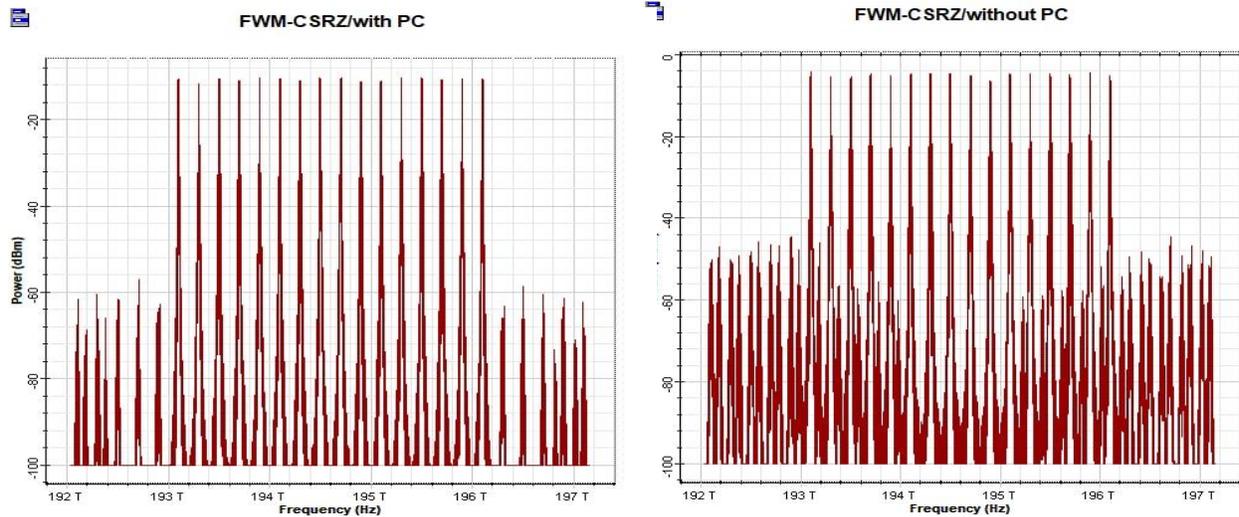

Figure 4.34: The spectrums of 16×10Gb/s, 200GHz channel spacing , 300km,channel No.8 CSRZ modulation format. without and with PC

From figures (4.12), (4.26) and (4.31) it has been noted that the Q factor is dependent on the number of channels and the fiber length, so that the BER is worsens as the fiber length is increased and that is due to the fiber nonlinearity (Kerr effects represented by XPM and FWM and the scattering effects represented by SRS). Whereas the effect of XPM is obvious. The number of Four Wave Mixing components is increased with the increase of the number of users. Thus, when the number of channels is increased from four to sixteen, the effect of FWM is becoming obvious. Then, the polarization combiner with modulation scheme has been applied to different optical system environments (different number of channels, different channel spacing and different fiber length). The improvement has been observed in each system logically .Table (4-8) listed the values of the Q-Factors at 10.5dBm input power for 4×10Gb/s, 8×10Gb/s and 16×10Gb/s optical systems for 200, 100 and 50 GHz spacing of channel for each system.

From figures (4.30), it has been noted that the Q factor is dependent on the number of channels and the channel spacing so that the Q factor is worsens as the channel spacing is decreased and that is due to the fiber nonlinearity (Kerr effects represented by FWM. In figures (4.11), (4.20) and (4.24)

by using the optical spectrum analyzer, the received Optical spectrums at 12.5dBm are measured after the SMF, so we can see that the number of generated spectrums (side lobes) are created due to the long haul transmission which is decreased with the proposed system. The received spectrum power of FWM with polarization combiner and modulation scheme is decreased. Therefore, from the results, we can see that PC-CSRZ modulation scheme can perform better at low input power than higher power to reduce the FWM.

 In figure (4.28) shows that FWM crosstalk power is increased when channel spacing is decreased. Our comprehensive model (CSRZ-with PC) gives much better effectiveness to reduce FWM power. A comprehensive model(NRZ with PC) gives better results in terms of reducing FWM crosstalk.

Table (4-8): values of the Q-Factors at 10.5dBm input power for 4×10Gb/s, 8×10Gb/s and 16×10 Gb/s optical system for different channel spacing.

Modulation format	Number of Channels																	
	4×10 Gb/s						8×10 Gb/s						16×10 Gb/s					
	Channel Spacing (GHz)						Channel Spacing (GHz)						Channel Spacing (GHz)					
	200		100		50		200		100		50		200		100		50	
	Q-factor		Q-factor		Q-factor		Q-factor		Q-factor		Q-factor		Q-factor		Q-factor		Q-factor	
	Without PC	With PC	Without PC	With PC	Without PC	With PC	Without PC	With PC	Without PC	With PC	Without PC	With PC	Without PC	With PC	Without PC	With PC	Without PC	With PC
CSRZ	16.523	63.584	23.1926	48.1169	11.38	47.947	14.4903	53.592	15.135	35.635	9.3483	25.699	12.7808	50.417	4.3266	30.3758	3.45177	20.4631
NRZ	4.63106	24.2547	3.07596	22.1641	3.01538	19.5736	9.72292	12.8075	3.7513	11.263	2.49246	10.0014	3.14359	11.37752	1.72417	9.18988	1.59612	7.92471

From the above results which are obtained from simulation, we can observe two effects that have been occurred to the optical transmission system that represent nonlinear effects. Linear effects occur by the transmitted optical fiber. These effects are increased when increasing the transmission length of the optical fiber in the optical communication system. Nonlinear effects occur to the performance of transmitted optical signal due to FWM crosstalk interference. This interference arises mainly due to the interaction between one wavelength and another one. Also, crosstalk always happens between adjacent channels because of the convergence between wavelengths. In addition, crosstalk is increased when spacing between channels is decreased .

Below is a comparison between the proposed system model modulation form with and without PC as shown in Table (4-9), at channel spacing100GHz and input power 12.5dBm.

Table.(4-9). Results summery of 8x10Gb/s system performance under with /without PC with modulation scheme

Length	Mod. forms	Q- Factor		Improving %	Bit Error Rate		P$_{FWM}$(dBm)		Mitigation Ratio %
		With PC	Without PC		With PC	Without PC	With PC	Without PC	
60Km	NRZ	45.2982	5.47939	87.9%	0	$6.27798*10^{-9}$	-72	-56	22.2%
	CSRZ	81.609	24.8446	69.6%	0	$6.7921*10^{-128}$	-64	-52	18.8%
	DBM-1	27.2281	20.078	26.3%	$2.21532*10^{-180}$	$2.7587*10^{-100}$	-56	-50.5	9.8%
120Km	NRZ	33.1967	4.54805	86.3%	0	$4.84681*10^{-6}$	-68	-56	17.6%
	CSRZ	75.5584	13.39	82.3%	0	$9.3858*10^{-44}$	-61.5	-42	31.7%
	DBM-1	20.9182	4.93084	76.4%	$1.50729*10^{-100}$	$2.66608*10^{-7}$	-62	-52.5	15.3%
300Km	NRZ	14.6276	1.87646	87.2%	$3.7234*10^{-18}$	0.01138	-66	-58	12.1%
	CSRZ	52.4821	5.31266	89.9%	0	$2.1441*10^{-23}$	-59	-42	28.8%
	DBM-1	15.6652	3.16896	79.8%	$5.8369*10^{-45}$	0.0015618	-66.5	-54.5	18.0%

From table (4-9), we can see that the proposed system CSRZ with PC is the best performance to improve the system and mitigate FWM.

A comparison between the proposed system method polarization combiner with modulation form as shown in Table (4-10), for the 16x10Gb/s at 100GHz, and 12.5dBm input power.

Table.4-10 Results summery of 16x10Gb/s system performance under with /without PC with modulation scheme

Length	Mod. forms	Q- Factor		Improving %	Bit Error Rate		P_{FWM}(dBm)		Mitigation Ratio %
		With PC	Without PC		With PC	Without PC	With PC	Without PC	
60Km	NRZ	12.4664	7.65822	38.6%	0	0	-66	-50	24.2%
	CSRZ	80.7854	20.5514	74.6%	0	0	-60	-43	28.3%
	DBM-1	21.6077	16.3511	24.3%	$7.5611*10^{-107}$	$1.337*10^{-20}$	-60.5	-44	27.3%
120Km	NRZ	11.9036	5.43593	54.3%	$1.855*10^{-35}$	$1.367*10^{-19}$	--60	-48	20.0%
	CSRZ	70.5152	12.7394	81.9%	0	$5.08*10^{-145}$	-60.5	-38	37.2%
	DBM-1	19.9956	9.22156	53.9%	$2.24*10^{--96}$	$2.24*10^{-27}$	-60	-43.5	27.5%
300Km	NRZ	10.2851	1.78794	82.6%	$1.18*10^{-16}$	0.01778	-66	-40	39.4%
	CSRZ	42.4706	4.31266	89.8%	0	$4.8*10^{-6}$	-58	-30	48.3%
	DBM-1	14.512	2.72496	81.2%	$2.94*10^{-19}$	0.0126	-59.5	-42.5	28.6%

The above results show an enhancement in the performance of the proposed system with different modulation schemes at different lengths which lead to mitigate the FWM. As a result, this leads to minimize the probability of lost the transmitted signal and enhance the optical communication system in overall. A comparison is done between the proposed systems with the other methods which is utilized to enhance the performance of transmitted optical signal.

Table 4-11 represents a comparison between the proposed optical system design the modulation scheme with polarizer combiner

Table 4-11comparison between proposed different modulation scheme with polarizer combiner and related previous works

Author	Input power of transmitter	Number of channel	Modulation form	Fiber Length	Spacing between channel	Date rate	FWM power	Q factor	Improving
[28] at 2014	2dBm	4	NRZ	70km	100GHZ	10 GB/S	-70dBm	13.24	8.5%
[29] at 2015	0dBm	8	RZ	100km	200 GHZ	10 GB/S	-80dBm	-	16.25%
[31] at 2017	0dBm	8	NRZ	50km	100 GHZ	10 GB/S	-78.4dBm	-	22.2%
[33] at 2019	0 dBm	16	NRZ	100km	100 GHZ	10 GB/S	-66dBm	-	15.2%
[37] at 2021	0dBm	16	NRZ	50km	100 GHZ	10 GB/S	-75dBm	11.55	9.33%
This work	2dBm	4	NRZ	300km	100GHZ	10 GB/S	-67dBm	32.3	22.3%
	0dBm	8	NRZ	120 km	100 GHZ	10 GB/S	-85dBm	13.17	24.7%
	0dBm	16	NRZ	60km	100 GHZ	10 GB/S	-76dBm	13.05	21.05%

Figure 4.35:Statistical presentation for improving various different works at NRZ modulation form

5.1 Conclusions:

   In this work, the impact of using polarization combiners on system performance is examined. Different modulation schemes and transmission spans are investigated with the aim of reducing the FWM effect.

The proposed approach has been tested under various guard spaced at the same input conditions. The results show that the proposed method revealed better performance than other methods for the same input parameters.   From the present work, the following conclusions can be drawn: **1.** For single channel (60 Km), 10Gb/s bit rate, it has been found that the performance of the system in case of CSRZ with PC is the best among the other types of modulation formats (NRZ-DBM-1 and DBM-2).   For   example the Q factor of CSRZ at 4.5dBm is 161.038 while in the case of NRZ, DBM-1, DBM-2, the Q –factors were   150.83, 25.9024 and 109.648, respectively.

2. By using the polarization combiner technique with the different modulation scheme, the rendering of the optical system generally is improved and for different numbers of channels. The performance of the optical system for four different modulation formats is the best in case of CSRZ when compared to others . For example, for 8×10 Gb/s, 300Km optical fiber system at input power 12.5dBm , FWM power reduced to -59dbm (improved by 28.8%). The value of Q-factor at 12.5dBm input power CSRZ was 52.48, so the improvement in the Q-factor in case CSRZ was 89.9%.

3. The performance of the multichannel optical systems in the case of CSRZ modulation format is better than NRZ- DBM-1 and DBM-2. For example, for 8×10 Gb/s system, 100GHz channel spacing and for 4th channel. It has been found that the log of BER was --245 for CSRZ while -25.315 and -98 for NRZ and DBM-2 respectively at 12.5dBm.

4. Design and simulate 4×10Gb/s, 8×10Gb/s and 16×10Gb/s, 300 Km of length each with 50, 100 and 200 GHz channel spacing with CSRZ modulation format. It is noted that there are

improvements in all these cases, but these improvements vary from one case to another. For example, for sixteen channels (channel No.8) , 200GHz channel spacing the Q factor 50.1417 improved by 74.5%, for 100 GHz channel pacing the Q factor 30.3758 improved by 85.75%, for 50GHz channel spacing the Q factor 20.463 improved by 83.13% . With 10.5dBm input power, 420km fiber length the value of the Q-factor for each case is listed in table (4-8).

5.2 Suggestions for Future Work:

The following points can be suggested as a future work:

1. Investigating and reducing the Fiber Nonlinearities based on OFDM-WDM System

2.Studying the nonlinear optical signal under the effect of adaptive pulse shaping approach.

3. Investigating the fiber nonlinearities based on Digital signal processing approach.

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الخلاصـــــــة

اصبح نظام الاتصالات البصرية جزءاً رئيسياً من البنية التحتية العالمية في السنوات الماضية بسبب فوائده العديدة. ان الهدف الرئيسي من الاتصال البصري هو زيادة الكفاءة الطيفية واستخدام الحد الأدنى من عرض النطاق الترددي عبر مسافات طويلة مع أدنى حد ممكن من الأخطاء أثناء ارسال الإشارات. في اتصالات الألياف الضوئية، تؤدي التأثيرات غير الخطية الى تدهور أداء نظام الاتصال. ويرجع ذلك الى الحالة التي بدأت فيها التأثيرات المدمرة للتأثيرات الغير الخطية في الظهور في القوى العالية في مضاعفة تقسيم الطول الموجي الكثيف، تعد خلط اربع موجات (FWM) هي مشكلة التدهور الرئيسية حيث تصبح شديدة عند تباعد الترددات المنخفضة للقنوات وعند الحد الادنى من قيم توسيع النبض. يمكن زيادة الكفاءة الطيفية باستخدام مضاعفة الاستقطاب مع تنسيقات التعديل المختلفة. يمكن زيادة السعة باستخدام استقطاب متعامد بين قنوات WDM المجاورة.

في العمل الحالي، تم اقتراح تقنية جديدة لقمع تأثير خلط اربع موجات (FWM) بناء على معايير موحد الاستقطاب مع تقنية مخطط التعديل. يتم إجراء مقارنة بين وضع مُجمع الاستقطاب في حالتين مختلفتين ولوحظ أن وضع PC مع تنسيقات تعديل مختلفة يؤدي اداءً جيداً لقمع FWM مع سهولة الصيانة. التركيز الرئيسي لهذه الرسالة هو التحقيق في ظهور FWM في نظام WDM على مسافات مختلفة ودراسة سلوك النظام لقنوات WDM المختلفة. يتم تقييم أداء النظام المقترح من حيث عامل الجودة (Q)،الحد الادنى لمعدلات الخطأ في البتات (BER) والقدرة (FWM Power) واظهرت النتائج أن الحد الأقصى لخلط اربعه موجات (FWM) يظهر لتباعد قنوات WDM (50، 100 و 200) جيجا هرتز وتقل FWM مع زيادة التباعد بين القنوات.

تم إجراء تحليل أداء السعة العالية لـ(40، 80، 160) جيجا بت/ ثانية WDM من خلال دمج تنسيقات تعديل مختلفة (NRZ& DBM-2 , DBM-1 CSRZ) مع PC. تكشف النتائج أن التقنية المقترحة قادرة على تقليل FWM Crosstalk وتحسين أداء النظام. على سبيل المثال في نظام 8×10 كيكابت/ثانية، عند طاقة إدخال (12.5ديسيبل) وطول الألياف 300كم يتم تقليل طاقة FWM إلى 12.1٪، 18٪ و 28.8٪ في (NRZ ، DBM-1 & CSRZ) على التوالي عند مقارنتها بنظام WDM التقليدي. كما حقق النظام المقترح تحسناً في عامل الجودة (Q) بنسبة 87.2٪، 79.8٪ و 89.9٪ لنفس تسلسل التعديل. تتوافق النتائج مع متانة تقنية الاستقطاب مع تعديل المخطط لتقليل FWM Crosstalk. تمت مقارنة العمل الحالي بالتقنيات السابقة، وأثبتت النتائج تفوق التقنية المقترحة على السابقة. يستخدم نظام Optisystem الاصدار (17) للتحقق من النتائج المختلفة وجميع التحليلات الرسومية والمخططات الاخرى.

وزارة التعليم العالي والبحث العلمي

جامعة بابـل / كلية الهندسة

قسم الهندسة الكهربائية

طريقة جديدة لتقليل التأثيرات اللاخطية في انظمة نقل الالياف الضوئية عالية السرعة مع معدل بيانات مرتفع

من قبل

نضال عبد محمد خضر

بكالوريوس علوم في الهندسة الكهربائية

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