PERFORMANCE ENHANCEMENT OF WAVELENGTH DIVISION PASSIVE OPTICAL NETWORKS

A Thesis Submitted in Fulfillment of the Requirement for the Award of the Degree of

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DECLARATION

*I, **Guneet kaur** hereby declare that the work presented in this thesis entitled "**Performance enhancement of wavelength division passive optical networks** "in fulfillment of the requirement for the award of degree of Master of Engineering (ECE) submitted at Electronics and Communication Engineering Department, Thapar Institute of Engineering & Technology (Deemed to be university), Patiala is an authentic record of work carried out under supervision of **Dr. Sanjay Sharma** (Professor, Electronics and Communication Engineering, TIET, Patiala) from January 2018 to June 2018. The matter presented in this has not been submitted either in part or full to any other university or institute for the award of any other degree.*

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CERTIFICATE

It is certified that the work contained in the thesis entitled ***"Performance enhancement of wavelength division passive optical networks"*** by **Guneet kaur**, 801661006 has been carried out under my supervision and that this work has not been submitted elsewhere for any other degree.

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ABSTRACT

Wavelength division multiplexed passive optical is promising technique to achieve a high data rate and large no. of user. The notable advantages of WDM PON is the combination of reliability, cheap in cost, accessible bandwidth, high security, large optical reach and it can support large number of ONU. There are multiple approaches to achieve colorless WDM PON using different transmission techniques. In this research work, we accentuated on the design of 4 channels WDM PON system incorporating different modulation formats for both uplink and downlink stages by using 10 Gbps and transmitter diversity. A 40-km-long colorless symmetrical WDM-PON with differential quadrature phase shift keying (DQPSK) in downstream and non return to zero (NRZ) modulation format in upstream to solve crosstalk issues. Also comparison has been made with the system using DPSK for downstream and NRZ for upstream in WDM PON system.

Further, WDM-PON at ultra dense channel spacing is investigated incorporating polarization interleaving. Polarization diversity is included in the system to reduce the polarization interference among WDM channels. This research article investigates the performance of 4 x 20 Gb/s WDM-PON system incorporating polarization interleaving technique at 25 GHz channel spacing and wavelength reuse is also done in the system over 40 km. Moreover, comparison of system with and without polarization diversity has also been done. It is evident that different states of polarizations increase the performance of the system as compared to single SOP.

Finally, a cost effective and easy maintenance based dispersion compensation technique is proposed in ONU of the wavelength reused WDM-PON. Moreover, in order to suppress intra-channel crosstalk DQPSK is employed for downstream and for inter-channel crosstalk suppression, polarization interleaving is used in the system. Furthermore, for the investigation of proposed system in terms of dispersion reduction, three different scenarios are considered such that system with only DCF, linearly chirped FBG and joint module of DCF+FBG. System has total 4 channels and each has bit rate of 20 Gb/s with 25 GHz channel spacings. It is observed that joint module of DCF+FBG has maximum ability to compensate dispersion and linearly chirped FBG has least performance. Proposed joint technique for pulse width reduction in ONU is cost effective, highly efficient to combat with pulse width reduction issues and also needs very less maintenance.

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LIST OF GLOSSARY

GPON	*Gigabit Passive Optical Network*
SMF	*Single Mode Fiber*
ONU	*Optical Network Unit*
FTTH	*Fiber To The Home*
PUS	*Pseudo Random User Scheme*
MZM	*Mach-Zehnder Modulator*
OLT	*Optical Line Terminal*
ODN	*Optical Distribution Network*
FTTC	*Fiber To The Curb*
CO	*Central Office*
TDM	*Time Division Multiplexing*
WDM	*Wavelength Division Multiplexing*
RN	*Remote Node*
NRZ	*Non-Return to Zero*
OCDMA	*Orthogonal Frequency Division Multiplexing*
SAC	*Spectral Amplitude Coding*
DDW	*Diagonal Double Weight*
MD	*Multi-Diagonal*
IM	*Intensity Modulator*
PD	*Photo-Detector*
LPF	*Low Pass Filter*

BER	*Bit Error Rate*
OFC	*Optical Fiber Communication*
BPON	*Broadband Passive Optical Network*
APON	*ATM Passive Optical Network*
EPON	*Ethernet Passive Optical Network*
SNR	*Signal to Noise Ratio*

CHAPTER 1

INTRODUCTION

1.1 OPTICAL NETWORKS

Optical communication is a type of communication which used a light signal for data transmission over large distance with multi terabit application. It takes low losses (0.2dB/km) and provides wide bandwidth. Another key advantage of OFC is that it is immune to electromagnetic interference or atmospheric interference. Because of its no. of benefits over other communication network, OFC is far ahead of other communication networks [1]. Capacity enhancement or potential to pack more than one channel to optical fiber is referred to (WDM) [2]. A PON is a network which is widely used in optical communication, gives a large series of broadband services to clients from starting to end fiber optic access. These networks give a permission to eliminate every single dynamic segment between the server host and customer presenting optical passive devices to manage the large signals of internet. Prominent technology which is used in these networks is PON. It is a point-to-multipoint arrangement. The fundamental design architecture of PON divided into three main units: An Optical network unit of terminal and Optical Network Terminal (OLTs). It works on single fiber optic cable for multiple channels [3]. Different network works on diverse multiplexing techniques such as multiplexing of diverse wavelengths (WDM), multiplexing using different time gaps (TDM). In these day's researchers are working at the ideas of hybridization of at least two techniques e. g. hybrid (WDM/TDM) PON [4].

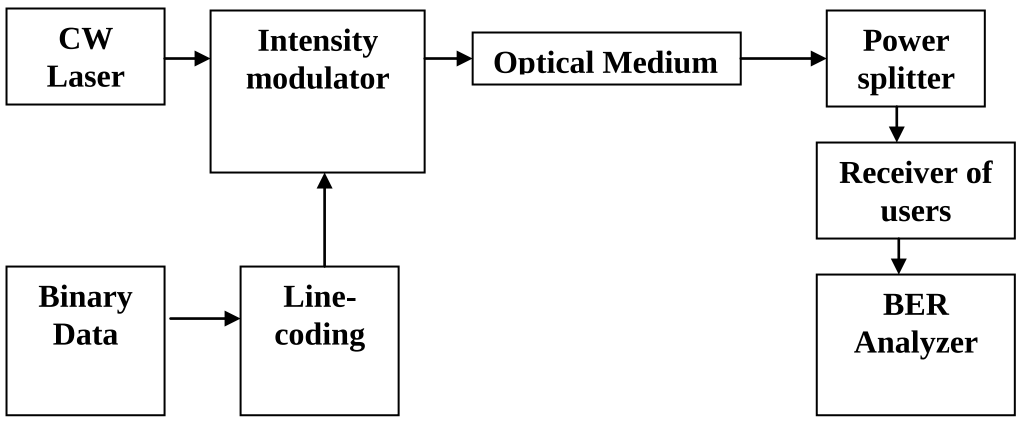


Figure 1.1 Block diagram of passive optical networks

Many researchers have discussed distinctive models for the deployment of fiber from central office to end user in order to provide access of triple play services. Diverse approaches are used in PON to reduce the cost of system [5]. Basic representation of the passive optical network is depicted in Figure 1.1.

1.2MULTIPLE ACCESS TECHNIQUES

Multiple access technique is a process of allowing amount of users to operate in the arrangement over the same medium of transmission at the same time and accomplish information exchange. Total bandwidth of the transmission medium is available to all the users in the system. Asynchronous and synchronous are the two essential categories of access techniques. Former technique is termed when the data transfer is not at same speed i.e. variable and due to these collisions amid users takes place. Delay in the data reception is the major limitation of this transmission. Synchronous transmission is bit different to the former technique such that the data speed is fixed in this and scheduled [5].

Different access techniques are:

1. Wavelength division multiple access (WDMA).
2. Time division multiple access (TDMA).
3. Code division multiple access (CDMA).

1.2.1 Wavelength Division Multiple Access

Wavelength division multiple access is prominent and simpler method of the multiple access which is widely used in the analog and digital services. This access is widely used in and incorporated in the systems where only analog transmission takes place. In this technique, number of channels are managed to pack into the single optical medium for the increase in the capacity of the system. These channels are basically differ in the wavelengths that falls around the central wavelength. This difference in the wavelengths is termed as channel spacings and is essential for the separation of the wavelengths so that data at one do not interfere with other. This is parallel phenomenon of the multiplexing and faster than the other techniques. Ease of implementation and operation makes it a potential method for optical networks. But, in this technique, the channel separation is through the frequency gap and this waste the bandwidth of the medium. If the spacing is fixed to larger values, it makes system bandwidth inefficient and if very closed spacings are considered, these introduce interference of adjacent channels.

However, for the capacity enhancement of optical system, WDM is a potential method in order to send several channels at the same time [6].

1.2.2 Time Division Multiple Access

In this method, number of channels are managed to pack into the single optical medium by providing then different time for the increase in the capacity of the system. These channels are basically differs in the time of each signal that calculated from the bit period. This difference in the wavelengths and time division is that in TDM, user can have the data for limited period of time and on the other hand in WDM, data is available all the time. Time delay is fixed at the transmitter to each channel and matched at receiver. Time interleaving is essential for the separation of the channels so that data one channel do not interfere with other. This is serial phenomenon of the multiplexing and slower than the WDM techniques because each channel come into action at their respective time frame. Ease of implementation and operation makes it a potential method for optical networks. But, in this technique, the channel separation is through the time gap and this waste the time of the operation. Frequency in this method is single and interferences between different channels is also near to negligible [7].

1.2.3 Code Division Multiple Access

This technique utilizes the spreading of spectrum and also termed as spread spectrum technology in cellular networks. Diverse codes are employed to cater different end users by assigning particular chips so that they can use entire transmission medium's bandwidth at the same instant of time. Prior to the transmission, unique codes are assigned in this technology. Advantage of this method is that it can serve high speed applications, and can offer high security. The fundamental theory in code division is that end clients who aspire to communicate from end to end using it is specified a shared code. At the same time multiple codes may present in the same medium, simply those channels posses the identical signature code can establish the information exchange with each other. Chip rate is spreading of the code and aforementioned term is used for it over the term bit rate. Moreover, the limitation of inter channel interference, time lapse or time skews are not present in the code division transmission. Further to make system more potential for large number of users, digital signal processing can also incorporated in the systems. Therefore, it is promising technique and has numerous benefits.

1.3 PASSIVE OPTICAL NETWORKS

Development of passive optical networks is required because of their numerous advantages. Major component of the passive optical networks is the passive power splitter. Difference in active components and passive component splitter is that it eliminates the need of external power in later case but power is needed for the former one [3]. Total transceiver is required N+1 and due to optical fiber communication and optical amplifiers, it does not require conversion (E/O). These are point to multipoint links that offers the high speed and has potential to support large number of channels and users. Point to point links are often between central office and single user that increase the cost of the system and waste the bandwidth as well as time. In order to save the cost and bandwidth, point to multipoint architectures is important as shown in Figure 1.2.

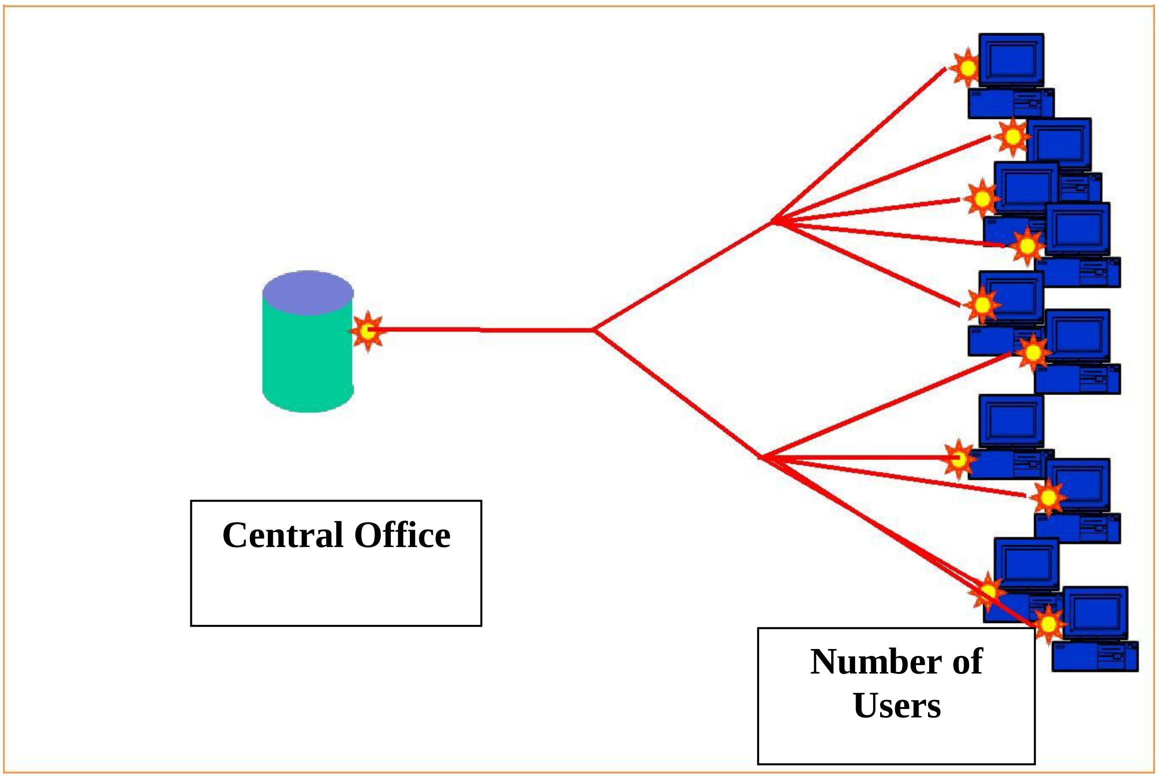


Figure 1.2 Representation of Passive optical network architecture

Essential components of the passive optical networks are elaborated under as:

1.3.1 Optical Line Terminal

Optical line terminal is also considered as the centralized source for signal generation in the central office. All the optical network units or end users are catered by the optical line terminal. OLT has two type of transmission such as from central office to optical network unit and vice versa. Former one is termed as downstream and later is upstream.

1.3.2 Optical Distribution Units

OLT and ONU are linked with each other by ODN using fiber and splitters/combiners. This component used at remote nodes for transferring the signals to or from OLT to various ONUs. There are devices are classified into two types such as; active and passive. Advantages of Passive devices over active devices, it does not require any external power supply [12].

1.3.3 Optical Network Units

Optical network unit is end component of PON which is placed or located in the building, user's premises, home etc. Also, it is termed as the optical network terminal. It provides the network access to the end user. It is basically an interface between the multiple users and also for single user. In former days, there are designs of ONU to receive the information only but now they are configured to act as transceiver. The main function of ONU to converts a optical signal from electrical signals of different electronics devices such as phones, computers, TVs.

1.4 FIBER ACCESS NETWORKS

With the numerous benefits of fiber optic transmission, it becomes the attractive technology for rapid communication systems such as low losses and wide bandwidth. These days, researchers are accentuating on the ways to lowers the overall cost of the transmission. Fiber optic is costlier than the other available transmission mediums. However, low maintenance and large bandwidth availability makes it right candidate for the high speed communication. Advantages such as small size, non presence of EMI, security makes it a better alternative in current networks. In the big cities, the web of copper cables is continuously replaced with the fiber optic cables. In fiber access networks, optical fiber always used in first preference compared to other co-axial and copper cables. The fiber can be deployed between central office (CO) to user's premises. Fiber access networks are signified by FTTx where x demonstrates different structures as Fiber to Home (FTTH), Fiber to Building (FTTB) as well as Fiber to Curb (FTTC).

1.4.1 Fiber To The Curb

In order to cover the large area for the transmission and to provide access to multiple users present in the curb, a high capacity medium is deployed between sender and recipient. Communication channel between the central office and curb is copper and efforts are to subordinate the expenditure of the system by locating the terminals at appropriate places. It has benefit that it decreases the cost of deployment for all users. This telecommunication system is cost effective but it requires large amount of power and appropriate space for proper working [2].

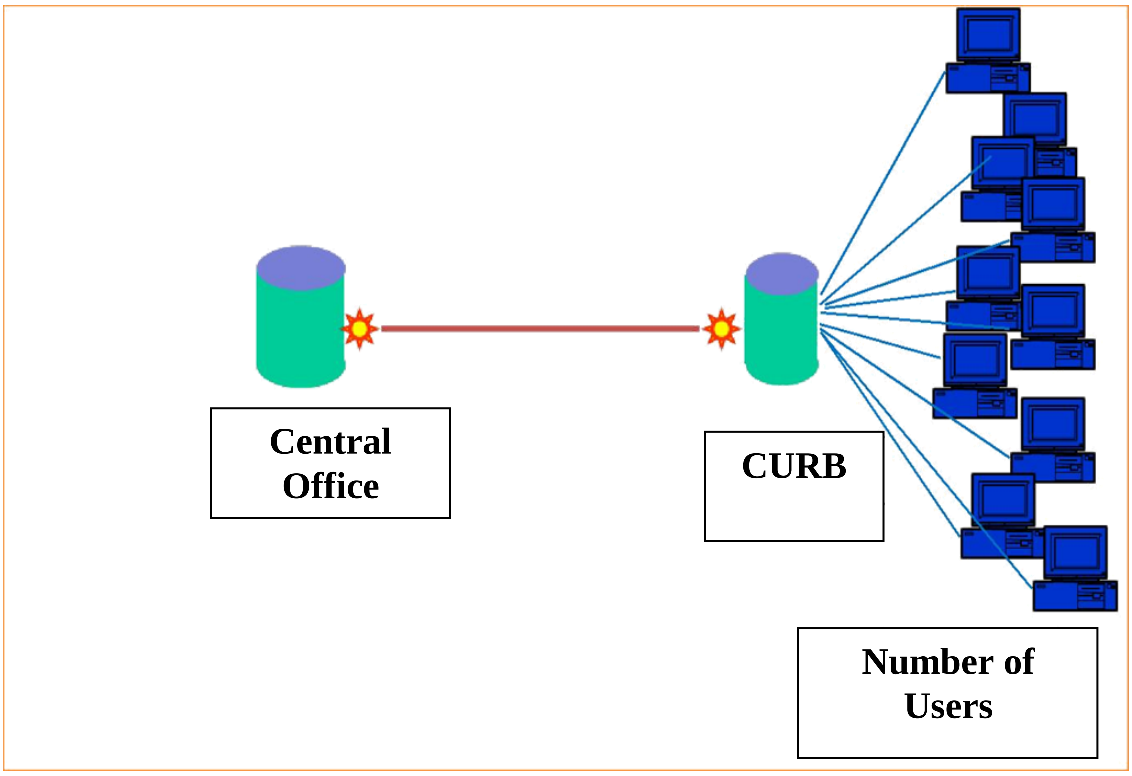


Figure 1.3 Representation of Fiber to the curb

A representation of fiber to the curb network is depicted in the figure 1.3. It has requirements of basically two transmitters and receivers. This is major benefit of the system. However, bandwidth is less and complexity increases at the curb.

1.4.2 Fiber To The Home

In FTTH, a potential transmission medium is deployed between end user and optical line terminal. End users are basically within the home and office. Optical fiber is link between them. It is represented in Figure 1.4. Largest bandwidth is offered in these systems. Total 2N sender and receivers are there in central office and home location. Use of passive switch or components of such as active switch can be used in the system to lower the use of components. Representation of fiber to the home active network is depicted in the 1.5. End users are catered with the network by the switch that present in basement of office or building. Therefore, it uses available space efficiently at the central office and network switch can be present in the basement. However, there is total need of 2N plus two (2N+2) transmitters and receivers. From which, 2N are employed at the curb and 2 are required in the main central office.

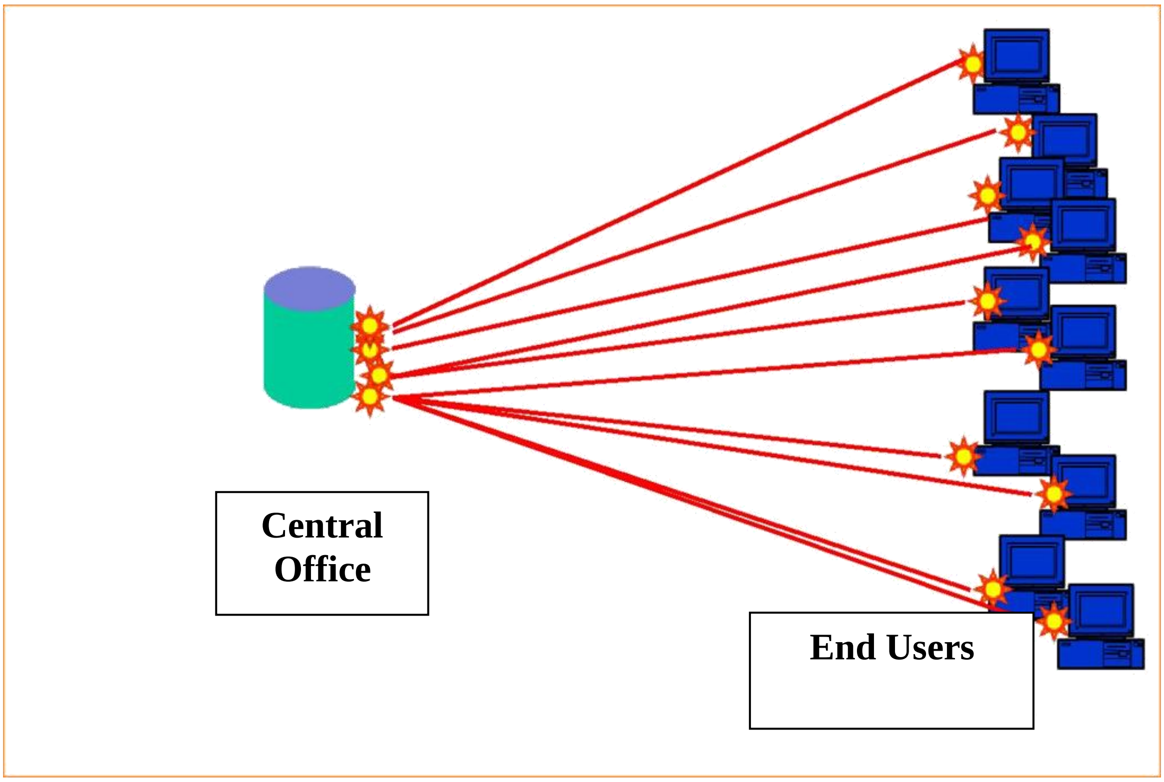


Figure 1.4 Representation of Fiber to the Home

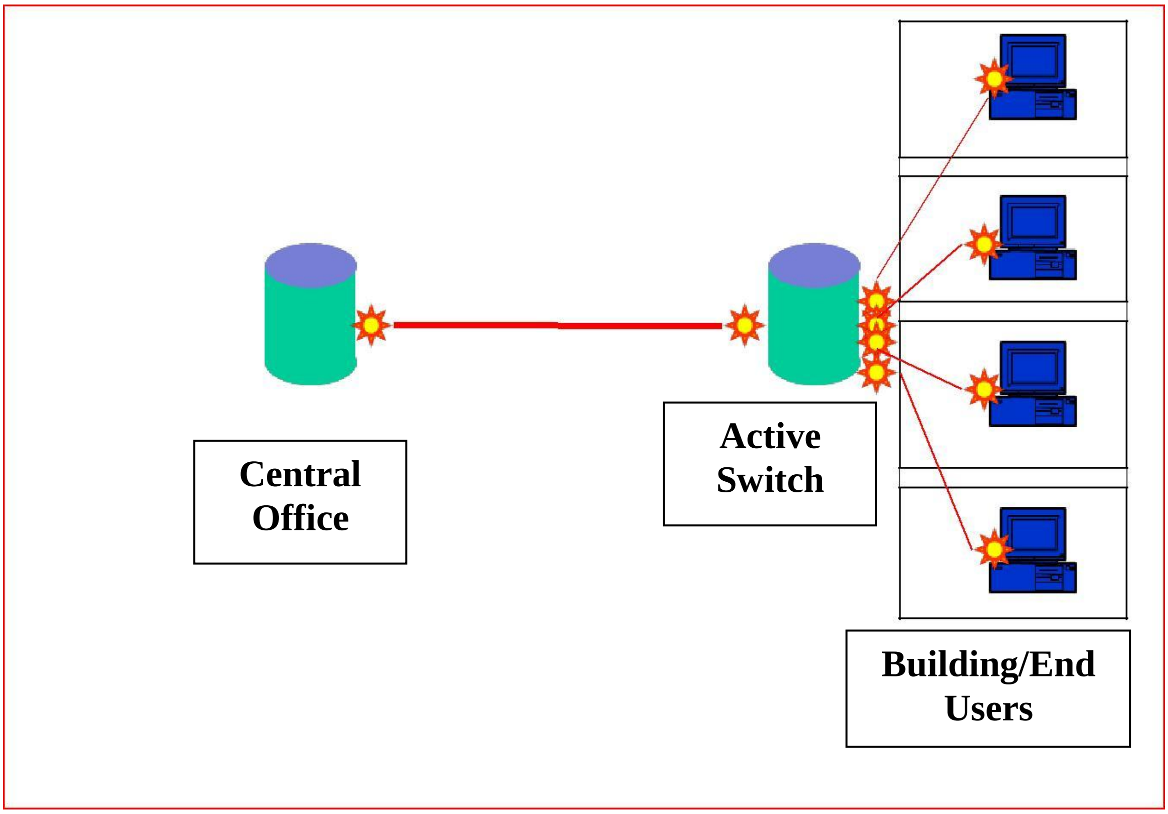


Figure 1.5 Representation of Fiber to the Home with active optical switch

1.5 PON TECHNOLOGIES

PON's are widely used due to their benefits and divided into diverse standards according to speed, distance and number of user supported etc. International telecommunication union has standardized some passive optical network systems. These are categorized on the basis of their bit rate, total splitting ratio, transmission link reach such as in BPON ITU-T G.983. Other systems of PON are also given the standards like Gigabit PON (GPON) ITU-T G 984 as well as IEEE 802.3 for Ethernet PON. Realization of passive optical networks is reported form diverse techniques such as WDM, TDM. In WDM, single wavelength is offered to each user and available bandwidth is sliced. Users can access the data at any time because there no time constraints. On other hand, time division multiplexing based passive optical network uses different times but wavelength is same for all channels. Hybrid passive optical network takes the benefit of both WDM and TDM technologies. On these basics, different types of PON are specified. Different standards of PON systems are described below.

1.5.1 APON (ATM PON)

First and foremost the network which was taken into the consideration was APON. Proper definition of this network was given as Full Service Access Network In this network, entire bit rate of the transmission was on 155 Mbps and it worked on the Asynchronous Transfer Mode. Aforementioned data speed in then distributed to the no. of end users i.e. ONTs. These networks known as APON (ATM Passive Optical Network)[7].

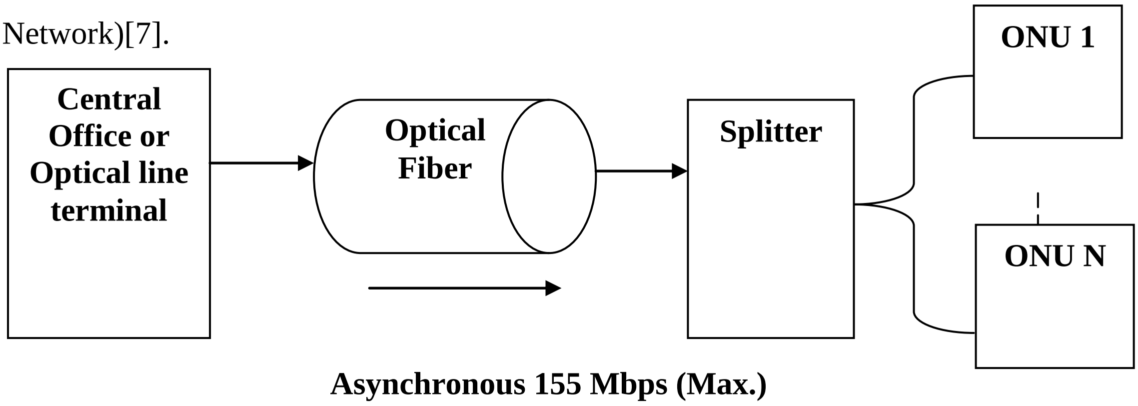


Figure 1.6 Block diagram of ATM passive optical network

1.5.2 BPON (BROADBAND PON)

BPON likes as APON, because speed of both networks is very slow or it is also based on ATM cell transmission. But BPON support other broadband standards. This characteristic of BPON is different form APON .Standard that set by International Telecom Union for BPON is ITUG.903. Information rates used for BPON networks are 1.2 Gbps and 622 Mbps for OLT to ONU and vice versa respectively [8]. Figure 1.7 represents the system diagram of BPON system.

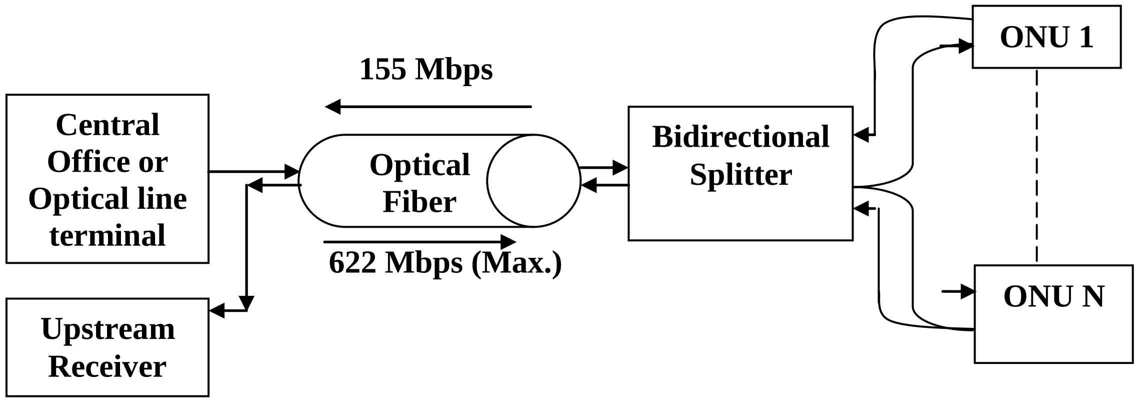


Figure 1.7 Representation of bidirectional PON

1.5.3 EPON (ETHERNET PON)

The EPON based on transmission of Ethernet traffic by encapsulates the data on ethernet frames but maintains the characteristics of the IEEE 802.3ah which comes under IEEE 802.3 standard [9]. Data rate used for EPON networks is 1.25 Gbps for the ONU to OLT and downlink transmissions and coverage link reach that used in EPON is 20 km with 32 users. It is a advantage of EPON over previous types. By owing this benefit EPON used for tansmited the information like data, voice and video. It collects the data on Ethernet frames. It also a point to multipoint access networks [7].

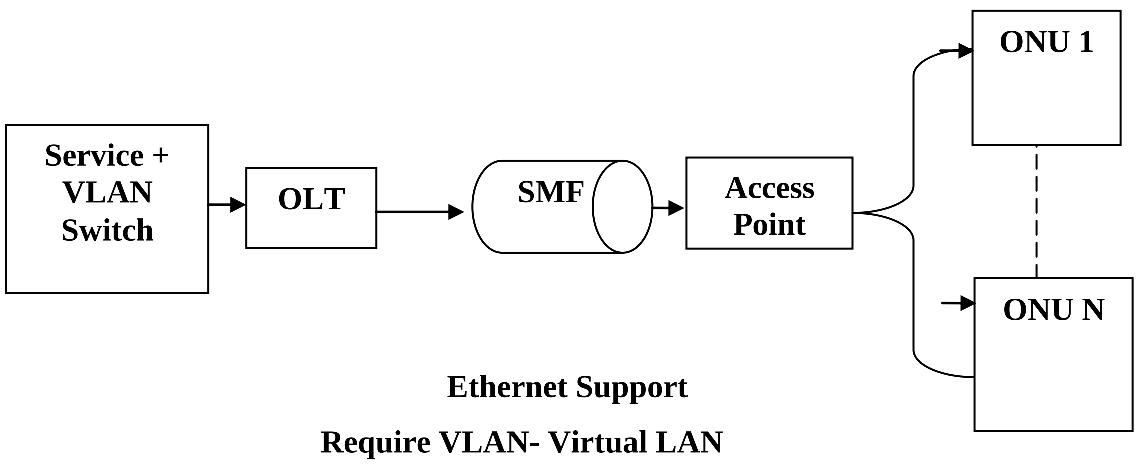


Figure 1.8 Representation of EPON

1.5.4 GPON (GIGABIT PON)

GPON is standardized by International Telecom Union as ITU.984. It is advanced standard of previous one. By increasing the demand of high data rate or high transmission speed, requires a networks that fulfils these requirements. GPON is best network to meet these requirements. It provides a longer distance is up to 60 km with 32 users. ITU-T created the standard GPON (Gigabit PON) [10]. Data rates that used for these networks are 2.4 Gbps for the downlink communication and 1.2 Gbps for the ONU to OLT transmission. The distance covered is 60 km for the users 32 in this standard [7].

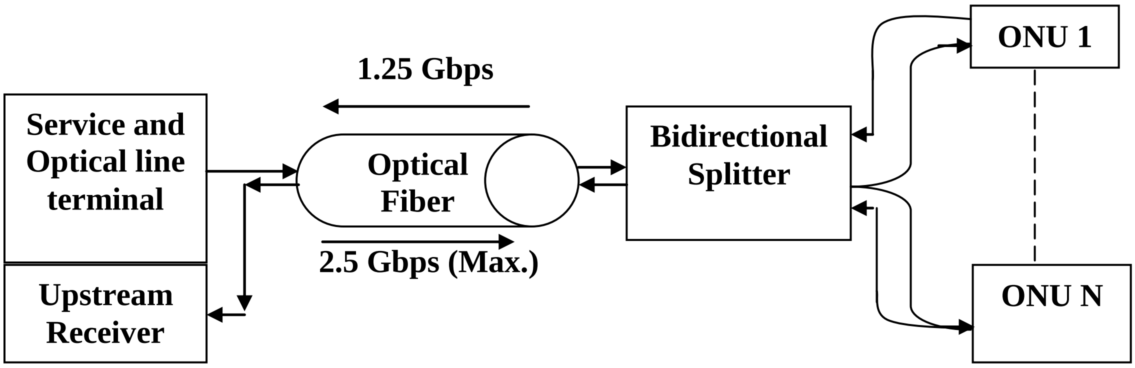


Figure 1.9 Block diagram of Gigabit passive optical network

1.5.5 XGPON

ITU-T series of standards ITU-T G.984.x for Gigabit capacity PON as G987.1, G987.2, and G987.3, It is advancement of GPON, where data rates are denoted by X ,like 10-100 Gbps.Two tpes of XPON: Asymmetric XGPON or Symmetric XGPON . GPON1 is term given to Asymmetic and bit rate of 10 Gbps for the OLT to ONU and 2.5 Gbps for the uplink. XGPON2 is term given to Symmetric XGPON that has bit rate of 10 Gbps for the both uplink as well as downlink transmissions [7].

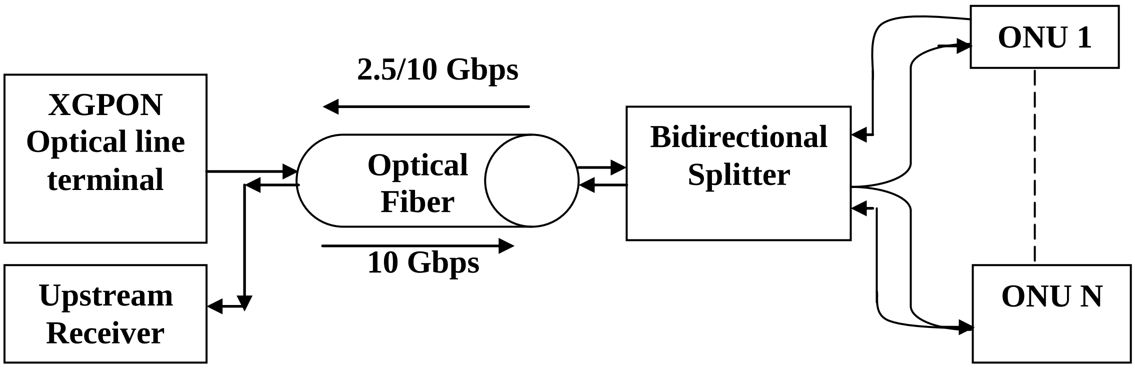


Figure 1.10 Representation XG-passive optical network

1.5.6 TDM PON

Time division based PON networks are prominent these days because of the reason of low cost point-to-multipoint (P2MP) architecture. The latest PON has been demonstrated as single point to multi point networks that are realized using TDM PONs. TDM PON is cheap in cost and less complex in structure. Three variants of TDM PON: EPON, GPON and BPON. The optical power is transmitted to all subscribers and the customers in order to access the information in appropriate time slot. These all three TDM-PON systems are having difference from each other by using different data rates. Bit rate for BPON is mentioned in 1.5.2. This is very low data rate for today's requirements. The EPON provides 1.0 Gb/s data rate and GPON supports speed of 2.5 Gbps for OLT to ONU and 1.25 Gb/s for vice versa asymmetrical operation [11]. The architecture of TDM PON is shown in Figure 1.11.

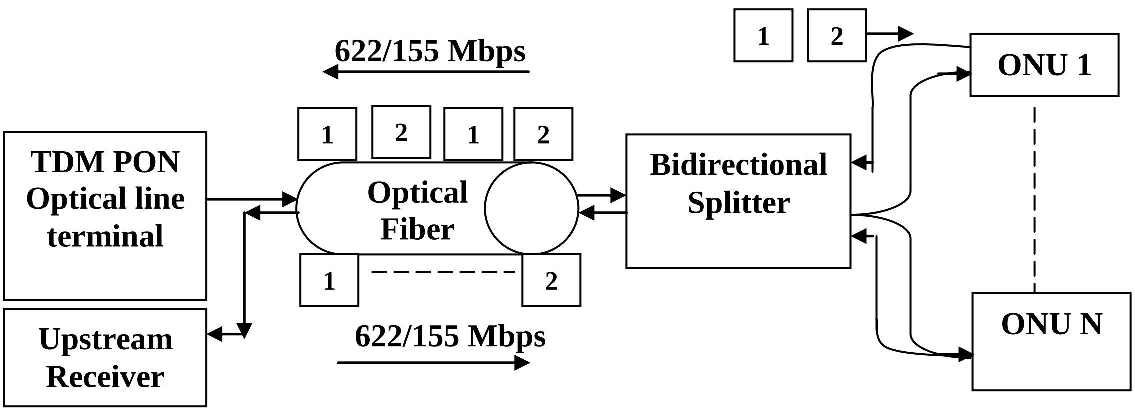


Figure 1.11 Network architecture of TDM passive optical network.

1.5.7 WDM PON

WDM PON is latest technology to fulfil the requirements of fast, effective and secure transmission capacity for passive optical networks. The ONUs destination part, it locates at the end user or it shares the accessible bandwidth in the TDM PON. The normal allotted bandwidth for each end-client is low basically when the no. of ONUs (N) is very extensive. However WDM PON provides high scalability by numerous multi channels over the solo fiber optic. WDM PON are different by its protocol, transparency, and upgradability to TDM PON. For getting the entire bandwidth, it rewarded specific channel wavelengths to each user. It requires large no of devices for each end user which increases the cost of system [11]. WDM PON representation is illustrated in Figure 1.12.

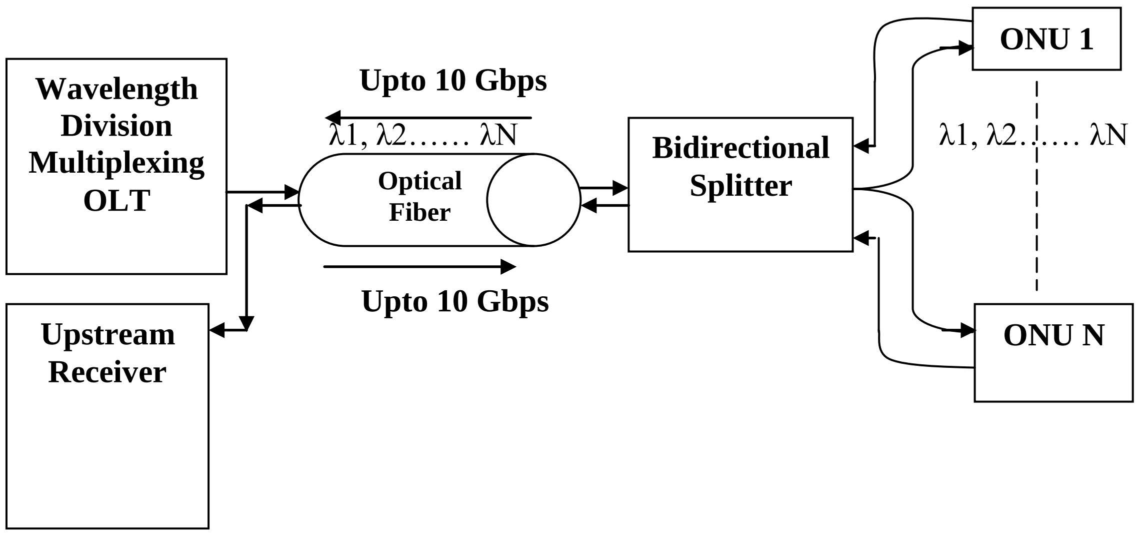


Figure 1.12 Network architecture of WDM PON.

1.5.8 Hybrid WDM TDM PON

Hybrid WDM TDM PON is a combination of TDM and WDM. Advantages of Hybrid WDMTDM PON over previous networks, it provides large bandwidth and multiple wavelengths to each end users over single optic fiber. But Only single wavelength used for each subscriber in WDM TDM ,it is not efficient and impractical. These PON's uses a point to point transmission and high bit -rate channel between Central office (CO) and each end user. So, combination of WDM and TDM was proposed to increase the network performance and high bandwidth requirements. It is a high security network. The OLT assigns multiple wavelengths to transmit the downstream which transmitted over single optical fiber [11]. hybrid WDM/TDM PON block diagram is depicted in Figure 1.13.

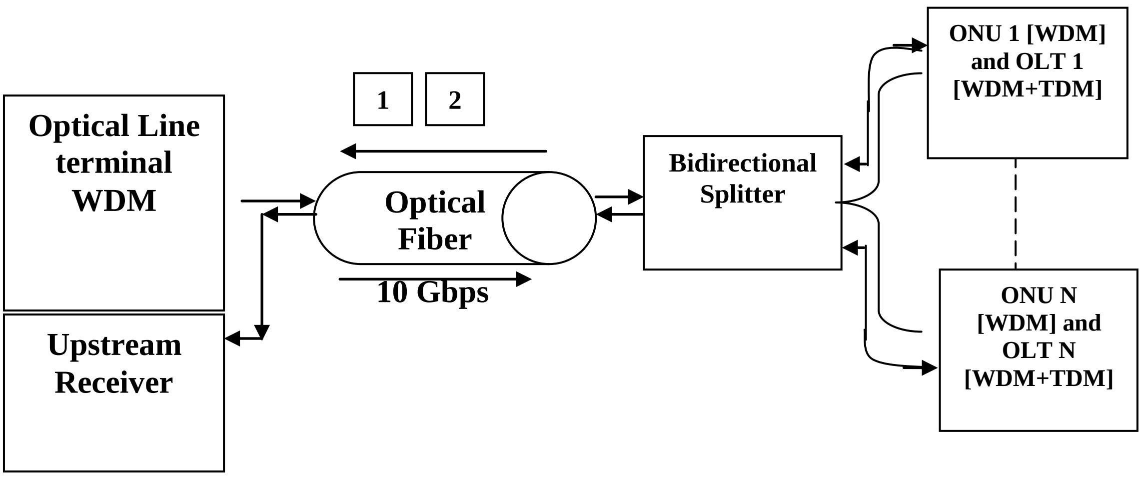


Figure 1.13 Network architecture of hybrid WDM TDM PON.

CHAPTER 2

LITERATURE REVIEW

In this chapter, we present a comprehensive literature survey of passive optical networks. The basic parameters used to determine the performance of PONs are bit rate (BER), Q factor, optical signal to power ratio (OSNR). Many authors have worked in this area. The work done by various authors on various PONs architectures and topologies has been summarized in the literature.

2.1 LITERATURE SURVEY

Nahal El. *et al.* [13] proposed and designed WDM PON with the direct detection modulation technique. It worked at 10 Gbps speed over 25 km distance by using on off keying and differential phase-shift keying (DPSK). Both scheme used for downstream and upstream respectively. DPSK and OOK reduce the distortion between DS and US signals. At receiving side ONU used a reflective semiconductor optical amplifier (RSOA) as an intensity modulator. IM reduces the cost of whole system and also it uses for demodulation with NRZ signals which diminishes the crosstalk. Power of DPSK is always constant. By this benefit, it stands out from other modulation techniques. System worked for 25 km with minimum bit error rate.

Kaler R.S. *et al.* [14] researched hybrid TWDM PON architecture and presented the system for total 256 no. of users/ONUs. Rayleigh scattering (RS) is a prominent factor of performance degradation along with Stimulated Brilliuon scattering (SBS) and these were quelled in the work by employing the phase modulating technique. Diverse wavelengths were studied and used in the OLT to ONU transmission and from ONU to OLT link. They have used a system of Common Carrier for All Optical Network Units (CCAONUs) that lowered the cost of overall system. They achieved the total link length in downlink was 185 km and in uplink transmission distance attained was 190 km with 256 ONUs at 10 Gbps bit rate within acceptable range of Q factor. It is noteworthy that they have not used any amplifier.

Singh S. *et al.* [15] demonstrated a novel hybrid WDM-OTDM technique by using Polarization, SCM modulation and DPSK modulation. These modulation schemes were used for unicast or multicast data transmission by using 120 Gbps and 40 Gbps data rate respectively. All performing factors like; link length reach, extinction ratio, launched power, depends upon total output power. For both the unicast and multicast data transmission, Q and BER were calculated. They proved that by using polarization and subcarrier multiplexed modulation potential to support more channels increases and system becomes less prone to chromatic and polarization dispersion,

Kaur A. *et al.* [16] showed an investigation of 4 channels TDM PON system using orthogonal frequency division multiplexing technique (OFDM) at 25 Gbps for transmission link of PON. Each channel uses a 10 Gbps data rate. Cost effective method of wavelength reuse was employed for uplink by incorporating NRZ 4 channels. By analyzing the performance of the system from constellation diagram, it was evident that system can attain the link length of 60 km for the downlink. Q-factor and BER attained a satisfactory value, 6.76 and 7.67 e-12 respectively. 24.56 dBm Power obtained at transmitted or received signal.

Houtsma *et al.* [17] presented some concepts for escalating the successive bit rate of TDM-PON further than 10 Gbps. Also, they presented methods to reduce the overall cost of networks. The author describes a different modulation and investigates the best one, which is generally appropriate for outlay as well as technological performance. They presented the trade-offs for each modulation scheme. They have discussed the experimental results on different bit rate like 25 and 40 Gbps. By using electrical duo binary (EDB) at 25 Gbps with 10 Gbps receiver parts, they described the idea to reduce the cost for future high speed NG-passive optical networks.

Abbas *et al.* [18] discussed a potential way to improve the performance of next generation PON. They put some new ideas to modify the performance of passive optical systems which are reliant on the diverse hybrid PONs by joining two different standards such as EPON and GPON. Also, author explored the ways to cater the bandwidth hungry services by suggesting the merger of standards to make hybrid PONs. These hybrid approaches are best way out to remove major disadvantages as well as to get better overall system performance.

Liu *et al.* [19] they analyzed the benefits of 5G wireless optical access networks with respect to these terms; less cost, less delays and high capacity power per bit. They exhibited some signal reception techniques and advanced modulations. Techniques were DSP and CPRI-compatible EMF techniques. They also elaborated the best approach for coordination between a radio access network (RAN) and PON to achieve high transmission speed and low latency by using MAC layer arrangement as well as the clock to synchronous mobile signals from beginning to end in PON. They also reviewed high bit rate PONs, at 100 Gbit⁄s

Andrade *et al.* [20] had investigated Hybrid TDM/WDM PON techniques with coherent detection based on novel performance enhanced model which arouse the factor of selecting cost efficient communication in hybrid TWDM PON for Mixed Integer Linear Programming (MILP). They also suggested the various ways to utilize available band width and splitting ratio in the WDM PON. Results are investigated and shown at different information capacity and link length reach in hybrid time and wavelength division.

Bindhaiq *et al.* [21] demonstrated a performance improved multi-stage system for broadband. Basically the improved system was hybrid TWDM PON which has potential to serve next generation systems. NGPON2 fulfil the needs of optical systems with high speed of 40 Gbps and also consisted of time division in upstream. Moreover, optical distribution network has no need to be changed. They accentuated on the cost efficiency of the hybrid system within corporation of tunnable transceivers. They reviewed the bit rate between downlink and uplink with high power budget of hybrid PON system.

Shaddad R. Q. *et al.* [22] studied the appropriate method for future access networks-FiWi (fiber-wireless) based on a hybrid WDM/TDM PON system at the bit rate of 2.5 Gb/s from OLT to ONU and for reverse also over the maximum reach of 24 km using single mode fiber which followed by a visible light link of 50 m with 54 Mb/s or 30Mb/s data rate by using FiWi Techniques like WiFi and Wi- MAX.

Emsia A. *et al.* [23] proposed a new technique DQPSK TDM/WDM to fulfill the requirements of improved bandwidth and less expensive system with large no. of users, with high bit rate. It also removes the unwanted impairments which appeared in DWDM. In this research work transmission of the signals is achieved at the data rate of 40Gbps for upstream and 120Gbps for downstream. A 33.4 dB, power used for every WDM channel at 10Gbps with 1:512 splitting ratio between DQPSK and per wavelength. 40Db obtained in case of DQPSK with as per wavelength splitting ratio of 1024.

Pandey G.*et al.* [24] presented colorless 16 channels WDM-PON using same 10 Gbps data rate for downstream and upstream. Upstream transmission consists into three devices: an intensity modulator EAM, RSOA and an optical coupler. Wavelengths of pump and intensity laser signal are coverts in RSOA by using cross gain modulation (XGM) to transmit the upstream data. They discussed the Carrier reuse scheme to operate the all ONUs in colorless mode. Investigation was done to comprehend the effects of ER of delay interferometer (DI) on OCSR.

Bi M. *et al.* [25] designed WDM-OFDM-PON up to 100km distance without any repeater. OFDM signals are transmitted for downstream using 10Gbps per wavelength and also on–off keying (OOK) signals for upstream transmission to cover a 100 km.To attained a simultaneously selection of both links, liquid tunable optical filter was used. A 35.6dB power was used for transmission over a fiber length of 25km for supporting 1:512 splitting ratios and optical power budget of 34.4dB for the transmission over a distance of 100km without using a repeater.

Jaumard B. *et al.* [26] proposed a novel optimization scheme for PON networks to decrease the general cost of the system. These new models evolve three phrases such as arrayed gratings, splitters, and switching equipment. Also placement of switching equipments was also explored in PON networks. They examine diverse bit rates in order to access that data instances with 128 ONUs

Dixit A. *et al.* [27] demonstrated new system architecture for a hybrid TWDM- PON using WSS. WSS used to enhance the adaptability of the network by providing maximum coverage distance, flexibility, security and cost effective requirement. They also investigate the energy saving scheme which saves 60% energy at the OLT. Network also achieved adequate multicasting gains, switching flexibility compared to a fully flexible network

Chow C. W. *et al.* [28] examined a migration scheme from TDM-PON to WDM-PON using DPSK and ASK modulation .They used for downlink and uplink signal respectively. To find an accurate wavelength for downlink transmission and reception simultaneously an optical filter was used at transmission side. Final results showed that the re-modulation process for wavelengths shifted ASK uplink which provides the successful transmission of signal less than 32 and up to 64 splits.

Chen *et al.* [29] demonstrated a system WDM-PON reliant on a single-fiber ring and centralized system. Demonstrated method has ability to cope with security issues and also was able to allocate wavelengths dynamically. The central ring can beefed up the protection for the ODN and RN system performs the function of dynamic wavelength assignment and provides the protection under the situation that the apparatus are single directional. It also provides the protection against the fiber cuts. For balancing the load of the system and reduced the power budget, CO system were designed. To drop the wavelength RN used a WB dynamically. To check the feasibility of the system, experimental results were examined at different stages of the networks

2.2 GAPS IN STUDY

Based upon theoretical studying of different fiber access networks and their research gap, we have listed some problems and enhancement factors which boost the performance of WDM passive optical networks. Discussions of these solutions include:

1. Till now, due to high requirements of bandwidth applications, high speed networks are needed. But very less work is reported in passive optical networks in the context of data speed. So, first requirement for this research work, to implement the system by boosting the speed.

2. When we designed a bidirectional WDM passive optical networks, congestion and channel crosstalk are major factor that reduce the performance of downstream and upstream signals. So, second requirement, to use different technique with PON which greatly improves the performance of the system.

3. Polarization crosstalk also degrades the performance of systems and this limitation also requires to be solved in bidirectional passive optical networks for betterment of the system.

4. Relating to increase the coverage area, many schemes are proposed, which are very expensive to use. Dispersion compensation is employed in pre, pos and symmetrical configuration in transmission line in reported researches. However, maintenance of these dispersion compensation units is difficult. Placement of these modules at OLT or ONU can reduce the maintenance issues. Moreover, DCF is costly and increase the total system cost. Fiber bragg gratings are cheap but on the other hand they are less efficient to reduce the dispersion. Optimal method is required which will increase the pulse width reduction efficiency and reduce the cost.

6. Wavelength reuse is an important requirement of WDM-PON is these days. Colorless PON can be fulfilling this requirement by using Mach-zhendar modulator. But MZM is

costly and also need amplifier for power boosting. By using reflective semiconductor optical amplifier, task of modulation and amplification can be accomplished at the same time.

Based on these factors, we proposed objectives in following section which greatly reduce the drawbacks in WDM passive optical networks.

2.3 RESEARCH MOTIVATION

The extensive growth in the requirements of massive bandwidth and high bit rate supported systems has exerted pressure on researchers to incorporate fiber optic in the transmission architectures. In order to cater the high speed system with large bandwidth per user, passive optical networks is an optimal technology. PON architecture has numerous advantages such as low cost per user, potential to support large data rates, security etc. Wavelength division passive optical networks are widely employed due to their unmatched benefits. Each user in these architectures can be different for different wavelengths. Transparency of wavelengths is very high in this system and also has very high capacity due to multiple channels. Numerous research works are reported in WDM PON. However, despite the advantages, it suffers from issues such as high cost, inter-channel interference, pulse broadening of the signal, and high maintenance. Many works are done so far to counter these problems. But, approaches used were either increment the unpredictability of the framework, increment cost and decrease execution of the system. Work needs to be done on these issues to provide cost efficient, performance enhanced, high speed, high capacity WDM PON system.

2.4 OBJECTIVES

Objectives are formulated by analyzing the problems of security breaching in the reported passive optical networks and listed as follows:

i. To study the effect of transmitter diversity in downstream and upstream of WDM-PON.

ii. To propose a polarization interleaved bidirectional passive optical network using different states of polarizations in ultra dense (25 GHz) WDM PON system

iii. To propose an dispersion compensated ultra dense maintenance free cost effective WDM-PON system

2.5 THESIS ORGANIZATION

This dissertation is categorized into six different chapters.

First step of the dissertation work was to study the optical access networks and passive optical networks as discussed in chapter 1. Further, variants of passive optical networks are studied and detailed comprehension of dispersion compensation, crosstalk's in PONs and other factors has been done.

In second chapter, literature of the passive optical networks has been discussed. Moreover, information on current trends in the technology is given. Based on the literature, a problem is formulated which are existing in the passive optical networks. Various methods to solve the issues are also mentioned and research motivation is written. Objectives are formulated on these bases.

In third chapter, transmitter diversity based WDM-PON is proposed. Investigation of DQPSK (differential quadrature phase shift keying) and DPSK (differential phase shift keying) has been done in the downstream. Different distances are taken into account for the investigation and results are observed in terms of Q factor and BER.

In fourth chapter, a crosstalk suppressed ultra dense WDM-PON is investigated by incorporating polarization interleaving. Comparison has been accomplished between with polarization interleaving and without polarization interleaving. Results analyzed in terms of signal to noise ratio, Q factor and log BER.

In fifth chapter, an approach is proposed to compensate the dispersion of the passive optical networks and placement of pulse width reduction unit is explored so that it lowers the maintenance issues. Dispersion compensation efficiency is analyzed of DCF, FBG ad DCF+FBG along with results in terms of Q and Log BER.

In sixth chapter, conclusion and future of the proposed systems is given.

CHAPTER 3

TO STUDY THE EFFECTS OF TRANSMITTER DIVERSITY IN DOWNSTREAM AND UPSTREAM OF WDM-PON

Wavelength division multiplexed passive optical is promising technique to achieve a high data rate and large no. of user. The notable advantages of WDM PON is the combination of reliability, cheap in cost, accessible bandwidth , high security , large optical reach and it can support large number of ONU. There are multiple approaches to achieve colorless WDN PON using different transmission techniques. In this research work, we accentuated on the design of 4 channels WDM PON system incorporating different modulations formats for both uplink and downlink stages by using 10 Gbps and transmitter diversity. A 40-km-long colorless symmetrical WDM-PON with DQPSK in downstream and NRZ pulse shape generator in upstream to solve crosstalk issues. Also comparison has been made with the system using DPSK for downstream and NRZ for upstream in WDM PON system.

3.1 INTRODUCTION

According to today's requirements to achieve high capacity per user, various multiplexing technique are used to cater these requirement. TDM is a best multiplexing technique for wide bandwidth requirements of internet services. But, it is time consuming technique due to time skews. On the other hand, wavelength division multiplexing is a noticeable and potential technology to conquer these constraints. For FTTH services, WDM-PON is considered as the definitive answer to offer wide bandwidth and quick communication. Bidirectional or full duplex passive optical networks are expected to provide increasing demands of bandwidth hungry services. Sometimes, bidirectional WDM PON networks experience a severe issue of crosstalk amongst downstream and upstream channels. In order to suppress this crosstalk, numerous approaches are proposed so far utilizing comparable and different modulations for upstream and downstream. At present, use of the NRZ is famous due to simple generation of this format. But in future, advanced modulations such as DQPSK and DPSK are needed due to their high spectral efficiency and have power to reduce the effects of nonlinearities. In addition wavelength reuse is a vital factor to consider in passive optical networks to design a cost effective.WDM bidirectional system. Numerous research articles are accounted to incorporate wavelength reuse. However, they utilized costly intensity modulators, which is itself an issue. Subsequently, we have designed a WDM passive optical network by considering these important factors.

3.2 THEORY OF DIFFERENTIAL QUADRATURE PHASE SHIFT KEYING

To enhance the system framework to eliminate the nonlinearities and, for achieving prolonged transmission reach, differential quadrature phase shift keying is promising candidate. Nowadays, DQPSK must be a consideration of researchers due to no. of benefits and also referred as true multilevel modulation. In this higher level modulation, generation of four phase shifts (0, +π/2,-π/2, π) at symbol rate of half the total data rate has been accomplished. A DQPSK is most appropriately implemented with two parallel Mach-zehnder modulators which are functional as phase modulators.

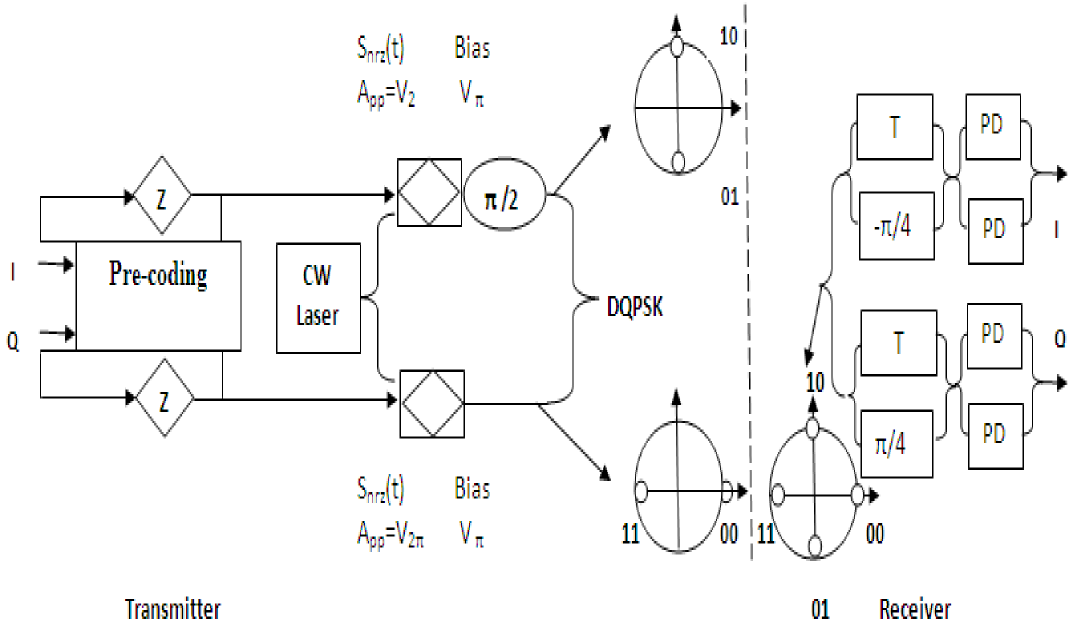


Figure 3.1 Depiction of Differential Quadrature Phase Shift Keying Transmitter and Receiver

As shown in Figure 3.1, a transmitter consisting of a continuous Laser source, a power divider with two transmission paths of equal energy, two mach-zehnder modulators, 90^0 phase shifter in one arm or path and power combiners are used to combines the signals . This diagram shows the schematic of parallel MZM generation of the multilevel modulation. Serial MZMs are used in place of parallel configuration for DQPSK generation. Constellations of upper/lower arms and signals transmission also specified in this schematic. Aforementioned arrangement exhibit the π shifts by modulators with respect to drive signal overshoot. Subsequently, this architecture is capable to provide high speed. Pulse carver is used to generate return to zero DQPSK. Due to compressed spectrum, it provides several advantages such high spectral efficiencies in wavelength division multiplexing systems, resistant to chromatic dispersion (CD), the longer symbol period compared to digital modulation formats makes DQPSK more rigid to reduce polarization mode dispersion (PMD). Reception of the signals is achieved by separation of input signal and these signals are fed to balanced receivers. Different biasing in delay interferometers is to demodulate binary data and delay is two time the duration of bit.

3.3 SYSTEM SETUP

Figure 3.2 depicts the proposed 4 channel WDM passive optical network at 10 Gbps employing differential quadrature phase shift keying (DQPSK) in downstream and non return to zero (NRZ) in upstream. DQPSK and NRZ combination are used to combat with crosstalk problem at 10 Gbps. A laser light wave source at 193.1 THz frequency and 0 dBm input power is used. It used a C-band frequency for the reason of low losses and less scattering effects over fiber optic cables. Four WDM channels are modulated in central office with DQPSK modulation. DQPSK signal is modulated the data on four channels and a 4 x 1 Multiplexer is used to combines the DQPSK and WDM signals. Further the signal sent to 40-km SMF-28 (single-mode fiber).

After transmission of 40 km, signal is de-multiplexed by 1 x 4 wavelengths with frequency spacing of 100 GHz. At receiving side, optical couplers with coupling ration of 50:50 and divide signal for two pairs of photo-detectors that receives drive with time delay and phase shift to input signal as shown in Figure 3.1. A PIN photo-detector with 100% responsivity and 10 nA dark current is used in receiver. Also shot, thermal and ASE (Amplifier spontaneous noise) distortions are considered. Electrical bias is provided to electrically subtracted output of balanced photo-detectors followed by 3-R regenerator. A 3-R regenerator employed for re-sampling, re-shaping and re-amplification of the received data. Bit error rate analyzer is resultant component used to find out the final received quality factor, bit error rate (BER), signal to noise ratio (SNR) etc of the received signals. At the mid of downstream DQPSK signal is demodulated and remaining signals are provided to the re-modulation. Reflective amplifier is used to forward the NRZ signal over four frequency channels and multiplexed the signals for upstream transmission. After 40 km transmission distance, signal is de-multiplexed and detected through PIN photo-diode followed by low pass filter and Eye diagram analyzer as shown in Figure 3.2.

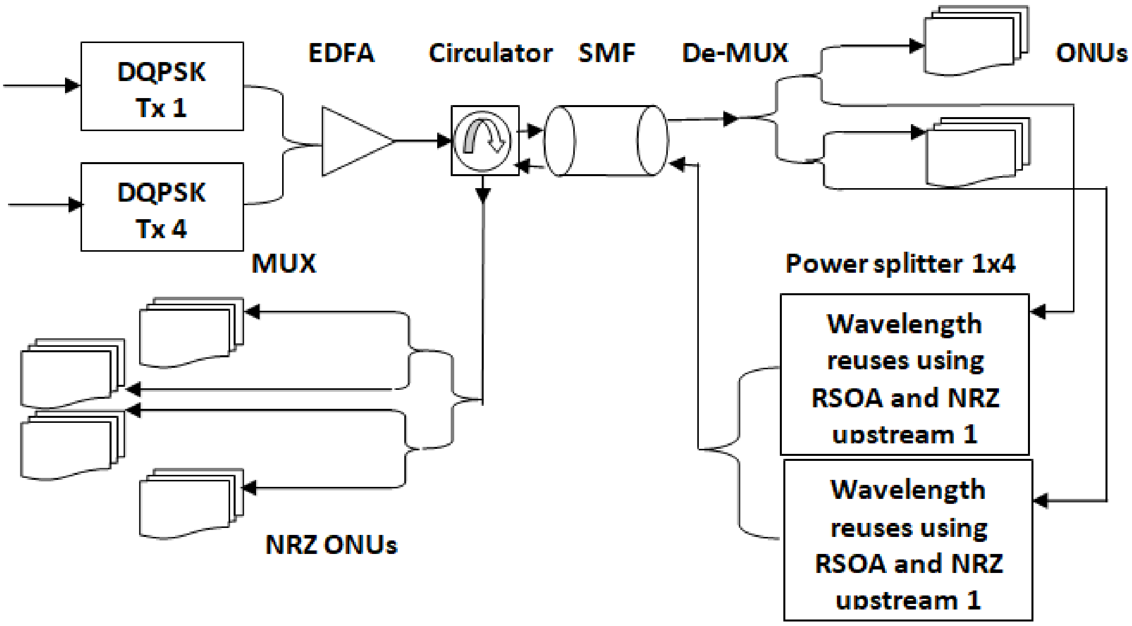
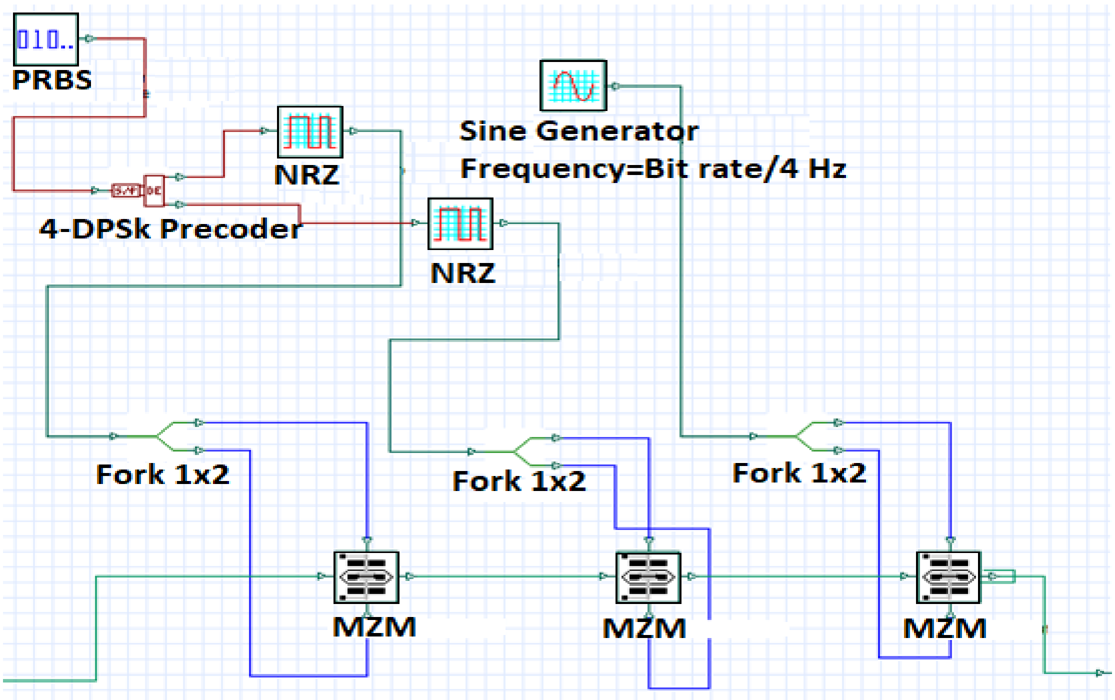
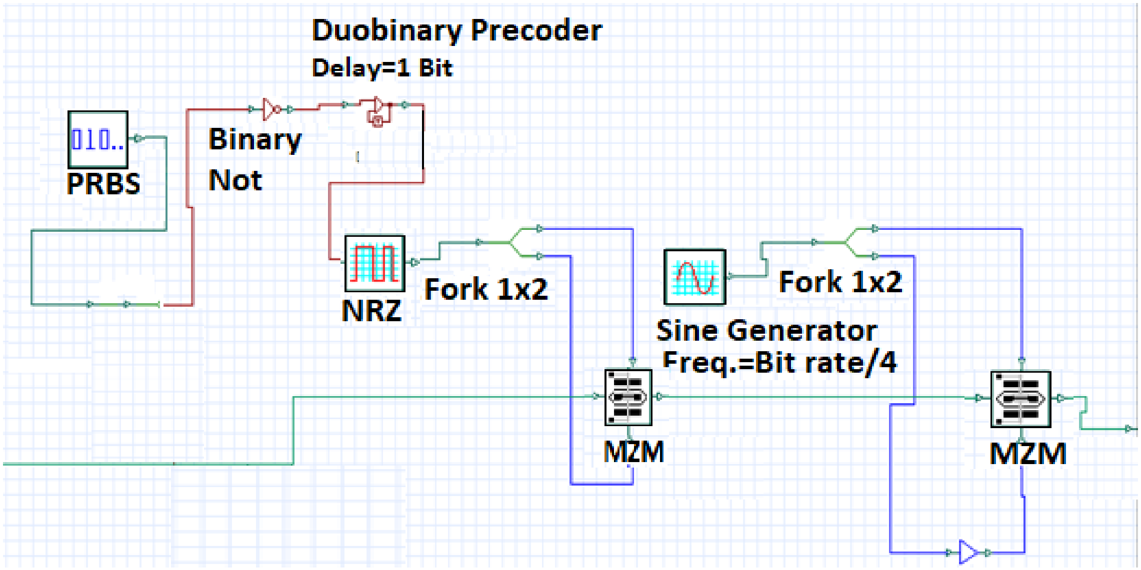


Figure 3.2 Block diagram of Proposed 10 Gbps WDM passive optical network

Here, we have considered two different cases such as case 1 for DQPSK in downstream and NRZ in upstream. In Case 2, DPSK is used in downstream and NRZ in upstream. Both cases are compared and results are evaluated to suggest the optical configuration to provide better crosstalk suppression. Internal structure of DQPSK and DPSK are shown in Figure 3.3 (a) and 3.3 (b) respectively.



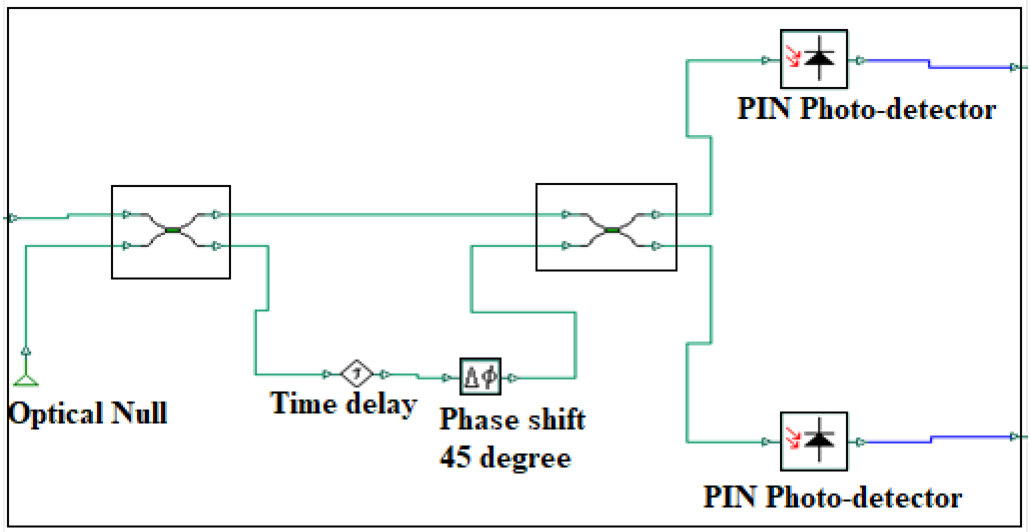
(a)



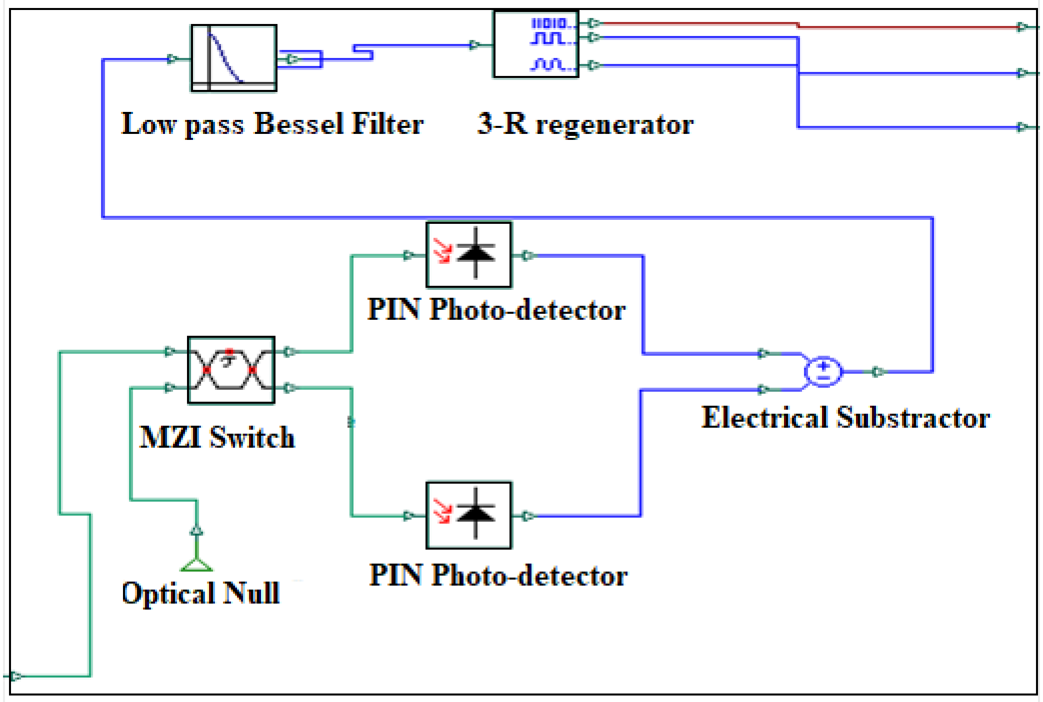
(b)

Figure 3.3 Representation of the internal structure of transmitter at OLT (Optical Line Terminal) for (a) DQPSK (b) DPSK

At transmitter side pseudo random bit sequence generator is used to provide binary bit streams. For DPSK, binary data is delayed by one bit and XOR function is performed for coding and then passed through NRZ line-coder for pulse shape. Mach zhendar modulator 1 is placed to modulate data into optical light signal. Then a sine generator with half the frequency of bit rate is modulated the data to provide 0 and 180 degree shifts to adjacent bits. Binary data is fed to 4-DPSK pre-coder and is performed for coding followed by two NRZ line-coders for pulse shape. Mach zhendar modulator 1, 2 are placed to modulate data into optical light signal and sine generator with 1/4 the frequency of bit rate is modulated the data to provide different shifts to adjacent bits.



(a)



(b)

Figure 3.4 The internal structure of receiver at ONU for (a) DQPSK (b) DPSK.

Figure 3.4 (a) shows the function of ONU in receiver for DQPSK end, the signal is passed through coupler and signal is divide into two parts. One signal is given to PD and another to time delay + phase delay. Signal detected and passed though regenerator and eye diagram analyzer. Figure 3.4 (b) depicts the receiver of DPSK. Received signal is passed though the MZI for delay compensation and detected at Eye diagram.

From above discussion we can summarize the general parameter we used in our system. These general parameter are listed below in Table 3.1.

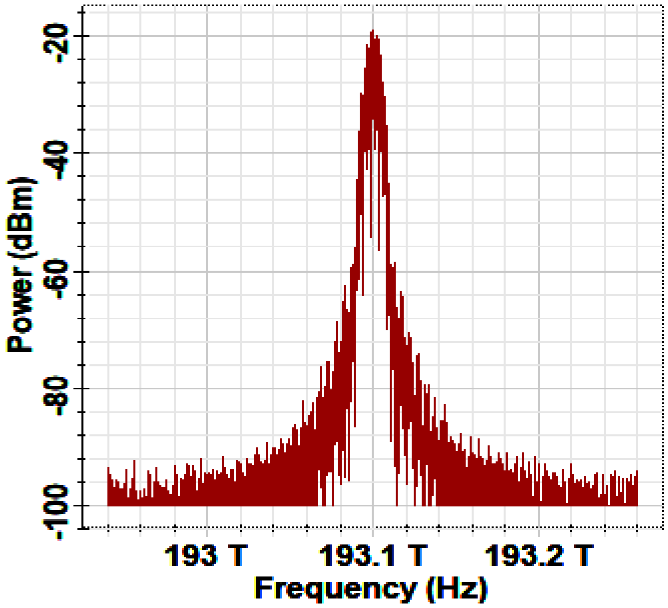
Table 3.1 General parameters required for simulation.

Parameters	**Values**
Bit rate (Gbps)	10 Gbps
Type of encoding	DQPSK-NRZ and DPSK-NRZ
WDM channels	4
Laser power	0 dBm
Sequence length	256
Samples per bit	64
Reference wavelength	1550nm
Fiber length	40 km
Optical fiber	SMF-28

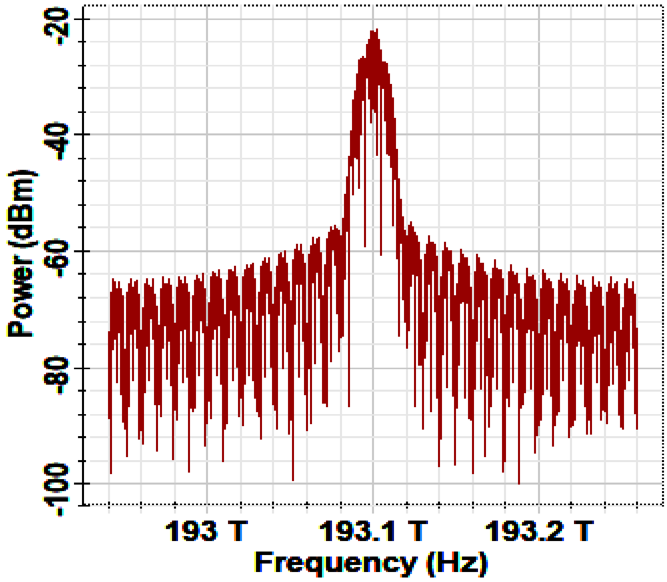
As shown in Table 3.1, for proposed system configuration, signal transmitted at equal bit rate 10 Gbps by using both DQPSK-NRZ and DPSK-NRZ modulation formats. The channels transmitted and received at 1550 nm reference wavelength. A bidirectional single mode is used for whole transmission process. The sequence length considered for our system is 64. It based on the simulation objectives and the length of the bit sequence depends on number of bits e.g. 2^N

3.4 RESULTS AND DISCUSSIONS

Comparison has been proposed for the several transmission distances in WDM passive optical network by incorporating DQPSK-NRZ and DPSK-NRZ. Optical spectrums of DQPSK and DPSK are depicted in Figure 3.5 (a) and (b) respectively and multiplexed signal of aforementioned modulations are in (c) and (d) respectively.



(a)



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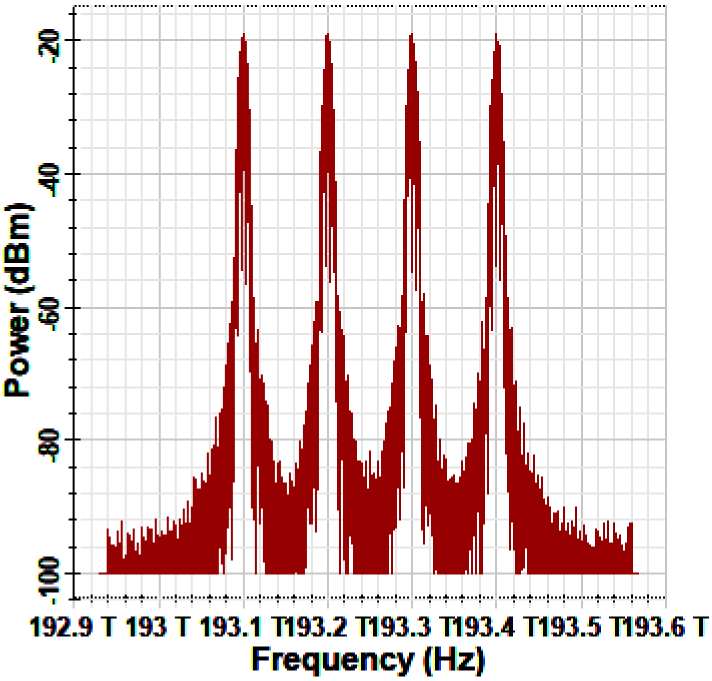
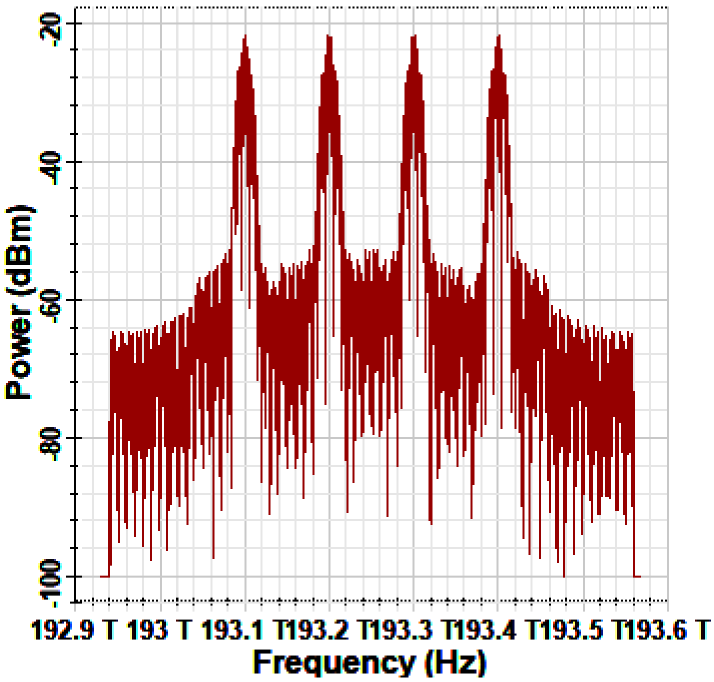


(c)



(d)

Figure 3.5 Optical spectrums of (a) single Channel DQPSK (b) Single channel DPSK (c) Multiplexed DQPSK (d) Multiplexed DPSK

Q-factor changes with respect to transmission distance. The distance varied from 10 km – 50 km, at every 10 km. Results are shown in Figure 3.6. in terms of Q factor over various considered distances. It is obvious that by enhancing the fiber length, system more effected by attenuations, dispersion and nonlinearities. Consequently it also influenced the Q factor and degrades the system performance. Results also revealed that

Q factor of DQPSK decreases to less extent as compared to DPSK. It is due to reason that in bidirectional DPSK-NRZ system, due to phase shifting of only two phases, more distortions are present as compared to DQPSK-NRZ WDM passive optical network.

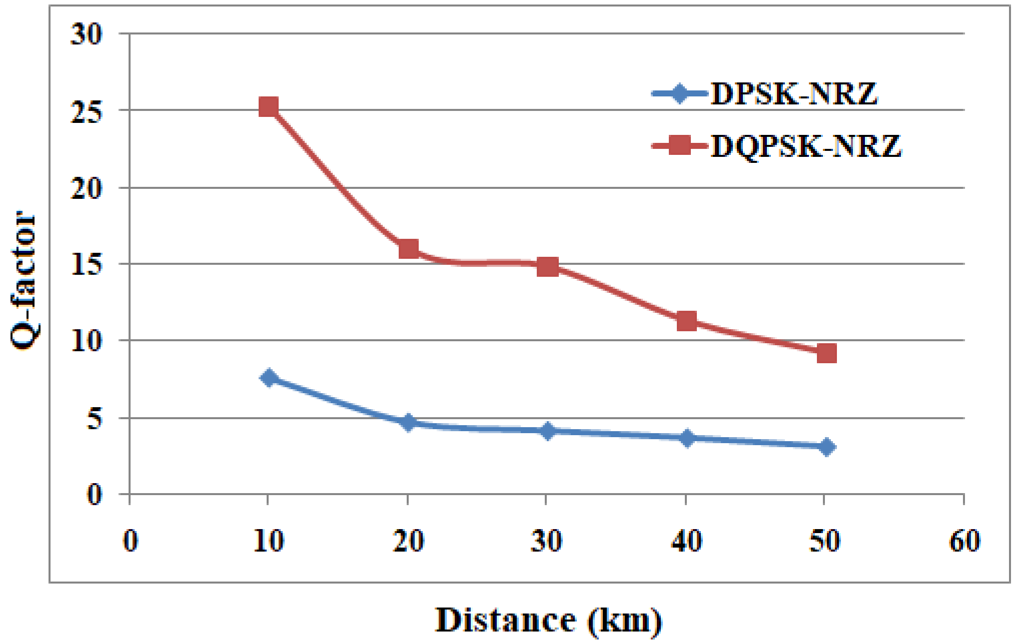


Figure 3.6 Representation of distance versus Q-factor for downstream

At 10 km coverage, value of the Q factor for DQPSK is 25.2 and at equal distance, 7.64 Q factor for DPSK. It is observed that DPSK-NRZ system works at only 25 km. But in DPSK-NRZ system signal forward to 50 km with acceptable value of Q i.e. 6.

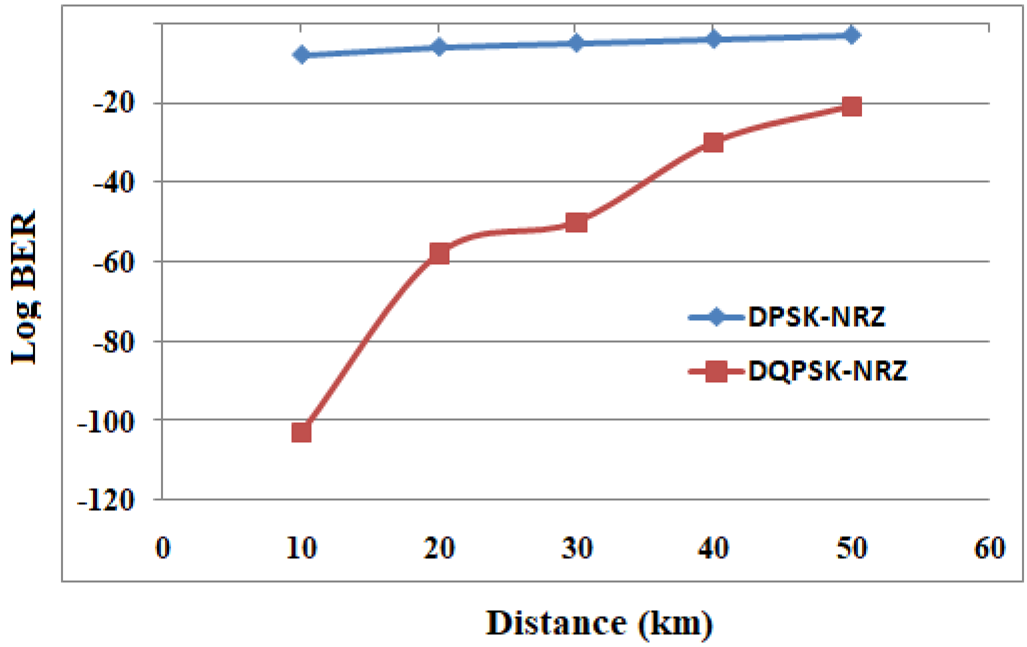


Figure 3.7 Representation of distance versus Log BER for downstream

Bit error rate is most imperative parameter for every system configuration. It tells the system performance of the system that whether it is valid or not for valid for specific communication. It is defined by the ratio of the errors in bits after transmission at receiver to the total bits transmitted from central office. Acceptable range of BER is 10^{-9} for appropriate modulation formats in optical communication. Figure 3.7 depicts the variation of LoG (BER) with respect to link length. Q factor and BER are inversely proportional to each other. If BER is higher in value, more errors are emerges at large distance area rather that less coverage area. Log BER is more in the DPSK NRZ system as compared to DQPSK-NRZ system. Reasons again are the different linear and nonlinear factors that emerge in fiber optic communication.

Again study and examination of the framework has been done for upstream with two different cases such as DQPSK-NRZ and DPSK-NRZ. NRZ is prominent line coding technique for both the upstream transmissions, irrespective of the transmitter modulation in the downstream. Figure 3.8 depicts the performance of NRZ signal in upstream for diverse link lengths. Fiber nonlinearities also degrade the performance of upstream signal. Q factor decreases as the link length increase from 10 km to 50 km. The value of Q factor for DQPSK-NRZ is 18.32 and for the DPSK-NRZ system, it is 7.32. From above comparison, system parameters functionalities for both techniques, DQPSK-NRZ is superior to DPSK-NRZ due to less errors and high Q in WDM-PON.

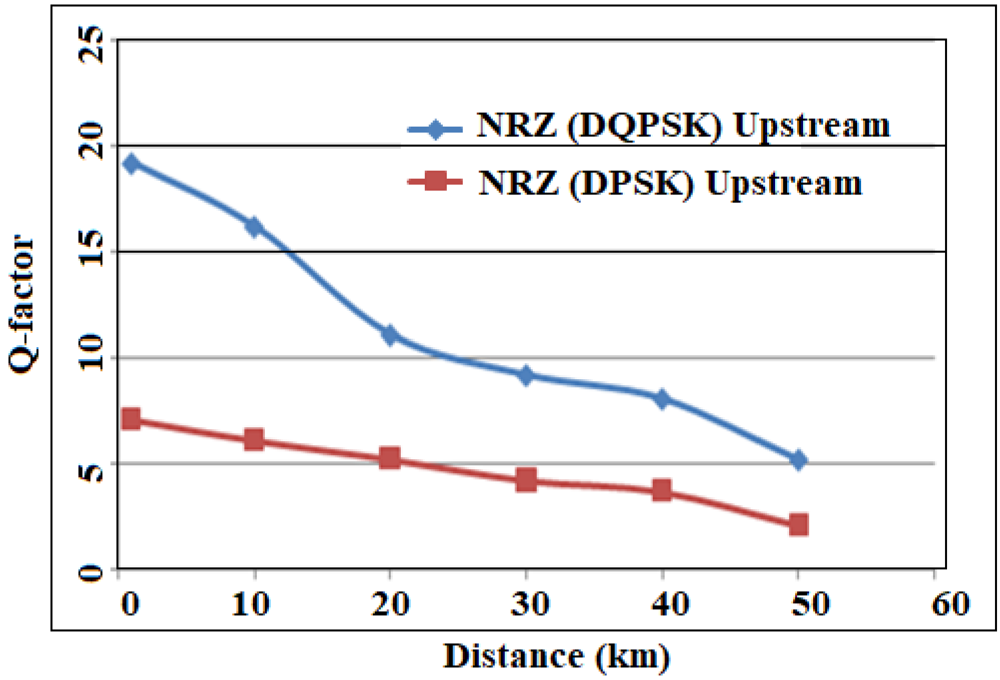


Figure 3.8 Representation of distance versus Q-factor for upstream

Eye diagram is the decision depiction of signals and provide results of Q factor, bit error rate etc. Eye diagrams of demonstrated system are shown in Figure 3.9. In case of DQPSK-NRZ WDM passive optical network, eye diagram is represented at 40 km in Figure 3.9 (b) and for DQPSK-NRZ signal back to back is depicted in Figure 3.9 (a).

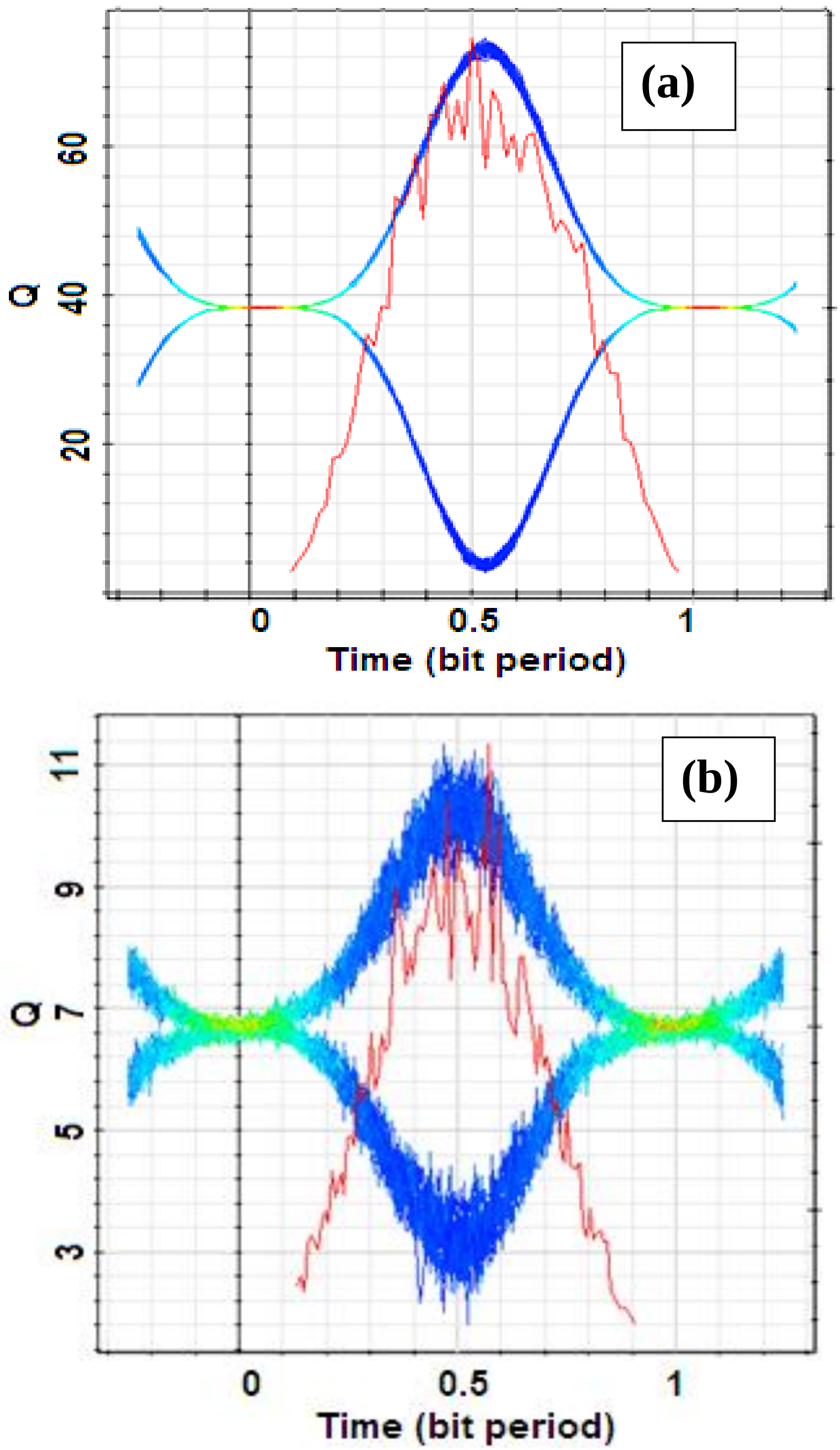
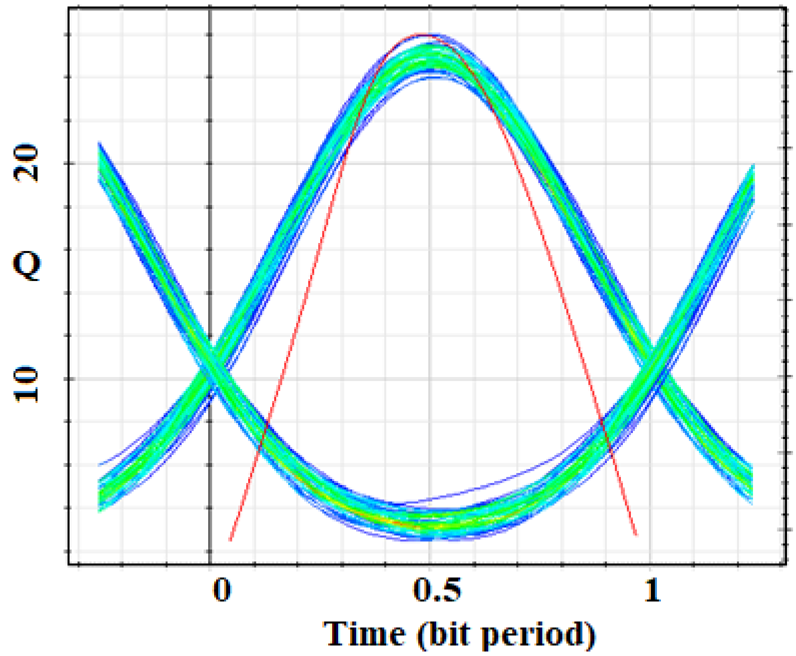
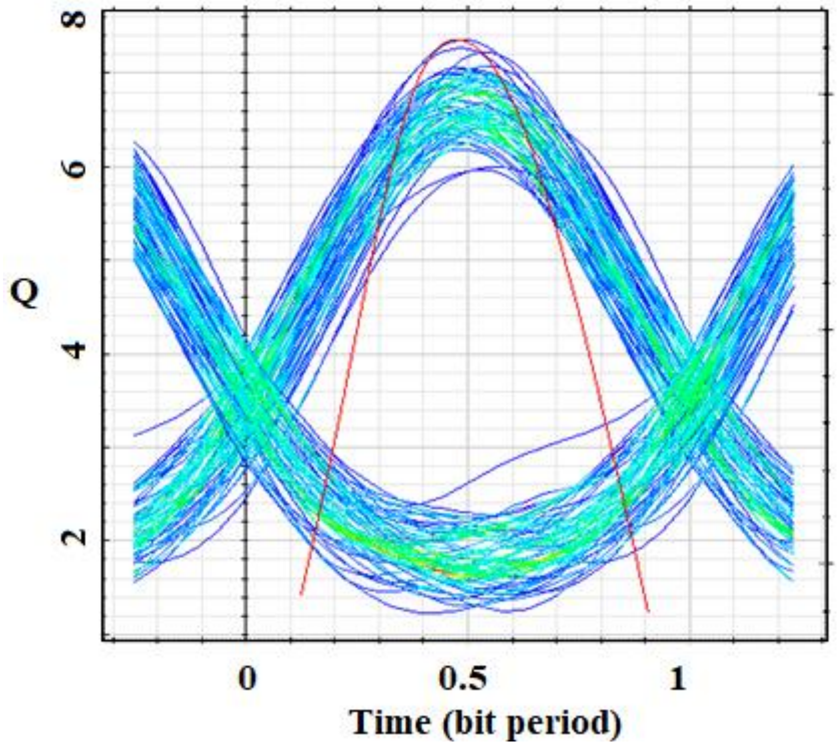


Figure 3.9 Eye diagram for (a) B-T-B (b) 40 Km for DQPSK

Fig.3.10 (a) (b) depicts the Eye diagram curves at back to back and after 40-km distance in the context of non return to zero modulation for upstream. RSOA is used to re-modulate the data from PRBS and NRZ. The results revealed that the Eye diagram is very sharp and thin for back to back analysis and it is thicker for 40 km distance. Furthermore, it is evident from Figure 3.10 that the 10 Gbit/s uplink NRZ signals can attain BER of 3.2×10^{-17}. Therefore, with DQPSK-NRZ, we successfully achieved the 40 km link distance.



(a)



(b)

Figure 3.10 Eye diagram for (a) B-T-B NRZ (b) 40 Km for NRZ

3.5 CONCLUSION

In this work, a transmitter diversity based bidirectional WDM-PON system with 4 channels at 10 Gbps for upstream and downstream incorporating different modulations such as DQPSK and DPSK is investigated. Reflective semiconductor optical amplifier has been used for re-modulation of a downlink signal. RSOA is cost effective and used as modulator well as amplifier. System is investigated over diverse distances and it is found that DQPSK-NRZ system performs better than the DPSK-NRZ system in terms of Q factor and BER. Transmitter diversity has great impact on the system performance and also reduces crosstalk between downstream as well as upstream channels.

CHAPTER 4

TO PROPOSE A POLARIZATION INTERLEAVED BIDIRECTIONAL WDM PASSIVE OPTICAL NETWORK INCORPORATING DIFFERENT STATES OF POLARIZATIONS IN ULTRA DENSE SYSTEM

In this chapter, WDM-PON at ultra dense channel spacing is investigated incorporating polarization interleaving. Polarization diversity is included in the system to reduce the polarization interference among WDM channels. Also, numerous performance betterment effects are perceived from the investigation and system works at data rate of 20 Gbps over the distance of 40 km. This research article investigates the performance of 4 x 20 Gb/s WDM-PON system incorporating polarization interleaving technique at 25 GHz channel spacing and wavelength reuse is also done in the system. Moreover, comparison of system with and without polarization diversity has also been done. It is evident that different states of polarizations increase the performance of the system as compared to single SOP.

4.1 INTRODUCTION

In access networks, mostly transmission channels are made out of copper, twisted pair and coaxial cables. These cables are more stable for all communication system for high reliability and better performance. But side by side, their no. of drawbacks including high maintenance cost and complex system design etc makes them unfit for the high speed transmission. These networks also require high power supply. In modern days, all systems requires a cost efficient and less complex infrastructure features. In PON, due to the non-presence of any active splitter, it needs only external power less components, for that reason power issues as well as heating effects are not play a role here. Therefore, in order to offer services of broadband to users, various network are realized for lowering the overall cost such as FTTH/FTTP network. However, power declines because of kerr effects such as Polarization crosstalk and inter-channel crosstalk. Different approaches are made to compensate these issues by using WDM and TDM technology, multiple modulators, hybrid modulations etc. But these approaches are complex and do not supports high speed.

In this work, Wavelength division multiplexing based passive optical network at ultra dense channel spacing is investigated incorporating polarization interleaving. Polarization diversity is included in the system to reduce the polarization interference among WDM channels.

4.2 POLARIZATION DIVERSITY

From all communication system, some system out of all the systems does not acquired polarized laser intensity. According to this statement of linear polarization is, a linear polarization is, where the electric field oscillates in only one path orthogonal to the propagation of the laser intensity. However, fiber lasers do not generate a one direction electric field. But not necessarily the laser output is always un-polarized, by using same powers in two polarizations simultaneously, not including any correlation of the consequent amplitudes. Due to several reasons, polarization is not stable such as temperature drifts, randomly switches between various directions are causes of limitation.

In order to generate the one direction variation of electrical field vector, various polarization fixing devices are required. Degree of polarization is basically measured with polarization extinction ratio (PER), defined as the ratio of powers in the diverse polarization directions and calculated by recording the orientation-reliant power transmission of a polarizer. Polarization diversity is an effective approach to suppress the impact of inter-channel nonlinear effects by fixing the adjacent channels polarization. Our goal is to design a WDM system, such that the bit streams in two neighbouring channels are orthogonally polarized. The even and odd number channels are multiplexed with each other into different branches that have orthogonal states of polarization (SOPs). To stable Polarizations, linear polarization controllers are used to keep channels orthogonal. Based on the polarization of adjacent channel polarization basic methods are kept in to suppress the cross phase modulation and four wave mixing. As a result, inter channel collisions generates smaller shifts of phase and direct to very less jitter and jitter amplitudes.

4.3 SYSTEM SETUP

Optiwave's OptiSystem^{TM} Simulation tool is used for proposed architecture to implement, investigate and simulate communication system in optical domain. Figure 4.1 represents the proposed DQPSK WDM passive optical network for downstream link and NRZ WDM PON for upstream link at 20 Gbps information rate with 4 WDM channel. Polarization interleaving is employed in WDM PON to eliminate the inter-channel crosstalk. A 193.1 THz frequency is used for laser light wave source with dBm input power. A polarization of even and odd channels is changed to decimate nonlinear effects. The linear polarizers are used to remove an orthogonal component by sending the linear polarization component that combine with the transmission axis of the polarizer. Odd channels from λ_1- λ_3 carry same polarization and state of polarization (SOP) is fixed to 0 degree in linear polarizer. Even channels λ_2- λ_4 have the state of polarization orthogonal to odd channels i.e 90 degree. The modulated DQPSK WDM signals are accumulated with the multiplexer of two 2 x 1, as well as the multiplexed signal is transmitted over 40km SMF-28 (single-mode fiber) and demultiplexed by 1 x 2 wavelengths by 25 GHz frequency spacing .

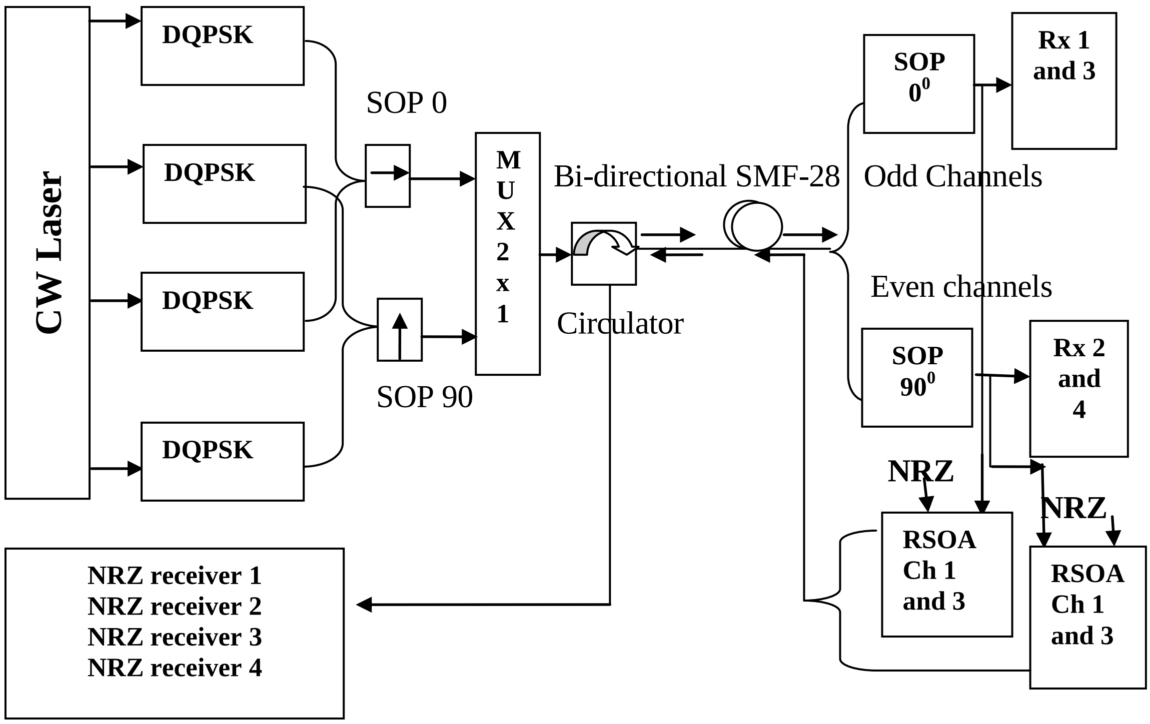


Figure 4.1 Proposed polarization interleaved WDM-PON

Optical couplers with 50:50 coupling ratio and PIN photo detector with 10 nA dark current are placed in the receiver by considering shot, thermal and ASE distortions. Electrical bias used to provide electrically subtracted output of balanced photo detectors followed by 3-R regenerator.

A 3-R regenerator is directly connect to BER analyzer to generate the eye diagram of downlink stage employed for re-sampling, re-shaping and re-amplification of the received signal and it directly connect to BER analyzer to generate the eye diagram of downlink stage. Bit error rate analyzer is used calculate the final received quality factor, BER, SNR. One half of downstream DQPSK signal is demodulated and other half is provided to the re-modulation. Reflective amplifier is used to demodulate the NRZ signal over four frequency channels and multiplexed to travel for upstream at 40 km transmission. PIN photo-diode used for detection and de multiplexing of received signal, it is followed by low pass filter and Eye diagram analyzer.

4.4 RESULTS AND DISCUSSIONS

In order to design a polarization crosstalk suppressed systems, a passive optical network employing polarization interleaving is proposed. A system consists of 4 wavelengths and each wavelength is modulated with DQPSK modulation for downstream at central office. Two WDM multiplexers are used to separately combine the 2-2 wavelengths. Even wavelengths and odd wavelengths are combined differently with these two multiplexers. Then odd channels are fed to polarization rotator that pass only horizontal polarization signals and even channels are projected to orthogonal polarizer. Polarizations combined and signal sent over 40 km long stretch of single mode fiber and followed by 1 x 4 de-multiplexer. Received wavelengths are divided into two parts such that half of the power provided to DQPSK decoder and other half is given to RSOA for re-modulation. Wavelengths are re-modulated at ONU with NRZ data and RSOA. Multiplexed signals are sent again over 40 km SMF and received with receiver that consists of photo-detector, low pass filter and BER analyzer.

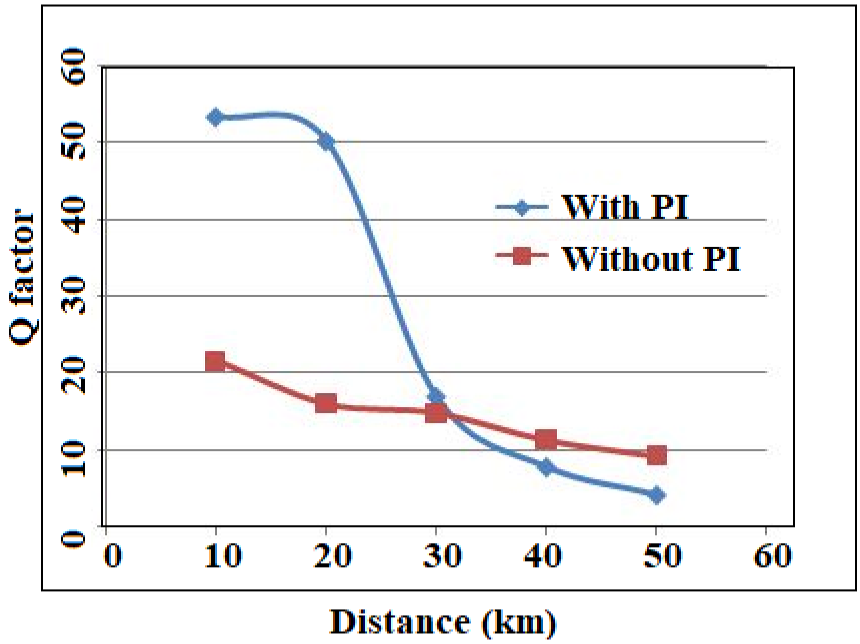


Figure 4.2 Graphical representation of Q factor with respect to different distances

First and foremost, the investigation of proposed system has been done by taking different distances into consideration. Loop length is varied from 10 km to 50 km with the gaps of 10 km. To evaluate the results, Q factor is noted from Eye diagram analyzer. Figure 4.2 represents the Q factor versus link length for with and without polarization interleaving in WDM-PON.

Table 4.1 Values of Q factor with respect to distance

Distance	With PI	W/O PI
10	53.48	21.59
20	50.33	16
30	16.96	14.84
40	7.76	11.33
50	4.11	9.26

It is reported that with the increase in the link length, there is significant reduction in Q factor of the signal. Also, two different scenarios are proposed by considering the polarization interleaving and without polarization interleaving. Q factor decreases due to numerous factors such as the attenuation, pulse broadening, crosstalk among different channels etc. However, in this work, we accentuated on polarization crosstalk that emerges in multi-channel WDM systems and plays a vital role in signal degradation. It is evident from the investigation that because of the different states of polarization in even and odd channels of the proposed system, Q factor is obtained better well than without polarization interleaved system.

By using different states of polarizations, minimize the interaction of signals between different wavelengths. This phenomenon led to increase the value of Q factor without polarization interleaving, Q factor greatly dropped at 45 km distance as compared to with polarization interleaved system as given in Table 4.2.

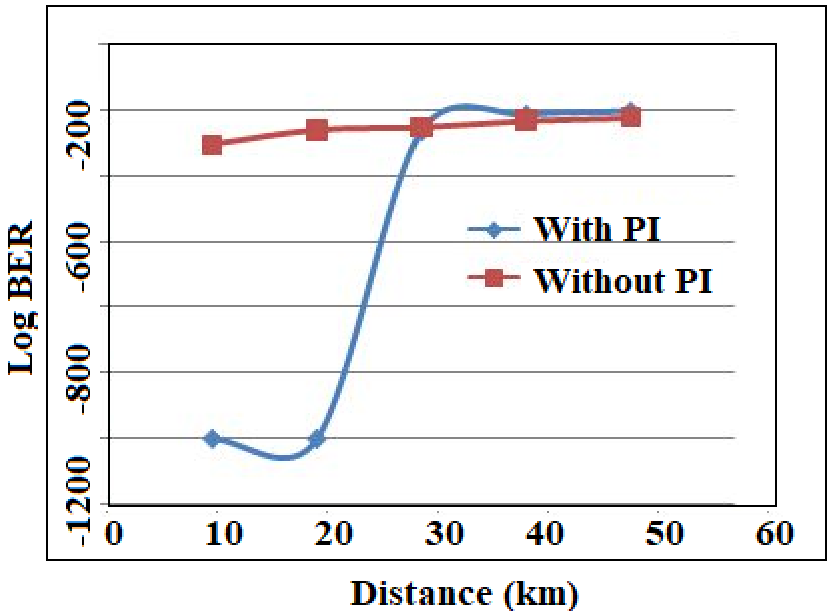


Figure 4.3 Graphical representation of LoG (BER) versus distance for proposed WDM PON

Figure 4.3 represents the LoG (BER) values when link length is varied from 10 km to 50 km. At this state link distance is directly proportional to Bit error rate. It is major parameter which degrades the System performance. But currently proposed system that incorporates polarization interleaving, shows less errors as compared to without interleaved WDM passive optical network. Differential quadrature phase shift is employed in the system to solve the crosstalk problem between upstream and downstream channels.

By using DQPSK modulation inter symbol interference (ISI) decimates due to four unique phases. Inter channel interference (ICI) also introduced in WDM PON. With employing polarization interleaving, this major disadvantages are reduced at extreme level. Value of the LoG (BER) is more in without polarization interleaved system and thus polarization inter leaving is recommended to use for better outcomes.

Maximum supported Distance is considered in terms of Q factor and BER is 40 km. Now, study the effect of input power on Q factor, LoG (BER) and signal to noise ratio (SNR) of the system. So, in the proposed WDM passive optical network, launched power is varied from the laser source from -10 dBm to 5 dBm with the difference of 5 dBm. Figure 4.4 depicts the variation of Q factor with the launched power for with and without polarization interleaved system.

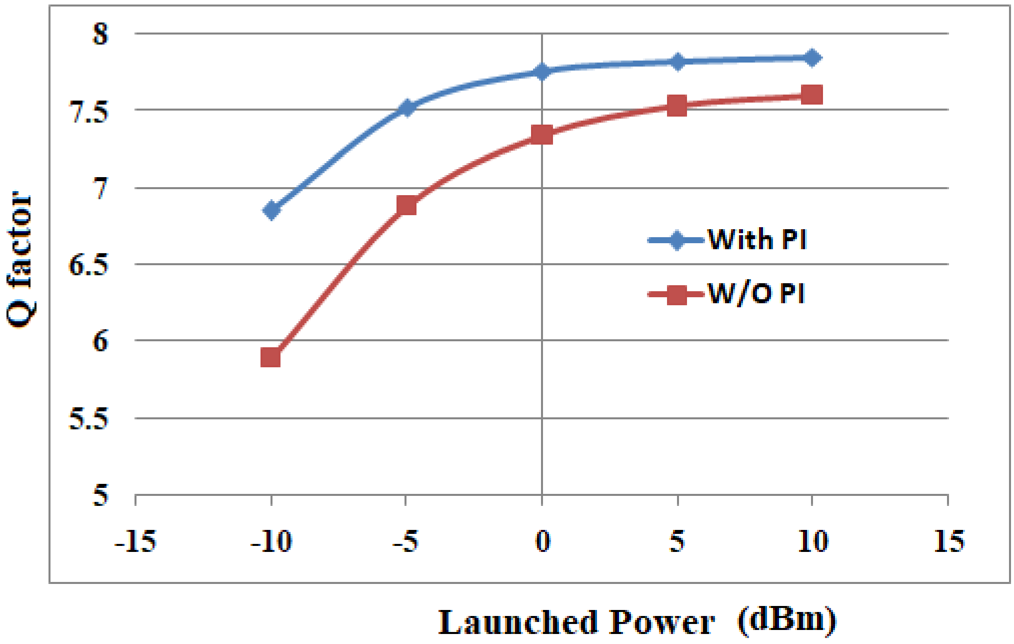


Figure 4.4 Representation of variation of Q factor with the launched power for with and without polarization interleaved system

Table 4.2 Values of Q factor versus launched power for with and w/o polarization interleaving

Power	With PI	W/O PI
-10	6.85	5.89
-5	7.52	6.88
0	7.76	7.34
5	7.82	7.53
10	7.85	7.6

From the results as given in Table 4.2, it is observed that with the more power coupling into optical fiber, Q factor rapidly increase and Increase in launched power serve as a power budget and it also initiates the nonlinear effects due to the refractive index variations. At 5 dBm setup power and these nonlinear effects do not degrades the system performance. By determining, WDM passive optical network with polarization interleaving, it provide better Q factor than without polarization interleaving.

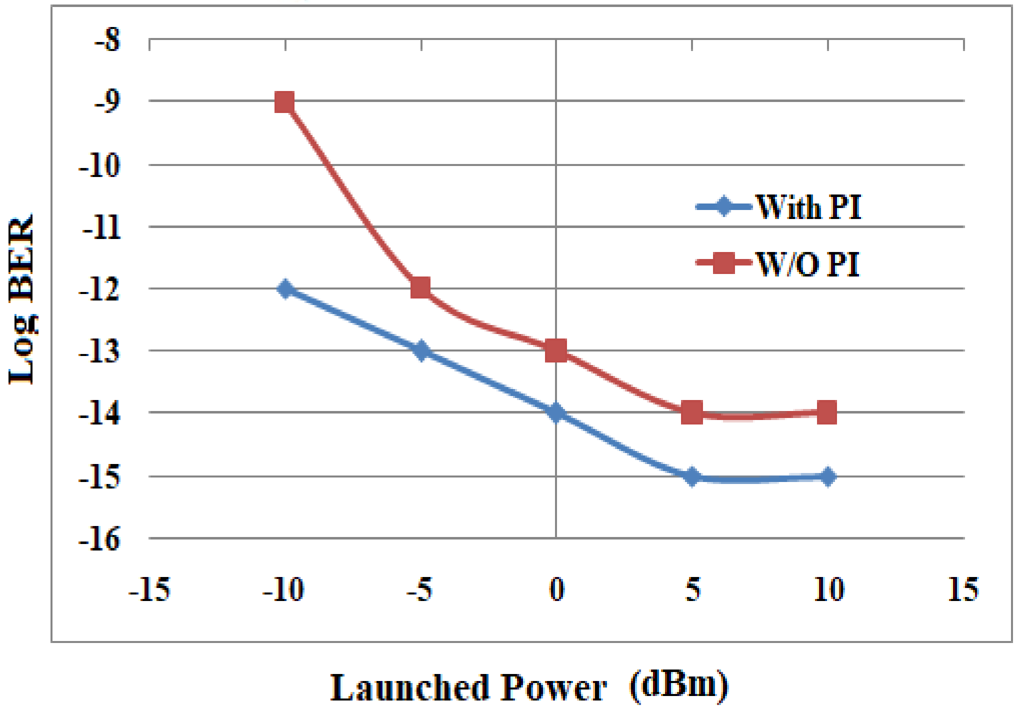


Figure 4.5 LoG (BER) versus launched power

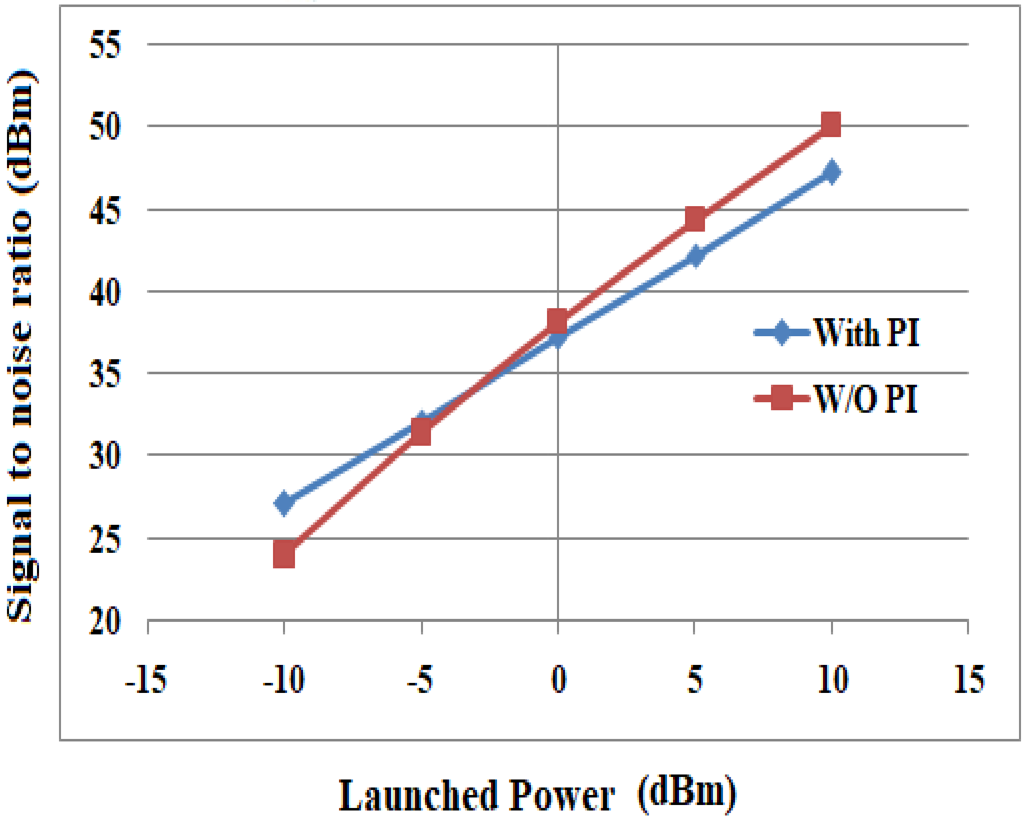


Figure 4.6 Signal to noise ratio of proposed system at 40 km for different levels of launched powers

Table 4.3 Values of SNR at different power levels

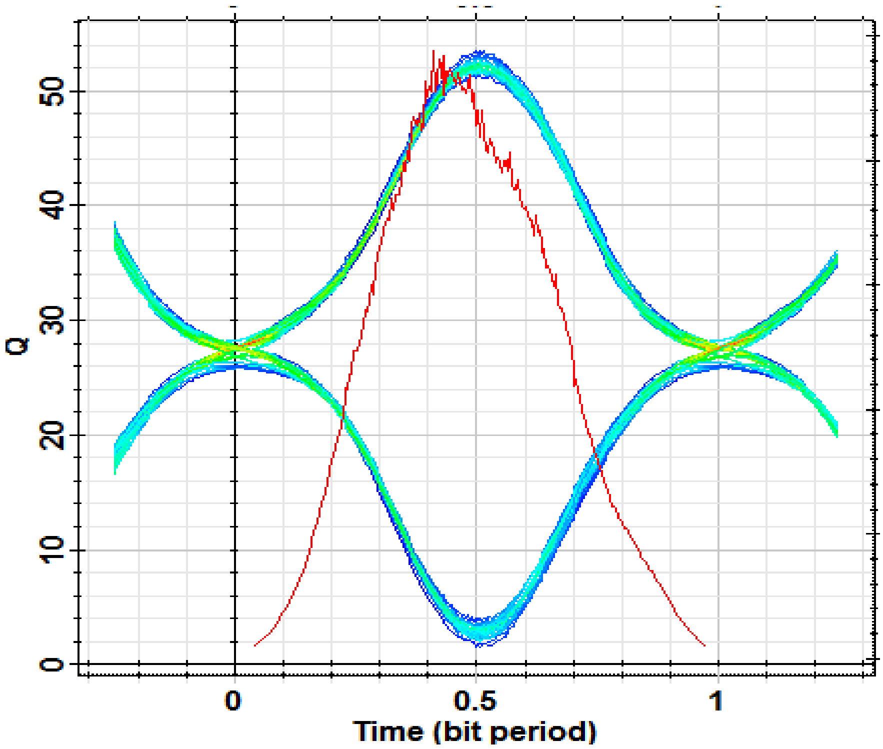
Power	With PI	W/O PI
-10	27.06	23.94
-5	32.14	31.4
0	37.19	38.18
5	42 .22	44.36
10	47.23	50.1

Figure 4.3 represents the LoG (BER) versus launched power in the system. It is observed that high power values improves the BER and provide less BER for high powers that are launched in optical fiber. Bit error rate is more in simple WDM passive optical network without incorporation of polarization interleaving.

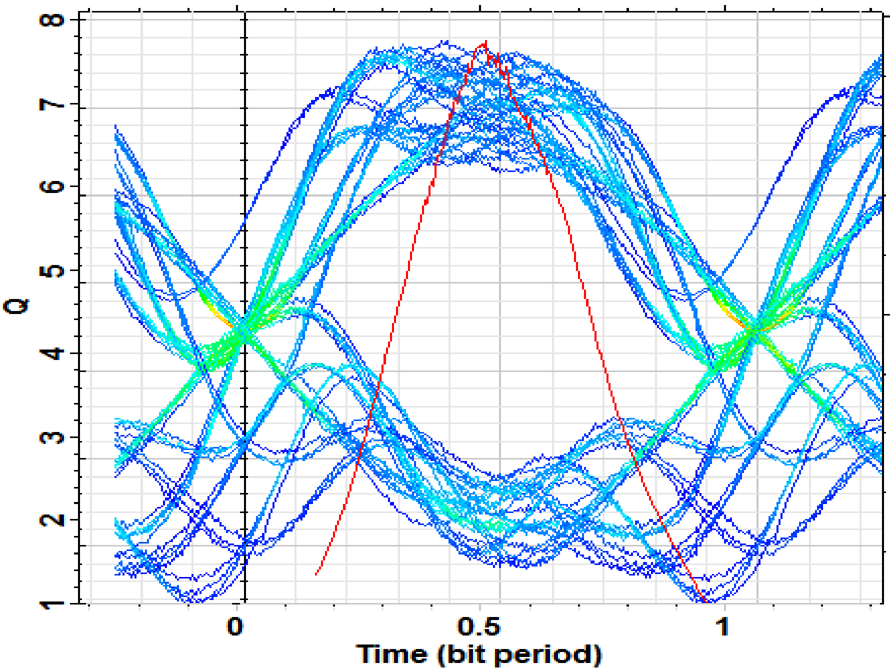
Values of SNR at various power level are shown in the Table 4.3. By increasing the launched power, signal to noise ratio SNR is also obtained more in the polarization interleaved system till the launched power level of 0 dBm and less in case of the powers more than 0 dBm due to negligible nonlinear effects. Without interleaving system, SNR is less till 0 dBm and increase further due to system distortions.

Q factor and no. of bits of the system with and without polarization interleaving are represented through the eye diagram in Figure 4.7 and Figure 4.8 for varied link lengths, powers respectively. It is reported that Eye opening is more in case of 10 km link distance and closer increase with the increase in the distance. This is main reason that there significant attenuation, dispersion and nonlinear effects the fiber optic system It is examined that at 10 km eye height is more as compared to 50 km and jitter is also less. Thickness of eye diagram is more at large no. of errors and less Q factor. Figure 4.7 (a)

(b) represents the Eye diagram at 10 km and 40 km in case of polarization interleaved system.



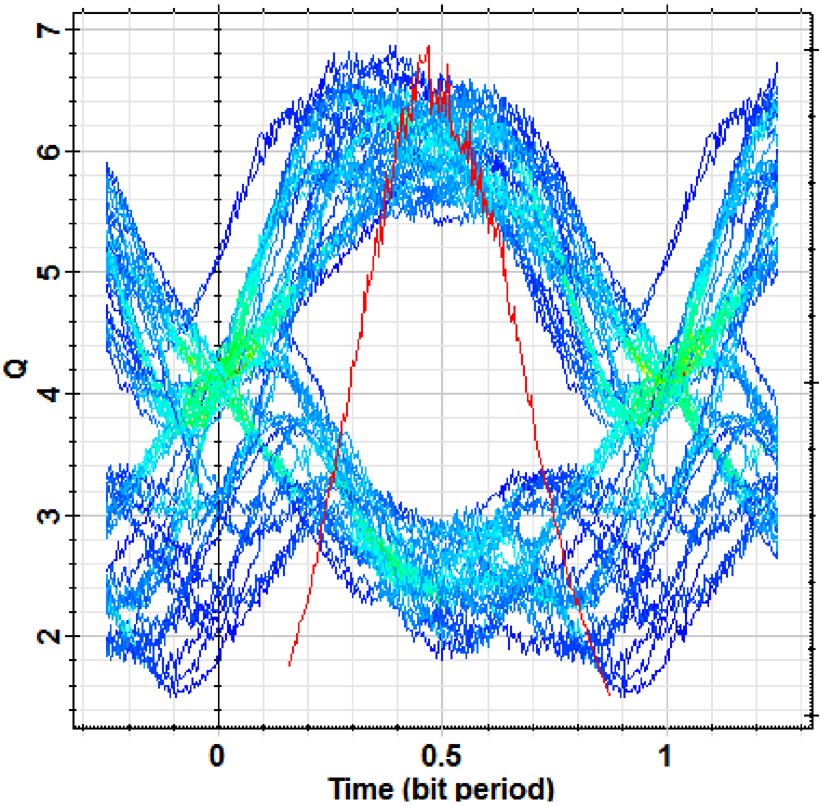
(a)



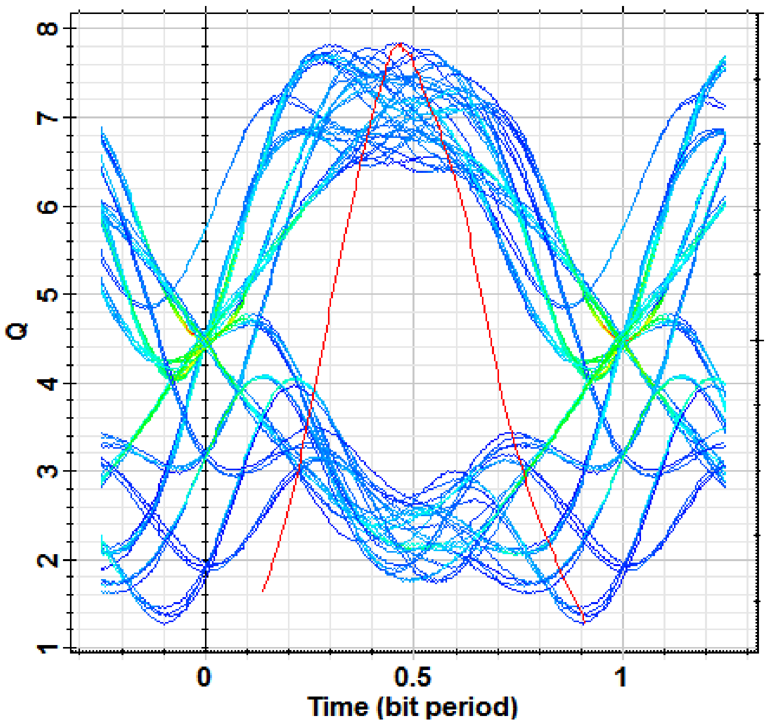
(b)

Figure 4.7 Eye diagrams for polarization interleaved WDM passive optical network at (a) 10 km and (b) 50 km

Also, Figure 4.8 depicts the performance of the polarization interleaved system at several launched power levels such that -10 dBm and 10 dBm. It is seen that the Eye opening is more in case of the 10 dBm and eye closer is more at low input power -10 dBm.



(a)



(b)

Figure 4.8 Graphical representation of the system Eye diagrams for (a) -10 dBm and (b) 10 dBm

4.5 CONCLUSION

A WDM passive optical network is to suppress inter channel and polarization crosstalk and solution for increasing the bandwidth is proposed. The combination of both techniques provides large data rate and high bandwidth demand .This research work enhanced the performance of 4 x 20 Gb/s WDM-PON system using polarization diversity. The high speed system is attained to fulfil the large bandwidth requirements of PON by employing WDM system at channel spacing of 25 GHz. Simulation Results are developed successfully by comparing a two different systems i.e. with and without polarization interleaved WDM-PON system. It is observed that WDM-PON with polarization interleaving cause fewer errors and provide enhanced performance as compared to without polarization system. At less distances link and less power levels, the values of Q factor and SNR are minimum and BER is more. By using DQPSK-NRZ and polarization interleaving technique, system successfully works at 50 km and is suppressed the polarization crosstalk and ISI effects Thus, WDM passive optical networks is good technique which is more suitable for new specification that the communication must contains to achieve the increase in demands in communication field with minimum cost and long distance as well as data high data.

CHAPTER 5

AN ULTRA DENSE MAINTENANCE FREE COST EFFECTIVE WDM-PON SYSTEM WITH POLARIZATION INTERLEAVING AND PULSE WIDTH REDUCTION

In this chapter, a cost effective and easy maintenance based dispersion compensation technique is proposed in ONU of the wavelength reused WDM reliant PON. Moreover, in order to suppress intra-channel crosstalk DQPSK is employed for downstream and for inter-channel crosstalk suppression, polarization interleaving is used in the system. Furthermore, for the investigation of proposed system in terms of dispersion reduction, three different scenarios are considered such that system with only DCF, linearly chirped FBG and joint module of DCF+FBG. System has total 4 channels and each has bit rate of 20 Gb/s with 25 GHz channel spacings. It is observed that joint module of DCF+FBG has maximum ability to compensate dispersion and linearly chirped FBG has least performance. Proposed joint technique for pulse width reduction in ONU is cost effective, highly efficient to combat with pulse width reduction issues and also needs very less maintenance.

5.1 INTRODUCTION

With the explosive increase in the bandwidth hungry internet applications, pressure is continuously increasing on the optical networks [30]. Passive optical networks (PON) are key technologies to cater the demand of high speed services with low cost and by supporting multiple users [31]. There are different variants of passive optical networks standardize by international telecommunication union [32]. Time division multiplexing is an attractive variant of PONs that has been employed to fulfill the demands of broadband services. However, time division multiplexing suffers from the issue of bandwidth sharing [33] [34]. In order to utilize the bandwidth of the optical fibers, researchers worked on the wavelength division multiplexing based PON. WDM based PON systems are well competent and has potential to support large distance and users. It rises as a key innovation for the next generation FTTH technology [35]. Wavelength reuse in the WDM PONs is widely employed because it saves the cost of the system by eliminating the requirement of laser source in the optical network unit [36]. Signals from the central office towards ONU is termed as downstream and are re-modulated in uplink i.e. transmitted back to OLT (optical line terminal) [37] [38]. Advantage of wavelength reuse is that downlink as well as uplink uses same wavelength for the operation and enhance the efficiency of wavelength utilization [39][40][41]. Modulation of the signal also plays a vital role to decide the performance of the optical networks [42]. Differential Quadrature phase shift keying provide high bandwidth or spectral efficiency and less prone to pulse broadening effects. Therefore competent enough to prolong the transmission distance between OLT and ONU. Phase shifting modulation offers high extinction ratio, less prone to dispersion and nonlinear effect [43][44]. Transmission distance enhancement at high data is limited to short distance due to effects of dispersion. Numerous works has been reported to compensate pulse broadening inside optical fiber. Dispersion compensation fiber [45], fiber bragg gratings [46] and optical phase conjugations [47] are widely employed in the optical networks. However, DCF has high efficiency to compensate pulse width broadening but comes at the high cost and increase the overall cost of the system. PWR efficiency of FBGs is less but they are cost efficient [48]. Similarly, optical phase conjugations (OPCs) make system complex and expensive [49]. High speed optical networks are severely vulnerable to PWB (pulse width broadening) issues and limit the total reach of the system.

In this work, a cost effective and easy maintenance based dispersion compensation technique is proposed in ONU of the wavelength reused ultra dense WDM-PON. Also, inter-channel and intra-channel crosstalk are suppresses by using polarization interleaving and DQPSK respectively. A cost effective and high efficiency PWR joint module is proposed for the ONUs.

5.2 SIMULATION SETUP

Proposed ultra dense wavelength reused WDM PON employing polarization interleaving is depicted in Figure 5.1. To realize the proposed system, an important and compendious tool Optiwave's OptiSystem^{TM} is used. Data rate of the proposed work is fixed to 20 Gbps and differential quadrature phase shift keying modulation is employed for downstream data transmission. To reduce the interference hetero modulations are given to downstream channels and upstream channels. For uplink, NRZ is incorporated and also to reduce inter-channel interference, polarization interleaving done among the different channels of WDM. Total 4 WDM channels in C-band are considered and frequency starts from 193.1 THz. Input power of the system is 0 dBm and it comes from the CW laser. Diverse polarizations are given to even and odd channels by linear polarizer that coincides with the transmission axis of the polarizer and eliminates the orthogonal component. State of polarization of odd channels λ_1- λ_3 is horizontal and even channels λ_2- λ_4 is vertical. These four PI channels are modulated with DQPSK and multiplexed with 4x1 mux. Multiplexed signal is fed to 40 km SMF-28 which has 0.2 dB/km attenuation and 17 ps/nm/km dispersion. After signal transmission inside optical fiber, it is demultiplexed at the specific frequencies according to the transmitter.

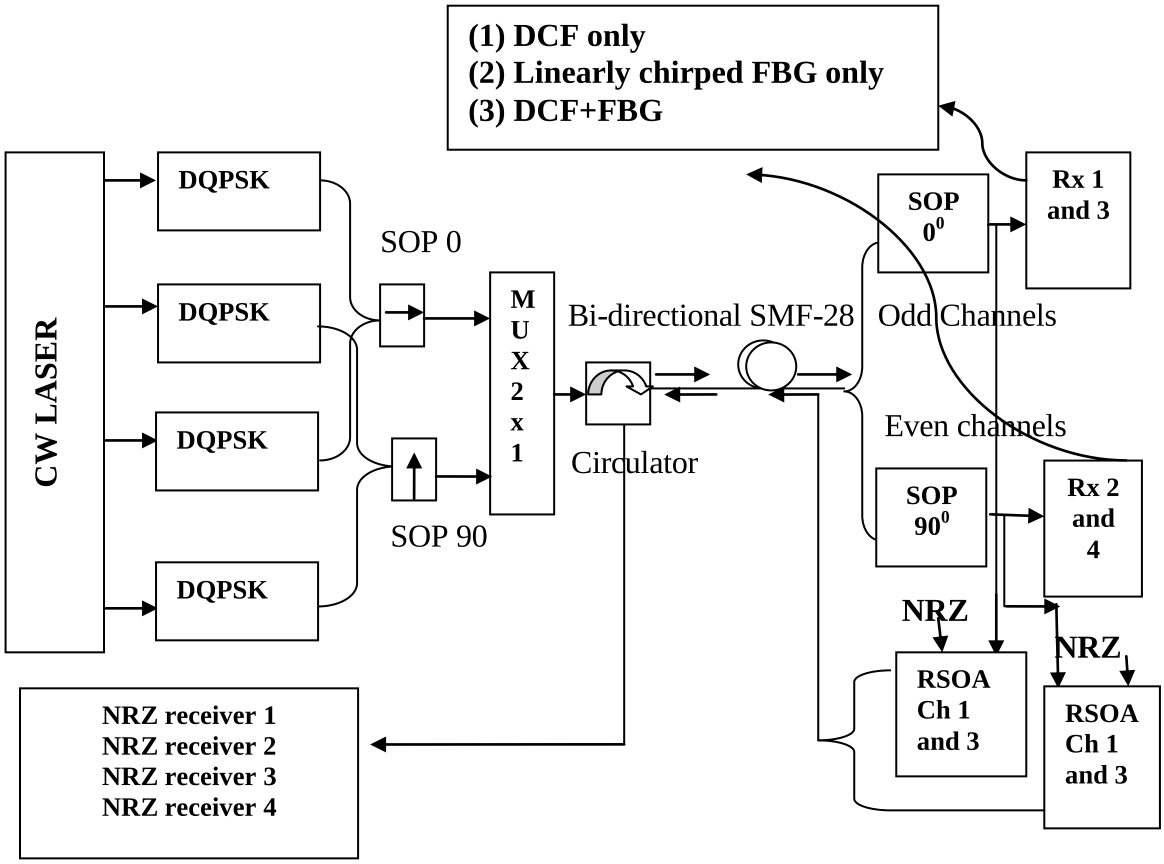


Figure 5.1 Proposed ultra dense and polarization interleaved DQPSK-NRZ WDM PON system

Each signal then passed through the PWR unit. Three different cases are used in PWR module (1) only DCF (2) Linearly chirped FBG and (3) joint module of DCF+linearly chirped FBG. System specifications of proposed model and PWR modules are shown in Table 5.1 and Table 5.2 respectively. After dispersion compensation, signals are decoded using DQPSK receiver which consists of photo-detectors, phase delay, MZI switch, 3-R regenerator and BER analyzer. One half of downstream DQPSK signal is demodulated and other half is provided upstream block for re-modulation. For uplink, 4 NRZ signals are modulated by wavelength reused signal and RSOA. Upstream signal made to pass from same bidirectional optical fiber and received by NRZ receiver.

Table 5.1 System specifications

Parameters	**Values**
Data rate	20 Gbps
WDM Channels	4
Freq. Spacing	25 GHz
Modulation DS	DQPSK
Modulation US	NRZ
Wavelength Re-use component	RSOA
SOP 1	0 degree
SOP 2	90 degree
Photo-detectors	PIN

Table 5.2 Specifications of PWR module

Parameters	**Values**
DCF attenuation	0.5 dB/km
DCF Dispersion	-85 ps/nm/km
FBG length	2 mm
FBG effective index	1.45
FBG chirping	Linear
Linear parameter	0.0001 um

5.3 RESULTS AND DISCUSSIONS

First and foremost, proposed system is investigated to find the pulse width reduction efficiency of the different techniques such as dispersion compensation fiber, linearly chirped FBG and joint module of DCF+FBG over the distance of 75 km of Bi-directional SMF-28. Data rate of the each channel is 20 Gbps and time of one bit is calculated as the 0.5 ns or 50 ps. Optical time domain analyzer is a component which used to represent the bits according to the time and power. An OTDV is placed after the channel 1 and output is as shown in Figure 5.2 (a).

In order to check the effects of pulse width broadening, OTDV is placed after the optical fiber and prior to the receiver of each channel i.e in optical network unit for downstream transmission. A pulse of time 100 ps is seen after 75 km of link distance as depicted in Figure 5.2 (b). For the calculation of the pulse width reduction efficiency of three different modules in ONU, they are employed in the ONU. First of all we consider the case of linearly chirped FBG. Filtered 193.1 THz signal is made to pass through FBG and it reflects the desired signal and compensates the effects of PWB. Time of the bit is observed 60 ps and efficiency of FBG comes out to be 40 % as shown in Figure 5.2 (c).

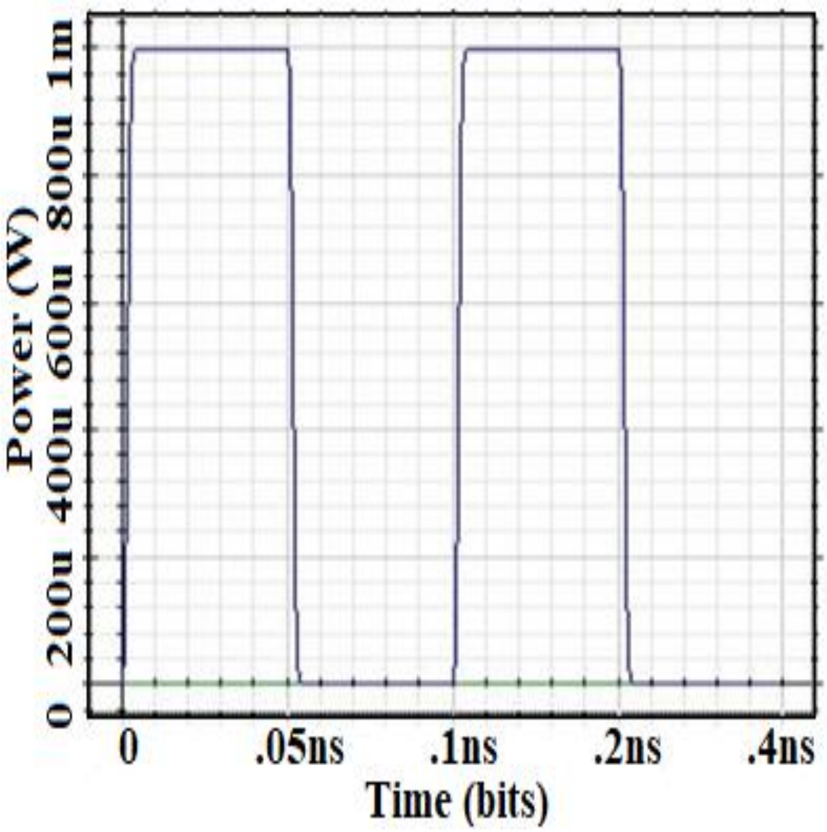
Further dispersion compensation fiber is investigated and it provides the time of pulse 55 ps and thus it is 45 % efficient. A DCF and linearly chirped combined module is placed in this case and it is noteworthy that maximum pulse width reduction is observed for the length of 6 km and 2 mm linearly chirped FBG. Length of DCF is iterated for different values from 5-20 km but optimal results are observed for 6 km. This joint technique provides the pulse of time 52 ns and thus it is 48 %. All the efficiencies are calculated from the formula as expressed in (1)

$$PWR\% = \frac{\text{Time of Broadened pulse} - \text{Time of original pulse}}{Time\ of\ brodened\ pulse} \qquad (1)$$

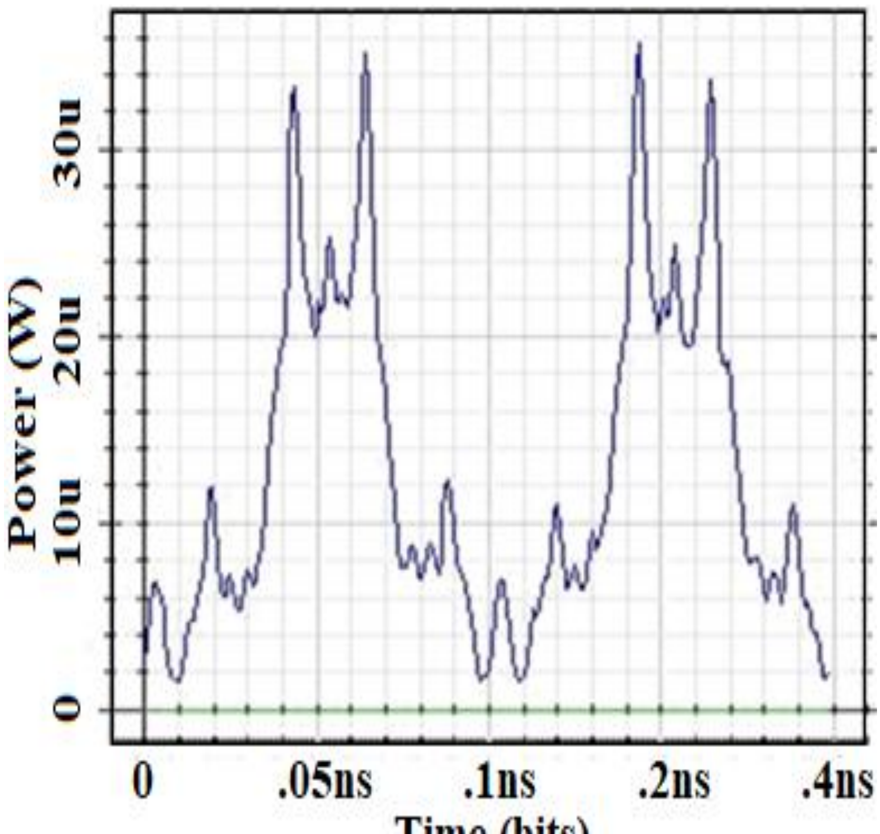
Where PWR-Pulse width reduction

Time of broadened pulse-Dispersed pulse due to dispersion

Time of original pulse-Pulse prior to the dispersion or after transmitter of the optical line terminal


Power (W)
0
200u
400u
600u
800u
1m
0
.05ns
.1ns
.2ns
.4ns
Time (bits)

(a)


Power (W)
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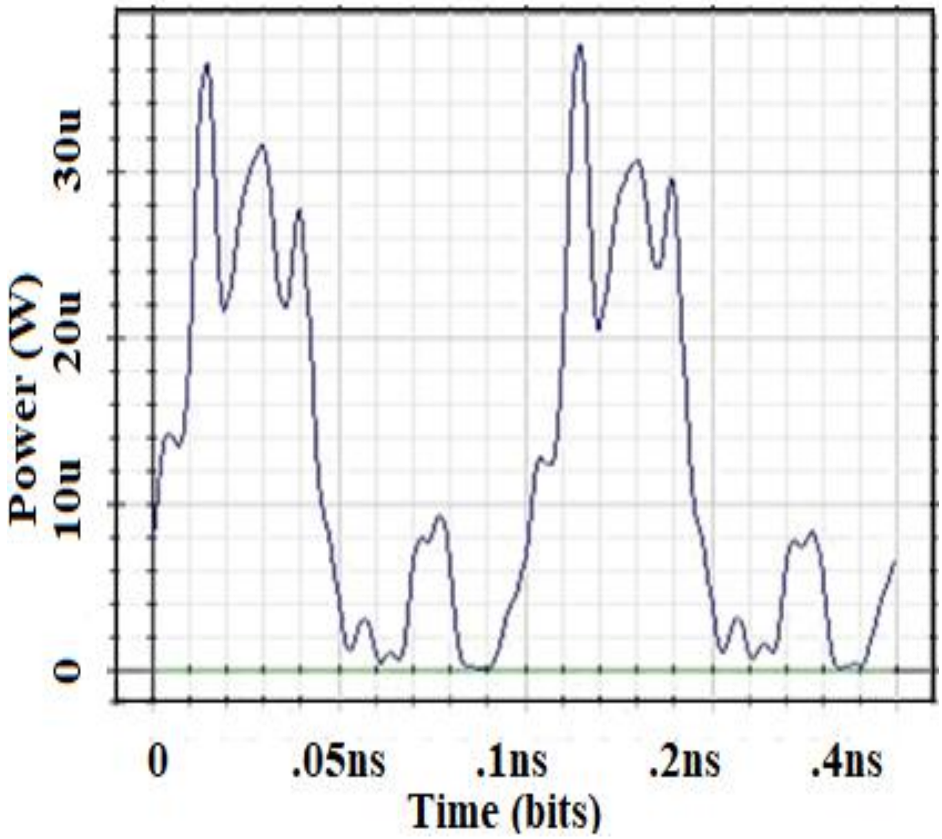
30u
0
.05ns
.1ns
.2ns
.4ns
Time (bits)

(b)


Power (W)
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10u
0
0
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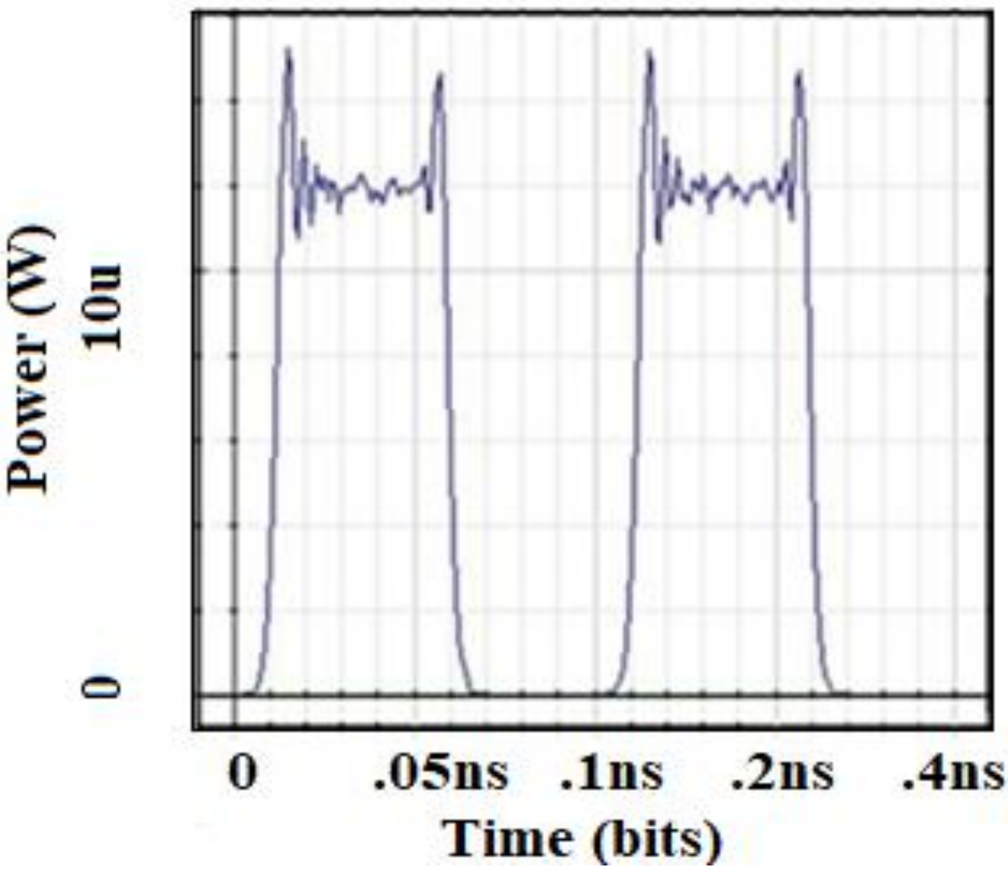
.2ns
.4ns
Time (bits)

(c)


Power (W)
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0
0
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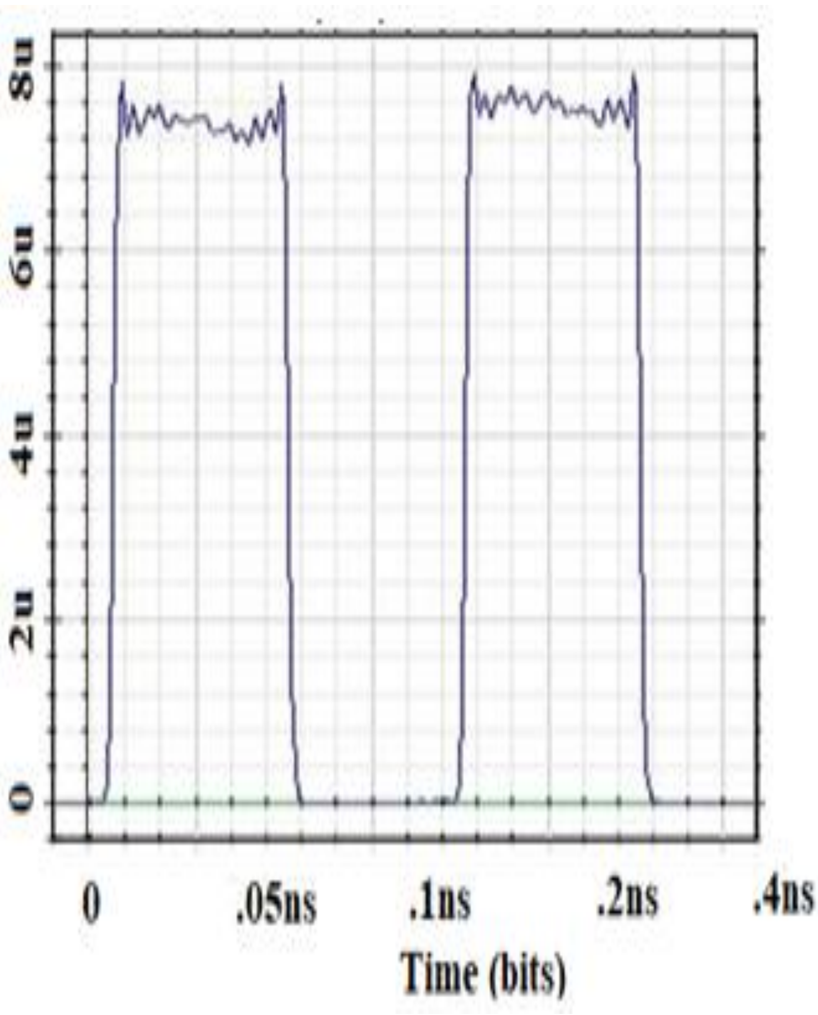
.2ns
.4ns
Time (bits)

(d)



(e)

Figure 5.2 OTDV representation of signal after (a) Transmitter (b) 75 km (c) FBG (d) DCF (e) DCF+FBG

Figure 5.3 represents the performance of the polarization interleaved ultra dense WDM PON in terms of Q factor at different distances for three different PWR cases. Distance is varied from 15 km to 75 km and DCF, FBG and DCF+FBG modules are employed in the ONU. Results reveal that Q factor of the downstream decreases with the increase in the link length. As mentioned in the former analysis, due to the high efficiency of pulse width reduction, joint module of DCF+FBG provide maximum Q factor and followed by the performance of dispersion compensation fiber. Least Q is obtained in the case of linearly chirped FBG due to least PWR efficiency. However, use of these dispersion compensation modules decreases the maintenance issues that are needed when they are placed in the transmission line.

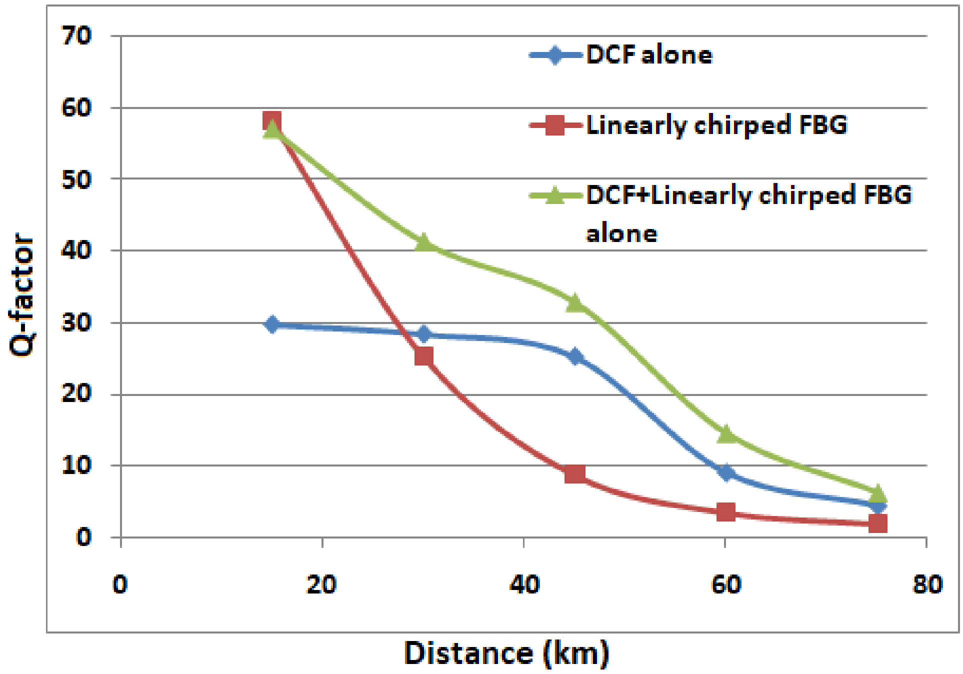


Figure 5.3 Representation of Q factor versus distance for different cases of PWR

Similarly, performance of the proposed system is evaluated in terms of Log BER at different distances for three different PWR cases. It is evident that Log BER of the downstream increases as the distance prolongs. Due to the high efficiency of pulse width reduction, joint module of DCF+FBG provides least Log BER. Performance of DCF is somewhat below the performance of joint module. Maximum Log BER is obtained in the case of linearly chirped FBD due to least PWR efficiency as depicted in

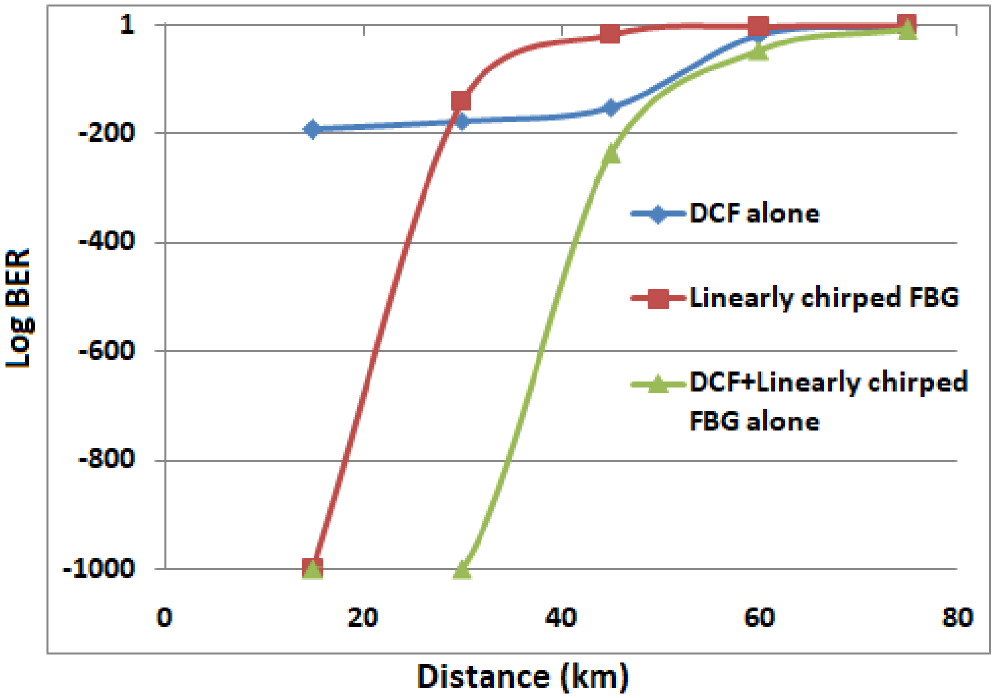
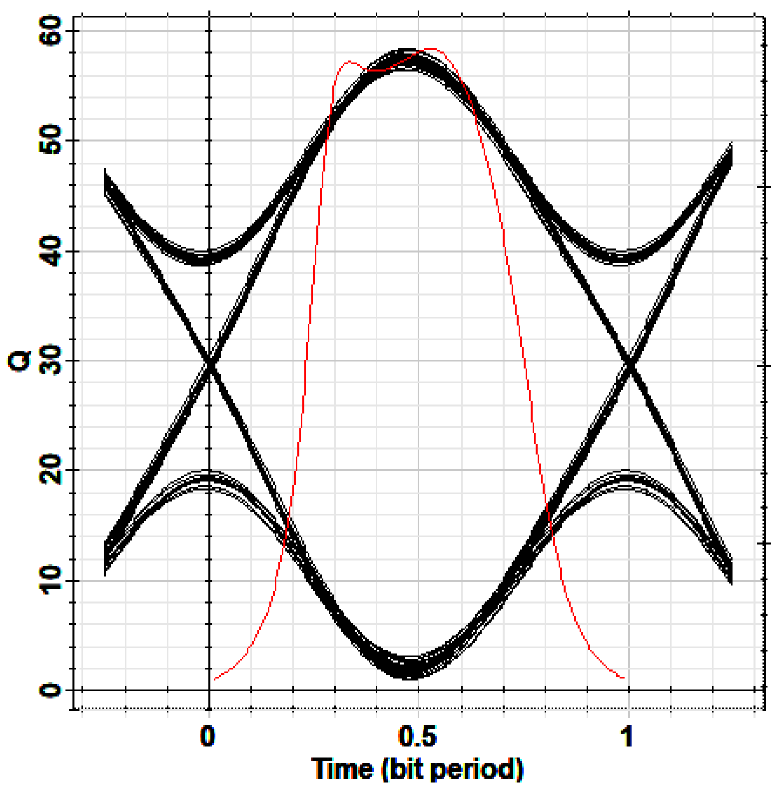


Figure 5.4 Representation of Log BER versus distance for different cases of PWR

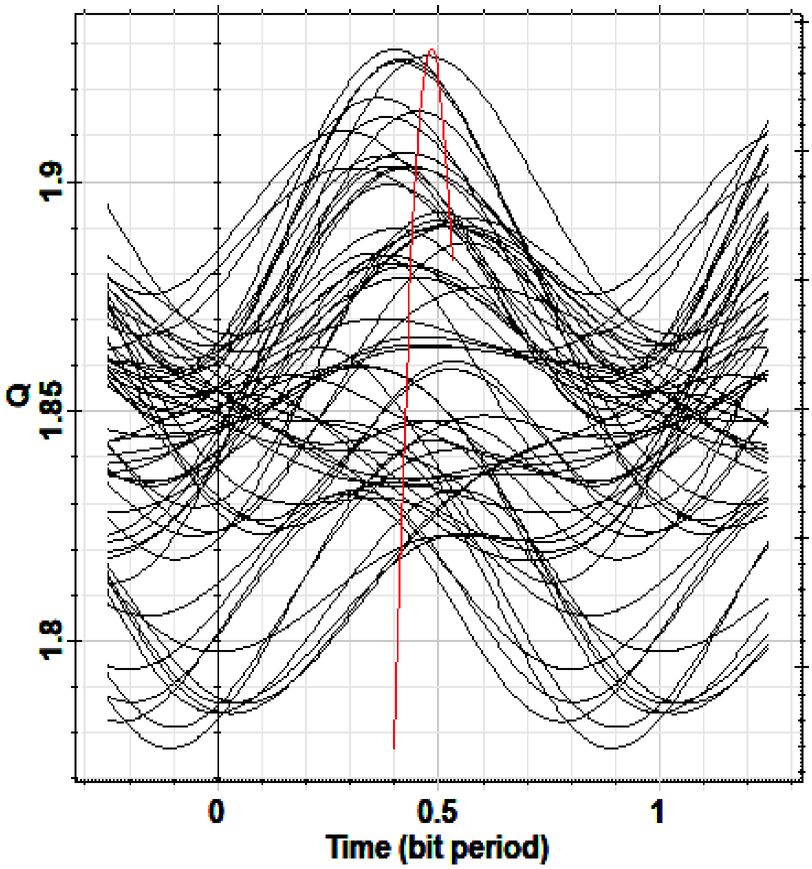
Figure 5.4 Therefore, joint module is suggested to use for the dispersion compensation and for the easy maintenance of the WDM PON systems.

Figure 5.5 depicts the Eye diagrams of the proposed system. It is decision component which calculates the Q factor and BER of the system. BER represents, the average number of ones and zeros, in the bit stream, and also average amplitudes. It has property that more Q factor be seen from the wide opening of the diagram. More is the opening of eye, more will be the Quality factor and less will be the BER. Where level of ones and zeros crosses each other, is termed as the jitter. Jitter is minimum for the Eye diagram with wide opening. At larger distances, due to the presence of attenuation, dispersion and other nonlinear effects, jitter comes out more. Figure 5.5 (a) (b) is diagram of the signal after 1 km and 75 km respectively in the case of linear chirped FBG.

It is perceived that eye closure is more at 75 km thus shows very distorted eye. However, eye opening is wide for 1 km analysis using FBG alone. Eye opening is little bit more at 75 km for dispersion compensation fiber as shown in Figure 5.5 (d). Q factor for the joint technique of DCF+FBG comes under acceptable limit and therefore this module provides best results as shown in Figure 5.5 (f).

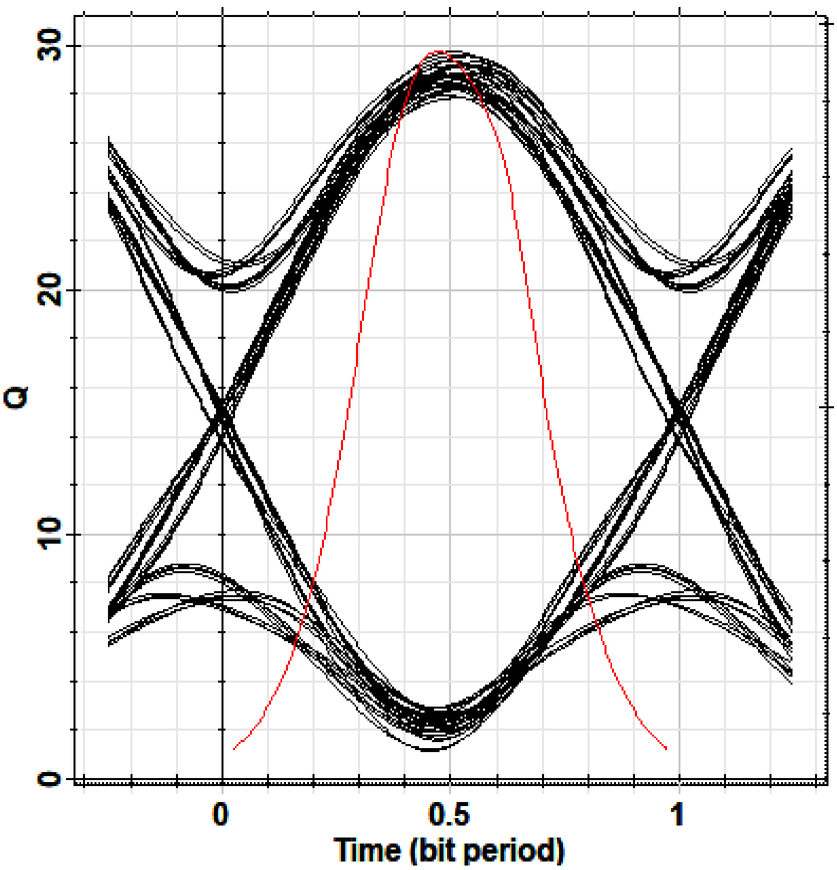


(a)



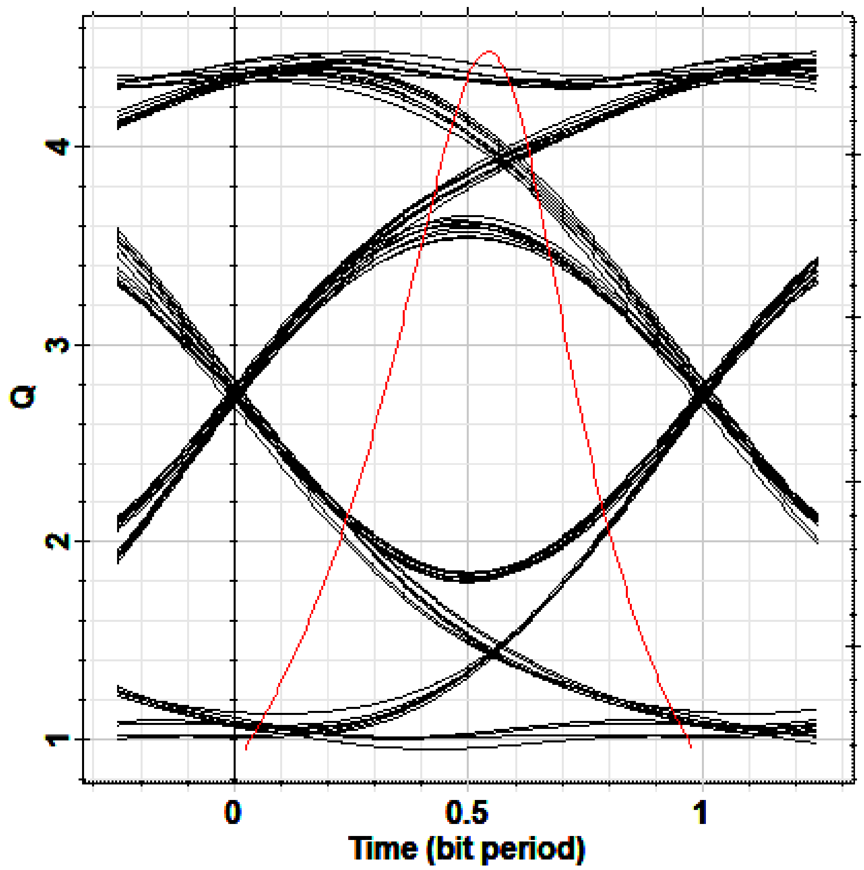
1.9
1.85
1.8
Q
0
0.5
1
Time (bit period)

(b)

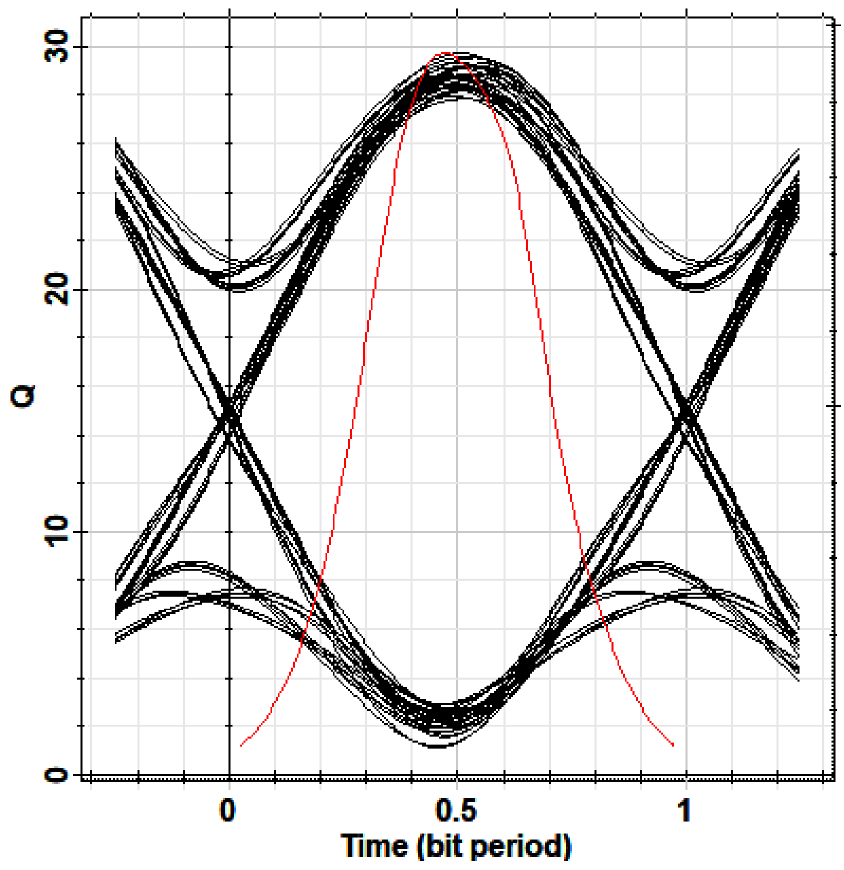


30
20
10
0
Q
0
0.5
1
Time (bit period)

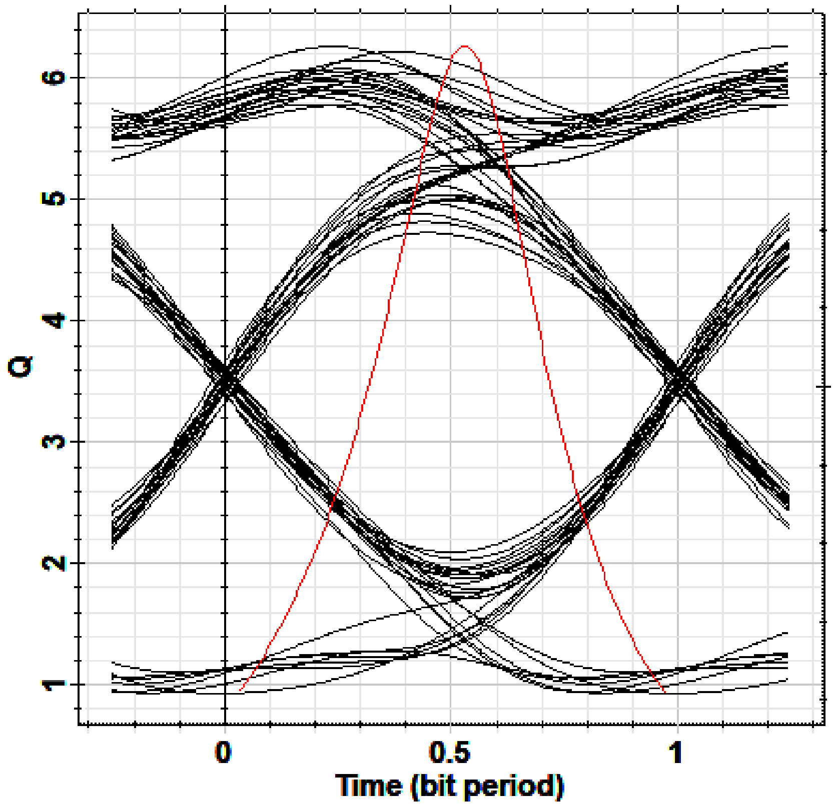
(c)



(d)



(e)



(f)

Figure 5.5 Eye diagram at1 km and 75 km of (a) (b) lineally chirped FBG (c) (d) DCF (e) (f) DCF+FBG

5.4 CONCLUSION

This work is accomplished though simulation design of a cost effective and easy maintenance based wavelength reused WDM passive optical network with dispersion compensation in ONU. Inter-channel and intra-channel interferences are suppressed by using polarization interleaving and DQPSK respectively. Pulse width reduction efficiency and performance of three different modules is analyzed such as DCF alone, linearly chirped FBG alone and DCF-FBG jointly. It is observed that due to maximum (48%) PWR% of joint module of DCF+FBG, it is preferred over DCF (45% PWR%) and FBG (40% PWR%). Moreover, proposed combined module is cost effective due to use of lesser length of DCF fiber in the joint module then required in DCF alone system. For the optical fiber of distance 40 km, DCF is needed 8 km for maximum dispersion compensation in systems using DCF alone, however, for optimal PWR in joint module, only 6 km DCF is required. Thus 25% of cost of DCF is saved in the ONU of the proposed system. Q factor and Log BER are also observed for all the three cases of dispersion compensation and results revealed that DCF+FBG perform best. Comparison of system for polarization interleaving and without PI is also investigated and it is perceived that WDM PON system with PI performs superior to normal passive optical networks. Joint module of DCF+FBG attains significant PWR in ONU of the WDM-PON with less maintenance and moderate cost.

CHAPTER 6
CONCLUSIONS AND FUTURE SCOPE

6.1 CONCLUSIONS

Conclusion and future scope of the work is as follows:

In this thesis, we have designed and implemented the WDM-PON. This system is very effective solution for dropping the nonlinearities. To investigate the system performance, three unique approaches are proposed (1) Crosstalk and inter symbol interference suppression (2) Polarization and inter-channel interference suppression (3) Easy maintenance based cost effective dispersion compensation.

Firstly, a transmitter diversity based bidirectional WDM-PON system with 4 channels at 10 Gbps for upstream and downstream incorporating different modulations such as DPSK and DQPSK is investigated. Reflective semiconductor optical amplifier has been used for re-modulation of a downlink signal. RSOA is cost effective and used as modulator well as amplifier. System is investigated over diverse distances and it is found that DQPSK-NRZ system performs better than the DPSK-NRZ system in terms of Q factor and BER. Transmitter diversity has great impact on the system performance and also reduces crosstalk between downstream as well as ustream channels.

Secondly, a WDM passive optical network is to suppress inter channel and polarization crosstalk and solution for increasing the bandwidth is proposed. The combination of both techniques provides large data rate and high bandwidth demand .This research work enhanced the performance of 4 x 20 Gb/s WDM-PON system using polarization diversity. The high speed system is attained to fulfil the large bandwidth requirements of PON by employing WDM system at channel spacing of 25 GHz. Simulation Results are developed successfully by comparing a two different systems i.e. with and without polarization interleaved WDM-PON system. It is observed that WDM-PON with polarization interleaving cause fewer errors and provide enhanced performance as compared to without polarization system. At less distances link and less power levels, the values of Q factor and SNR are minimum and BER is more. By using DQPSK-NRZ and polarization interleaving technique, system successfully works at 50 km and is suppressed the polarization crosstalk and ISI effects Thus, WDM passive optical networks is good technique which is more suitable for new specification that the communication must contains to achieve the increase in demands in communication field with minimum cost and long distance as well as data high data.

Finally, work is accomplished though simulation design of a cost effective and easy maintenance based wavelength reused WDM passive optical network with dispersion compensation in ONU. Inter-channel and intra-channel interferences are suppressed by using polarization interleaving and DQPSK respectively. Pulse width reduction efficiency and performance of three different modules is analyzed such as DCF alone, linearly chirped FBG alone and DCF-FBG jointly. It is observed that due to maximum (48%) PWR% of joint module of DCF+FBG, it is preferred over DCF (45% PWR%) and FBG (40% PWR%). Moreover, proposed combined module is cost effective due to use of lesser length of DCF fiber in the joint module then required in DCF alone system. For the optical fiber of distance 40 km, DCF is needed 8 km for maximum dispersion compensation in systems using DCF alone, however, for optimal PWR in joint module, only 6 km DCF is required. Thus 25% of cost of DCF is saved in the ONU of the proposed system. Q factor and Log BER are also observed for all the three cases of dispersion compensation and results revealed that DCF+FBG perform best. Comparison of system for polarization interleaving and without PI is also investigated and it is perceived that WDM PON system with PI performs superior to normal passive optical networks. Joint module of DCF+FBG attains significant PWR in ONU of the WDM-PON with less maintenance and moderate cost.

6.2 FUTURE SCOPE

In future, the present work may be extended on the following lines:

1. Investigation of differential quadrature phase shift and comparison with different phase shift keying has been done in this work. Comparison of other modulations such as quadrature amplitude modulation, pulse amplitude modulation etc can be studies in near future.
2. Work will be possible on inter-channel interference reduction. In this work, polarization interleaving is considered. Mode division multiplexing, optical code division can be used further.
3. Work can be studies on the hybrid WDM-PONs/TDM PONs in near future.
4. In this work, only non-return to zero modulation is considered. More modulation formats can studied in the same work in future.

5. Dispersion compensation is studied in WDM PONs and a cost effective module is proposed. Dispersion compensation fiber and fiber bragg grating are used in the joint module, in near future optical phase conjugation can be included and analyzed.

6. Nonlinear effects can be suppressed in the future. Nonlinear effects are not compensated in this work

7. No amplifier is taken for the amplification. However, due to presence of the wavelengths of different windows, wide band hybrid optical amplifier can be placed in the system in future.

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