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AND MATHEMATICS

Evaluation of Wavelength Division Multiplexing (WDM) and Its Applications Based On Optical Networks

Essa Ibrahim Essa Al-Juborie

Ph.D./Thesis

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Supervised by

Asst. Prof. Dr. Khalil I. Al-Saif

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بسم الله الرحمن الرحيم

﴿وَمنْ يَتق الله يَجعل
لهُ مَخْرَجاً وَيرزُقهُ منْ
حَيثُ لا يَحتسّب﴾

صدق الله العظيم
(سورة الطلاق- الآية ٢)

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ESSA I. AL-JUBORIE
October 2011

DIDICATION

TO...
MY PARENTS,
MY FAMILY,
AND
MY BELOVED, ALI...

ESSA IBRAHIM ESSA

Supervisor's Certification

I certify that this thesis entitled ***"Evaluation of Wavelength Division Multiplexing (WDM) and its Applications Based On Optical Networks"*** *was prepared by* ***Essa Ibrahim Essa Al-Juborie*** *under my supervision at Computer Science Department, College of Computer Sciences and Mathematics, University of Mosul in Partial Fulfillment of the Requirements for The Degree of Doctor of Philosophy of Computer Sciences.*

Supervisor

Signature:
Name: Dr. Khalil I. Al-Saif.
Title: Associate Professor.
Address: Computer Sciences Department, College of Computer
Sciences and Mathematics, University of Mosul.
Date: / / 2011

Supervisors Certification

I certify that this thesis was prepared under my supervision at the Department of Computer Sciences, College of Computer Sciences and Mathematics, University of Mosul, as a partial fulfillment of the requirements for the Degree of Doctor of Philosophy in Computer Sciences.

Signature
Name: Asst. Prof. Dr. Khalil I. Al-Saif
Date: / /2011

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I certify that the linguistic evaluation of this thesis was carried out by me and it is accepted linguistically and in expression.

Signature
Name: Asst. Prof. Dr. Hussein A. Ahmed
Date: / /2011

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According to the recommendations presented by the supervisor of this thesis and linguistic evaluator, I nominate this thesis to be forwarded for discussion.

Signature
Name: Asst. Prof. Dr. Najla Badee Al-Dabagh
Date: / /2011

Report of the Head of the Department of Computer Sciences

According to the recommendations presented by the supervisor of this thesis and linguistic evaluator and the Director of Postgraduate Studies Committee, I nominate this thesis to be forwarded for discussion.

Signature
Name: Asst. Prof. Dr. Khalil I. Al-Saif
Date: / /2011

Committee Certification

We, examining committee, certify that we have read the entitled thesis ***(Evaluation of Wavelength Division Multiplexing (WDM) and its Applications Based On Optical Networks)*** *and we have examined the graduate student,* ***Essa Ibrahim Essa Al-Juborie.*** *In its contents, on 21/9/2011 and that in our opinion it meets the standard of thesis for the Degree of Doctor of Philosophy in Computer Sciences.*

Signature
Prof. Dr. Basil Y. Thanoon
Chairman
Date: / /2011

Signature
Prof. Dr. Abdul Monem S. Rahma
Member
Date: / /2011

Signature
Asst. Prof. Dr. A. I. A. Jabbar
Member
Date: / /2011

Signature
Asst. Prof. Dr. Eng. Ibtesam R. Karhiy Al-Saedi
Member
Date: / /2011

Signature
Asst. Prof. Dr. Manar Younis Kashmola
Member
Date: / /2011

Signature
Asst. Prof. Dr. Khalil I. Al-Saif
Member & Supervisor
Date: / /2011

Abstract

Through this project work, a wavelength division multiplexing (WDM) optical network has been simulated and applied, by using erbium-doped fiber amplifiers (EDFA) to amplify the degradation in signals through round trip, and dispersion compensating fiber (DCF) to compensate the dispersion in optical signals, based on a standard single mode fiber (SSMF-28) that is currently used as a backbone optical fiber infrastructure by the Ministry of Communications in Republic of Iraq.

To evaluate the performance of the network use, three test bed systems with multiple channels at data rates of (8×10Gb/s WDM, 16×40Gb/s WDM and 8×40Gb/s AWG multiplexer/demultiplexer) over optical transmission link with minimum system impairments have been applied, taking into consideration the presence of (Passive/Active) components. By monitoring (Q-Factor, Min BER, and output signal power) through visualization system, results are acceptable. These results are tested and verified by using OptiSystem 7.0; a license product of Optiwave Corporation (Canadian Based Company).

In experiment (1) the nonlinearities effects do not managed thereby do not get an output power signals and eye opening at the receiver side. On the other hand, to overcome the problems in previous experiment, the EDFA was used to reduce the nonlinearities effects. For experiment (2) the optimum fiber length is (150km), the ($BER < 10^{-15}$), the average total power is (-5dBm), and the average noise power is (-37dBm). For the experiment (3) the best fiber length is (120km), the ($BER < 10^{-30}$), the average optical power level for all channels is (-47.5dBm), while the average maximum Q-factors for all 16-channels are (10.4875), and finally in experiment (4), the optimum fiber length is (242.5km) the total gain is (-3.6856dBm), input signal is

(4.0402dBm), output signal is (0.3545dBm), and output noise is (1.4248dBm). So, from the optical power meter, the average power is (-6.4255dBm).

An optical WDM network and its applications can contribute to and provide unlimited bandwidth with minimum costs, for all ranges of fiber optics communication systems services such as Internet access, E-society, fiber-to-the-home (FTTH), voice over internet protocol (VoIP), video, and other multimedia interactions.

The simulation results show that data transmission rates can be successfully transmitted with low-cost effective infrastructure with good system performance. WDM network provides valuable features such: scalability, flexibility, transparency, and elimination of optical-electrical-optical (O-E-O) operations.

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Symbol	Description
$\overline{P}_{rec}$	**Average Received Power**
λ_0	**Center wavelength**
Δf	**Frequency spacing**
$\Delta\lambda$	**Wavelength spacing**
P_t	**Power**
γ	**Link loss**
L_{eff}	**Effective length**
%	**percentage**
μm	**micrometer**
c	**Speed of light in free space**
d	**Diameter of Fiber**
D_0	**Pulse width at the output of the fiber**
D_1	**Pulse width at the input of the fiber**
dB	**Decibel**
E	**energy**
erfc	**Complementary Error Function**
exp	**Expontial (constant)**
f	**Received signal**
hv	**Photon energy**
I	**Sampled value**
I_{10}	**intensity**
I_{20}	**initial intensity**
km	**kilometer**
log	**Logarithm**
m	**meter**
mW	**milliwatt**
N	**Refractive Index**
nm	**nanometer**
P_{in}	**Power Input**
ps	**picoseconds**
s	**second**
S_m	**Speed of Light in Medium**
S_v	**Speed of Light in Vacuum**
v	**volt**
y_0	**signal when a 1 is being sent**
y_1	**signal when a 0 is being sent**
α	**Attenuation**
Θ_1	**Angle of incidence**
Θ_2	**Angle of Refractive**

λ	**Wavelength of light**
σ_0	**standard deviation of the 0 signal**
σ_1	**standard deviation of the 1 signal**
ω_1	**Stokes wave**
ω_2	**pump wave**

Abbreviation	Description
ADM	Add/Drop Multiplexer
ANSI	American National Standardization Institute
APD	Avalanche Photodiodes
API	Application Program Interface
ASE	Amplified Spontaneous Emission
ASK	Amplitude Shift Keying
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Gratings
BER	Bit-Error Rate
BL	Bit-Rate Distance Product
BW	Bandwidth
CD	Chromatic Dispersion
CO	Central Office
CS	Channel Spacing
CW	Continuous Wave
CWDM	Coarse Wavelength Division Multiplexing
D	Dispersion
DCF	Dispersion Compensation Fiber
DCM	Dispersion Compensation Modules
DEMUX	Demultiplexer
DFB	Distributed Feed-Back
DSF	Dispersion Shifted Fiber
DSL	Digital Subscriber Line
DSLA	Digital Subscriber Line Access
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
EMI	Electro-Magnetic Interface
Er	Erbium
FBG	Fiber Bragg Gratings
FDDI	Fiber Distributed Data Interface
FDM	Frequency Division Multiplexing
FDPA	Fiber Optical Parametrical Amplifier
FP	Farby Perot
FPZ	Free Polarization Zone
FR	Frame Relay
FSK	Frequency Shift Keying
FSO	Free Space Optics
FSR	Free Space Range
FTTH	Fiber to The Home
FWM	Four Wave Mixing
G	Gain

GaAs	Gallium and Arsenide
GEQ	Gain Equalizer
GUI	Graphical User Interface
GVD	Group Velocity Dispersion
IAWG	Interleaved Array Waveguide Gratings
IC	Integrated Circuits
IM/DD	Intensity Modulation/Direct Detection
InGaAs	Indium Gallium and Arsenide
InGaAsP	Indium Gallium Arsenide and Phosphate
InP	Indium and Phosphate
IP	Internet Protocol
ISI	Intersymbol Interference
ISO	International Standardization Organization
ISP	Internet Service Provider
ITU	International Telecommunication Union
LAN	Local Area Network
LED	Light Emitting Diode
$LiNbO_3$	Lithium Niobate Oxide
MAN	Metropolitan (Metro) Area Network
MEMS	Micro Electrical Mechanical System
MI	Modulation Instability
MMF	Multi Mode Fiber
MSM	Metal-Semiconductor Metal Photodiodes
MTDM	Maximum Time Division Multiplexing
MUX	Multiplexer
MZ	Mach Zehnder
MZI	Mach Zehnder Interferometer
NA	Numerical Aperture
NF	Noise Figure
NMS	Network Management System
NNI	Network-Network Interface
NRZ	None-Return-to-Zero
OADM	Optical Add/Drop Multiplexer
OBLSR	Optical Bidirectional Line Switched Ring
OC	Optical Channel
OCDMA	Optical Code Division Multiple Access
ODN	Optical Distribution Network
OFA	Optical Fiber Amplifier
OH	Hydroxide Ion
OOO	Optical-Optical-Optical
OPA	Optical Parametric Amplifier

OPS	**Optical Packet Switch**
OSI	**Open System Interconnect**
OSNR	**Optical Signal to Noise Ratio**
OTDM	**Optical Time Division Multiplexing**
OTN	**Optical Transport Network**
OXC	**Optical Cross Connect**
PDL	**Polarization Dependent Loss**
PDW	**Polarization Dependent Wavelength Shift**
PIC	**Photonic Integrated Circuits**
PIN	**Positive Intrinsic Negative**
PLC	**Planner Lightwave Circuits**
PMD	**Polarization Mode Dispersion**
P-N	**Positive-Negative**
PON	**Passive Optical Network**
POP	**Point of Presence**
PRBSG	**Pseudo-Random Bit Sequence Generator**
PSK	**Phase Shift Keying**
RA	**Raman Amplifier**
RDF	**Reverse Dispersive Fiber**
RF	**Radio Frequency**
ROADM	**Reconfigurable Optical Add/Drop Multiplexer**
RoF	**Radio Over Fiber**
RWA	**Routing and Wavelength Assignment**
RZ	**Return-to-Zero**
SBS	**Stimulated Brillion Scattering**
SCM	**Subcarrier Multiplexing**
SDH	**Synchronous Digital Hierarchy**
SiO_2	**Silicon Dioxide**
SMF	**Single Mode Fiber**
SNR	**Signal to Noise Ratio**
SOA	**Semiconductor Optical Amplifier**
SONET	**Synchronous Optical Network**
SPM	**Self Phase Modulation**
SRS	**Stimulated Raman Scattering**
SSMF	**Standard Single Mode Fiber**
STM	**Synchronous Transmission Model**
Ta_2O_5	**Tantalum Oxide**
TDFA	**Thulium Doped Fiber Amplifier**
TDM	**Time Division Multiplexing**
TDMA	**Time Division Multiple Access**
TDW	**Temperature Dependent Wavelength Shift**

TFF	**Thin Film Filter**
TFR	**Tellurite Based fiber Raman Amplifier**
TIR	**Total Internal Reflection**
TODC	**Tunable Optical Dispersion Compensator**
TV	**Television**
UNI	**User Network Interface**
VB	**Visual Basic**
WAN	**Wide Area Network**
WDM	**Wavelength Division Multiplexing**
WGR	**Waveguide Grating Router**
WP	**Water Peak**
XPM	**Cross Phase Modulation**

1.1. Historical Perspective:-

Prehistoric Early societies used signal fires to send digital messages to distant locations. Polybious, a Greek mathematician, developed a method of sending characters using fires by setting up a matrix of characters where one set of fires represented rows of the matrix and the other set represented the columns of the matrix. The rapidly changing face of data communications and telecommunications has seen a continued growth in the need to transfer enormous amounts of information across large distances.

Optical fibers were first envisioned as optical elements in the early 1960s. It was perhaps those scientists well-acquainted with the microscopic structure of the insect eye who realized that an appropriate bundle of optical waveguides could be made to transfer an image and the first application of optical fibers to imaging was conceived. It was Charles Kao1 who first suggested the possibility that low-loss optical fibers could be competitive with coaxial cable and metal waveguides for telecommunications applications. It was not, however, until 1970 when Corning Glass works announced an optical fiber loss less than the benchmark level of 10dB/km that commercial applications began to be realized. The revolutionary concept which Corning incorporated and which eventually drove the rapid development of optical fiber communications was primarily a materials one. It was the realization that low doping levels and very small index changes could successfully guide light for tens of kilometers before reaching the detection limit. The ensuing demand for optical fibers in engineering and research applications spurred further applications. Today, there are tremendous varieties of commercial and laboratory applications of optical fiber technology [1].

A communication system transmits information from one place to another, whether separated by a few kilometers or by transoceanic distances. Information is often carried by an electromagnetic carrier wave whose frequency can vary from a few megahertz to several hundred terahertzes. Optical communication systems use high carrier frequencies (~100 THz) in the visible or near-infrared region of the electromagnetic spectrum. They are sometimes called lightwave systems to distinguish them from microwave systems, whose carrier frequency is typically smaller by five orders of magnitude (~1GHz). Fiber optic communication systems are lightwave systems that employ optical fibers for information transmission. Indeed, the lightwave technology, together with microelectronics, is believed to be a major factor in the advent of the "information age".

However, there were evolving international telecommunication standards that were predicting very high data rate requirements. Although transmission capacity could be obtained from conventional cable, microwave and satellite technologies, there was a definite shortage of transmission capacity for the term data transfer requirements. Fiber optic transmission systems have provided the enormous capacity required to overcome the potentially disastrous short falls.

With the introduction of fiber optic communications systems, the solution to the problems of transmission capacity shortage and to noisy industrial environments has been successfully found. An optical fiber is simply a very thin piece of glass which acts as a pipe, through which light can pass. The light that is passed down the glass fiber can be turned on and off to represent digital information or it can be gradually changed in amplitude, frequency, or phase to represent analog information.

The use of the telephone has increasingly grown from a pair of telephones to telephone networks. Therefore, technology in transmission has had to be continuously developed in order to sufficiently increase the capacity of telephone networks. At first, wire pairs were replaced by coaxial cables to improve the capacity; however, the capacity of the coaxial cables is also not sufficient. This led to the development and deployment of microwave communication systems. The capacity is usually measured in term of the bit rate-distance product (BL); where B is the bit rate and L is the repeater spacing. Increasing the BL depends largely on the frequency value, when distance is constant. Due to the relationship: (when carrier wave increase, the bandwidth are increase), also the data rate increase, even though can be estimate the high value of BL in the optical wave frequency. Such an increase is shown in the Figure 1.1[2, 3, and 4].

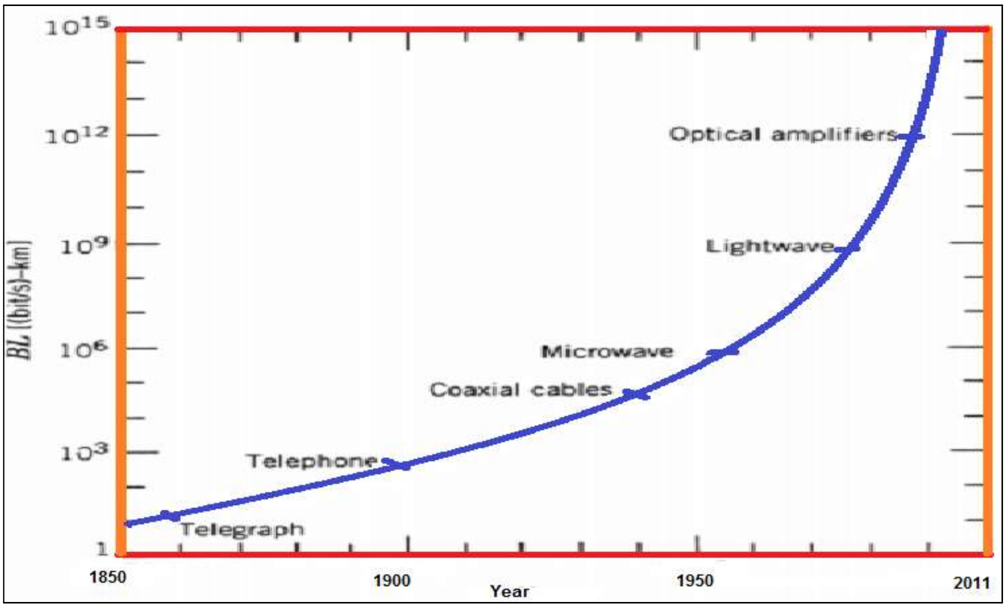


Figure (1-1):- Increase in bit rate-distance product.

1.2. The Existing Optical Fiber Communication System:-

The prevalent utilization of Internet by business and consumer has been generating a global demand for huge bandwidth. In recent years, as new bandwidth applications like internet video and audio and new access technologies such as Digital Subscriber Line (DSL) have become more popular, optical communication networks are finally feeling the bandwidth constraints already faced in many other communications networks such as wireless and satellite communication systems. Service providers are searching for ways to increase their fiber optic network capacity. In order to solve this problem, people have been trying to make full use of the huge bandwidth provided by optical fibers. Technologies like Time Division

Multiplexing (TDM), wavelength division multiplexing (WDM), and their combinations are used and improved [5].

The TDM strategy is to increase the bit rate carried by a single optical wavelength. These systems use very short pulses to achieve very high bit rate and thus they are subject to the influence of dispersion (because of the wide bandwidth of the signal) and nonlinearities (because of the required high power to overcome the noise). High speed TDM systems are very sensitive to the Polarization Mode Dispersion (PMD) effect and they are also limited by the achievable speed of electronic components and devices. Because of those constraints, the data rate of commercial optical fiber systems is currently limited at 10Gbps (Giga bit per second). For some old fiber plants, the maximum per-channel data rate is 2.5Gbps due to the limitation in their poor PMD characteristic. Later, as technology advanced, WDM came along. The WDM strategy is to make better use of optical fiber bandwidth by stacking many TDM channels into the same fiber. The advantage of WDM over TDM is that WDM usually uses much lower bit rates and optical power in each channel while achieving a higher total capacity [6, 7, and 8].

Internet services have been available since many years ago. However, until today there is no current internet infrastructure (backbone) that uses optical fiber. As a consequence, the connectivity is over satellite links to the rest of the world. At the present, many companies provide internet access by means of microwave links, leased lines, and optical fiber in some commercial areas, which provide Internet access to their customers by means of microwave links and very small aperture terminal fixed satellite communication technology; their customers are mostly private or government organization. However, many people who live in rural areas do not have Internet access, and those who live in urban areas depend only on the digital leased lines or microwave links. Their Internet connection to the rest of the world is through a satellite; hence, they only have limited

Internet access due to the high connection costs of satellite [9, 10, 11, and 12].

Internet access is a key part of communications and the basis of socio-economic development. Therefore, for a developing country like Iraq, Internet access needs to be given priority so that it can be accessible by the majority of the population. At the moment, there is existing infrastructure project implemented in Republic of Iraq as a national backbone by using optical fiber to connect it to the rest of the world through (Hashimite Jordanian Kingdom, Turkey, and Arab Gulf), by connecting to the submarine cable. The national backbone goal is to reduce the Internet connection charge and provide Internet access to the majority of the people who live in both urban and rural areas.

The first standardized local area network (LAN) operating at 100Mbit/s (Mega bit per second) was the fiber distributed data interface (FDDI). Introduced in the mid-1980s, the original FDDI standard called for use of multimode graded-index fiber with either (62.5 or 85μm) cores and signal transmission using (1.3μm) LEDs, which cost less than diode lasers and could transmit signals up to 2km between nodes. Each node regenerated the output signal, and the entire network could contain up to 200 km of cable. But at a time when 1200-baud modems were standard for personal computers, few systems required 100Mbit/s, and FDDI was not widely used, because it used the multimode fiber. The companies trying to sell fiber optic LANs could argue that installing fiber would provide room for future growth, but they did not succeed in selling many fiber-optic LANs, nor did they expect the steady improvements in the bandwidth of copper cables, widely used in 100Mbit/s Fast Ethernet, established as a standard in the mid-1990s [13, and 14].

1.3. Why Optical Networks?

Initially, the term optical networks referred to collections of optical cable routes that were used for high-capacity point-to-point transmission links. In these networks, much of the telecommunication network infrastructure still relied on using electronic signals, particularly in critical functions such as routing and switching of signals. Currently, the next generation of optical networks is transitioning some of the routing, switching, and network intelligence into the optical domain. Networks are communication systems used to interconnect a number of terminals within a defined geographic area. Networks also deal with the routing and switching aspects of communications. Passive optical networks (PON) utilize couplers to distribute signals to users. In an N × N ideal star coupler, the signal on each input port is uniformly distributed among all output ports [15].

The simplest protocols are those for which fixed-wavelength receivers and tunable transmitters are used. However, the technology is simpler when fixed wavelength transmitters and tunable receivers are used, since a tunable receiver may be implemented with a tunable optical filter preceding a wideband photodetector. Fixed-wavelength transmitters and receivers involving multiple passes through the network are also possible, but this requires the utilization of terminals as relay points. Protocol, technology, and application considerations for gigabit networks (networks having access at gigabit rates and throughputs at terabit rates) are an extensive area of current research [1].

As many scientific research labs expand on a global scale, collaborative resource sharing between different parts of the same organization, or between different research institutions, has become a key enabler for new scientific discoveries. The concept of interconnecting computer systems over an infrastructure reminiscent of the electrical power utility grid has become a reality in recent years through the availability of high-bandwidth fiber optic connectivity. A large public sector national research laboratory was faced with the challenge of interconnecting many of their facilities so that they could share resources (storage, processing power, network bandwidth, and function in essence as a large, distributed supercomputer). These facilities included a major nuclear physics facility, the national space agency and astronomy labs, several universities, and research hospitals, all of which generated on the order of several terabytes of new information each year. The first step in building this grid was to enhance the legacy network connections between two of their principal locations, which were limited to 2Mbit/s, while their objective was for both locations to behave as if they were part of the same LAN in order to allow several virtual networks to operate over the same fiber using different wavelengths. To provide the necessary reliability, protection switching was enabled on a per-wavelength basis. The inherent security of the optical network and the ability to detect when fibers were connected or disconnected from the equipment provided an additional layer of security for this application. The resulting network allowed researchers to build a computing environment with a performance (in floating-point operations per second) on a par with the top 500 supercomputers in the world [13, and 14].

The need to support new high-capacity applications such as video, backup and LAN extension without loss of service quality puts network economics under severe pressure. Optical networks using wavelength division multiplexing (WDM) give service providers the flexibility, scalability, protocol transparency and cost efficiency they require to meet these challenges. A WDM technology provides highest scalability in optical networks, with lowest cost in access and feeder links. Modern WDM solutions incorporating Reconfigurable Optical Add/Drop Multiplexing (ROADM) capabilities are easy and efficient to operate while providing flexibility, performance and protection for an unpredictable future.

Service providers around the world are seizing the clear market opportunities, but there are challenges to overcome:

1. Existing revenue streams must be maintained, and the legacy networking platforms supporting them have been optimized for voice traffic only.
2. The new, high-bandwidth services must be transported across the same fiber infrastructure, without performance degradation. This is especially true where new fibers cannot be drawn into the ground.

WDM provides a compelling answer to these challenges. New architectures (such as Optical Transport Network (OTN)), functionalities (such as ROADMs) and technologies (such as 40Gbit/s) bring tremendous advantage and flexibility to service providers in their quest for network evolution towards a converged future [16, 17, 18, and 19].

1.4. Next Generation Optical Network:-

Networks can be classified broadly as a LAN, metropolitan-area network (MAN) or metro network, and wide-area network (WAN). When a network is owned and deployed by a private enterprise, it is referred to as an enterprise network. The networks owned by the telecommunication carriers provide services such as leased lines or real-time telephone connections to other users and enterprises. Such networks are referred to as public networks.

A lightpath is an end-to-end optical connection that may go through one or more intermediate nodes. For example, in an eight-channel WDM link there are eight lightpaths, which may go over a single physical line. The synchronous optical network (SONET) and synchronous digital hierarchy (SDH) standards allow network engineers to interconnect fiber optic transmission equipment from various vendors through multiple-owner trunk networks. The American National Standardization Institute (ANSI) Standard T1.105.06 describes SONET, and international telecommunication union (ITU-T) Recommendation G.957 describes SDH. To ensure interconnection compatibility between equipment from different manufacturers, the SONET and SDH specifications provide details for the optical source characteristics, the receiver sensitivity, and transmission distances for various types of fibers. Table 1.1 shows commonly used SDH and SONET signal levels and the associated optical channel (OC) rates.

Table (1-1):- The SONET/SDH Data Rates.

Seq. No.	SONET Name	SDH Name	No. of Channels	BW (Mbps)
1	OC-1	STM-0	672	51.84
2	OC-3	STM-1	2.016	155.52
3	OC-12	STM-4	8.064	622.08
4	OC-48	STM-16	32.256	2.488.32
5	OC-192	STM-64	129.024	9.953.28
6	OC-768	STM-256	516.096	39.813.12

Ethernet could mark a milestone in the history of local network communications. It looks like being the very first networking system where the cost of implementation on optical media is less than the cost on electrical media. The basic principle of a shared medium network such as an Ethernet network is that all end users connect to a common medium. When one sends, others listen and we achieve any-to-any connectivity [20].

Ethernet is deployed widely in LANs with interfaces available at line rates ranging from 10Mbps to 10Gbps. Ethernet is also being used in MANs and is extending into wide-area networks. In these environments, Ethernet uses optical fiber transmission links to increase network capacity cost-effectively and has the ability to offer a wide range of services in a simple, scalable, and flexible manner.

Emerging next generation transport networks are referred to as OTNs. In these networks, it is envisioned that DWDM based dynamic optical network elements such as optical cross-connect (OXC) switches and OADMs will have full control of all wavelengths. In addition, they are expected to have full knowledge of the traffic carrying capacity and the status of each wavelength. With such intelligence, these networks are envisioned as being self-connecting and self-regulating. Various means of using fibers in the access network have been explored. These schemes are known by the all-inclusive term fiber-to-the-x (FTTx), where x is some letter designating at what point the fiber terminates and copper wires (or wireless links) again take over [15].

1.5. Literature Survey:-

A study of existing information in the literature helps a researcher to plan and conduct his experiments and ultimately to express the results he arrives at. A lot of information regarding WDM, AWG, and many different optical network topologies are available in the literature. A part of that and relative to present study is reported below:

George and Mostafa 1992 [21] “consider single-hop lightwave networks with stations interconnected using WDM. The stations are equipped with tunable transmitters and/or receivers”. **Yu et al.** 1998 [22] “analyzed the effects of channel separation, cross-phase modulation (XPM), and input power on nonlinear WDM systems with conventional single-mode fiber (SMF) combined with dispersion-compensating fiber (DCF)”. **Kamal and Janssen** 1999 [23] “had introduced a protocol for ring networks employing WDM”. **Biswanath** 2000 [24] “summarized the basic optical-networking approaches (focusing on functionalities of various devices and technologies rather than exact vendor implementations), reported on the WDM deployment strategies”. **Killey et al.** 2000 [25] “investigated intrachannel nonlinear effects in 40-Gb/s WDM transmission over standard-fiber links. These effects were shown to be potentially more damaging than interchannel XPM. By optimizing the amount of precompensation”. **Yoshinori** 2000 [26] “introduces the principles, of the AWG and its application for future optical network”. **Rudra Dutta** 2001[27] “design a virtual topology for traffic grooming in WDM networks and deals with static and dynamic grooming and how can be avoid them in WDM systems". **André Richter** 2002 [28] "presented summarizes a contribution to the investigation of timing jitter in long-haul WDM transmission systems". **Neophytos et al.** 2002 [29] "had investigated the feasibility of transparent metropolitan-area WDM optical networks using computer simulation. According to **Samir et al.** 2002 [30] "a symmetric Robust WDM circuit-switched network was modeled and analyzed". **Klekamp and Wessel** 2002 [31] "explain how to use the AWG multiplexers as the key elements for DWDM in optical networks". **Lin et al.** 2003 [32] "present the effect of filter bandwidth and channel spacing on 40 Gbit/s WDM system incorporated with transmission lines was investigated". **Edward Mutafungwa** 2004 [33] "focuses on flexibility improvement techniques that enable dynamic provision of bandwidth in optical networks within acceptable costs. The potential application of hybrid WDM for radio-over-fiber systems is explored for urban network". **Lavanya et al.** 2004 [34] "describe an optical time-division-multiplexed (OTDM)/WDM network architecture that integrates high-speed optical time-division multiplexing at speeds of 40 Gbit/s and higher with lower-bit-rate WDM channels". **Gurvan and Pallab** 2005 [35] "consider the reconfiguration problem in multifiber WDM optical networks. In a real-time network as the traffic evolves with time". **Fischer et al.** 2005 [36] "present an instruction system, which works on the basis of a WDM system in the visible spectrum. It is specialized for the academic training at universities to demonstrate the principles of the WDM techniques". **Shin et al.** 2005 [37] "propose a cascade-connected AWG as a solution to the problem of crosstalk accumulation in a large-scale AWG multiplexer/demultiplexer". **Chou and Sheng** 2007 [38] "propose and demonstrate experiment transport of 32×40Gbit/s DWDM system structure in C band and L band wavelength range which use the combination of SMF and Reverse

Dispersion Fiber (RDF) as dispersion compensation device". **Kwanil et al.** 2007 [39] "propose a novel bidirectional OADM using AWG for the OTNs". **Yueting and Rongqing** 2007 [40] "demonstrate how a general design rule for interleaved arrayed waveguide gratings (IAWGs) is derived. A 1×N WDM switches based on a phase shifter array". **Yasin et al.** 2007 [41] "present a theoretical analysis to investigate the WDM network transmission system in the presence of crosstalk". **Benjamim et al.** 2007 [42] "studied blocking performance of a bidirectional WDM ring network with 16 nodes". **Ragini and Nar** 2007 [43] "describe various design considerations of an ultra high speed long-haul WDM link. Power budget, optical signal to noise ratio (OSNR) budget and dispersion budget equations, based on loss and dispersion management, are derived". **Fa et al.** 2007 [44] "present a hybrid WDM and optical code division multiple access (OCDMA) scheme over fiber-to-the-home (FTTH) networks". **Mu and Lung** 2007 [45] "propose a bidirectional reconfigurable scheme of multichannel-selective OADM by applying fiber Bragg gratings (FBGs)". **Jesse Tuominen** 2008 [46] "Novel device concepts for optical WDM communications based on photonic fiber demonstrated to be capable of multi-channel clock recovery in WDM applications where return-to-zero modulation is applied". **Frank Smyth** 2008 [47] "examined in detail using a reconfigurable wavelength division multiplexed (WDM) network test bed and results show the severe impact that channel reconfiguration can have on transmission performance". **Ooba et al.** 2008 [48] "propose hybrid AWG-free space focusing optics system and demonstrate a 40-channel 100GHz spacing wavelength blocker". **Ismahayati et al.** 2008 [49] "designed AWGs on silica substrate used to multiply an optical fiber's transmission capacity by sending signals simultaneously at multiple wavelengths over a single fiber". **Gu et al.** 2008 [50] "demonstrate a 40Gb/s capacity (1.25Gb/s×32 channel) WDM-PON based on wavelength locked Fabry-Perot laser diodes". **Ching and Nung** 2009 [51] "developed robust WDM-PON architectures with full protection capability". **Jayashree et al.** 2009 [52] "present examination resources provisioning aspects in a PON employing WDM and OCDMA techniques". **Abd El–Naser et al.** 2009 [8] "investigated the recent applications of optical parametric amplifiers (OPAs) in hybrid WDM/TDM local area PON". **Shin** 2009 [53] "describe recent progress in relation to the key requirements for athermal AWG multiplexers, namely a wide passband". **Abd El–Naser et al.** 2009 [54] "investigated two characteristics of three different waveguides employed in AWG in PON where rates of variations were processed". **Yuichiro and Hiroyuki** 2009 [55] "propose an AWG-based tunable optical dispersion compensator (TODC) that uses a multiple lens structure". **Kazumasa and Tomohiro** 2009 [56] "report a phase-modulation method for measuring arrayed waveguide grating (AWG) phase error in the frequency domain by combining the method with a digital sampling technique". **Abd El–Naser et al.** 2009 [57] "presented a high transmission bit rate of athermal arrayed waveguide grating AWG based on Maximum Time Division Multiplexing (MTDM) technique". **Yuk et al.** 2009 [58] "propose a new architecture for bidirectional gigabit colorless WDM-PON and subcarrier multiplexing (SCM)". **Quan and Avner** 2010 [59] "studied the deterministic effects of Raman-induced crosstalk in amplified WDM optical fiber transmission lines".

1.6. Aim of The Research:-

The present research is mainly concerned with:

1. The theoretical and practical analysis performance of WDM network employing transmission over conventional single mode fiber (SMF).
2. The ultimate objective is to design, simulate, and analyze WDM systems employing single mode fibers with 10Gbps and 40Gbps of bit rate.

3. Also, by introducing the principal techniques and recent progress of arrayed waveguide grating (AWG) multiplexer/demultiplexer, which have been developed for wavelength division multiplexing based optical networks.

As WDM systems are still in their infancy, hoppy this work will be helpful in understanding the nature of these systems, and useful in their practical design and implementation.

1.7. Tools and Techniques:-

To facilitate application over a broad range of conditions, the analytical results are expressed in terms of simulated parameters in the OptiSystem 7.0; a license product of Optiwave Corporation (Canadian Based Company). (For more details see Appendix A).

1.8. Thesis Contributions:-

Our thesis contribution is to upgrading and expanding the current optical network infrastructure that currently used by the Ministry of Communication in Republic of Iraq, by adding multi-channel and high bit rate through the WDM, and to be provide Internet and resources access to both urban and rural areas.

1.9. Composition of The Thesis:-

This thesis is divided into five chapters. The **second chapter** relates to the important equipment employed in the optical fiber communication systems. More specifically, they are transmitter, optical fiber (channel), and receiver. The fundamental concepts and their applications are discussed. Moreover, the methods of making them practically suitable for actual deployment are explained. **Chapter three** is dedicated to the WDM systems. Their development and progress are also discussed in this chapter. Included in this chapter are the details on some prior publications, which are significant to the consider problem. Chapter three helps in understanding the fundamental characteristic and concepts of WDM systems, and study of the AWG; this is an important component in field application as a multiplexer/demultiplexer as it explains and demonstrates how it works. **Chapter four** demonstrates the system setup and implementation in four test bed, and presents the simulation results, and discussion with their many graphs that help in understanding this project. The final chapter, **chapter five**, is the conclusion and perspectives of this work.

2.1. Motivation:-

The motivation for developing optical fiber communication systems started with the invention of the laser. The operational characteristics of this device encouraged researchers to examine the optical spectrum as an extension of the radio and microwave spectrum to provide transmission links with extremely high capacities. As research progressed, it became clear that many complex problems stood in the way of achieving such a super broadband communication system. However, it was also noted that other properties of optical fibers gave them a number of inherent cost and operational advantages over copper wires and made them highly attractive for simple on/off keyed links [15].

Current state-of-the-art systems operate at bit rates ~10Gb/s, indicating that there is considerable room for improvement. Figure 2.1 shows a generic block diagram of an optical communication system. It consists of a transmitter, a communication channel (optical fiber, repeaters, and amplifiers), and a receiver; the three elements common to all communication systems.

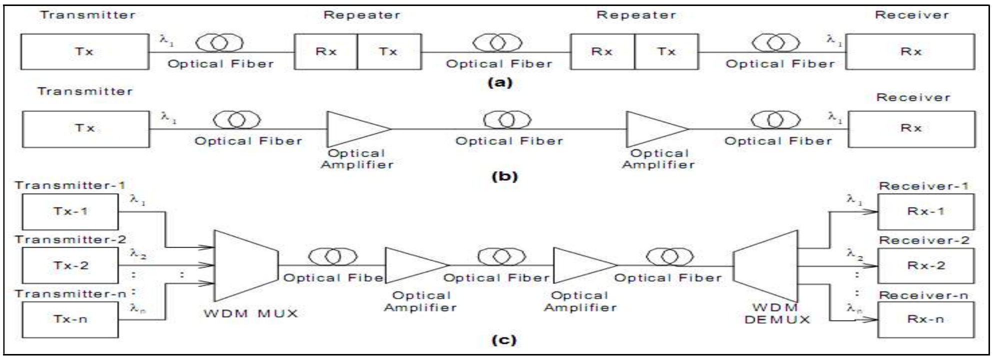


Figure (2-1):- Block diagram of optical fiber communication systems: (a) conventional single-channel systems; (b) single-channel systems with optical amplifiers; (c) single channel WDM systems with optical amplifiers.

Optical communication systems can be classified into two broad categories: guided and unguided. As the name implies, in the case of guided lightwave systems, the optical beam emitted by the transmitter remains spatially confined. Since all guided optical communication systems currently use optical fibers, the commonly used term for them is fiber optic communication systems. The term lightwave system is also sometimes used for fiber optic communication systems, although it should generally include both guided and unguided systems. In the case of unguided optical communication systems, the optical beam emitted by the transmitter spreads in space, similar to the spreading of microwaves. However, unguided optical systems are less suitable for broadcasting applications than microwave systems because optical beams spread mainly in the forward direction (as a result of their short wavelength) [2].

The use of generally requires accurate pointing between the transmitter and the receiver. In the case of terrestrial propagation, the signal in unguided systems can deteriorate considerably by scattering within the atmosphere. This problem, of course, disappears in free-space communications above the earth atmosphere (e.g., inter satellite communications). Although free-space optical communication systems are needed for certain applications and have been studied extensively, most terrestrial applications make use of fiber optic communication systems [13].

The application of optical fiber communications is in general possible in any area that requires transfer of information from one place to another. However, fiber optic communication systems have been developed mostly for telecommunications applications. This is understandable in view of the existing worldwide telephone networks which are used to transmit not only voice signals but also computer data and fax messages. The telecommunication applications can be broadly classified into two categories, long-haul and short-haul, depending on whether the optical signal is transmitted over relatively long or short distances compared with typical intercity distances (~100km). Long-haul telecommunication systems require high-capacity trunk lines and benefit most by the use of fiber optic lightwave systems. Indeed, the technology behind optical fiber communication is often driven by long-haul applications. Each successive generation of lightwave systems is capable of operating at higher bit rates and over longer distances. Periodic regeneration of the optical signal by using repeaters is still required for most long-haul systems. However, more than an order-of-magnitude increase in both the repeater spacing and the bit rate compared with those of coaxial systems has made the use of lightwave systems very attractive for long-haul applications. Furthermore, transmission distances of thousands of kilometers can be realized by using optical amplifiers [60].

Short-haul telecommunication applications cover intracity and local-loop traffic. Such systems typically operate at low bit rates over distances of less than 10km. The use of single-channel lightwave systems for such applications is not very cost-effective, and multichannel networks with multiple services should be considered. The concept of a broadband integrated-services digital network requires a high-capacity communication system capable of carrying multiple services. The asynchronous transfer mode (ATM) technology also demands high bandwidths [61].

2.2. Evolution in Optical Fiber Communication Systems [13]:-

As their name implies, these kinds of communication systems use optical waves as carriers; hence, the BL can be improved via several orders of magnitude compared to the microwave and coaxial systems. The most appropriate media that are used as channels in these systems are the optical fibers. However, the first-encountered problem was that available fibers during that time had extremely high loss which exceeded 1000dB/km. This problem challenged the researchers and engineers to find processes by which low-loss optical fibers could be fabricated. Finally, this problem was solved in 1970, when optical fiber having acceptable attenuation was first obtained. The progress in the BL of the optical fiber communication systems is usually divided into five generations which are briefly described as follows.

2.2.1. First Generation:-

The first generation of optical fiber communication systems utilized multimode optical fibers and operated in the 0.8μm wavelength region. The advantage of the multimode fibers is that their core is large; thus, coupling of the light from the source into the fiber is not difficult. However, a large core diameter also leads to an unavoidable drawback. The major drawback is that the optical waves travel in the fiber with different paths; therefore, the optical waves arrive at the receiver with slightly different time delays which cause pulse spreading. In addition, there is another type of dispersion called intramodal dispersion or chromatic dispersion, which is due to nonlinear phase response of the optical fiber. Both types of dispersion generate intersymbol interference (ISI), which limits the system performance. The BL of the first generation is therefore limited by both types of dispersion and fiber loss.

2.2.2. Second Generation:-

One way to eliminate intermodal dispersion is to utilize a single mode optical fiber, and has less internal (Rayleigh) scattering. Thus, the attenuation is also less than that of the multimode fiber. Both advantages could lead to higher BL product. With the advance in semiconductor technology, operating the systems at 1.3μm window was finally realized. As a result, larger BL of the order of 200Gbps-km was achieved and it was solely limited by fiber attenuation. The first transatlantic system called TAT-8 was implemented, and started operating in 1988. It consists of three pairs of single-mode optical fibers (one pair for backup purpose), and each pair operated at 296Mbps (one for each direction) due to limitation on FDDI interfaces.

2.2.3. Third Generation:-

As seen in Figure 2.2, the attenuation in the single mode fiber is lowest in the 1.55μm wavelength region (0.2dB/km). However, the intramodal dispersion in this wavelength region is so severe that its effect is intolerable for very high BL systems. Dispersion- shifted fibers are fibers that are tailored to provide minimum dispersion near 1.55μm; thus, allowing the use of conventional lasers exhibiting relatively large spectral width (several nm). On the other hand, the narrow line width lasers have to be employed in the systems that use conventional optical fibers in order to take advantage of lowest attenuation. With both approaches, the BL of 500Gbps-km was achievable.

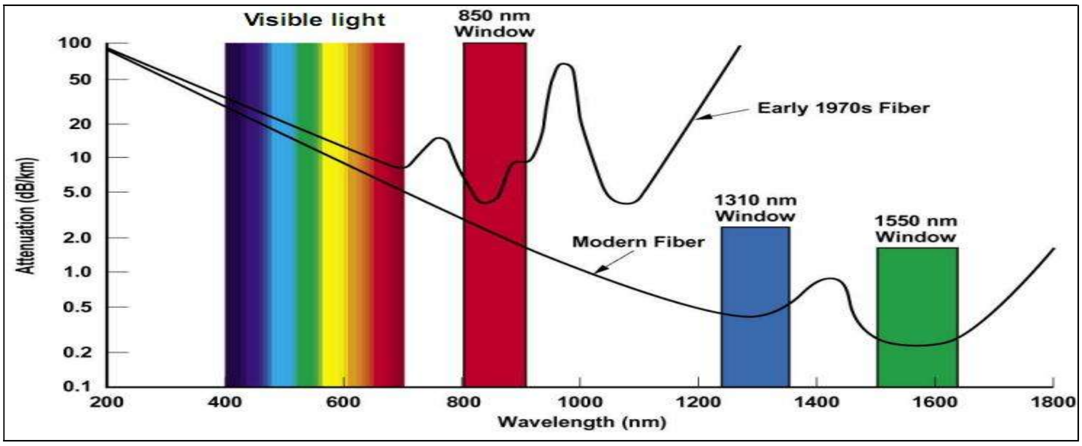


Figure (2-2):- The wavelength (nm) versus attenuation (dB/km).

The 0.85μm window was the first to be used for fiber optic communications because the transmission sources and the receiving detectors were easy to manufacture and very efficient. A typical range of attenuation figures for an optical fiber at this wavelength is (2 to 3.2dB/km).

For the majority of fiber optic systems, the 1.3μm window is the preferred window of operation because the overall losses are much lower than the 0.8 μm window. A typical range of attenuation figures for an optical fiber at this wavelength is 0.3-0.9dB/km. Although the light sources are readily available, they are expensive and difficult to manufacture. Hence, this wavelength is generally used for high speed data and long distance telecommunication applications.

The third window, which operates at 1.55µm, exhibits less loss than the second window. A typical range of attenuation figures for an optical fiber in this band is 0.15–0.6dB/km. The trade off unfortunately is that the transmitting and receiving devices are not as advanced or as efficient as those operating in the 1.3µm window. It is anticipated that recent technological developments will make this the most popular window of operation in the future.

2.2.4. Fourth Generation:-

It is clearly seen that the increase in the BL product for single channel seemed to reach its saturation point. The systems were designed to operate at lowest attenuation region to overcome the attenuation problem and the narrow line width lasers were utilized to minimize the dispersion effect. However, the modulation technique was still primitive intensity modulated/direct detection (IM/DD) which offered simple system configuration. Such systems are referred to as coherent optical communication systems. Nevertheless, the system configurations were too complex to implement in practice. Consequently, the coherent systems are not commercially attractive.

2.2.5. Fifth Generation:-

With the development of optical amplifiers, the extreme improvement in the BL product became practically possible. The huge amount of bandwidth offered by the optical fiber could be utilized by using the WDM technique. In addition, with the help of optical amplifiers all channels could be simultaneously amplified without optical-electrical-optical conversion. Thus, the spacing between regenerative repeaters could be extended considerably. As a result, the BL was increased and could be larger than 100,000Gbps-km. There is another approach that can combat the dispersion effect; hence, increasing the repeater spacing. Such an approach is to make use of fiber nonlinearity, which results in the shape of the optical pulses being preserved while traveling in the fiber. The systems that utilize this technique are called Soliton-based systems.

2.3. Optical Fiber Communication System Components:-

The optical fiber communication systems consists of three sections, each of them has many components. These components fall into two categories. The first one is passive components and the second is the active components. Reference will be made to these components in the following subsections:

2.3.1. Transmitter:-

The role of the optical transmitter is to convert an electrical input signal into the corresponding optical signal and then launch it into the optical fiber serving as a communication channel. The major component of optical transmitters is an optical source. Fiber optic communication systems often use semiconductor optical sources such as LEDs and semiconductor lasers due to several inherent advantages offered by them.

Although the operation of semiconductor lasers was demonstrated as early as 1962, their use became practical only after 1970 when semiconductor lasers operating continuously at room temperature became available. Since then, semiconductor lasers have been developed extensively because of their importance for optical communications. They are also known as laser diodes or injection lasers [1, 2, and 62].

The optical signal is produced by the optical transmitter which is a laser (light amplification by stimulated emission of radiation). The laser is a device that converts electrical energy to monochromatic light. The lasers used in optical networks are semiconductor lasers, and they are very small (size of a grain of salt). They are designed specifically to give a precise and intense light, since in a WDM network it is very important to obtain the light at a precise wavelength. Different materials are used to obtain different wavelengths from the laser. In optical networks, the wavelength range is in infrared region, between (1300nm - 1550nm). A relatively young technology permits producing tunable lasers. These are light sources that can be adjusted to emit light at different wavelengths. They are also semiconductor-based and their design principle is similar to non-tunable laser. The transmitter consists of four components, namely (optical source to generate continues light waves, pseudo random bit sequence generator (PRBSG), electrical signal generator, and optical modulator to modulate the electrical signal and optical signals and launched into the fiber). PRBSG patterns have been standardized by the ITU for testing digital transmission systems patterns [63]. Figure 2.3 shows the block diagram for the transmitter.

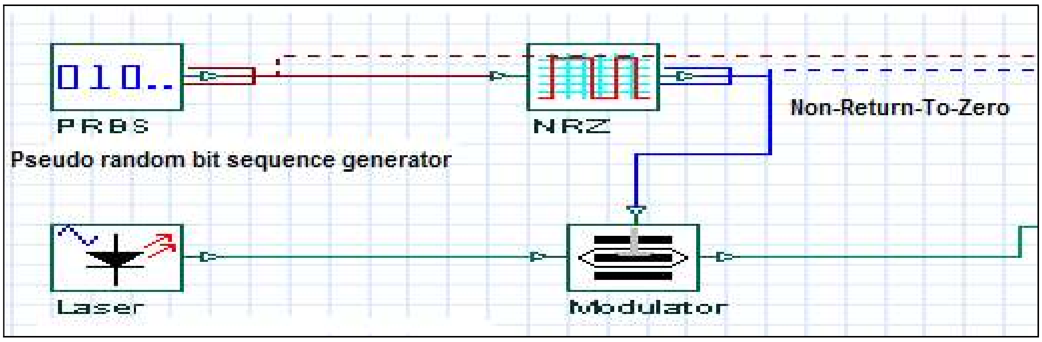


Figure (2-3):- The optical transmitter components [64].

2.3.1.1. Basic Concepts:-

Under normal conditions, all materials absorb light rather than emit it. The absorption process can be understood by referring to Figure 2.4, where the energy levels E_1 *and* E_2 correspond to the ground state and the excited state of atoms of the absorbing medium. If the photon energy $h\nu$ of the incident light of frequency ν is about the same as the energy difference $(Egap), E_g = E_2 - E_1$, the photon is absorbed by the atom, which ends up in the excited state. Incident light is attenuated as a result of many such absorption events occurring inside the medium. The excited atoms eventually return to their normal “ground” state and emit light in the process. Light emission can occur through two fundamental processes known as spontaneous emission and stimulated emission. Both are shown schematically in Figure 2.4. In the case of spontaneous emission, photons are emitted in random directions with no phase relationship among them. Stimulated emission, by contrast, is initiated by an existing photon. All lasers, including semiconductor lasers, emit light through the process of stimulated emission and are said to emit coherent light. In contrast, LEDs emit light through the incoherent process of spontaneous emission.

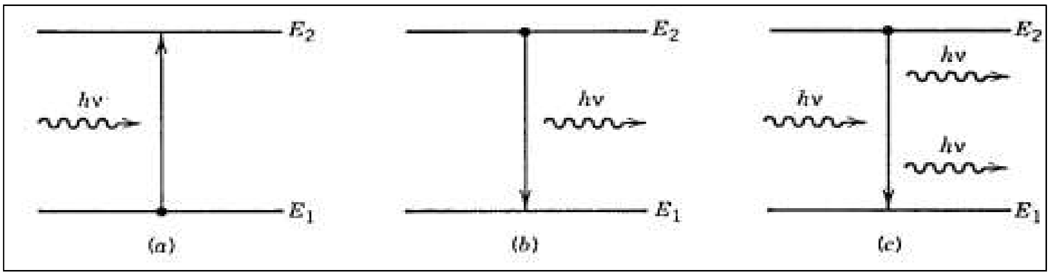


Figure (2-4):- Three fundamental processes occur between the two energy states of an atom: (a) absorption; (b) spontaneous emission; (c) Stimulated emission.

2.3.1.2. Optical Transmitter Design:-

The design of optical transmitters requires attention to many details that differ from one application to another. For example, applications related to computer-data and access networks have low cost as a major design objective and need relatively low- power optical transmitters, based on LEDs. For metropolitan networks, low cost remains important, but bit rates are also higher (typically 2.5Gbps). Such networks require semiconductor lasers that can be directly modulated at such bit rates. In contrast, submarine and terrestrial long-haul lightwave systems operate at high speeds and employ multiple WDM channels, each operating at 10Gbps or more. The design requirements are most stringent for such systems. A distributed- feedback laser (DFB) is invariably used for stabilizing the channel wavelength. Continuous wave (CW) light from the DFB laser is coupled to a modulator as efficiently as possible. The modulator is often integrated with the laser. If that is not possible, an external $LiNbO_3$ modulator is employed. In both cases, the optical bit stream generated needs to be launched into the fiber link without experiencing significant coupling losses and without undesirable feedback into the transmitter.

Although an optical source is a major component of optical transmitters, it is not the only component. Other components include a modulator for converting electrical data into optical form (if direct modulation is not used) and an electrical driving circuit for supplying current to the optical source. An external modulator is often used in practice at bit rates of 10Gbpsor more for avoiding the chirp that is invariably imposed on the directly modulated signal [65]. The design objective for any transmitter is to couple as much light as possible into the optical fiber, and optical modulators.

I. Source–Fiber Coupling:-

In practice, the coupling efficiency depends on the type of optical source (LED versus laser) as well as on the type of fiber (multimode versus single mode). The coupling can be very inefficient when light from an LED is coupled into a single mode fiber.

II. Optical Modulators:-

Digital modulation is a process that impresses a digital symbol onto a signal suitable for transmission. For short distance transmissions, baseband modulation is usually used. Baseband modulation is often called line coding. A sequence of digital symbols is used to create a square pulse waveform with certain features which represent each type of symbol without ambiguity so that they can be recovered upon reception. These features are variations of pulse amplitude, pulse width, and pulse position. Figure 2.5 shows several baseband modulation waveforms such as NRZ, RZ, and Manchester.

For long distance and wireless transmissions, bandpass modulation is usually used. Bandpass modulation is also called carrier modulation. A sequence of digital symbols is used to alter the parameters of a high-frequency sinusoidal signal called carrier. It is well known that a sinusoidal signal has three parameters, namely (amplitude, frequency, and phase). Thus amplitude modulation, frequency modulation, and phase modulation are the three basic modulation methods in passband modulation. Figure 2.6 shows three basic binary carrier modulations such as ASK, frequency shift keying (FSK), and phase shift keying (PSK) [66].

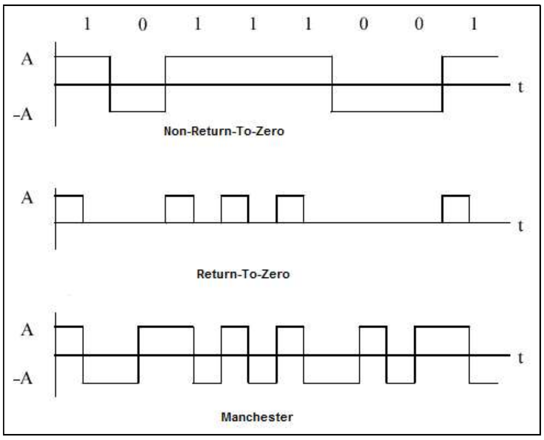


Figure (2-5):- Baseband digital modulation examples.

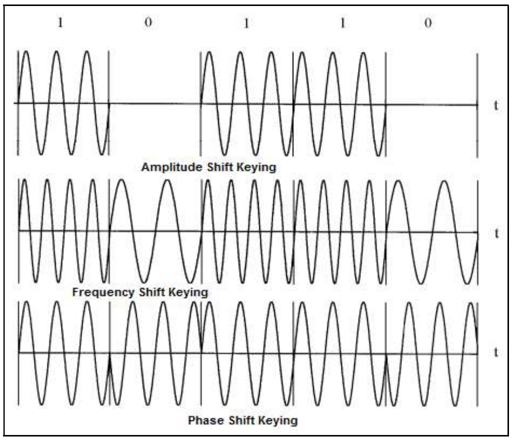


Figure (2-6):- Three basic bandpass modulation schemes.

At bit rates of 10Gbps or higher, the frequency chirp imposed by direct modulation becomes large enough that direct modulation of semiconductor lasers is rarely used. For such high-speed transmitters, the laser is biased at a constant current to provide the CW output, and an optical modulator placed next to the laser converts the CW light into a data-coded pulse train with the right modulation format. Two types of optical modulators developed for lightwave system applications are shown in Figure 2.7, according to which the band gap of a semiconductor decreases when an electric field is applied across it. Thus, a transparent semiconductor layer begins to absorb light when its band gap is reduced electronically by applying an external voltage. An extinction ratio of 15dB or more can be realized for an applied reverse bias of a few volts at bit rates of up to 40Gbps. Although some chirp is still imposed on coded pulses, it can be made small enough so as not to be detrimental for the system performance. An advantage of electro-absorption modulators is that they are made to use the same semiconductor material that is used for the laser, and thus the two can be easily integrated on the same chip.

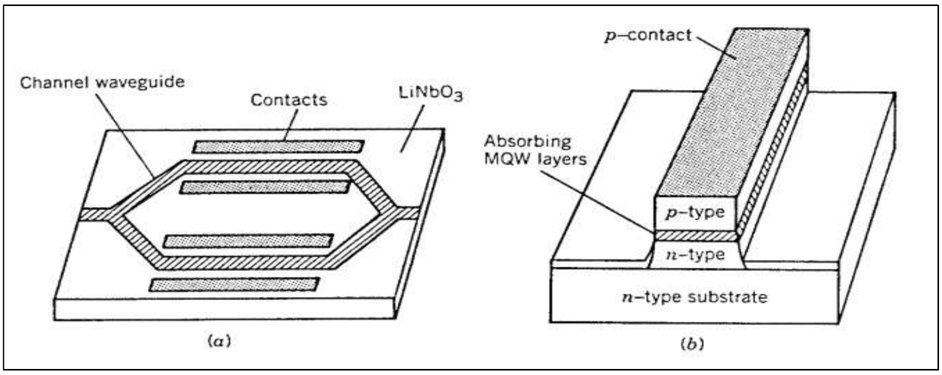


Figure (2-7):-Two kinds of external modulators: ($LiNbO_3$) modulator in the Mach-Zender configuration; (b) semiconductor modulator based on electro-absorption.

2.3.2. Optical Fiber Link and its Principles:-

This section demonstrates the theory of transmission of information over optical fibers. Areas to be covered in this section include fundamental principles and the basic mathematical representation of light transmission down a glass fiber, modes of light transmission, construction of a fiber, transmission capacities and limitations, fabrication processes and future developments.

2.3.2.1. Fundamental Principles of Operations [3]:-

The fundamental principle behind communicating through optical fibers is that electromagnetic energy is tunneled down a tube of glass from a transmitter to a receiver. The tube of glass acts like a pipe that ducts all the electromagnetic energy from one point to another. The electromagnetic energy that is used in this transmission system is in the near visible light section of the electromagnetic spectrum. Therefore, glass is the ideal medium to duct this electromagnetic energy, as light passes through glass with low levels of attenuation. Figures (2.8 and 2.9) illustrate the electromagnetic energy passing through a glass duct, and the reflection process respectively.

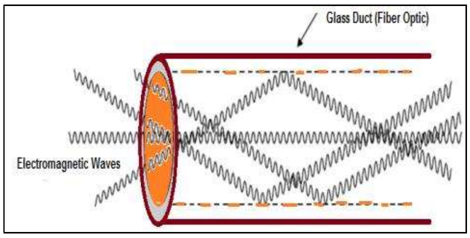


Figure (2-8): Electromagnetic energy passing through a glass duct.

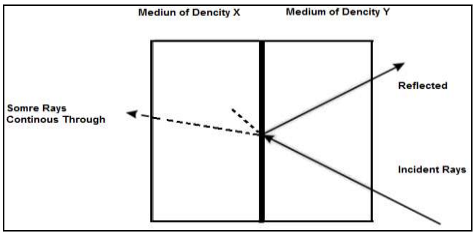


Figure (2-9):- Reflection of ray.

2.3.2.2. Reflection, Refraction, and Diffraction [3]:-

The following section is a brief revision of some fundamental principles of physics. Reflection, refraction and diffraction are the three main effects that cause changes to the direction of an electromagnetic wave (this includes light, radio waves, x-rays, gamma rays etc). So, concentration will be on the specific behavior of light.

a) Reflection:-

This occurs where a light ray that is traveling through a medium of a particular density strikes a medium of a density different from the one in which it is traveling and partially or totally bounces off the interface of the two mediums.

b) Refraction:-

This occurs where a light ray totally or partially passes into a medium of a density different from the one in which it is traveling and changes direction slightly, compared to its direction in the previous medium.

c) Refractive Index:-

The light by nature travels at different speeds in different mediums. The denser the medium, the slower will be the speed at which the light travels. A measure of these factors has been established, which relates directly to both the density of the material and the speed of light through the material.

This is referred to as refractive index. This measure for any material is made relative to the speed of light in a vacuum (the vacuum is often referred to as free space). The following formula describes this relationship.

$$N=S_m/S_v \qquad \ldots (2\text{-}1)$$

Where

N is the Refractive Index of a Medium,

S_m is Speed of light in a medium (m/s), and

S_v is Speed of light in a vacuum (m/s).

The higher the refractive index of a material, the denser that material is. As a ray of light passes from one medium to another, where each medium has a different refractive index, the angle of refraction will differ from the angle of incidence. A ray of light passing into a medium of lower refractive index will leave at an angle greater than the angle of incidence. A ray of light passing into a medium of higher refractive index will leave at an angle less than the angle of incidence. This is illustrated in Figure 2.10, where θ_1 is the angle of incidence and θ_2 is the angle of refraction.

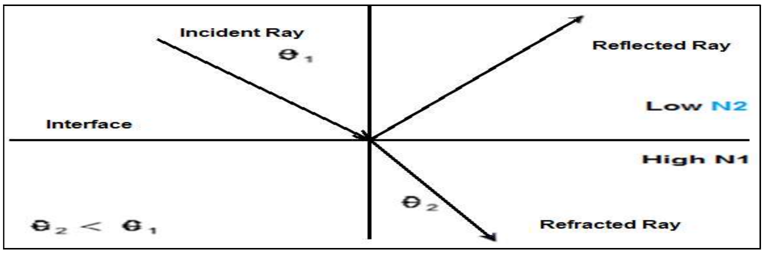


Figure (2-10):- Reflected ray passing from high N_1 to low N_2.

2.3.2.3. Snell Law's [3]:-

In 1621, a Dutch Astronomer and mathematician of the name Willebrod Van Roijen Snell described a relationship of the refraction of light traveling through different mediums. The relationship is expressed as follows:

$$N_1 \times \sin(\theta_1) = N_2 \times \sin(\theta_2) \qquad \ldots (2\text{-}2)$$

where N_1 and N_2 are the refractive indices of medium 1 and medium 2 respectively; (θ_1) and (θ_2) are the corresponding angles of incidence or refraction in the respective mediums.

Therefore, from the above equation the following is arrived at:

$$\frac{N_1}{N_2} = \frac{\sin(\theta_2)}{\sin(\theta_1)} = \frac{C_2}{C_1} \qquad \ldots (2\text{-}3)$$

where C_1 and C_2 are the speeds of light in medium 1 and medium 2 respectively.

2.3.2.4. Internal Reflection:-

When light is travels from one medium into a medium of different density, a certain amount of incident light is reflected. This effect is more prominent where the light is travels from a high-density medium into a lower density medium. The exact amount of light that is reflected depends on the degree of change of refractive index and on the angle of incidence. If the angle of incidence is increased, the angle of refraction is increased at a greater rate. This is illustrated in Figure 2.11, where total internal reflection occurs. The angle of incidence equals the angle of reflection [3].

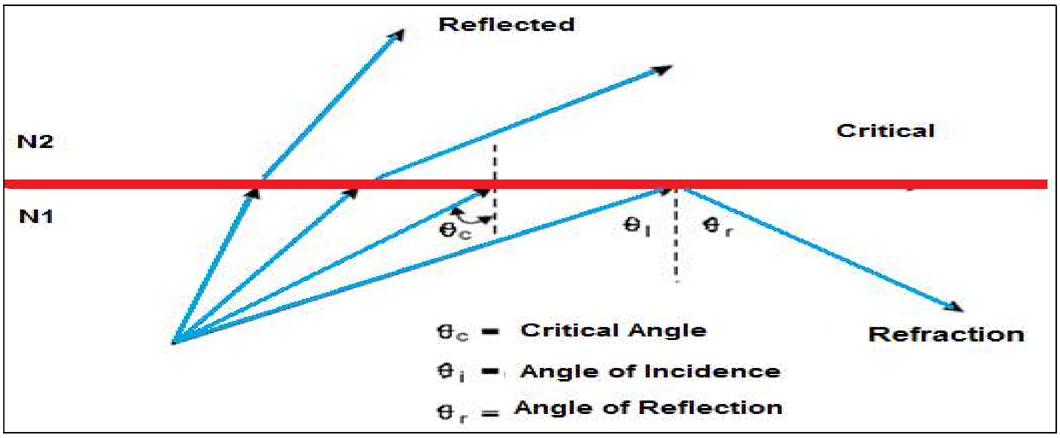


Figure (2-11): Critical Angles.

2.3.2.5. External Reflection:-

When a light ray is travels in a medium and strikes an interface with a denser medium at greater than the critical angle, the same effect occurs as internal reflection but to a lesser degree. This is referred to as external reflection. Total external reflection only occurs when the angle of incidence equals to ($\theta_i + \theta_r = 90^\circ$).

2.3.2.6. Construction of an Optical Fiber:-

An optical fiber consists of a tube of glass constructed of a number of layers of glass, which when looked at in profile, appears to have a number of concentric rings. Each layer (or ring) of glass has a different refractive index. To achieve total internal reflection, the outer glass rings require a lower refractive index than the inner glass tube in which the light is traveling. Figure 2.12 illustrates the construction of a typical optical fiber. The core and the cladding will trap the light ray in the core provided that the light ray enters the core at an angle greater than the critical angle. The light ray will then travel down the core of the fiber, with minimal loss in power, by a series of total internal reflections. Figure 2.13 illustrates this process.

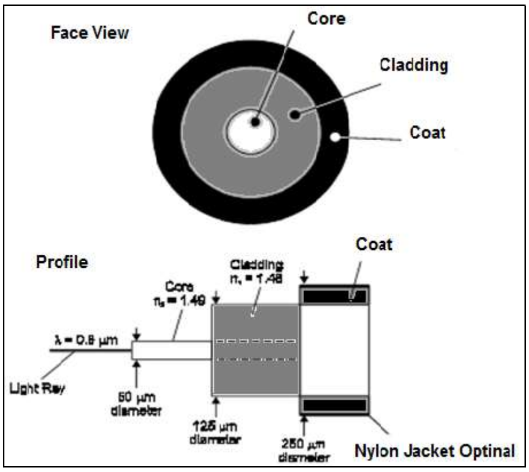


Figure (2-12):- Construction of an Optical Fiber.

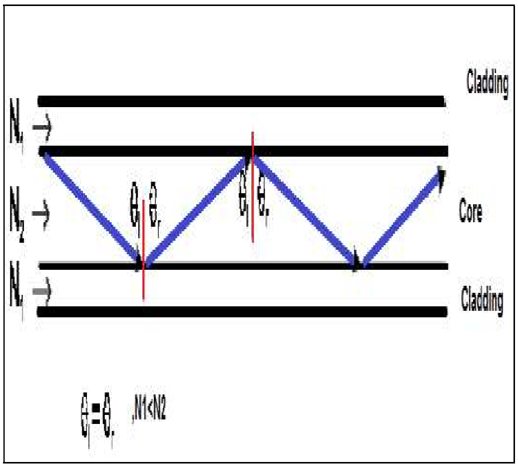


Figure (2-13):- Light ray traveling through an optical fiber.

2.3.2.7. Numerical Aperture (NA):-

Previous sections have discussed the process of light traveling through an optical fiber. This section will discuss the requirements for transmitting into an optical fiber. Due to the refractive changes to the direction of the light as it enters the core of a fiber, there is a limit to the angle at which the light can enter the core to successfully propagate down the optic fiber. Any light striking the cladding at less than the critical angle will go straight through into the cladding and be lost. This is illustrated in Figure 2.14.

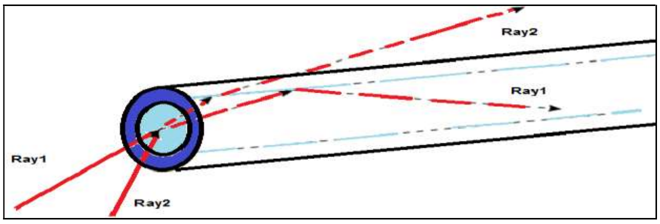


Figure (2-14):- Light entering the core of a fiber.

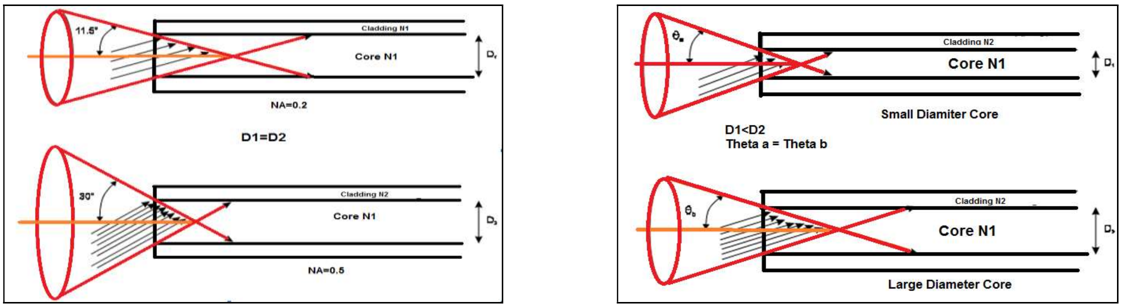
A measurement is used to specify the light collecting ability of a fiber. This is referred to as the NA. NA is the Sine of the acceptance angle, that is:

$$NA = \sin(\theta_1) \qquad \dots (2\text{-}4)$$

It can also be expressed as a factor of the refractive indices of the fiber.

$$NA = \sqrt{\left(N_1^2 - N_2^2\right)} = N_1 \sin(\theta_2) \qquad \dots (2\text{-}5)$$

If there are two fibers with the same core diameter but different NAs, the fiber with the larger NA will accept more light energy radiated from a light source than the fiber with smaller NA. If there are two fibers with the same NAs but different diameters, the fiber with the larger diameter will allow more light energy into the core than the fiber with the smaller diameter. This is illustrated in Figure 2.15.



(a) **(b)**

Figure (2-15):- NA concepts (a): Fibers with different NAs but same diameters, (b): Fibers with same NAs but different diameters.

To summarize, NA carries the following information:

1) The ability of the optical waveguide to gather light at the input.
2) The contrast in refractive index between the core and the cladding,.
3) The number of modes and the dispersion of the signal in multimode fiber.
4) The level of dopant in the cladding. Hence the attenuation becomes due to the level of dopant.

2.3.2.8. Modal Propagation in Fiber:-

Optical fibers are classified according to the number of rays of light that can be carried down the fiber at one time. This is referred to as the 'mode of operation' of the fiber. Therefore, a mode of light is simply a ray of light. The higher the mode of operation of an optical fiber, the more are the rays of light that can travel through the core. It is possible for a fiber to carry as many as several thousand modes or as few as only one. The following section discusses various modes of propagation in optical fibers and the effects of modal dispersion [67].

A. Modal Dispersion:-

It is important firstly to explain the nature and effects of modal transmission. A fiber that has a high NA and/or diameter will have a large number of modes (rays of light) operating along the length of that fiber. An omnidirectional light source (i.e. one that effectively radiates light rays equally in all directions) such as an LED will emit several thousand rays of light in a single pulse. Because the light source injects a broad angle of beam into the core, each mode of light traveling at a different angle as it propagates down the fiber will therefore travel different total distances over the whole length of the fiber. It follows, therefore, that it will take different lengths of time for each light ray to travel from one end of the fiber to the other. This is illustrated in Figure 2.16. The light ray that travels down the center axis of the fiber is referred to as the fundamental mode and is the lowest order mode possible. The light rays that travel shorter distances down the length of fiber are the lower order modes, and the light rays that travel longer distances down the length of fiber are the higher order modes. If the input pulses are too close together, then the output pulses will overlap on each other, causing ISIs at the receiver. The effect of modal dispersion would rely on this development. This situation will make it difficult for the receiver to distinguish between pulses and will introduce errors into the data. This is the major factor in fiber optic cables (multimode types) that limits transmission speeds. This is illustrated in Figure 2.17.

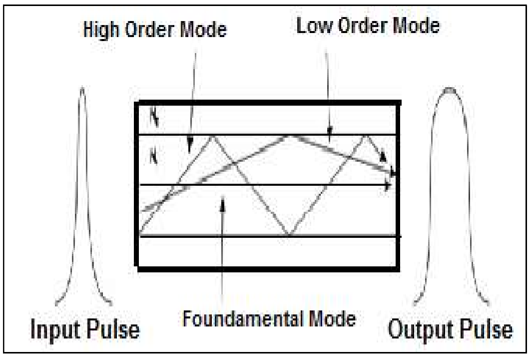


Figure (2-16):- The dispersion effect on a pulse.

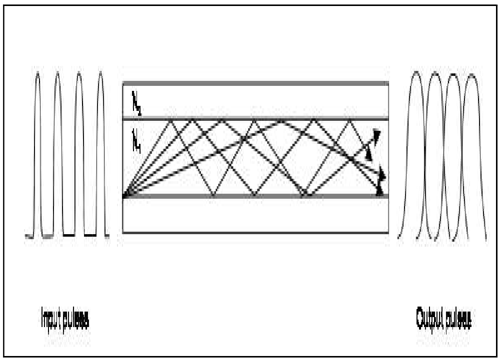


Figure (2-17):- ISI due to modal dispersion

It can be seen from Figure (2.17) that it will be difficult for the receiver to distinguish between the output pulses as they overlap on each other as they exit the fiber core ISI. Modal dispersion is measured in nanoseconds and is given by the following formula [3]:

$$D = \sqrt{\left(D_0^2 - D_1^2\right)} \qquad \dots (2\text{-}6)$$

where:

D is the total dispersion of pulse,

D_0^2 is pulse width at the output of the fiber in nanosecond, and

D_1^2 is pulse width at the input of the fiber in nanosecond.

Modal dispersion increases with increasing NA, and therefore, the bandwidth of the fiber decreases with an increase in NA. The same rule applies to the increasing diameter of a fiber core. This is illustrated in the graphs in Figure 2.18.

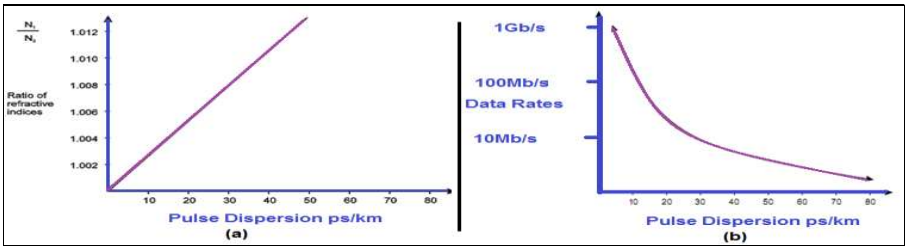


Figure (2-18):- Pulse Dispersion (a): Pulse dispersion versus the ratio of refractive indices, and (b): Pulse dispersion versus data rates.

Cable suppliers provide a dispersion figure in the cable specification. The unit of measure will be given as picoseconds (or nanoseconds) of pulse spreading per kilometer of fiber (ps/km).

B. Number of Modes:-

When the core and cladding have a constant refractive index across their cross sectional area but the core refractive index being different to the cladding refraction index, they behave like an optical waveguide. This is referred to as 'step index' and is discussed in the next section. In this waveguide, only a specific number of modes can propagate. The number of discrete modes is determined by the following formula [3]:

$$M = \frac{0.5\left(\theta d\left(NA^{2}\right)\right)}{\lambda} \qquad \dots (2\text{-}7)$$

where:

d is the diameter of the fiber core,

λ is the wavelength of the light,

NA is the Numerical Aperture, and

Θ is the acceptance angle.

It can be seen from this formula that as the diameter and NA decrease, so do the number of modes that can propagate down the fiber. The decrease in modes is more significant with a reduction in diameter than a reduction in NA. The NA tends to remain relatively constant for a wide range of diameters.

2.3.2.9. Optical Fiber Types:-

Fibers are frequently classified by the number of modes they transmit. A single-mode fiber is efficient only for a single mode and is frequently used in communications that require long distances and high data rates. This is because they do not experience multimode dispersion. They have diameters less than that of a human hair (about 10microns), although the cladding is typically about 125microns. Multimode fibers allow the transmission of many modes. This type of fiber is usually low in cost, and it is easy to successfully inject (in fiber jargon, this is called launch) a pulse into it. However, it suffers from painfully low data rates for long distances. Therefore, these fibers are usually used within hotels, within buildings, and for enterprise networks 300m or less in length, and the bandwidth (2-300Mbps), wavelength window (850-1300nm), it has two types (step index, and graded index). So, the main differences between the two types are related to the fiber dimensions, and the refractive index, which will define how many modes (paths) will be allowed to be transmitted via the fiber. In the next sections, this will be discussed in detail.

A single mode fiber (or sometimes referred to as a single mode cable) is basically a step index fiber with a very small core diameter. In theory, because the cores are so small, only a few modes of light can travel down the fiber. To further reduce the number of modes, the fiber is constructed with very little difference between the refractive indices of the core and the cladding, as the difference between the refractive indices of the core and cladding decrease, the critical angle increases. Therefore, only light approaching a very large angle of incidence will be internally reflected and all other rays will dissipate into the cladding. Because of this construction, only a single mode of light is able to transverse down the fiber (i.e. the fundamental mode). Figure 2.19 illustrates the fiber optic types.

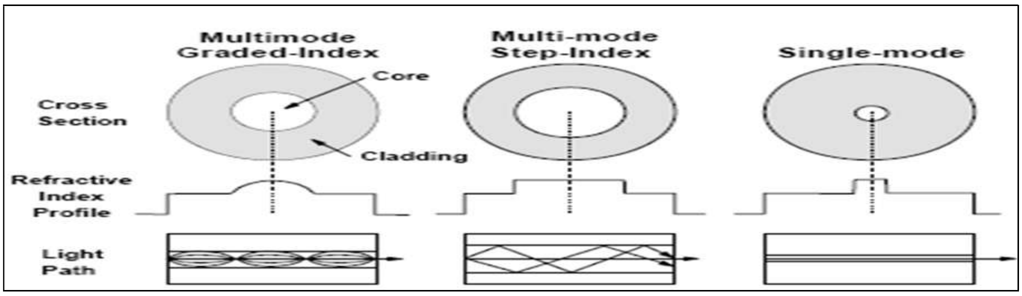


Figure (2-19): Fiber optics types.

For the transmission of light down a single mode fiber to operate as described above, the pulse of light that is injected into the core must be very precisely aimed down the center of the core, otherwise the majority of the light will be lost in the cladding. If the system is implemented correctly, the input signal pulse into the fiber will appear at the output of the fiber as a signal pulse with almost exactly the same shape. With only the fundamental mode traveling down the fiber, there can theoretically be no modal dispersion in single mode fiber. The core diameter of a single mode fiber is generally in the region of (8 to 9μm), attenuation is (0.2dB/km) at wavelength 1550nm, bandwidth between (10 and 40Gbps), and wavelength of operation (1300nm and 1550nm). In general, optical fiber has many advantages that make it preferred as a link. Transmission infrastructure is summarized as follows:-

i. Large Capacity, (i.e., Open Bandwidth),
ii. Immunity to Electrical Fields,
iii. High Security, (i.e., No Tapping, and No Crosstalk),
iv. Low Attenuation Loss over Long Distances,
v. Light Weight, and Small Diameter Cable, and
vi. Low Cost for Long Distance Communication.

2.3.2.10. Effects Optical Signal Transmission [3, 20, 65, 68, and 69]:-

There are a number of physical characteristics that are inherent in optical fibers. These characteristics affect the bandwidth, attenuation, and signal quality of the transmission. In multimode fibers, the main factor that affects signal transmission quality is modal dispersion. This was discussed in detail in section 2.3.2.8. The following section explains other factors that affect the transmission characteristics of an optical fiber. The losses that are incurred in optical fibers behave in a manner similar to losses that are incurred in most other dielectric physical environments by electromagnetic energy.

I. Chromatic Dispersion (CD):-

The major dispersion effect in multimode fibers is modal dispersion. In single mode fibers, there are no modal dispersion effects. More complex dispersion problems occur with single mode fibers and also to a significant degree with graded index multimode fibers. There are two further types of dispersion to be discussed:

a. Material dispersion.
b. Waveguide dispersion.

Material dispersion is a phenomenon that occurs because light sources put out a signal which contains a number of different wavelengths. No light source can produce just one frequency (wavelength). It will rather produce a spectral spread around a central frequency. As the different wavelengths travel through the same material, they will effectively encounter different refractive indexes. Relating this to Snell's law, this means different rays of light will be traveling at different speeds.

The second form of dispersion that makes up chromatic dispersion is waveguide dispersion. Waveguide dispersion occurs in single mode fibers (which are of step index construction) where a certain amount of light travels in the cladding. The dispersion occurs because the light moves faster in the low refractive index cladding than in the higher refractive index core. The degree of waveguide dispersion depends on the proportion of light that travels in the cladding. CD in real terms is a measure of the change in the refractive index with wavelength (ps/nm/km).

II. Absorption Losses:-

During the manufacturing process of optical fiber, every effort is made to fabricate the glass as pure as possible. The requirements for cleanliness, purity and quality control in the manufacturing process are as stringent as those applied to the semiconductor industry. Unfortunately, it is impossible to produce 100% pure glass. The impurities that are left in the glass will absorb light. These impurities are in the form of ionized molecules. The absorption losses caused by metal ion impurities are substantial in poor quality glass. Glass will also contain significant amounts of water ion (OH^-) impurities that resonate at certain frequencies.

III. Scatter Losses:-

There are two types of scatter losses that occur in fibers. The first type occurs because all manufactured or naturally occurring material is never perfect in its molecular structure throughout the entire volume of the material. This type of scatter loss is referred to as Rayleigh scattering.

The second type of scatter loss that occurs is due to irregularities in the core/cladding interface. These appear as physical imperfections and are introduced during the fabrication process. When a light ray strikes one of these imperfections, it may change to a higher order mode and be dissipated through the cladding. This results in higher signal attenuation.

IV. Bending Losses:-

It is sometimes assumed intuitively that if a fiber is bent, losses will be introduced into the transmission path. This is not true as the inside of a fiber is normally seen as a mirror to light rays, and slight bends in the fiber do not introduce losses. Losses occur only when the radius of the bend causes the light ray to be incident at an angle less than the critical angle.

There are two types of bend that cause losses. The first is referred to as a ‘Macrobend’. This is where the cable is installed with a bend in it that has a radius less than the minimum bending radius. This is illustrated in Figure 2.20.

The second type of bending loss is referred to as 'Microbending'. The microbend takes the form of a very small sharp bend (a kink) in the cable. Microbends can be caused by imperfections in the cladding, ripples in the core/cladding interface, tiny cracks in the fiber and external forces.. This is illustrated in Figure 2.21.

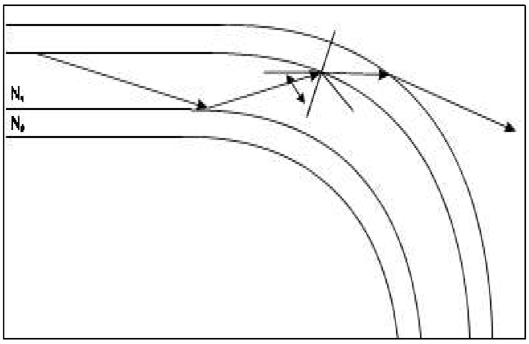


Figure (2-20):- Losses due to macrobending.

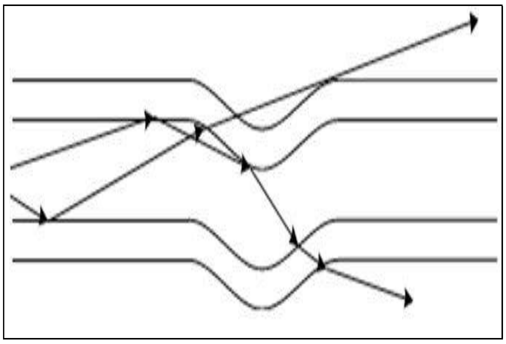


Figure (2-21):- Losses due to microbending.

V. Radiation Losses:-

A close analysis of the energy fields of the light pulses that are carried down the fiber shows that a certain amount of the total light energy is carried in the cladding of the fiber. When there is a bend in the fiber, the light energy traveling through the larger outer curve will be required to travel faster than the energy traveling in the center of the core. The light will naturally resist this and will tend to radiate away.

VI. Fiber Size and NA Mismatch:-

Although it is not desirable, the occasion does arise when it is required to connect fibers of different sizes and of different NAs. If the fiber from which the light is emanating is larger than the fiber, that receives the light, light rays will escape out of the fringes of the larger fiber. If the two fibers have the same diameters but have different NAs and the fiber from which light is emanating has the larger NA, this fiber will lose a small amount of its energy through refraction into the cladding of the second fiber Eqs. (2-8, and 2-9) approximates the losses incurred.

$$loss(dBs) = -20\log({}^{NA_1}\!\!/_{NA_2}) \quad \forall NA_1 \rangle NA_2 \qquad \ldots (2\text{-}8)$$

$$loss(dBs) = -20\log({}^{D_1}\!\!/_{D_2}) \quad \forall D_1 \rangle D_2 \qquad \ldots (2\text{-}9)$$

Note that it is implicit that there is a NA mismatch if there is a diameter mismatch because NA is dependent upon diameter (D).

2.3.3. Optical Receiver:-

The role of an optical receiver is to convert the optical signal back into electrical form and recover the data transmitted through the lightwave system. The main component of an optical receiver is a photodetector that converts light into electricity through the photoelectric effect. The requirements for a photodetector are similar to those of an optical source. It should have high sensitivity, fast response, low noise, low cost, and high reliability. Its size should be compatible with the fiber core size. These requirements are best met by photodetectors made of semiconductor materials. Optical receivers detect incoming lightwave signals and convert them to an appropriate signal for processing by the receiving device. The optical signal is converted into photocurrent by photodetectors which are semiconductor photodiodes. The carried signal is detected from the photocurrent by detection circuit. The signal is processed for clock recovery, sampling and threshold detection to extract the digital bit stream from the received signal. As tunable transmitters, there are also tunable receivers which range can be as large as 500nm.

2.3.3.1. Receiver Design [63, 64, and 69]:-

The design of an optical receiver depends on the modulation format used by the transmitter. Since most lightwave systems employ the binary intensity modulation. Figure 2.22 shows a block diagram of such a receiver. The receiver components can be arranged into three groups: the front end, the linear channel, and the decision circuit.

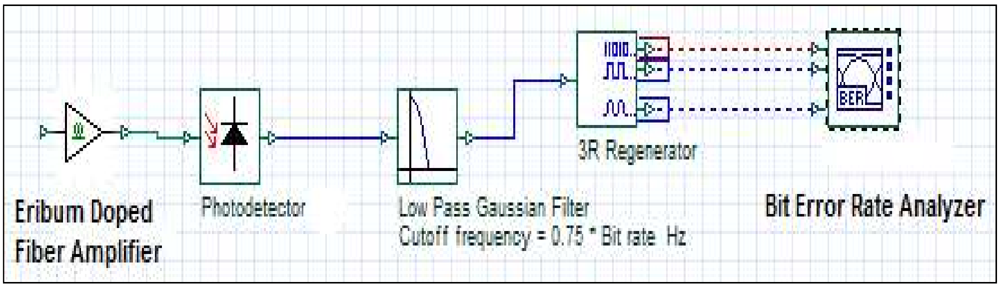


Figure (2-22):- The block diagram of an optical receiver [64].

A. Front End:-

The front end of a receiver consists of a photodiode followed by a preamplifier. The optical signal is coupled onto the photodiode by using a coupling scheme similar to that used for optical transmitters, but coupling is often used in practice. The photodiode converts the optical bit stream into an electrical time-varying signal. The positive-negative junctions are commonly used for making optical receivers. Many types of photodetectors are used in optical communication system such as (Positive-Negative (p–n) Photodiodes, Positive-Intrinsic-Negative (PIN) Photodiodes, Avalanche Photodiodes (APD), and Metal-Semiconductor-Metal (MSM) Photodetectors). The role of the preamplifier is to amplify the electrical signal for further processing. The negative feedback reduces the effective input impedance by a factor of G, where G is the amplifier gain. The bandwidth is thus enhanced by a factor of G compared with high-impedance front ends. Trans-impedance front ends are often used in optical receivers because of their improved characteristics. A major design issue is related to the stability of the feedback loop.

B. Linear Channel:-

The linear channel in optical receivers consists of a high-gain amplifier (the main amplifier) and a low-pass filter. An equalizer is sometimes included just before the amplifier to correct the limited bandwidth of the front end. The amplifier gain is controlled automatically to limit the average output voltage to a fixed level irrespective of the incident average optical power at the receiver. To reduce the noise without introducing much ISI, a good low-pass filter that shapes the voltage pulse, must be selected.

C. Decision Circuit:-

The data-recovery section of optical receivers consists of a decision circuit and a clock-recovery circuit. The purpose of the latter is to isolate a spectral component at $f = B$ from the received signal. This component provides information about the bit slot $TB = 1/B$ to the decision circuit and helps to synchronize the decision process. In the case of RZ format, a spectral component at $f = B$ is present in the received signal; a narrow-bandpass filter such as a surface-acoustic-wave filter can isolate this component easily. A commonly used technique generates such a component by squaring and rectifying the spectral component at $f = B/2$ that can be obtained by passing the received signal through a high-pass filter. The decision circuit compares the output from the linear channel to a threshold level, at sampling times determined by the clock-recovery circuit, and decides whether the signal corresponds to bit 1 or bit 0. The best sampling time corresponds to the situation in which the signal level difference between 1 and 0 bits is maximum. It can be determined from the eye diagram formed. The resulting pattern is called an eye diagram because of its appearance. The best sampling time corresponds to maximum opening of the eye. Because of noise inherent in any receiver, there is always a finite probability that a bit would be identified incorrectly by the decision circuit.

2.3.3.2. Receiver Noise:-

Optical receivers convert incident optical power P_{in} into electric current through a photodiode. The relation in Eq. (2-10) assumes that such a conversion is noise free. However, this is not the case even for a perfect receiver. Two fundamental noise mechanisms, shot noise and thermal noise lead to fluctuations in the current even when the incident optical signal has a constant power.

$$I_p = RP_{in} \qquad \dots (2\text{-}10)$$

The relation in Eq. (2-10) still holds if we interpret I_p as the average current. However, electrical noise induced by current fluctuations affects the receiver performance. The signal-to-noise-ratio (SNR) is also affected by the avalanche gain mechanism in APDs. Of course, additional noise is generated if P_{in} is itself fluctuating because of noise produced by optical amplifiers.

2.4. Nonlinear (Kerr) Effects:-

Fiber nonlinearities are important in optical communications. They must be considered when designing long range high-data- rate systems that involve high optical power levels and in which signals at multiple wavelengths are transmitted. The consequences of nonlinear transmission can include:

(1) The generation of additional signal bandwidth within a given channel,

(2) Modifications of the phase and shape of pulses,

(3) The generation of light at other wavelengths at the expense of power in the original signal, and

(4) Crosstalk between signals at different wavelengths and polarizations.

The first includes nonlinear effects that affect the shape of an optical pulse and includes: (SPM, and XPM); nonlinear effects that affect the energy of an optical pulse and include: (stimulated Raman scattering (SRS), stimulated Brillion scattering (SBS), four wave mixing (FWM), and modulation instability (MI)).

2.4.1. Self-Phase Modulation (SPM):-

Self-phase modulation can occur whenever a signal having a time varying amplitude is propagated in a nonlinear material. The origin of the effect is the refractive index of the medium, which will change with the instantaneous signal intensity. First, additional frequency components are placed on the pulse, and increasing its spectral width. Second, a frequency sweep (chirp) is imposed on the pulse direction. The latter feature is particularly important in optical fibers since the imposed frequency sweep from SPM will either add to or subtract from the chirp imposed by linear group dispersion [2, and 70].

2.4.2. Cross-phase modulation (XPM):-

XPM is similar to SPM, except that two overlapping but distinguishable pulses (having, for example, different frequencies or polarizations) are involved. One pulse will modulate the index of the medium, which then leads to phase modulation of an overlapping pulse. XPM thus becomes a cross-talk mechanism between two channels if phase encoding is employed or if intensity modulation is used in dispersive systems [2, 71, and 72].

2.4.3. Stimulated Raman Scattering (SRS):-

In SRS, coupling occurs between copropagating light waves whose frequency difference is in the vicinity of resonances of certain molecular oscillation modes. In silica-based fibers, stretch vibrational resonances occur between *Si* and *O* atoms in several possible modes within the glass matrix. In the Stokes process, light at frequency ω_2 (pump wave) is downshifted to light at ω_1 (Stokes wave), with the excess energy being absorbed by the lattice vibration modes (manifested in the generation of optical phonons).

Apart from the need to reduce SRS, the effect can be used to advantage in wavelength conversion and in amplification. Fiber Raman lasers have proven to be good sources of tunable radiation and operate at multiple Stokes wavelengths. Figure (2.23) show SRS [2, 70, and 73].

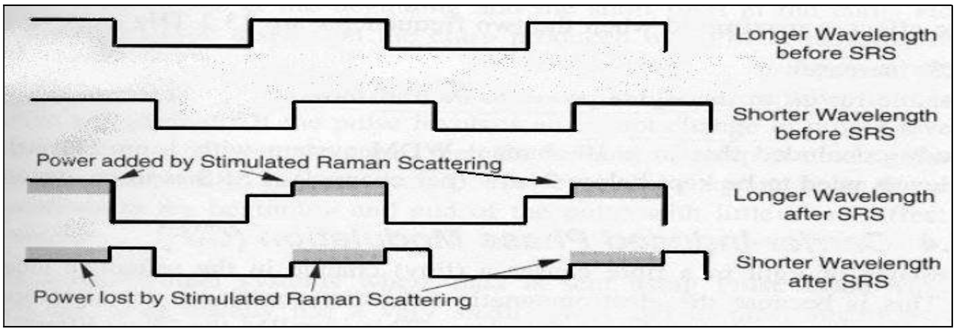


Figure (2-23):- Stimulated Raman scattering in an optical fiber.

2.4.4. Stimulated Brillion Scattering (SBS):-

The stimulated Brillouin scattering process involves the input of a single intense optical wave at frequency ω_2, which initiates a copropagating acoustic wave at frequency ω_p. The acoustic wave is manifested as a traveling index grating in the fiber, which back-diffracts a portion of the original input. With a single input, spontaneous scattering from numerous shock waves occurs, with preferential feedback from the acoustic wave that matches the condition just described. With the Stokes wave generated (although it is initially weak), the acoustic wave is reinforced, and so backscattering increases. Figure (2.24) illustrated the SBS [2].

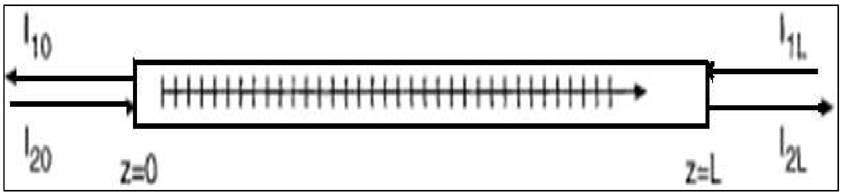


Figure (2-24):- Beam geometry for SBS in an optical fiber.

2.4.5. Four-Wave Mixing (FWM):-

The term FWM in fibers is generally applied to wave coupling through the electronic nonlinearity in which at least two frequencies are involved and in which frequency conversion is occurring. For example, with light at two frequencies present, electron positions can be modulated at the difference frequency, thus modulating the refractive index. Additional light will encounter the modulated index and can be up- or downshifted in frequency. In such cases, the medium plays a passive role in the interaction, as it does not absorb applied energy or release energy previously stored. The self- and cross-phase modulation processes also involve the electronic nonlinearity, but in those cases, power conversion between waves is not occurring only phase modulation.

As an illustration of the process, consider the interaction of two strong waves at frequencies $\omega_1 \, and \, \omega_2$, which mix to produce a downshifted (Stokes) wave at ω_3 and an upshifted (anti-Stokes) wave at ω_4. The frequencies have equal spacing, as the following Eqs. :-

$$\omega_3 + \omega_4 = \omega_1 + \omega_2 \quad \text{... (2-13)}$$

$$\omega_3 = 2\omega_1 - \omega_2 \quad \text{... (2-14)}$$

$$\omega_4 = 2\omega_2 - \omega_1 \quad \text{... (2-15)}$$

The significance of these polarizations lies not only in the fact that waves at the sideband frequencies ω_3 and ω_4 can be generated, but that preexisting waves at those frequencies can experience gain in the presence of the two pump fields at ω_1 and ω_2. The sideband waves will contain the amplitude and phase information on the pumps, thus making this process an important crosstalk mechanism in multi wavelength communication systems. Under phase-matched conditions, the gain associated with FWM is more than twice the peak gain in SRS. The wave equation, when solved in steady state, yields the output intensity at either one of the sideband frequencies i. e. ($\omega_1 = \omega_2$).

Methods that were found to reduce four-wave mixing in such cases include the use of cross-polarized signals in dispersion-managed links and operation within a longer-wavelength band near 1.6μm at which dispersion is appreciable and where gain-shifted fiber amplifiers are used. In another case, coupling through FWM can occur between a signal and broadband amplified spontaneous emission (ASE) in links containing EFDA. As a result, the signal becomes spectrally broadened and exhibits phase noise from the ASE. The phase noise becomes manifested as amplitude noise under the action of dispersion [2, and 71]. Figure 2.25 illustrate how all fields assume the real form.

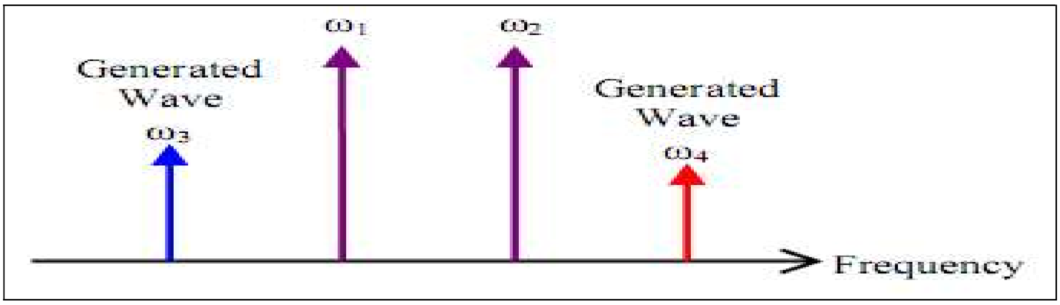


Figure (2-25):- Frequency diagram for FWM, Showing pump frequencies (original waves), (ω_1 and ω_2) and sideband frequencies (ω_3 and ω_4).

2.4.6. Modulation Instability (MI):-

MI is essentially the overall instability affecting both the pulse shape and intensity due to the interplay between the nonlinear and dispersive effects occurring under positive dispersion. Distribution specific dispersion compensation modules (DCM) strategically along an optical link to achieve a parabolic dispersion profile minimize MI. The dispersion profile should be zero at the end of the link so that the receiver sees the smallest distortion possible. Product specific link budget rules typically account for MI by incorporating this effect into recommendation link budgets and link engineering rules [1, 2, and 9].

2.5. Performance Measurements By Noise and BER [62]:-

Among a group of optical receivers, a receiver is said to be more sensitive if it achieves the same performance with less optical power incident on it. The performance criterion for digital receivers is governed by the bit-error rate (BER), defined as the probability of incorrect identification of a bit by the decision circuit of the receiver. Hence, a BER of 2×10^{-6} corresponds to on average 2 errors per million bits. The receiver sensitivity is then defined as the minimum average received power $\overline{P}_{rec}$ required by the receiver. Since $\overline{P}_{rec}$ depends on the BER.

2.5.1. Noise:-

In this subsection, will be introduce a number of rules related to the influence of noise in the performance of optical communication system. Distinction should be made between the definitions of SNR as commonly used the electrical engineering context and the analogous definition for optical systems; the most common way to estimate the signal level and some statistically derived measure of the noise. The SNR is then simply the ratio of two numbers: the mean signal power and the standard deviation of the noise power. For completeness, the noise is expected to have a zero mean value, a Gaussian distribution, and a randomness that allows the total variance in a system to be computed by adding the variance of each of the noise terms. The variance is the square of the standard deviation.

The measure of performance of the detector is its responsivity, which has the units of amps/watt. In photovoltaics and photoconductors, commonly used in optical telecom, watts of power are delivered by the photons and are converted to electrical current in amps or a potential difference in volts.

2.5.2. BER:-

Now, the eye diagram's "Q" can be discussed. They have already pointed out that modern communication systems use binary coding; only two states can exist. Each has its own signal and noise levels. That is, there are actually two distinct SNRs, one for a "1" and one for a "0." Q is a parameter that captures information about both SNRs in the time domain. It does so by making a measure of the difference between a "1" and a "0" and comparing that difference to the noise in the system. The plot of this is called an "eye diagram" (as discussed below). Incidentally, the "eye diagram" does more, as it also shows the rise and fall (in the time domain) of the "1" and "0." In equation form, Q-Factor looks like as:

$$Q = \frac{y_1 - y_0}{\sigma_0 + \sigma_1} \qquad \ldots (2\text{-}16)$$

where

y_1 = signal when a 1 is being sent,

y_0 = signal when a 0 is being sent,

σ_0 = standard deviation of the 0 signal, and

σ_1 = standard deviation of the 1 signal

From Eq. (2-16), if the signal levels for a "1" and a "0" are close, or if each has a lot of noise, Q will be small. Large Q assures (either because the signal levels are very distinct or because the noise level is low) that a "1" and a "0" will not be confused. The high-Q case is desirable; since it assures that the intended signal level is correctly received. As will be see below, Q can be used to make estimates of bit error rate (BER). One key indicator of signal quality and of noise in an optical telecom system is the eye pattern. This is a plot of the measured signal (generally in amperage, but it could be volts or photons or other units) of a bit meant to represent a one overlaid with a bit meant to represent a zero. These frequently take the form of images from an oscilloscope, optical channel analyzer, or some other practical electronic measurement test equipment. When well defined, the shape of the curve resembles a human eye; hence the name eye diagram, as shown in Figure 2.26. When such signals are sent down a fiber and through amplifiers, switches, and other network elements, they will be corrupted. The corruption can take many deleterious forms including having the variance of the highs (for one) and lows (for zero) increased, the distance between the ones and zeros can be decreased, and the slopes may become more gradual. Figure 2.27 shows highly corrupted eye diagrams from self-phase modulation and dispersion. An eye diagram essentially illustrates Q in a graphic way.

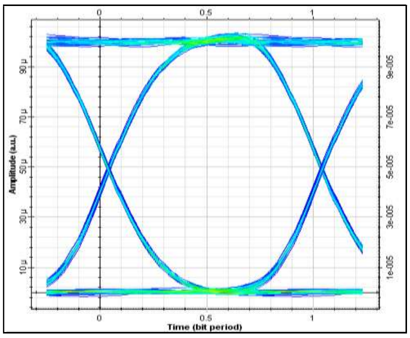


Figure (2-26):-Eye diagram patterns for the NRZ format [64].

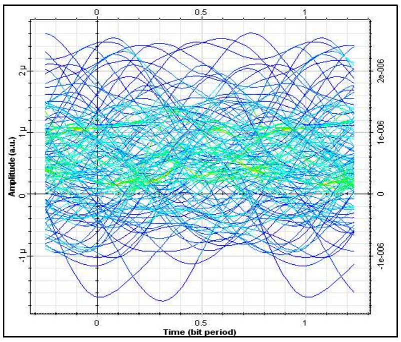


Figure (2-27):- Highly corrupted eye diagrams from SPM and dispersion [64].

Figure 2.28a shows schematically the fluctuating signal received by the decision circuit, which samples it at the decision instant t_D determined through clock recovery. The sampled value I fluctuates from bit to bit around an average value I_0 or I_1, depending on whether the bit corresponds to 1 or 0 in the bit stream. The decision circuit compares the sampled value with a threshold value I_D and calls it bit 1 if $I > I_D$ or bit 0 if $I < I_D$. An error occurs if $I < I_D$ for bit 1 because of receiver noise. An error also occurs if $I > I_D$ for bit 0. Both sources of errors can be included by defining the *error probability* as:

$$BER = P(1)P(0/1) + P(0)P(1/0) \qquad \ldots (2\text{-}17)$$

where $P(1)$ and $P(0)$ are the probabilities of receiving bits 1 and 0, respectively. $P(0/1)$ is the conditional probability of deciding 0 when 1 is received, and $P(1/0)$ is the conditional probability of deciding 1 when 0 is received. Since 1 and 0 bits are equally likely to occur, $P(1)= P(0)= 1/2$, and the BER becomes:

$$BER = \frac{1}{2}[P(0/1) + P(1/0)] \qquad \ldots (2\text{-}18)$$

The BER with the optimum setting of the decision threshold is obtained by the following Eqs.:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \qquad \ldots (2\text{-}19)$$

where the parameter Q is obtained from Eq. (2-16)

Figure 2.28b shows how *P*(0/1) and *P*(1/0) depend on the probability density function *P*(*I*) of the sampled value *I*. The functional form of *P*(*I*) depends on the statistics of noise sources responsible for current fluctuations.

One of the wonderful attributes of digital communication is that relatively noisy signals can be read accurately. The receiving electronics must only determine if the signal was meant to be a one or a zero. This determination can be made on rather poor-looking eye diagrams, with only an occasional error. The rate at which errors occur is referred to as the BER, which is the frequency of mistaking a one for a zero or vice-versa.

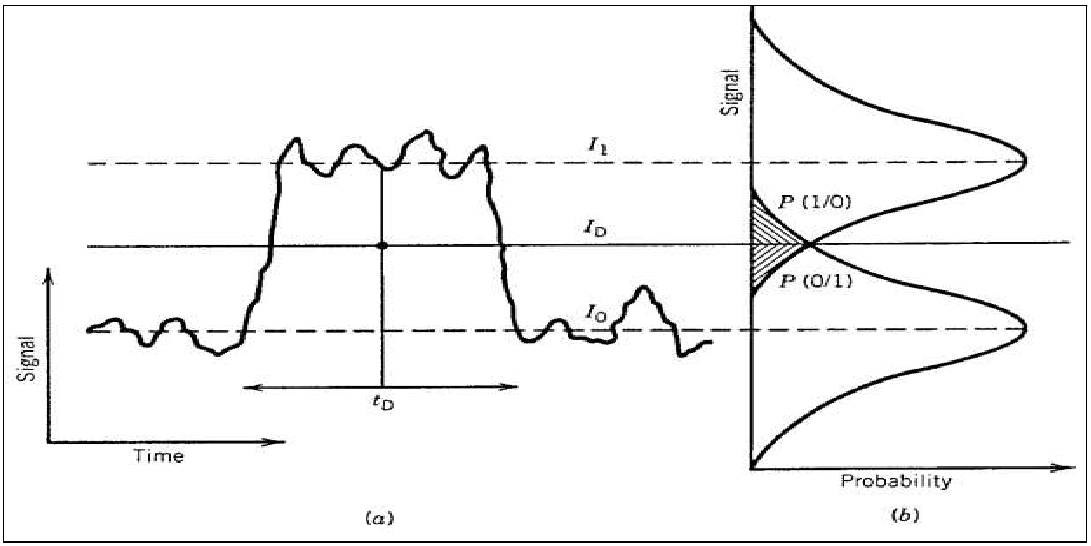


Figure (2-28):- Received Signal probability (a) Fluctuating signal generated at the receiver; (b) Gaussian probability densities of "1" and "0" bits. The dashed region shows the probability of incorrect identification.

3.1. Motivation:-

The WDM innovation represents a revolution within the optical communications revolution, allowing the latter to continue its exponential growth. The existence and advance of optical fiber communications are based on the invention of the laser, particularly the semiconductor junction laser, the invention of low-loss optical fibers, and related disciplines such as integrated optics. WDM technology is progressing in rapid manner enabled by new high-speed electronics, the potential bit-rate per WDM channel has increased to 40Gbps and higher. Broadband Raman fiber amplifiers are being employed in addition to the early EDFA, and there are new fibers and new techniques for broadband dispersion compensation and broadband dispersion management. New designs are being explored that take advantage of the fact that WDM has opened up a new dimension in networking: It has added the dimension of wavelength to the classical networking dimensions of space and time [74].

Specifically, WDM is the current favorite multiplexing technology for long-haul communications in optical communication networks since all the end-user equipment needs to operate only at the bit rate of a WDM channel, which can be chosen arbitrarily, e.g., peak electronic processing speed. Hence, all the major carriers today devote significant effort to developing and applying WDM technologies in their businesses [24, 75, and 76].

WDM access technologies are ideally suited for backhauling traffic to the optical networks. Traffic originating from Digital Subscriber Line Access Multiplexers (DSLAMs) or provider edge routers can be further multiplexed via TDM technology and economically transported to the carrier's point of presence (PoP).

A flexible architecture supporting ROADM and fixed OADM with seamless and hybrid migration capability will be beneficial in meeting the demands of the varying applications. Evolution of ROADMs and enabling technologies like the unified control plane and standardized User-Network and Network-Network Interfaces (UNI, NNI) is expected going forward. While the first benefits of ROADMs are realized by easier planning and less restrictive network engineering, a migration to true dynamic optical networking is ultimately achievable in support of network reconfigurations, flexible service provisioning and cost-efficient restoration.

Service providers are rightly concerned about the uncertain future that new services and applications hold. Video is expected by many to be a significant revenue generator in years to come, yet the potential traffic demands simply cannot be cost-efficiently met by today's network. The key to success comes in matching technology deployment in real network deployments to service revenue. While stand-alone SONET/SDH systems still have a role to play, it is clear that their future importance is declining. Flexible WDM optical networks will play a key role in providing the underlying bandwidth infrastructure as well as direct service delivery and will continue to be deployed by service providers of all types [16].

With the recent exponential growth of Internet users and the simultaneous deploying of new Internet protocol applications such as web browsing, E-commerce, Java applications, and video conferencing, there is an acute need for increasing the bandwidth of the communications infrastructure allover the world. The bandwidth of the existing SONET and ATM networks is pervasively limited by electronic bottlenecks, and only recently was this limitation removed by the first introduction of WDM systems in the highest capacity backbone links.

The communication industries are thus at the onset of a new expansion of WDM technology necessary to meet the new and unanticipated demand for bandwidth in elements of the telephony and cable television (CATV) infrastructure previously unconsidered for WDM deployment. To serve this community involved with the optical networking, a series of volumes covering all WDM technologies (from the optical components to networks) is introduced [75].

WDM technologies, on the other hand, enable optical MUX/DEMUX because individual signals have different light wavelengths and can be separated easily by wavelength-selective optical elements. This may enable us to construct WDM networks in which node functionality is supported by optical technologies without electrical MUX/DEMUX wavelength channel level. The AWGs are thus conventional ones whose wavelength channel resolution matches the ITU-T grid. The length of each waveguide/fiber connecting the two AWGs is arbitrary and hence the device can be smaller due to the inherent layout flexibility [77].

Hybrid optoelectronics integration based on the terraced-silicon platform technologies is also important, both to the FTTH applications and high-speed signal processing devices. Synthesis theory of the lattice-form programmable optical filters has been developed, and implemented to the fabrication of variable group-delay dispersion equalizers. However, there are another parameter in the AWG that is attenuation or transmission loss makes signal strength fade with distance in an optical waveguide. There are three main types of attenuation in optical waveguide which are absorption, scattering, and leakage of light from core [78].

3.2. The Concept of Optical WDM Network:-

Internet infrastructures in most places of the world have been supported by the advancement of optical fiber technology. Most notably, WDM systems have revolutionized long distance data transport and have resulted in high capacity data highways, cost reductions, extremely low bit error rate, and operational simplification of the overall Internet infrastructure. Thus, it is vital to upgrade existing optical communication systems to WDM system in order to implement the Internet infrastructure to provide Internet access to the majority of people who live in both urban and rural areas, as it is often very expensive to install new fibers in the ground. The fiber network can be connected to the rest of the world.

3.3. Optical WDM Network Requirements:-

To implement an optical WDM network, many factors must be taken into account. The system design is influenced by them. They are listed in the following subsections:

3.3.1. Network Topology:-

Ring topology has become very popular in the telecommunication system infrastructure community. A ring is the simplest network that provides two separate paths between any pair of nodes that do not have any nodes or links in common except the source and destination nodes. This allows a WDM ring network to be resilient to failures, and also imposes low network requirements on the optical hardware, network protection and on the network management system [79].

3.3.1.1. Broadcast-and-Select (Local) Optical WDM Network:-

A local WDM optical network may be constructed by connecting network nodes via two-way fibers to a passive star topology. A node sends its transmission to the star topology on one available wavelength, using a laser which produces an optical information stream. The information streams from multiple sources are optically combined by the star and the signal power of each stream is equally split and forwarded to all of the nodes on their receiving fibers [80].

3.3.1.2. Wide-Area Optical Network:-

A wide-area optical WDM network consists of a photonic switching fabric, comprising “active switches” connected by fiber links to form an arbitrary physical topology. Each end-user is connected to an active switch via a fiber link. The combination of an end-user and its corresponding switch is referred to as a network node. Each node (at its access station) is equipped with a set of transmitters and receivers, both of which may be wavelength tunable [79].

3.3.1.3. Passive Optical Networks (PON):-

PON is a point-to-multipoint fiber to the buildings network architecture in which unpowered optical splitters are used to enable a single optical fiber to serve multiple premises (up to 256). PON configuration reduces the amount of fiber and central office equipment required compared with point to point architectures. As shown in Figure 3.1, depending on where the PON terminates, the system can be called Fiber-to-the-x (FTTx), where x can be: C (Curb), B (Building), H (Home) or Cab (Cabinet). PON can use single or multiple fibers for upstream and downstream traffic, with or without WDM [81, 82, and 83].

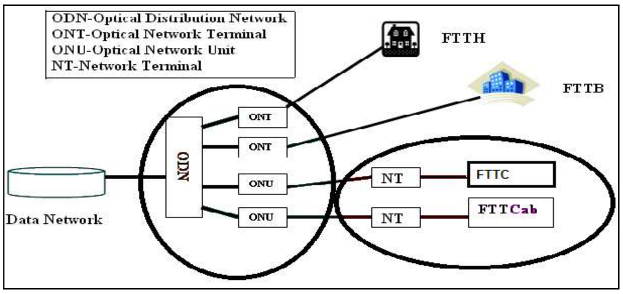


Figure (3-1):- The PON architecture.

3.3.2. Wavelength Blocking:-

This kind of blocking can only occur in the WDM networks. It happens when there is no capability to assign a lightpath request (i.e., Internet traffic) to an unused wavelength in the WDM network. The network is assumed to be in equilibrium, that is, the rate of arrival and the rate of termination of lightpaths are equal. Therefore, dynamic routing and wavelength assignment (RWA) algorithms were used to avoid this crawdad [84, and 85].

3.3.3. Data Transmission:-

Data are converted into electrical signals, and coded to the NRZ modulation format, then converted into light signal, and assigned a wavelength channel for transmission by means of a transmitter. The signals from the different wavelengths channels are combined into a single mode fiber by an optical multiplexer and depending on transmission distance, and amplified using EDFAs along the link. A post amplifier is used to increase the output power. A line amplifier is used typically in the middle of the link to compensate for link loss on a single mode fiber. A preamplifier amplifier is used just in front of a receiver to improve the BER [75].

3.4. Transmission Basic:-

In this section, will be introduce and define the units for common parameters associated with optical communication systems such as (wavelength, frequencies, channel spacing, optical power, and loss). When dealing with WDM signals, will be talk about the wavelength, or frequency, of these signals. The wavelength λ and frequency f are related by Eq. (3-1):

$$c = f\lambda \qquad \dots (3\text{-}1)$$

where c denotes the speed of light in free space, which is 3×10^{8} m/s.

Another parameter of interest is the channel spacing, i.e., the spacing between two wavelengths or frequencies in a WDM system. Again the channel spacing can be measured in units of wavelengths or frequencies. The relationship between the two can be obtained starting from Eq. (3-2):

$$f = \frac{c}{\lambda} \qquad \dots (3\text{-}2)$$

At a wavelength λ_0=1550nm, a wavelength spacing of 0.8nm corresponds to frequency spacing of 100GHz, a typical spacing in WDM systems.

Digital information signals in the time domain can be viewed as a sequence of pulses, which are on or off, depending on whether the data is a 1 or a 0.

The wavelength and frequencies used in WDM systems have been standardized on a frequency grid by the ITU. However, the ITU grid standard has helped accelerate the deployment of WDM systems because component vendors can build wavelength-selective parts to specific grid which helps significantly in inventory management and manufacturing. The nominal center frequency and corresponding nominal center wavelength for the100GHz spacing are shown in Table 3.1. In optical communication, it is quite common to use decibel units (dB) to measure power and signal levels, as opposed to conventional units. Decibel units are used to represent relative as well as absolute values [85].

Table (3-1):- ITU Frequency Grid, and Corresponding Wavelength [2].

Frequency (THz)	Wavelength (nm)	Frequency (THz)	Wavelength (nm)	Frequency (THz)	Wavelength (nm)	Frequency (THz)	Wavelength (nm)
197.20	1520.25	194.20	1543.73	191.20	1567.95	188.20	1592.95
197.10	1521.02	194.10	1544.53	191.10	1568.77	188.10	1593.79
197.00	1521.79	194.00	1545.32	191.00	1569.59	188.00	1594.64
196.90	1522.56	193.90	1546.12	190.90	1570.42	187.90	1595.49
196.80	1523.34	193.80	1546.92	190.80	1571.24	187.80	1596.34
196.70	1524.11	193.70	1547.72	190.70	1572.06	187.70	1597.19
196.60	1524.89	193.60	1548.51	190.60	1572.89	187.60	1598.04
196.50	1525.66	193.50	1549.32	190.50	1573.71	187.50	1598.89
196.40	1526.44	193.40	1550.12	190.40	1574.54	187.40	1599.75
196.30	1527.22	193.30	1550.92	190.30	1575.37	187.30	1600.60
196.20	1527.99	193.20	1551.72	190.20	1576.20	187.20	1601.46
196.10	1528.77	193.10	1552.52	190.10	1577.03	187.10	1602.31
196.00	1529.55	193.00	1553.33	190.00	1577.86	187.00	1603.17
195.90	1530.33	192.90	1554.13	189.90	1578.69	186.90	1604.03
195.80	1531.12	192.80	1554.94	189.80	1579.52	186.80	1604.88
195.70	1531.90	192.70	1555.75	189.70	1580.35	186.70	1605.74
195.60	1532.68	192.60	1556.55	189.60	1581.18	186.60	1606.60
195.50	1533.47	192.50	1557.36	189.50	1582.02	186.50	1607.47
195.40	1534.25	192.40	1558.17	189.40	1582.85	186.40	1608.33
195.30	1535.04	192.30	1558.98	189.30	1583.96	186.30	1609.19
195.20	1535.82	192.20	1559.79	189.20	1584.53	186.20	1610.06
195.10	1536.61	192.10	1560.61	189.10	1585.36	186.10	1610.92
195.00	1537.40	192.00	1561.42	189.00	1586.20	186.00	1611.79
194.90	1538.19	191.90	1562.23	188.90	1587.04	185.90	1612.65
194.80	1538.98	191.80	1563.05	188.80	1587.88	185.80	1613.52
194.70	1539.77	191.70	1563.86	188.70	1588.73	185.70	1614.39
194.60	1540.56	191.60	1564.68	188.60	1589.57	185.60	1615.26
194.50	1541.35	191.50	1565.50	188.50	1590.41	185.50	1616.13
194.40	1542.14	191.40	1566.31	188.40	1591.26	185.40	1617.00
194.30	1542.94	191.30	1567.13	188.30	1592.10	185.30	1617.88

3.5. Multi-Channel Lightwave Systems:-

In optical communication systems, the optical carrier frequency is typically on the order of 100THz, in contrast with the microwave carrier frequencies of 1-10GHz. In principle, taking 1% as the limiting value, the signal bandwidth in optical communication systems can exceed 1THz because of such a large carrier frequency associated with the optical signal; thus resulting in the potential of carrying information at bit rates in the order of 1Tb/s. Therefore, the development of multi-channel lightwave systems which transmit signal information through multiple optical channels over the same fiber has attracted considerable attention to enhance transmission capacity. Channel multiplexing can mainly be performed in either time or wavelength using optical domain techniques. It is common to refer to the former case as OTDM to distinguish it from TDM in electrical domain and the latter case as WDM which is called the Frequency-Division Multiplexing (FDM) in electrical domain [2].

3.5.1. Optical Time-Division Multiplexing Systems:-

In OTDM Systems, as shown in Figure 3.2, optical signals modulated at the bit-rate B in each channel with different delay time are multiplexed optically to form a composite optical signal at the bit-rate NB, where N is the number of multiplexed optical channels. The width of the optical pulse generated by a transmitter should be less than $(NB)^{-1}$ to ensure that the pulse will fit within the allocated time slot. The multiplexing of N channels can be achieved by a delay technique with the fiber segments of controlled lengths, which is optically implemented so that the modulated optical signals in nth branch is delayed by an amount $(n-1)/(NB)$, where $n=1, \ldots, N$.

The demultiplexing of the individual channels in OTDM systems can be achieved by either electro-optical or all-optical techniques. All-optical techniques are more common because electro-optical techniques require a variety of expensive components and its performance is limited by the speed of modulator. Moreover, all techniques for demultiplexing in OTDM systems require control signals at the same bit-rate of a single channel requiring an all-optical scheme because of the high bit rates associated with OTDM systems.

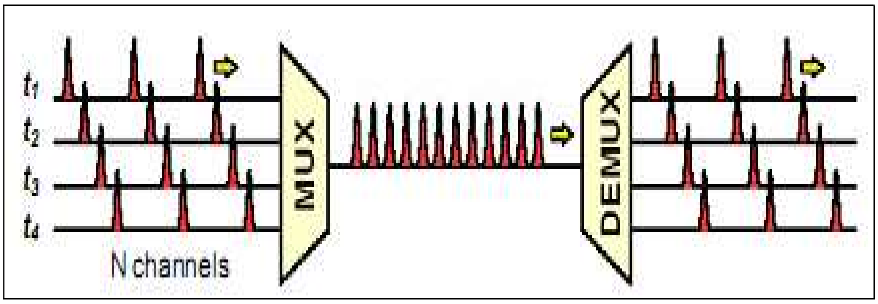


Figure (3-2):- OTDM Systems.

3.5.2. Wavelength-Division Multiplexing Systems:-

Figure 3.3 shows the basic diagram of WDM systems. WDM has much higher potential than OTDM for achieving huge transmission capacities. The transmission window near 1.55μm in optical fibers covers a bandwidth of more than 10THz with low loss. Therefore, in principle, it is possible to transmit hundreds of 10Gbps signal channels over the same fiber if the channel spacing is reduced to the desired level.

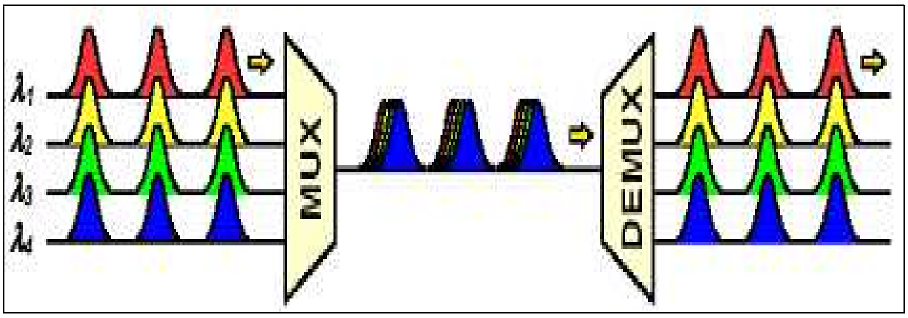


Figure (3-3):- Wavelength-Division Multiplexing Systems.

3.6. Mitigation of WDM Impairments:-

The WDM systems relate to the linear and nonlinear effects (discussed in section 2.4). In the following subsections, they will be listed the linear effects in details.

3.6.1. Linear Effects:-

There are many factors that need to be taken into account such as (Attenuation, CD, and PMD). These factors are due to manufacturing problems in fiber. In the following sections, focus will be on them.

3.6.1.1. Attenuation:-

This leads to a loss of signal power as the signal propagates over a prescribed distance. Since most of the optical fibers deployed in infrastructure are SSMF-28, these optical fibers have attenuation loss of 0.2dB/km in the 1550nm band in which a WDM system operates. To overcome attenuation, optical amplifiers EDFAs are used to amplify the signal power as explained above, and are spaced in appropriate distance apart [70].

3.6.1.2. Chromatic Dispersion:-

This type of dispersion occurs in SMF, and is the widening of pulse duration as it travels through an optical fiber. As a pulse widens, it can broaden enough to interfere with neighboring pulses on the fiber, leading to a bit error at the receiver. SSMF has a total dispersion of 17ps/nm/km in the lower loss wavelength region of 1550nm. To overcome this, a laser source with a narrow spectral width can be used [86].

3.6.1.3. Polarization Mode Dispersion (PMD):-

This is caused by the difference of propagation velocities of light in the orthogonal polarization states of the transmission medium. Like fiber dispersion, PMD causes the transmitted optical pulse to spread out due to the polarization modes traveling at different speeds. This can scramble the signal. This often occurs at high data rates, from 10Gbps or more per wavelength channel. Figure 3.4 shows the PDM [87].

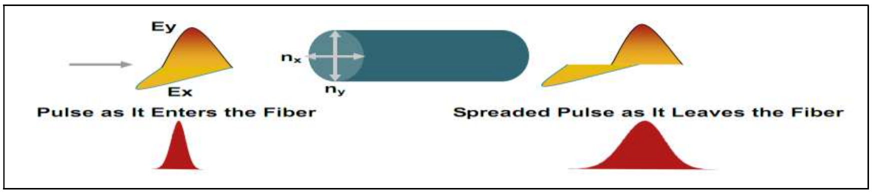


Figure (3-4):- The PMD Scheme.

3.7. Optical Network Management:-

One of the most important and difficult issues involved in the optical networks are network management for several reasons: restoration, performance, and wavelength services. Although network management of optical networks is a topic too large to cover extensively here, some of the important issues are briefly discussed in this section.

First, the optical network is evolving and being implemented on top of an existing SONET architecture, which provides its own restoration and protection schemes. Without a highly intelligent network-management system (NMS), it becomes extremely difficult to ensure that restoration schemes between the electrical and optical layer do not conflict. In addition to mediation between the optical and SONET layer, the NMS must be able to prevent possible conflicts or, at the minimum, enable the service provider to identify conflicts.

In addition to managing the overall network architecture, NMSs must be able to monitor signal performance for each wavelength. With the addition of OADM, and OXC, the end-to-end performance of wavelength becomes more difficult. NMSs for optical network must assist providers in troubleshooting the network by isolating questionable wavelengths and the possible location of degradation. According to the number of wavelengths on each fiber, it is important to have an intelligent method to monitor all of them. Finally, and perhaps most important to the service providers, the ability to manage and provide new services quickly to customers is crucial. An intelligent NMS can help providers establish and monitor new end-to-end wavelength services to maximize their bandwidth revenues [88].

In a WDM network (as well as in other networks), the failure of a network element (e.g., fiber link, cross-connect, etc.) may cause the failure of several optical channels, thereby leading to large data (and revenue) losses. There are several approaches to ensure fiber-network survivability.

Survivable network architectures are based either on dedicating backup resources in advance, or on dynamic restoration.

Generally, dynamic restoration schemes are more efficient in utilizing capacity due to the multiplexing of the spare-capacity requirements, and they provide resilience against different kinds of failures, while dedicated restoration schemes have a faster restoration time and provide guarantees on the restoration ability.

3.7.1. Traffic Grooming in WDM Networks:-

The minimum granularity of a connection in a wavelength-routed network is the capacity of a wavelength. The transmission rate on a wavelength increases with advances in the transmission technology. However, the requirement of end-users such as internet service providers (ISPs), universities, and industries are still much lower than that of the capacity of a wavelength. The bandwidth requirement is projected to increase in the future. However, even doubling the current bandwidth would be more than sufficient to handle the projected demand for the near future. The current transmission rate on a wavelength is 10Gbit/s (OC-192). 40Gbit/s (OC-768) technologies are commercially available, however they are not widely deployed.

The merging of traffic from different source–destination pairs is called traffic grooming. Nodes that can groom traffic are capable of multiplexing or demultiplexing lower rate traffic onto a wavelength and switching them from one lightpath to another. The grooming of traffic can be either static or dynamic. In static traffic grooming, the source–destination pairs for which requirements are to be combined are predetermined. In dynamic traffic grooming, connection requests from different source–destination pairs are combined depending on the existing lightpaths at the time of the request [76, 79, 89, and 90].

3.7.2. Optical Packet-Switched Networks:-

As telecommunications and computer communications continue to converge, the data traffic is gradually exceeding the telephony traffic. This means that many of the existing circuit-switched networks will need to be upgraded to support packet-switched data traffic. While WDM has provided us with an opportunity to multiply the network capacity, current optical switching technologies allow us to rapidly deliver the enormous bandwidth of WDM networks. In a WDM optical packet-switched network, there are three domains to explore contention-resolution schemes: wavelength, space, and time. Combination of wavelength conversion, path (space) deflection, and optical delay-lines to resolve contention can be used. Each scheme has its own advantages and disadvantages: wavelength conversion is very efficient and able to resolve contention without introducing extra delay to the packet, but it is expensive to implement and no full-range wavelength converters are available today. Path deflection has the lowest cost since it shifts the burden of resolving contention to the whole network while lowering network overall throughput. Optical delay-lines (time buffering) have medium cost. It might introduce non negligible delay to the packet, depending on the packet length [24, 29, 30, and 76].

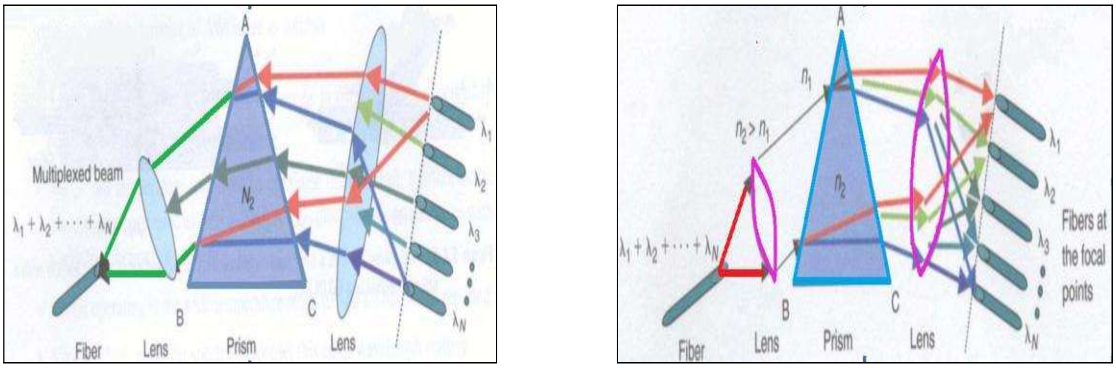
3.8. WDM Components:-

The implementation of WDM technology for fiber-optic communication systems requires several new optical components. Among them are multiplexers which combine the output of several transmitters and launch it into an optical fiber; demultiplexers which split the received multichannel signal into individual channels destined to different receivers; couplers which mix the output of several transmitters and broadcast the mixed signal to multiple receivers; tunable optical filters which filter out one channel at a specific wavelength that can be changed by tuning the passband of the optical filter; multi-wavelength optical transmitters whose wavelength can be tuned over a few nanometers; ADM and wavelength shifters which switch the channel wavelength [2]. The following subsection focuses on the WDM components:

3.8.1. Optical Multiplexer/Demultiplexer:-

The vast progress in advanced WDM networks has been the main driver of the recent rapid growth of the telecommunications industry. The key passive component in the WDM system is the wavelength division multiplexing and demultiplexing (MUX/DEMUX) device, which combines/splits lights with different wavelengths into different outputs. Several technologies have been used to fabricate MUX/DEMUX devices; each of them has some distinguishing key features and is suitable for different applications. The schematic diagrams for the MUX/DEMUX devices are illustrated in Figure 3.5. There are most important parameters related to the MUX/DEMUX listed below [75]:

1) Insertion loss,
2) Channel uniformity,
3) Passband ripple,
4) Temperature dependent wavelength shift,
5) Polarization dependent wavelength shift,
6) Adjacent channel isolation, and
7) Non-adjacent channel isolation.



(a) **(b)**

Figure (3-5):- Multiplexing Scheme (a): Multiplexer; (b): Demultiplexer.

3.8.2. Fiber Bragg Grating (FBG):-

Most of the passive components used in optical communication systems, such as thin-film filter-based devices, are based on bulk optics and require coupling light in and out of the optical fibers, leading to certain loss and the need for active positioning of the optical fiber. With the discovery of the photosensitivity in the optical fiber, fiber Bragg grating-based devices have been important components for enabling WDM and optical networks. A FBG is a small section of fiber that has been modified to create periodic changes in the index of refraction. Depending on the space between the changes, a certain frequency of light, the Bragg resonance wavelength, is reflected back, while all other wavelengths pass through. The wavelength-specific properties of the grating make fiber Bragg gratings useful in implementing OADM. Also, Bragg gratings are being developed to aid in dispersion compensation and signal filtering as well [91, and 92].

3.8.3. Circulator:-

The optical circulator has become one of the indispensable elements in advanced optical communication systems, especially WDM systems. The applications of the optical circulator expanded not only within the telecommunications industry (together with EDFA and FBG), but also in the medical and imaging fields. An optical circulator is a multi-port (minimum three ports) non-reciprocal passive component; Figure 3.6 shows a four port circulator. The function of an optical circulator is similar to that of a microwave circulator to transmit a lightwave from one port to the next sequential port with a maximum intensity, but at the same time to block any light transmission from one port to the previous port. Optical circulators are based on the non-reciprocal polarization rotation of the Faraday effect.

The operation of optical circulators is based on two main principles; polarization splitting and recombining together with nonreciprocal polarization rotation, and asymmetric field conversion with nonreciprocal phase shift. Figure 3.7 illustrates the polarization based circulator. Important performance parameters of optical circulators include insertion loss, isolation, PDL, directivity, PMD, and return loss. Finally, Optical circulators are powerful devices for extracting optical signals by using it in a bi-directional transmission system. The transmission capacity of the network can be easily doubled without the need for deploying additional fibers[20].

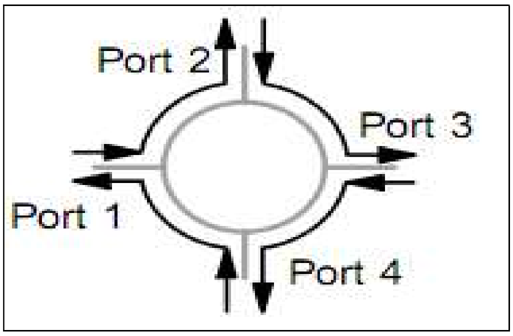


Figure (3-6):- A four-port circulator.

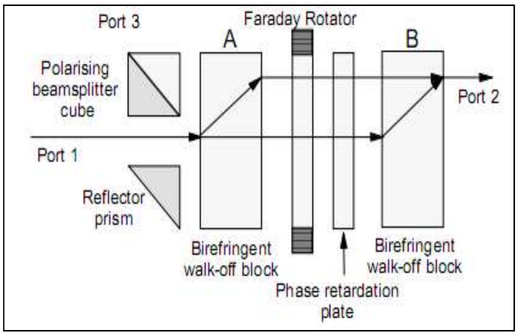


Figure (3-7):-The polarization based 3-port circulator.

3.8.4. Optical Add/Drop Multiplexer (OADM):-

The OADM enhances the WDM terminals by adding several significant features. The OADM systems have the capacity of up to 40 optical wavelengths. They efficiently drop and add various wavelengths at intermediate sites along the network resolving a significant challenge for existing WDM. Most important, OADM technology introduces asynchronous transponders to allow the optical network element to interface directly to high revenue generating services. It is now possible for ATM, frame relay (FR), native LANs, high bandwidth IP, and others to connect directly to the network via a wavelength in the optical layer. Transponder technology also extends the life of older lightwave systems by accepting its bandwidth directly into the optical layer, converting its frequency to an acceptable standard, and providing protection and restoration. Figure 3.8 shows the OADM functionality. The OADM is also the foundation of optical bidirectional line switched rings (OBLSRs) [93, 94, and 95].

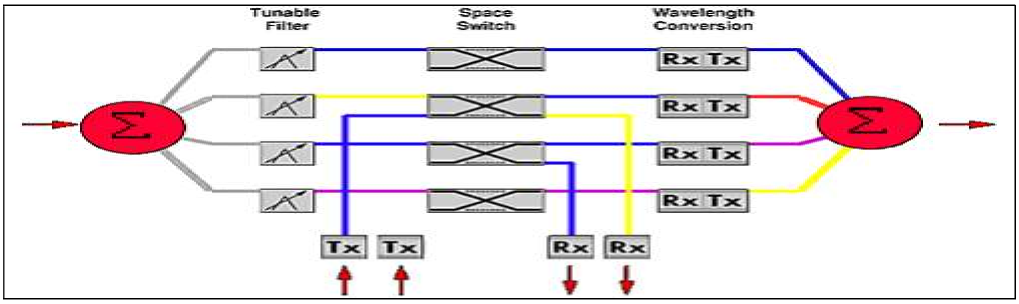


Figure (3-8):- Optical ADM Functionality.

3.8.5. Optical Cross Connects (OXCs):-

Optical crossconnects (OXC) have emerged as a critical network element for constructing next-generation provisioning and restoration vehicles for emerging mesh-based optical networks. Figure 3.9, shows a block diagram of OXC. The core optical switching technology required by such network elements, however, has not progressed at a speed matching the needs of optical networks, and has so far lagged behind rival electronic-fabric-based technology. Furthermore, optical switch fabrics will need to achieve low insertion loss, low switching time (on the order of a few milliseconds), low crosstalk, low polarization dependence, and low wavelength dependence. It is moreover desired that they should be transparent to bit rate in the interval of roughly 2.5Gbps to 40Gbps. These requirements impose stringent challenges on all optical switching technologies [96, and 97].

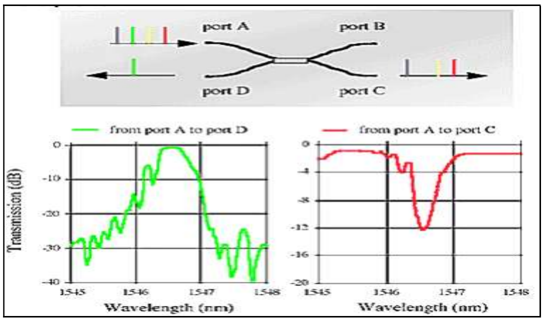


Figure (3-9):- A block diagram of OXC.

3.8.6. Optical Switching:-

Because modulators (in general) turn the signal on and off, they make excellent switches. Indeed, a digital modulator is just a very fast switch. In some situations might be prepared to tolerate some light transmission in the "off" state of a modulator (particularly an analogue one). Also, may be prepared to allow significantly more crosstalk in a modulator than in a switch (all depending on the application). Sometimes, need switches to direct their output to one of two different paths, whereas with a modulator we usually only want to control the light intensity on one particular path. Figure 3.10 illustrates the schematic diagram of the switch [20].

Optical switches can be grouped into four types by their schemes for routing the optical signal (Figure 3.11). The figures depict devices based on optical waveguide technology. The first method (Figure 3.11a) uses an optical deflector or scanner. The direction of the light beam is controlled by an analog signal. The deflection angle is proportional to the control signal. The second method (Figure 3.11b) uses diffraction of the light by electrically induced gratings. In the first two methods, the deflected light travels through free space or a planar optical waveguide to the destination. In the last two methods (Figure 3.11 (c, d)), the destination of the light signal is selected by alternating between two possible switching states of the switching elements. In the method using 1×2 (One input two output), 2×1 (Two input one output), or 2×2 (two input two output) switching elements (Figure 3.11c), a device with many port numbers is constructed by connecting switching elements in multiple ranks with optical waveguide interconnections to form a switching network. In Figure 3.11d, an optical gate switch is used to set up a path between input and output ports. An optical gate switch is a one-input one-output device that is capable of changing states between transparent and cut off by a control signal. Optical gate switches placed at each connection establish the desired path by setting an optical gate switch on the desired path to the transparent state and leaving other optical gate switches in the cut-off state.

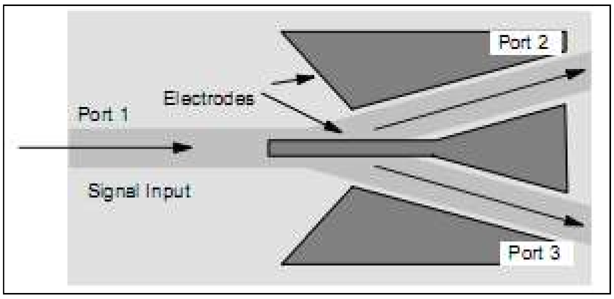


Figure (3-10):- Schematic diagram for optical switch.

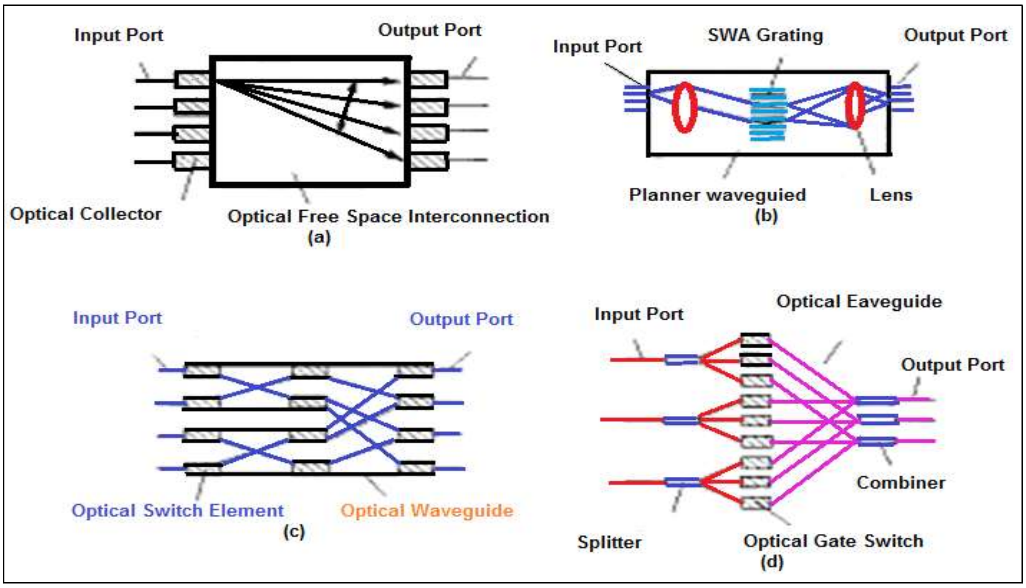


Figure (3-11):- Optical switch variations.

3.8.7. Coupler:-

The role of a coupler, as seen in Figure 3.12, is to combine the optical signals entering from their multiple input ports and divide them equally among their output ports. In contrast with demultiplexers, couplers do not contain wavelength-selective elements, as they do not attempt to separate individual channels. The number of input and output ports need not be the same.

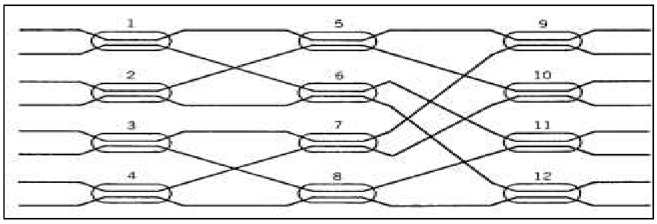


Figure (3-12):- An 8×8 star coupler diagram.

3.8.8. Tunable Optical Filters:-

It is instructive to consider optical filters first since they are often the building blocks of more complex WDM components. The role of a tunable optical filter in a WDM system is to select a desired channel at the receiver. The filter bandwidth must be large enough to transmit the desired channel but, at the same time, small enough to block the neighboring channels. All optical filters require a wavelength-selective mechanism and can be classified into two broad categories depending on whether optical interference or diffraction is the underlying physical mechanism. Each category can be further subdivided according to the scheme adopted. The desirable properties of a tunable optical filter include:

(1) Wide tuning range to maximize the number of channels that can be selected,
(2) Negligible crosstalk to avoid interference from adjacent channels,
(3) Fast tuning speed to minimize the access time,
(4) Small insertion loss,
(5) Polarization insensitivity,
(6) Stability against environmental changes (humidity, temperature, vibrations, etc.), and
(7) Last but not least, low cost.

Tuning can be realized in several different ways. In one approach, an InGaAsP/InP waveguide permits electronic tuning. Silicon-based FP; a chain of Mach–Zehnder (MZ) interferometers can also be used for making a tunable optical filter.

3.9. Alternatives WDM:-

There are two alternatives for WDM metro networks: dense WDM (DWDM) and coarse WDM (CWDM). In high capacity environments, DWDM is used. In DWDM, the channel separation can be as small as 0.8 or 0.4 nm, for up to 80 optical channels at line rates up to 10Gbps. DWDM technologies are very expensive, so their application to access networks is difficult. Instead, CWDM is merging as a robust and economical solution. The advantage of CWDM technology lies in its low-cost optical components. CWDM offers solutions for (850, 1.300, and 1.500nm) applications at (10 and 40Gbps) on up to 15 optical channels spaced 20nm apart. Both CWDM and DWDM technology have their place in current and emerging metro-network infrastructure. When these technologies are used in combination with appropriate optical fibers, the economic benefits, which help to lower system costs, are significant.

3.9.1. Coaser Wavelength Division Multiplexing (CWDM):-

Originally developed in the 1980's for adding capacity to multi-mode fiber cable routes in campus LAN's, the channel spacing equal to 25nm in the 850nm window. About 1995, CWDM was revitalized with SMF wavelengths from metro area fiber route capacity increases. The original band at 1310nm was used. Currently, the latest ITU-G.694.2 defines 18 channels in five bands with 20nm channel spacing; the bands are the O, E, S, C, and L. The E band includes the 2385nm water peak (WP), so is the last one implemented unless low WP cable is used [98, and 99]. Figure 3.13 illustrates the CWDM wavelength specified by ITU.

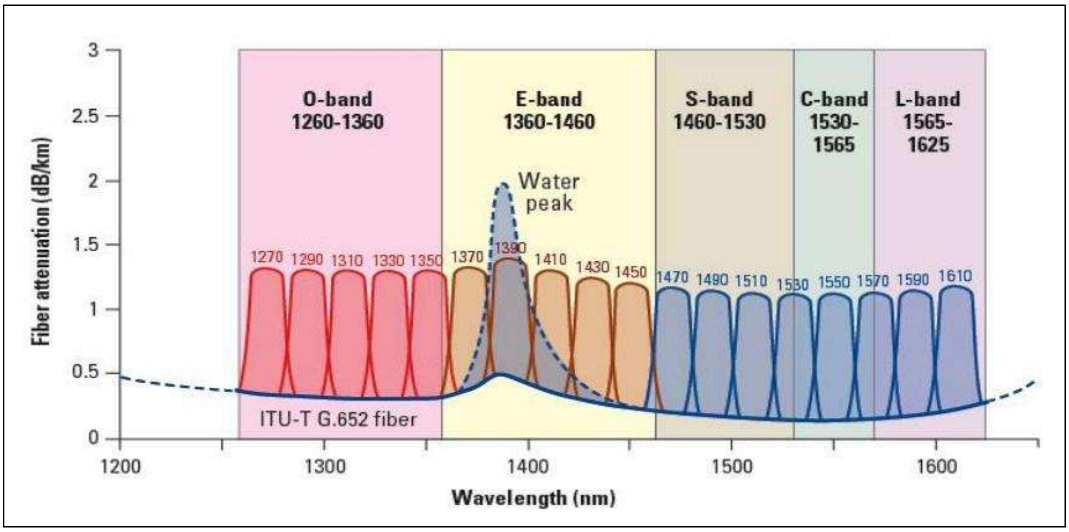


Figure (3-13):- The CWDM wavelength grid specified by ITU-T G.694.2.

3.9.2. Dense Wavelength Division Multiplexing (DWDM):-

To meet today's growing demands for bandwidth, DWDM technology had been developed in early 1990's to multiply the capacity of a single fiber and to add capacity to undersea and transcontinental routes. Bandwidth increases the carrying capacity of the physical medium, whether existing or new fiber optic backbone, by carrying multiple light waves of different frequencies on a single fiber. In a DWDM system, multiple signals with independent bit rates and formats are multiplexed into a single fiber with multiple wavelengths. The signals are then demultiplexed at the receiving side. DWDM carries each input signal independently of the others. This allows each channel to have its own dedicated bandwidth and to arrive at the receiving end simultaneously. Hence, each signal carried can be at a different rate (i.e. OC-3, OC-12…) or in a different format (i.e. SONET, and Ethernet), (See Table 1-1). This innovative technology not only takes us to the next level in bandwidth and speed, but also provides a convenient and economical solution. Because multiple signals can be transported on a single pair of fiber, less equipment is required, thereby reducing current equipment costs.

Although DWDM networks require less equipment, the complexity increases tremendously due to the multiple wavelengths. For a TDM system, critical factors affecting performance can be examined on a two-dimensional, power vs. time, representation. Because DWDM transports multiple wavelengths on a single fiber, a wavelength dimension must be factored into the representation, making it a power vs. time vs. wavelength representation. With multiple wavelengths, many more factors, including crosstalk, EDFA range, EDFA gain, and wavelength stability, become critical. The use of DWDM provides a simple yet powerful method of increasing channel capacity for digital multimedia systems. By using different lasers with systems that already have been designed for single wavelength, the capacity can be increased in direct proportion to the number of lasers. There is no need to redesign the electronics for a higher bandwidth and existing components and modules can, to a large extent, be used in the higher capacity system. In addition, the use of lasers in the 1550nm spectral region allows DWDM to be combined with optical fiber amplifiers to extend the length of data link or more generally to be used with links with greater loss. The evolution of WDM started from using two different operating wavelengths such as 1500nm and 1600nm with channel spacing of 0.8nm. With enabling technologies such as EDFA, ITU channel plan is G.694.1; DWDM boosts the network transmissions and provides more bandwidth. Figure 3.14 shows the ITU grid with DWDM, and Figure 3.15 illustrates the DWDM wavelength grid as specified by ITU-T G.694.1.

Another technology that enables the increased use of DWDM is OADM. The OADM is specially suited to dropping traffic at smaller sites. Consequently, this opens up WDM transmission in the metropolitan areas where connectivity is a key issue as compared to long-haul transmissions where cost managed per bit-kilometers is crucial.

The stand-alone DWDM system is a good choice for increasing fiber capacity and reducing cost, yet it lacks many features like protection and path/traffic management. To summarize, the integrated SDH/DWDM system provides numerous benefits compared to stand-alone systems [38, and 100].

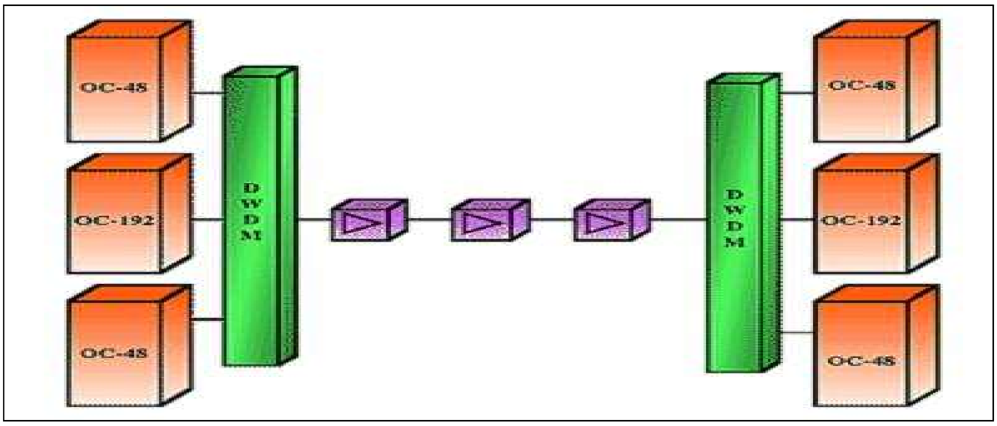


Figure (3-14):- The ITU grid with DWDM.

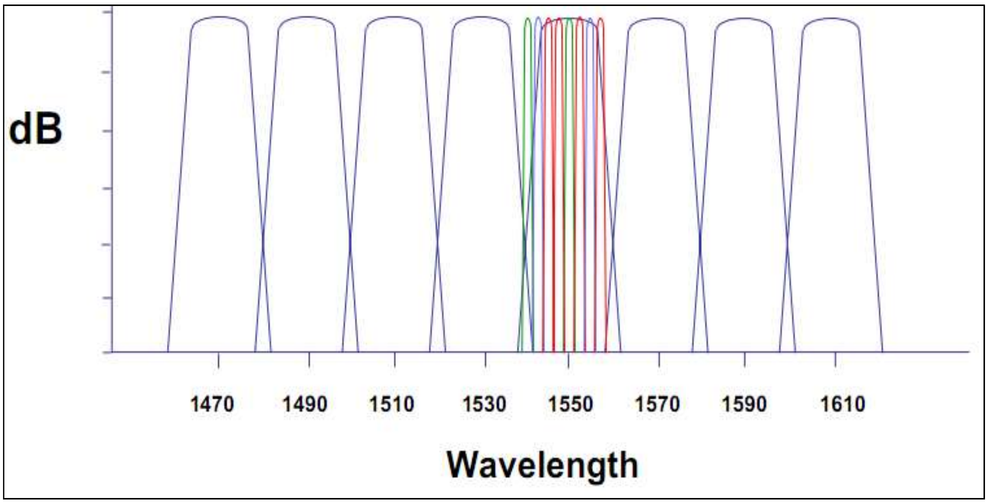


Figure (3-15):- The DWDM wavelength grid specified by ITU-T G.694.1.

3.10. Optical Fiber Amplifiers (OFAs):-

As the optical signal moves along a standard single mode fiber SSMF, it gets attenuated along the fiber and if the data speed is high enough (> 10 Gb/s), it gets distorted due to chromatic and polarization dispersions. To counter attenuation OFA's are used. Introducing OFA's into the system causes additional problems such as ASE noise which accumulates as the number of OFA's which the signal goes through increases. The bandwidth of optical fibers is really great if the S-band (short 1460-1530 nm), C-band (central 1530-1565 nm), and L-band (long 1565-1625nm) are utilized efficiently. So OFA must be designed to amplify the signal along the fiber. The more the gain is, the more is the span distance between amplifiers as long as the signal is not distorted due to high optical power. To make use of this great bandwidth, DWDM is used, but each type of OFA has different bandwidth. Design of amplifiers depends on the type of the application used such as long distance under the sea or terrestrial, short distance with a lot of add-drop locations such as in metro projects. In the next subsections, brief characteristics of each type of optical amplifiers will be mentioned. Today, optical amplifiers and WDM technology are offering an unprecedented cost-effective means for meeting the ever-increasing demand for transport capacity, networking functionality, and operational flexibility [70, 75, 101,102,103, and 104].

3.10.1. Erbium-Doped Fiber Amplifiers (EDFA):-

In all existing optical fiber projects, EDFAs are used. The gain medium in the amplifier is a specially fabricated optical fiber with its core doped with erbium (Er). The erbium-doped fiber is pumped by a semiconductor laser, which is coupled by using a wavelength selective coupler, also known as a WDM coupler, that combines the pump laser light with the signal light. The pump light propagates either in the same direction as the signal (co-propagation) or in the opposite direction (counter-propagation). Optical isolators are used to prevent oscillations and excess noise due to unwanted reflection in the assembly, and the energy levels of the Erbium ions that participate in the amplification process. The Erbium ions can be either pumped by 980nm, in which case the ions pass through an unstable short lifetime state before rapidly decaying to a quasi-stable state, or by 1480nm in which case they are directly to the quasi-stable state. Once in the quasi-stable state, they decay to the ground state by emitting a photon in the 1530-1560nm band. This decay can be stimulated by pre-existing photons, thus resulting in amplification. Figure 3.16 illustrates these processes [104, and 105].

An application of EDFAs as repeaters in WDM systems is particularly important because they offer a cost-effective means of faithfully amplifying all the signal wavelengths within the amplifier band simultaneously, thereby eliminating the need for costly opto-electronic regenerators transparent to data rate and format, which dramatically reduces cost. The EDFA which provide high gain, high power, and low noise figure. In the following subsections, reference will be made to some important factors that contribute to the amplification process.

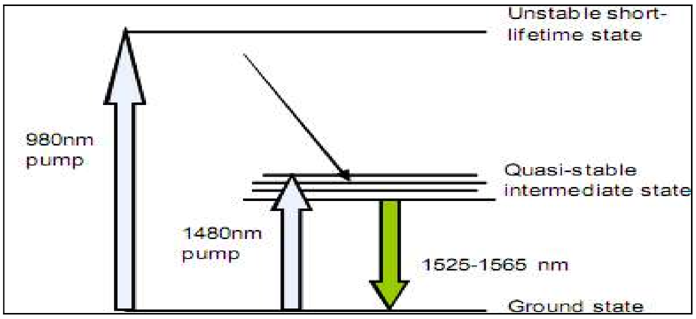


Figure (3-16):- Erbium ion energy- level scheme.

3.10.1.1. Optical Signal-to-Noise Ratio (OSNR):-

In an optically amplified system, channel power reaching the receiver at the end of the link is optically degraded by the accumulated ASE noise from the optical amplifiers in the chain. At the front end of the receiver, ASE noise is converted to electrical noise, primarily through signal-ASE beating, leading to BER flooring. System performance therefore places an important requirement on OSNR of each of the optical channels. OSNR, therefore, becomes the most important design parameter for an optically amplified system.

Although optical amplifiers are conventionally classified into power, in-line, and pre-amplifiers, state-of-the-art WDM systems require all three types of amplifiers to have low noise figure, high output power, and uniform gain spectrum. Will be not distinguish between these three types of amplifiers in the discussion presented in this section. The nominal OSNR for a 1550nm WDM system with N optical transmission spans can be given by the following formula:

$$OSNR_{nom} = 58 + P_{out} - 10\log_{10}(N_{ch}) - L_{sp} - NF - 10\log_{10}(N) \quad \ldots (3\text{-}3)$$

where OSNR is normalized to 0.1nm bandwidth, *Pout* is the optical amplifier output power in dBm, A N_{ch} is the number of WDM channels, L_{sp} is the fiber span loss in dB, and *NF* is the amplifier noise figure in dB. For simplicity, it has been assumed here that both optical gain and noise figure are uniform for all channels. The simple formula in Eq. 3-3 highlights the importance of two key amplifier parameters: noise figure and output power [75].

3.10.1.2. Amplifier Gain Flatness:-

Amplifier gain flatness is another critical parameter for WDM system design. As the WDM channels traverse multiple EDFAs in a transmission system, the spectral gain nonuniformity adds up to create a divergence in channel powers. The worst WDM channel, the channel that consistently experiences the lowest amplifier gain, will have an OSNR value lower than the nominal value given in Eq. 3-3. The power deficit, which can be viewed as a form of penalty given rise to by amplifier gain nonuniformity, is a complicated function of individual amplifier gain shape, and correlation of the shapes of the amplifiers in the chain. The gain flatness is a parameter that can have a significant impact on the end-of-system OSNR. The penalty is especially severe for a long amplifier chain as in the case of long-haul and ultra-long-haul applications [75, and 101].

3.10.1.3. Amplifier Control:-

In an amplified system, optical amplifiers may not always operate at the gain value at which their performance, especially gain flatness, is optimized. Many factors contribute to this non-optimal operating condition. Among them is the fact that the span loss can be adjusted at system installation and maintained in the system's lifetime only to a finite range with respect to the value required by the amplifiers for optimal performance. As a result, amplifier gain will be tilted, and such tilt can have significant impact on system performance in ways similar to gain nonuniformity. Gain slope can, if not corrected, result in OSNR penalty and increased power divergence. Control of optical amplifier tilt is often necessary to extend the operational range of the amplifiers and compensate for loss tilt in the system due to, for example, fiber loss variation in the signal band. Control of amplifier gain tilt can be achieved by varying an internal optical attenuator [75, and 101].

3.10.2. Raman Amplifiers (RA):-

Raman scattering occurs in any silica glass. This means that if inject an optical beam (pump) in an optical fiber, a signal passing through that fiber will be amplified if its frequency is around the shifted frequency of the pump. This is called Stock shift, which is a round 13GHz (equivalent to about 100nm) from the pump propagating beam frequency assuming that its wavelength is 1450nm .This means that signal will be amplified if its wavelength is 1550nm. RAs are based on this phenomenon. There are two main RAs distributed and discrete or lumped like EDFA's. In distributed types, amplification occurs all along the fiber between say two stations with the pump placed either near the transmitter in which case it is called forward pumping or near the receiver in which case it is called backward pumping. So in distributed RA, the fiber itself is acting as an amplifier which is of great advantage. What is exciting in RAs is the use of DCF to compensate for chromatic dispersion and loss. This can be done by increasing the pump power. But if the number of cascaded amplifiers increases, gain fluctuation might occur. One way to deal with this situation is to optimize the multi-span amplifiers jointly rather than individually.

3.10.3. Thulium-Doped Fiber Amplifier (TDFA):-

The TDFA gain band has middle wavelength region of the S-band, and uses dual-wavelength pumping techniques. It uses high Thulium concentration of 6000 part per million (ppm), compared with 20ppm of Erbium used in EDFA. S-band complements the conventional C-band of EDFA's, and can be used effectively in dispersion shifted fibers (DSF) because we can avoid degradation due to FWM in the S band.

3.10.4. Tellurite-Based Fiber Raman Amplifier (TFR):-

It was reported that by using multi wavelength-pumped Raman Amplifier TFRA, a bandwidth of 160nm (1490-1650)nm was achieved but with dual peak profile and two bottoms. But with three-stage hybrid, FRA consists of T-FRA with backward pump (P1) as first stage, DCF-RA with forward and backward pumps as a second stage, followed by a gain equalizing filter or gain equalizer (GEQ),and T-FRA with backward pump (P2) as the third stage. Pumps P1 and P2, pump two wavelengths each in order to achieve a wide, high gain and flat spectrum, while the DCF-RA is bidirectionally pumped to lower its noise figure (NF).

3.10.5. Semiconductor Optical Amplifier (SOA):-

Output-level control that accepts a wide range of input power and delivers constant output power is essential for in-line optical amplifiers, optical burst and packet systems and in all optical regeneration and reshaping (2R). Semiconductor optical amplifiers SOA's can meet this demand. The reason for this is because SOA has short carrier lifetime of about several tenths to several hundreds of picoseconds compared to several hundred microseconds to several milliseconds in EDFA's. To control the output level of SOA's, external light injection can be used. It was found out that even if the level of the input signal changed by 13.5-18.5dB at 1530-1560nm modulated at 10Gbps, the output level remained constant at +10dBm. This method of level control is used in photonic networks. In a lightwave transmission system, as the optical signal travels through the fiber, it weakens and gets distorted. Regenerators are used to restore the optical pulses to their original form. Because of its simplicity, an optical amplifier is an attractive alternative for new lightwave systems. Semiconductor optical amplifier is a device very similar to a semiconductor laser. Hence its operating principals, fabrication, and design are also similar.

3.10.6. Fiber Optical Parametrical Amplifiers (FOPA):-

Optical parametric generation based on nonlinear optical principle and also optical parametric amplifiers were known for years. But recently its advantage was recognized, so many experiments were conducted. When the input signal power equals a power called the saturation power, the parametric gain will amplify the signal and idler waves equally [75, and 101].

3.11. Important Issues in WDM networks:-

Important issues that relate to the WDM systems, crosstalk, and chromatic dispersion compensation, will be discussed in details in the following subsections:

3.11.1. Crosstalk:-

Crosstalk is generally caused by a combination of six mechanisms which are receiver crosstalk, truncation, mode conversion, coupling in the array and phase transfer, incoherence, and background radiation. The first four can be kept low by proper design but the other two are caused by the imperfections in the fabrication process. The most obvious crosstalk will be the receiver crosstalk which is caused by the coupling between the receivers through the exponential tails of the field distribution. Mode conversion is caused by the "ghost" image which exists due to the multimode junction. The "ghost" image that occurs at different locations may couple into an undesired receiver thus degrading the crosstalk performance. Coupling in the array is the crosstalk incurred by phase distortion when coupling in the array input and output. Phase transfer incoherence and background radiation is the crosstalk caused by the imperfections in fabrication process which include the deviation of propagation constant and rough waveguide edges. To guarantee satisfactory performance, the link's maximum possible BER floor position must be below the required BER. Improving WDM components and/or design to reduce amount of leakage, and this will reduce**.** Investigated the cascading connection for AWGs can reduce the crosstalk, the crosstalk can also be also enhanced by controlling its nonadjacent crosstalk [[41,106, and 107].

3.11.2. Chromatic Dispersion Compensation:-

Static dispersion compensation is now well established by using dispersion-compensating fibers and chirped fiber gratings. Tunable dispersion-compensation technology, on the other hand, is still in its infancy, though it will in general become necessary as systems move from 10Gbps to 40Gbps per wavelength. The reflectivity is wavelength dependent, and therefore results in a difference in group-delay between different wavelengths. In addition, the refractive index of the silicon substrate can be adjusted by temperature tuning, which is also wavelength dependent. The refractive index affects the effective optical path length in the cavity. This provides another degree of freedom for adjusting group-delay between different wavelengths. By cascading such multiple devices, and using the combination of voltage and temperature tuning a variety of dispersion values and slopes can be achieved [85, and 105].

3.12. Principle and Fundamental Characteristics of AWG:-

An AWG is a generalization of Mach-Zehnder interferometer (MZI). The device is illustrated in Figure 3.17. It consists of two multiport couplers interconnected by an array of waveguides. The MZI can be viewed as device where two copies of the same signal, but shifted in phase by different amounts, are added together. The AWG is a devise where several copies of the same signal, but shifted in phase by different amounts, are added together.

The AWG has several uses. It can be used as an nx1 wavelength multiplexer. In this capacity, it is an n-input, 1-output device where the n inputs are signals at different wavelengths that are combined onto the single output. The inverse of this function, namely, 1×N wavelength demultiplexing, can also be performed using an AWG. Although these wavelength multiplexers and demultiplexer can also be built using MZIs interconnected in suitable fashion, it is preferable to use an AWG. Relative to an MZI chain, an AWG has lower loss, flatter passband, high stability, low cost, and is easier to realize on an integrated-optic substrate. The input and output waveguides, the multiport couplers, and the arrayed waveguides are all fabricated on a single substrate. The substrate material is usually silicon, and the waveguides are silica, Germanium-doped silica or Silicon Dioxide (SiO_2)- Tantalum Oxide (Ta_2O_5).Thirty two channel AWGs are commercially available, and smaller AWG multiplexer is very attractive in optical WDM networks since it is capable of increasing the aggregate transmission capacity of SSMF. Their temperature coefficient $(0.01nm/\overset{\circ}{C})$ is not as low as those of some other competing technologies such as fiber gratings and multilayer thin-film filters.

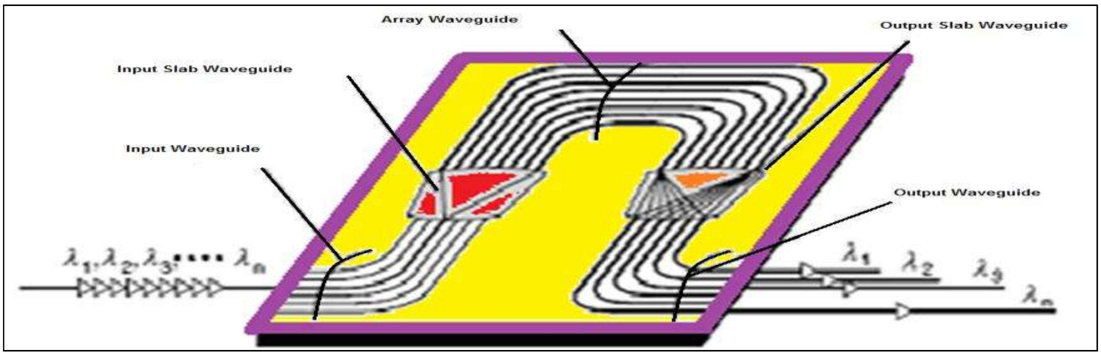


Figure (3-17):- Schematic configuration of AWG multiplexer.

3.12.1. Theory of Optical Waveguide:-

Optical waveguide is a transparent structure that can guide light. Most of optical waveguides are made of glass material, especially very pure glass material. From a chemical standpoint, the most efficient waveguide used in telecommunication is essentially pure silicon dioxide, known as silica (SiO_2). However, some of the waveguides do exist in other types of materials beside glass such as plastic and fluoride compounds for specific usage.

3.12.2. What is a Planar Lightwave Circuit (PLC)?

PLC is a waveguide circuit that is fabricated on a flat substrate such as silicon wafer. PLC is a type of optical waveguide. An optical waveguide is a physical structure that guides electromagnetic waves in the optical spectrum. The light is guided within the core layer which has a different refractive index compared to the surrounding material called cladding. The principle for optical waveguide is based on the phenomenon of total internal reflection (TIR). PLC was introduced amongst other things to address some of the mentioned challenges. The development of PLC has brought the optical network to the 4th generation which we call optical DWDM networking. With PLC, the transmission capacity can be increased at far lower costs by multiplexing several wavelengths on a single optical fiber without the need to deploy any additional fibers. The optical DWDM network system is able to increase the network links to 10Gbps and towards 40Gbps and faster transmission speeds by increasing the channels. Apart from applications in the telecommunication system, PLCs are also utilized in other fields. There are researches on developing the PLC for sensing devices, private data network, CATV, medical, military and also aerospace use. The application of PLC will become wider with time due to the reasons mentioned earlier [106, and 107].

3.12.3. Theory of Arrayed Waveguide Gratings (AWGs):-

AWGs are formed by three main parts, two input/output waveguide, two slab waveguide (or free propagation zones (FPZ)) and one arrayed waveguide with equal length difference between adjacent array waveguides as shown in Figure 3.18. For a demultiplexer, multiplexed optical signals with different wavelength from λ_1 to λ_n are transmitted from the input waveguides to the first FPZ. When the input signals enter the first FPZ they will diverge in the FPZ and be transmitted to the arrayed waveguide as shown in Figure 3.19. The length of the arrayed waveguides is designed so that the optical path length difference ΔL between adjacent waveguides is equal. The equal length difference between adjacent array waveguides will create a phase difference, so that focusing occurs at spatially separated points at the end of the second FPZ depending on the wavelength as shown in Figure 3.20. Thus signals of differing wavelengths can be coupled to separate output waveguides that will lead to the end of the AWGs. The basic operation of the AWGs demultiplexer is the same as the basic operation of AWGs multiplexer. Hence the AWGs demultiplexer can be used as a multiplexer in the reverse direction because of the reciprocity [108].

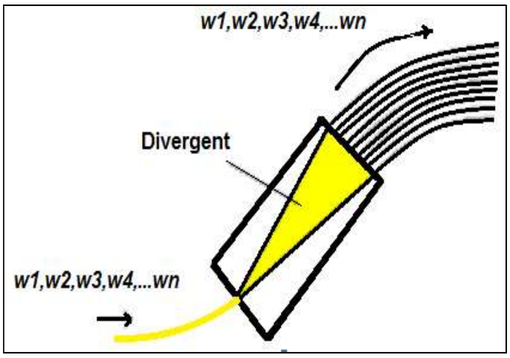


Figure (3-18):- Divergence of Multiplexed Wavelengths to Arrayed Waveguides in first FPZ.

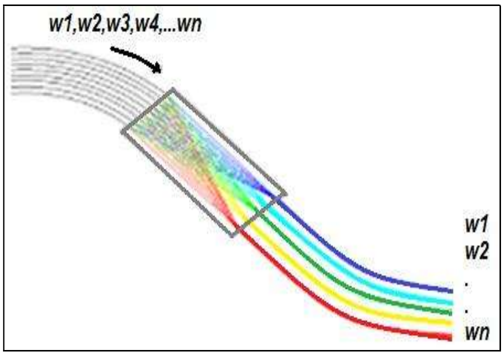


Figure (3-19):- Optical ray path of different wavelengths at second FPZ.

3.12.4. Issues Affecting The Performance of AWGs:-

There are a few issues affecting the performance of AWGs. The main issues include (crosstalk (See section 3.11.1.), insertion loss, and polarization).

3.12.4.1. Insertion loss:-

Insertion loss in AWGs is mainly caused by the inefficient coupling between the FPZ and the arrayed waveguide. First is the diffraction loss in the first FPZ due to the finite number of arrayed waveguides. Second is the imperfect focusing loss in the second FPZ due to the waveguide gap between arrayed-waveguides at the slab-array interface that is determined by the mask process. Other reasons that cause insertion loss include the fiber to waveguide coupling loss, bending loss at the arrayed waveguide, material’s intrinsic loss, scattering loss due to fabrication errors and waveguide roughness, and more.

3.12.4.2. Polarization:-

There appear two kinds of polarization in AWGs, one is the polarization dependent dispersion and the other one is polarization rotation. Polarization dispersion may cause the wrong coupling at the output waveguide, hence causing crosstalk problems. Curve waveguide like arrayed waveguide will exhibit a certain amount of polarization rotation by nature [64, and 85].

3.12.5. Evolution of AWGs [109]:-

Starting from 1994 when the optical fiber communication first employed DWDM system, the MUX/De-MUX of the various channels was achieved via Thin-Film Filter (TFF) and FBG. Both TFF and FBG based MUX/De-MUX filters require manual integration of discrete components in direct proportion to the number of optical channels. Additional channels of such filter system in serial form action produce more losses and additional cost that increase directly with the number of channels. Unlike the TFF and FBG filters system, the number of channels in AWGs are added in parallel form, and hence the lost is lower in large number of channels. The high number of optical channels is achieved in a single process step with AWGs, which is also much more cost effective than TFF and FBG filters system. The one step process fabrication of AWGs has reduced the cost per channel as the numbers of optical channels increase in single AWGs.

Table 3.2 shows the achievement in AWGs in DWDM system from 1997 to 2007. From Table 3.2, the number of channels has increased from 16 in 1997 to 80 in 2007. With the increment in the number of channels, the speed and the capacity of the DWDM system also increases. Applications of AWGs are not only confined to MUX/DEMUX application in DWDM network and routing but are also expanding to other fields. Researchers are now looking for applications of AWGs in optical signal processing field, generation of flat-topped femtosecond pulse trains, optical sensors, wavelength interrogation and Photonic IC's (PIC's).

Table (3-2):- Expansion of Leading Edge Transmission System Achieved with AWGs.

Year	System	Mux/Demux Fiber	Optical Carrier	Speed (Gbps)	Capacity
1990	1-λ point to point	Ideal	OC-48	2.5	2.5Gbps
1994	8- λ point to point DWDM	TFF or FBG	OC-48	2.5	20Gbps
1997	16- λ point to point DWDM	AWG	OC-48	2.5	40Gbps
1999	40- λ point to point DWDM	AWG	OC-192	10	400Gbps
2003	64- λ point to point DWDM	AWG	OC-192	10	640Gbps
2007	80- λ point to point DWDM	AWG	OC-768	40	3.200Tbps

3.12.6. Application of AWGs in WDM Network:-

There are a lot of AWGs advantages in WDM system compared to TFF and FBG filters. The main advantages are the lower loss, higher number of channels, and lower cost per channel. All these advantages carry DWDM network to a much higher speed and capacity. Besides that, AWGs also carry the characteristic of narrow and accurate channel spacing, polarization insensitivity, high stability and reliability. Because the channels for AWGs are added in parallel form, the size of AWGs device will not increase much although the number of channels increases significantly.

The key advantage of the AWG is that its cost is not dependent on wavelength count as in the dielectric filter solution. Therefore, it suits metropolitan applications that require the cost-effective of large wavelength counts. Another advantage of the AWG is the flexibility of selecting its channel number and channel spacing. As a result, various kinds of AWG's can be fabricated in a similar manner [49, and 109].

3.12.7. Application of AWG in PON:-

The progressive introduction of WDM technology is currently being considered for the implementation of the access networks using fiber infrastructure: the so called WDM-PONs feature unique properties including the possibility of offering simultaneously both broadcast and switched services plus additional advantages in terms of signal transport flexibility, privacy, easy fault location and direct capacity upgrade. A special interesting type of WDM-PON is the AWG-PON, where a Waveguide Grating Router (WGR or AWG) is placed in the central office (CO) for routing and multiplexing operations [110].

Current PON systems are generally based on TDM-PON. The key issues in these systems are how to increase their transmission capacity and how to diversify their transmission data. Since video streams are used in the access network, broadcast is a very important issue in PON systems. In TDM-PON, there are several ways to broadcast data to the ONUs: SCM, FDM, and Time Division technique which multiplexes digital base-band and RF video signals in frequency domain and modulates the mixed signal onto single wavelength, and a CWDM-based approach which uses a separate wavelength for video. Meanwhile, new demands from subscribers require more capacity than that of TDM-PONs can provide so that WDM-PONs have used. However, it is difficult in WDM-PON architectures to be able to broadcast a data or video stream to all subscribers at once because the output ports of the wavelength selective devices of the Optical

Distribution Network (ODN) only passes a specific wavelength channel on each specific port [54].

Wavelength multiplexers and demultiplexer, capable of combining and separating different spectral channels, are the key components of WDM network. The planar waveguide based MUX/DEMUX devices include AWG, and grating devices. State-of-the-art silica-on-silicon AWGs become prohibitively large for devices with higher channel counts and narrower channel spacing (CS), and the integration of different functions on a single chip is not feasible for practical systems unless the size of the individual functional elements is significantly reduced. Silicon-based photonic waveguide circuits have recently emerged as commercially viable optoelectronic devices [111].

In silicon on-insulator (SOI) waveguide devices, several orders of magnitude reduction of device size can be achieved as compared to devices based on silica-on-silicon materials. AWG demultiplexer in SOI platform had been demonstrated. Ultra compact AWG devices using silicon wire waveguides have recently been reported, but practical application of similar devices will require substantial improvements in quality of silicon waveguides of sub micrometer cross-sectional dimensions, particularly the sidewall roughness. At the same time, AWG dispersion, and hence minimum achievable CS, is limited by a maximum available length difference between the waveguides in the phased array. Here, a new dispersive element comprising the straight waveguides with sections of modified group index that, if placed in the phase array of a conventional AWG, can enhance dispersion properties of the latter [112].

4.1. Model Assumption and Simulation Setup:-

There are totally two kinds of bandwidth done in a series of computer simulations. To compare between these two kinds of bandwidth with NRZ modulation format, and their performance over SSMF link, both 10Gbps and 40Gbps are investigated in this research. To present the results of WDM optical systems, performance of system with multichannel is also presented for comparison. An AWG multiplexer/demultiplexer and its characteristics are also presented.

It is then desirable to observe the transmitter waveform in a reduced bandwidth also. The lower bandwidth its, the lower will be the noise. However, if the bandwidth is reduced too much, there will eventually be ISI, as the waveform takes longer to move from one logic level to another. This results in waveform trajectories that begin to close down the eye. The presentation of simulation results and setup are grouped into 10Gbps, and 40Gbps of bandwidth.

Figure (4.1) demonstrate the schematic diagram for all test beds. Table (4.1) shows the model assumption and properties for components in this research.

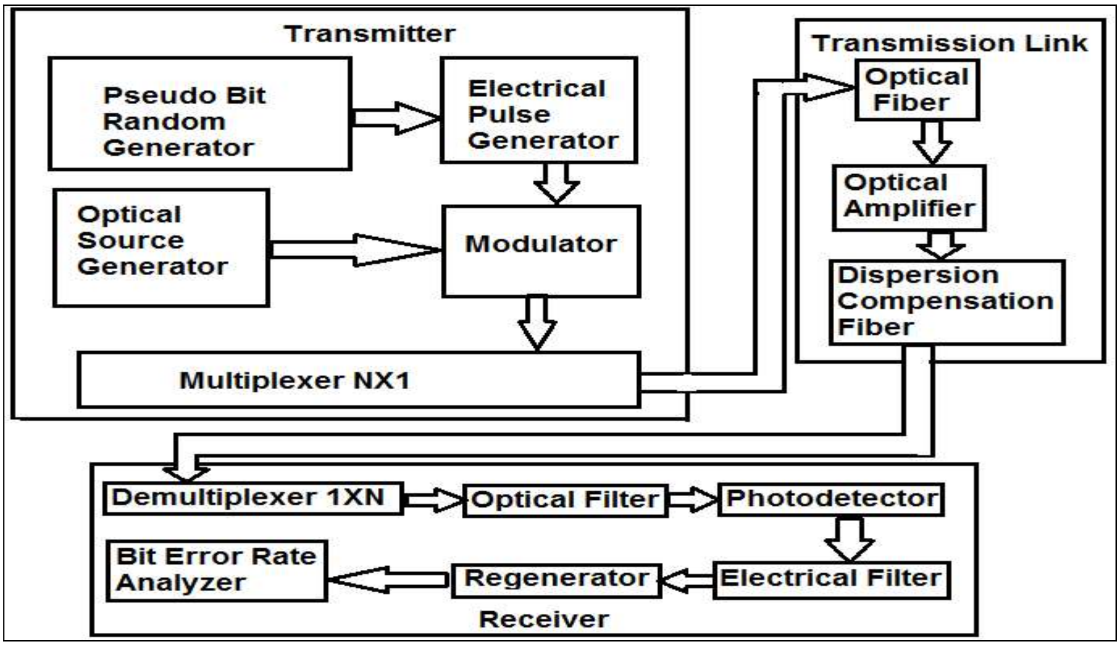


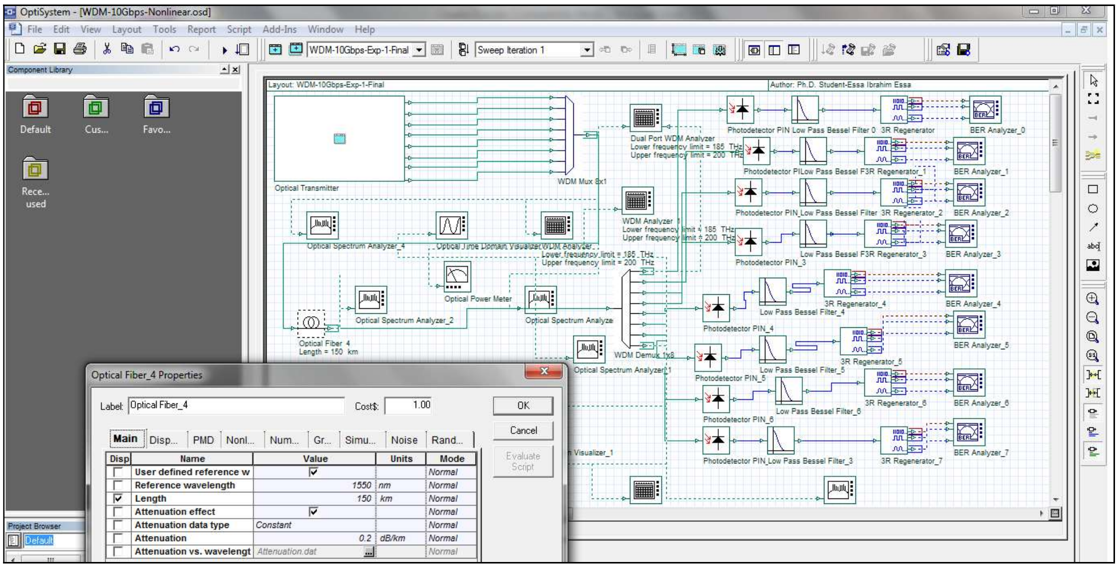
Figure (4-1):- Schematic diagram for all four test beds.

Table (4-1) :- Show the main properties for components used in all test bed.

Components	Properties	Exp.#2	Exp.#3	Exp.4
		10GbpsWDM	40GbpsWDM	40Gbps AWG
Transmitter	Channel No.	8	16	8
	CW Laser Power (dBm)	0	0	0
SSMF	Length (km)	130	100	200
	Dispersion (ps/nm/km)	16.75	17	17
	Attenuation (dB/km)	0.2	0.2	0.2
	Effective Area (µm^2)	80	80	80
	Dispersion Slope (ps/nm^2/km)	0.075	0.075	0.09
DCF	Length (km)	20	20	42.5
	Dispersion (ps/nm/km)	-80	-80	-80
	Attenuation (dB/km)	0.6	0.5	0.6
	Effective Area(µm^2)	30	22	30
	Dispersion Slope (ps/nm^2/km)	0.21	-0.3	0.21
EDFA	Gain (dB)	11.8	10,10,10,10	40
	Noise Figure (dB)	Script	6,6,6,6	6
Receiver	(Photodiode) PIN/APD	PIN	PIN	PIN
	Filter	Low Pass Bessel	Low Pass Bessel	Gaussian
	3R Regenerator	Used	Used	Not Used

4.2. WDM Network System 8×10Gbps without Nonlinearities Problems Management:-

The nonlinearities problem and dispersion compensation do not managed by optical amplifier and DCF in this experiment. The schematic diagram and SSMF properties for this experiment are shown in **Figure 5.2**; includes subsystem optical transmitter, optical channel, and receiver**).** This system consists of three sections which will be described in the following subsections.



Optical Fiber_4 Properties

Label: Optical Fiber_4 Cost$: 1.00

Main | Disp... | PMD | Nonl... | Num... | Gr... | Simu... | Noise | Rand...

Disp	Name	Value	Units	Mode
☐	User defined reference w	☑		Normal
☐	Reference wavelength	1550	nm	Normal
☑	Length	150	km	Normal
☐	Attenuation effect	☑		Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.2	dB/km	Normal
☐	Attenuation vs. wavelengt	Attenuation.dat		Normal

OK
Cancel
Evaluate Script

Figure (4-2): Schematic diagram and main optical fiber properties.

4.2.1. Transmitter:-

The WDM signals are generated by (8) continuous-wave (CW) lasers emitting in C-band (from 1546.92nm to 1552.52nm). Table 5.2 shows the frequencies for each channel, with a channel spacing of (100GHz), and power is (0dBm) for all channels separately modulated using NRZ format (10Gbps) in external Mach-Zender (MZ) modulator. The signal data patterns are generated by pseudorandom bit sequences (PRBS), as sequence length equal to (128bits), sample per bit is (64), and number of samples is (8192). PRBS patterns have been standardized by the ITU for testing digital transmission systems. The most commonly used patterns in digital transmission system testing are ($2^N - 1$) with N = 7, 10, 15, 20, 23 and 31. The corresponding pattern length (sometimes referred to as word length) is 127, 1023, 32767, 1048575, 8388607, and 2.1475×10^9 bits, respectively, per pattern**.** Because of the properties of PRBS, a precoder was not used in this experiment. Figure (4.3) illustrate the transmitter subsystems.

Table (4-2):- Channel (Wavelength and frequency), used in 8×10Gbps system.

Item(s)	Channel Number	Channel Wavelength (nm)	Channel Frequency (THz)
1.	1	1552.52	193.1
2.	2	1551.72	193.2
3.	3	1550.92	193.3
4.	4	1550.12	193.4
5.	5	1549.32	193.5
6.	6	1548.51	193.6
7.	7	1547.72	193.7
8.	8	1546.92	193.8

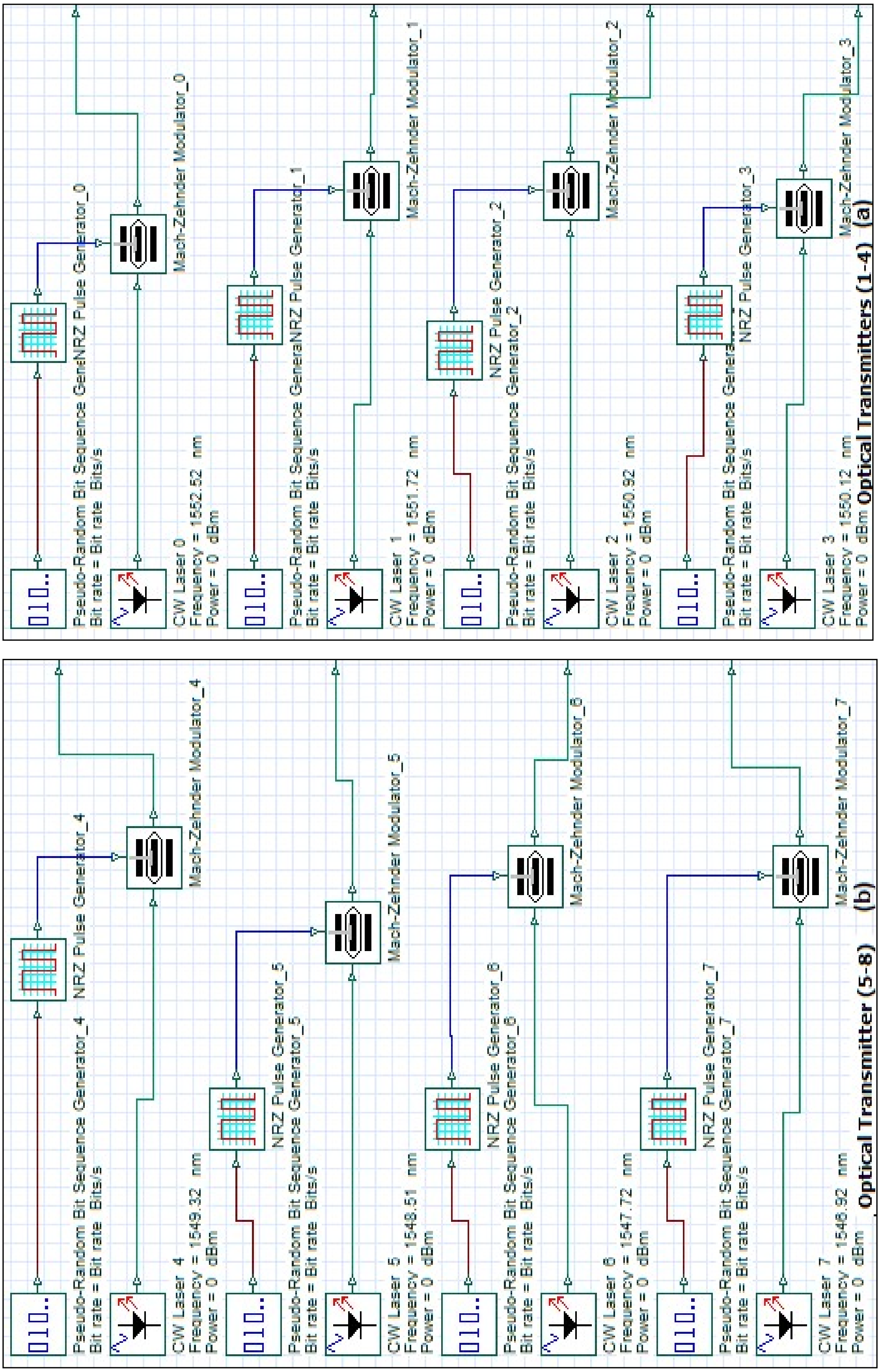


Figure (4-3):- Main layout for experiment_1 (a): The optical transmitter subsystem (1-4), (b): optical transmitter subsystem (5-8).

4.2.2. Transmission Link:-

All WDM optical signals are launched into the transmission line through the (8 × 1) optical multiplexer, after the span of (150km) fiber with the dispersion equal to (17ps/nm/km), attenuation loss is (0.2dB/km), and effective area ($80\mu m^2$).The WDM signals are demultiplexed by WDM (1×8) demultiplexer.

4.2.3. Receiver:-

After signal round trip corresponding to (150km), the 8-channel WDM signals are demultiplexed optical WDM (1 × 8). The 8- signals output sent to positive intrinsic negative (PIN) photodiodes connected directly to 8-low pass Bessel filter, each of them has cutoff frequency that is equal to (0.75×Bitrate Hz). 3R regeneration with wavelength conversion optical 3R regeneration will prove beneficial in all optical networks. As optical signals travel in fiber link, they can be affected by a number of different factors such as dispersion, attenuation interference from other channels, noise etc... These detrimental effects cause serious distortion of the signal which must be repaired at each node. 3R regeneration of a signal includes amplification, re-shaping and re-timing. Currently 3R regeneration is performed in electrical domain with expensive optical-electrical-optical (OEO) conversions required for each channel. The 3R is connected to the bit error rate BER analyzer to monitor and evaluate transmission performance.

4.3. WDM Network System with 8×10Gbps with Nonlinearities Problems Management:-

To overcome the nonlinearities problems that appear in WDM systems will be use optical amplifiers (EDFA) to improve the degradation in received power signals, and dispersion compensator fiber to managed the dispersion that appear in experiment_1 in previous section (4.2). The schematic diagram for this experiment shown in Figure 4.4; includes two subsystems (optical transmitter (see Figure (4.3)), and optical channel Figure (4.5)). The main layout properties are shown in Figure 4.6. This system consists of three sections which will be described in the following subsections.

4.3.1. Transmitter:-

In this transmitter all components properties used as the same in transmitter in section (4.2.1). See Figure (4.3), and Table (4.2).

4.4.2. Transmission Link and Amplification:-

In Figure 4.4, the WDM signals power are launched into the transmission line through the (8 × 1) optical multiplexer, and amplified by $EDFA^{+3}$ with length equal to (6m), after the first span of (50km) fiber with the dispersion equal to (17ps/nm/km), attenuation loss is (0.2dB/km),and effective area ($80\mu m^2$). The forward pump laser is with (980nm), and power equals (23dBm). After signal propagates the dispersion is accumulated. This can be compensated by DCF with length (20km), has a dispersion slope of ($0.21 ps/\mu m^2/km$), 2-Ideal EDFAs are used in two stage link. The gain and noise values are fairly straightforward, as the gain is set to compensate for power loss in this fiber, and the gain is set to (11.8dB), and (10dB) respectively. The last span link is (80km) SSMF. The WDM signals are demultiplexed by WDM demultiplexer.

4.4.3. Receiver:-

After signal journey corresponding to (150km), the 8-channel WDM signals are demultiplexed optical WDM (1 × 8). All other components and their properties was be used as the same as in section (4.2.3).

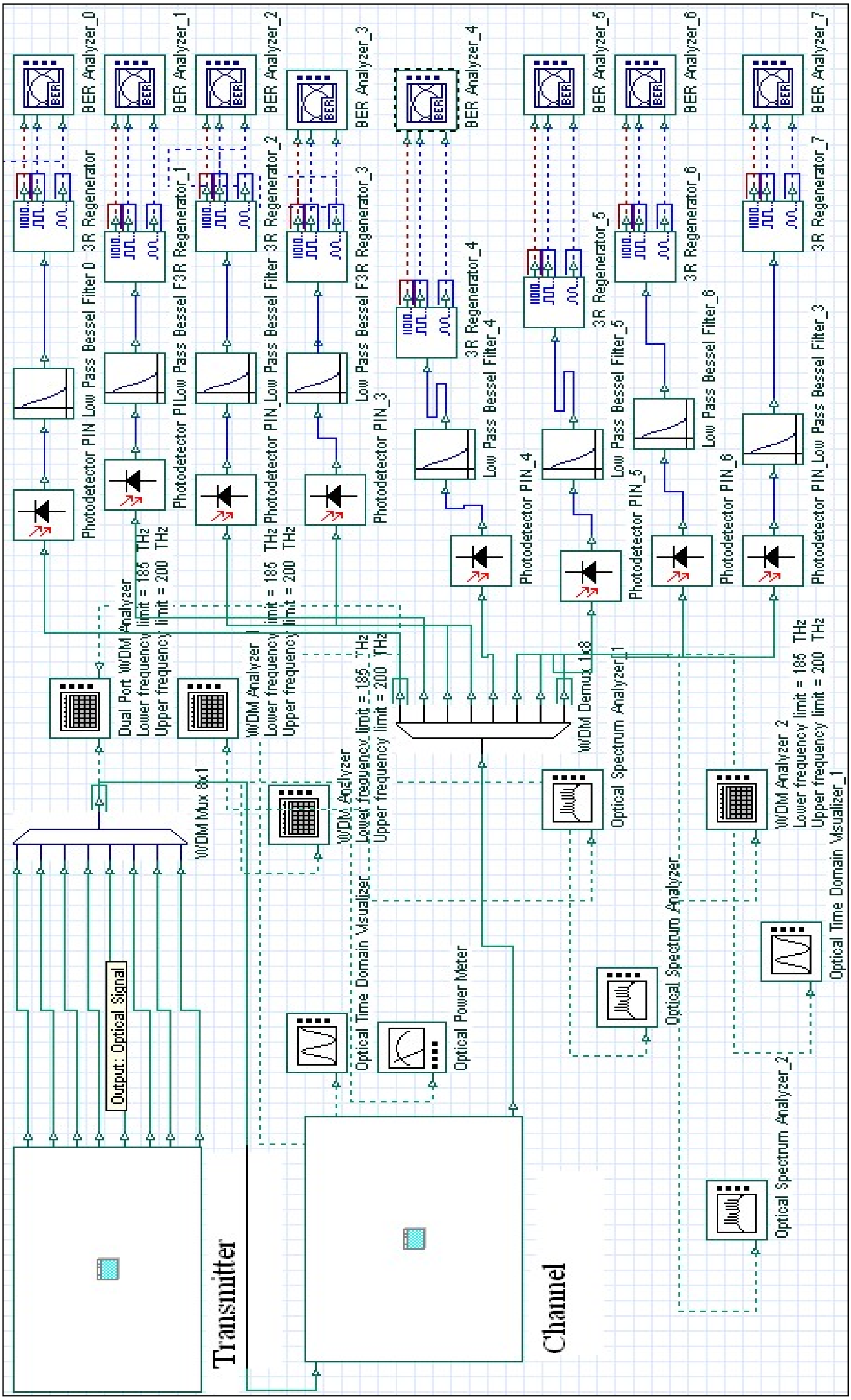


Figure (4-4):- The schematic diagram for the 8×10Gbps WDM.

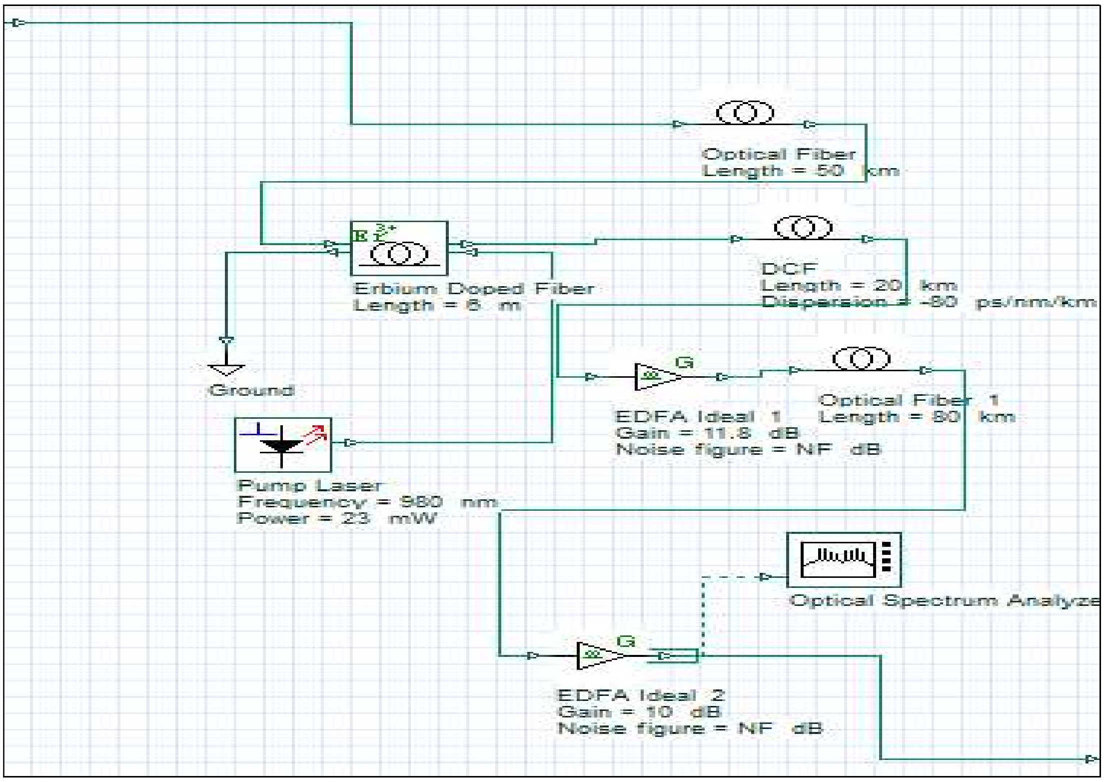
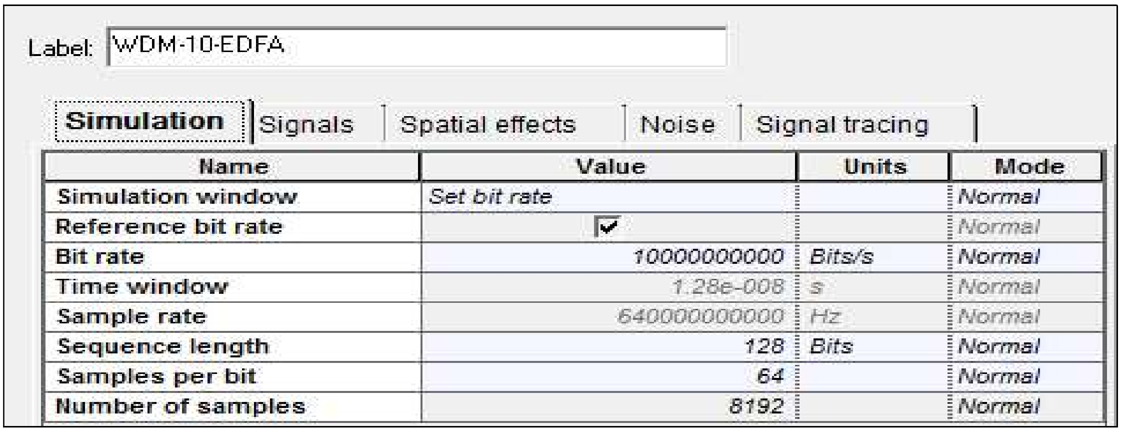


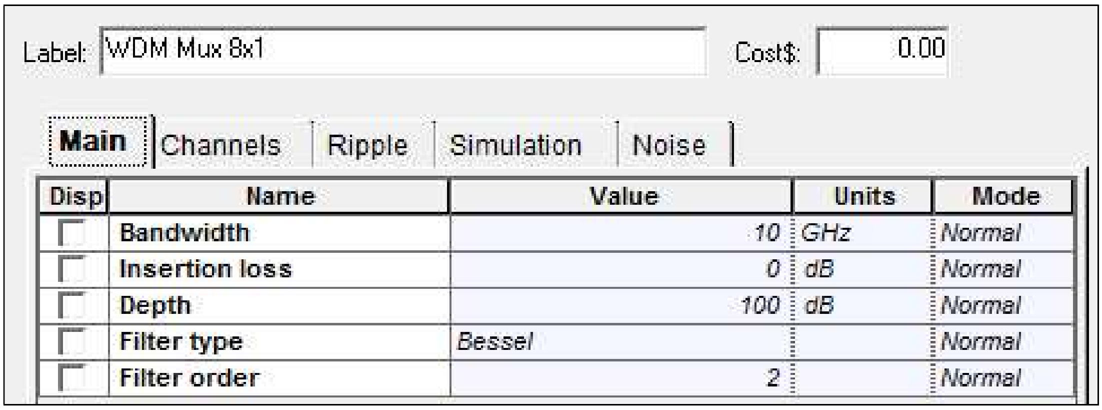
Figure (4-5):- The schematic diagram for the linear channel subsystem.



Label: WDM-10-EDFA

Name	Value	Units	Mode
Simulation window	Set bit rate		Normal
Reference bit rate	☑		Normal
Bit rate	10000000000	Bits/s	Normal
Time window	1.28e-008	s	Normal
Sample rate	640000000000	Hz	Normal
Sequence length	128	Bits	Normal
Samples per bit	64		Normal
Number of samples	8192		Normal

Figure (4-6):- The main layout properties for 10Gbps WDM system.

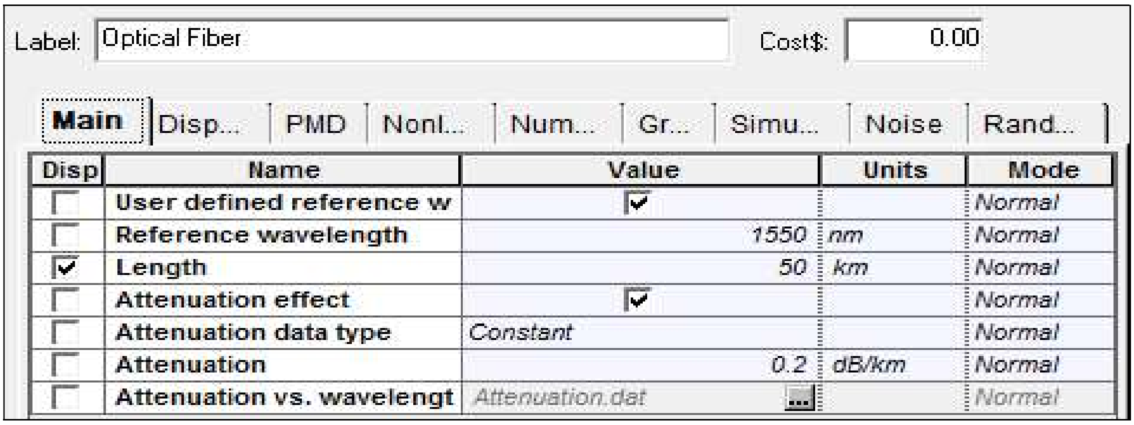


Label: WDM Mux 8x1

Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Bandwidth	10	GHz	Normal
☐	Insertion loss	0	dB	Normal
☐	Depth	100	dB	Normal
☐	Filter type	Bessel		Normal
☐	Filter order	2		Normal

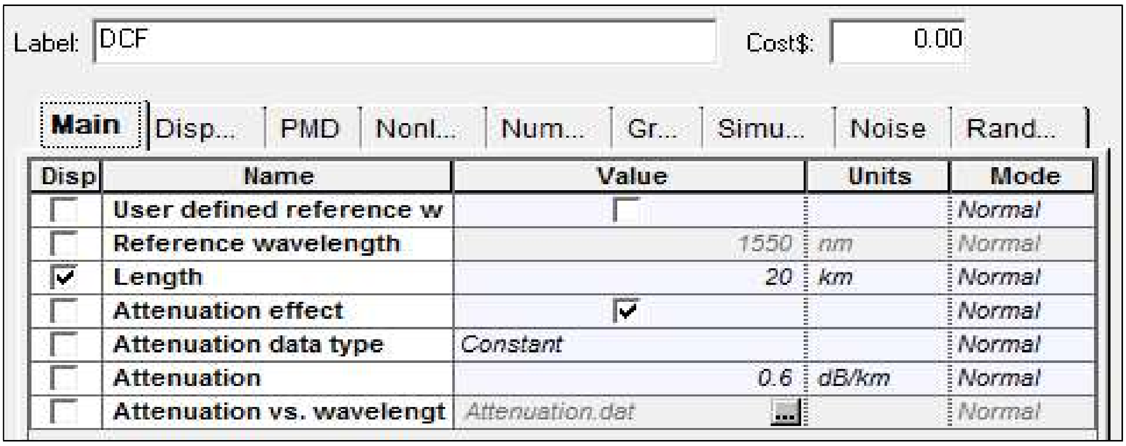
Figure (4-7):- The WDM (8×1) multiplexer.



Label: Optical Fiber
Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	User defined reference w	☑		Normal
☐	Reference wavelength	1550	nm	Normal
☑	Length	50	km	Normal
☐	Attenuation effect	☑		Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.2	dB/km	Normal
☐	Attenuation vs. wavelengt	Attenuation.dat ...		Normal

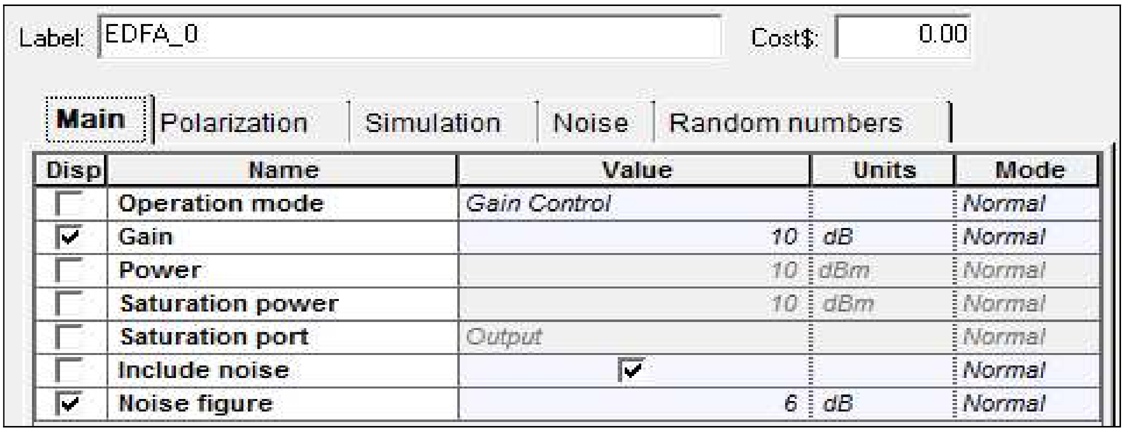
Figure (4-8):- The main properties for SSMF.



Label: DCF
Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	User defined reference w	☐		Normal
☐	Reference wavelength	1550	nm	Normal
☑	Length	20	km	Normal
☐	Attenuation effect	☑		Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.6	dB/km	Normal
☐	Attenuation vs. wavelengt	Attenuation.dat ...		Normal

Figure (4-9):- The main properties for the DCF.



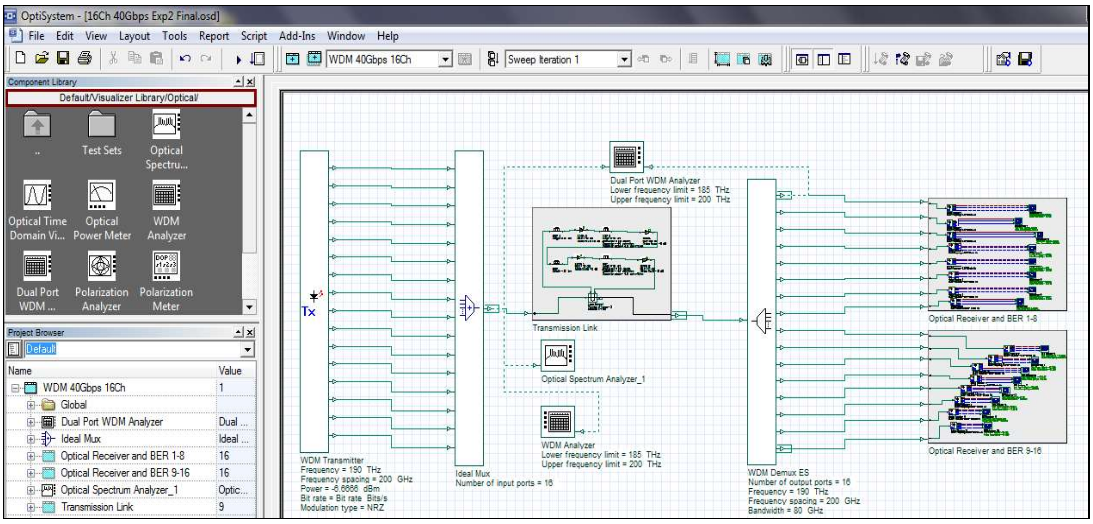
Label: EDFA_0
Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Operation mode	Gain Control		Normal
☑	Gain	10	dB	Normal
☐	Power	10	dBm	Normal
☐	Saturation power	10	dBm	Normal
☐	Saturation port	Output		Normal
☐	Include noise	☑		Normal
☑	Noise figure	6	dB	Normal

Figure (4-10):- The main properties for the EDFA.

4.5. The WDM Network System with 16×40Gbps:-

This design is to simulate a multi-channel WDM system (16-channels at 40Gbps). A multiplexer must be added at the transmitter site to combine all the channels so that they can be transmitted through the optical fibers. Respectively, a de-multiplexer must be added at the receiver site which will provide the separation of the channels in the frequency domain and they can be analyzed separately. The schematic diagram for this experiment is shown in Figure 4.11. The sequence length of pseudo random bit is (64bit), sample per bit is (256), and the number of samples is (16384). The main layout properties are shown in Figure 4.12.



Name	Value
WDM 40Gbps 16Ch	1
Global	
Dual Port WDM Analyzer	Dual ...
Ideal Mux	Ideal ...
Optical Receiver and BER 1-8	16
Optical Receiver and BER 9-16	16
Optical Spectrum Analyzer_1	Optic...
Transmission Link	9

WDM Transmitter
Frequency = 190 THz
Frequency spacing = 200 GHz
Power = -6.6666 dBm
Bit rate = Bit rate Bits/s
Modulation type = NRZ

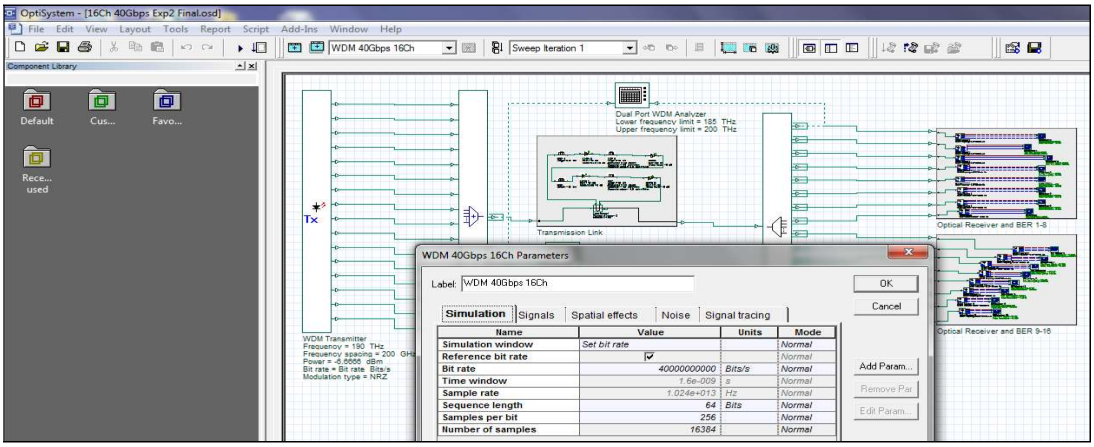
Ideal Mux
Number of input ports = 16

Dual Port WDM Analyzer
Lower frequency limit = 185 THz
Upper frequency limit = 200 THz

WDM Analyzer
Lower frequency limit = 185 THz
Upper frequency limit = 200 THz

WDM Demux ES
Number of output ports = 16
Frequency = 190 THz
Frequency spacing = 200 GHz
Bandwidth = 80 GHz

Figure (4-11):- The block diagram of 40Gbps WDM system.



Label: WDM 40Gbps 16Ch

Name	Value	Units	Mode
Simulation window	Set bit rate		Normal
Reference bit rate	☑		Normal
Bit rate	40000000000	Bits/s	Normal
Time window	1.6e-009	s	Normal
Sample rate	1.024e+013	Hz	Normal
Sequence length	64	Bits	Normal
Samples per bit	256		Normal
Number of samples	16384		Normal

Figure (4-12):- The main layout properties with 40Gbps.

4.5.1. WDM Transmitter:-

WDM systems require multiple transmitters and different parameters for each of them. In addition, they also require different modulation schemes and formats. By using multiple components, users can customize designs, but it is time consuming. The WDM Transmitter encapsulates different components, allowing users to select different modulation formats and schemes for multiple channels in one single component. It is a transmitter array that allows for different modulation types and schemes. Table (4.3) illustrates the channel frequencies for the WDM transmitter. The block diagram for each WDM channel transmitter is shown in Figure 4.13.

Table (4-3):- The channels wavelength and its frequencies used in the WDM 16×40Gbps.

Item(s)	**Channel Number**	**Channel Wavelength *(nm)***	**Channel Frequency *(THz)***
1.	1	1577.85	190
2.	2	1577.02	190.2
3.	3	1576.19	190.4
4.	4	1575.36	190.6
5.	5	1574.53	190.8
6.	6	1573.7	191.0
7.	7	1572.87	191.2
8.	8	1572.04	191.4
9.	9	1571.21	191.6
10.	10	1570.38	191.8
11.	11	1569.55	192
12.	12	1568.72	192.2
13.	13	1567.89	192.4
14.	14	1567.06	192.6
15.	15	1566.23	192.8
16.	16	1565.4	193

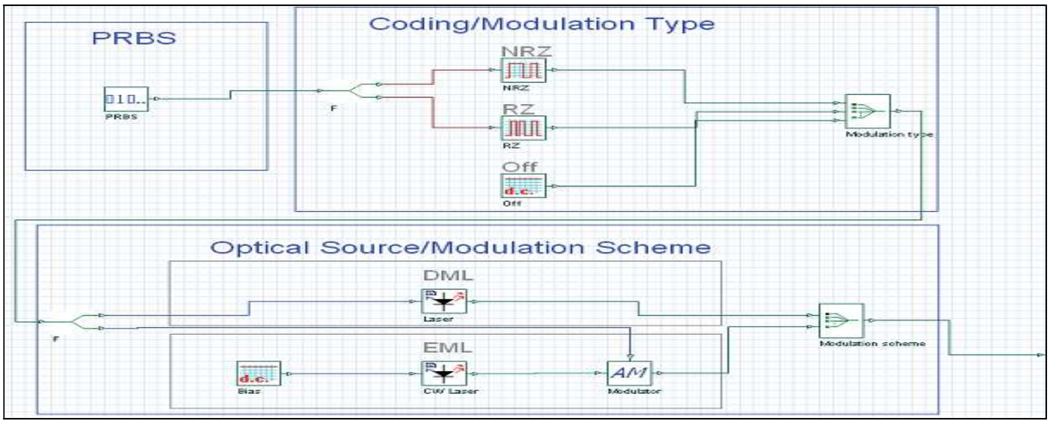


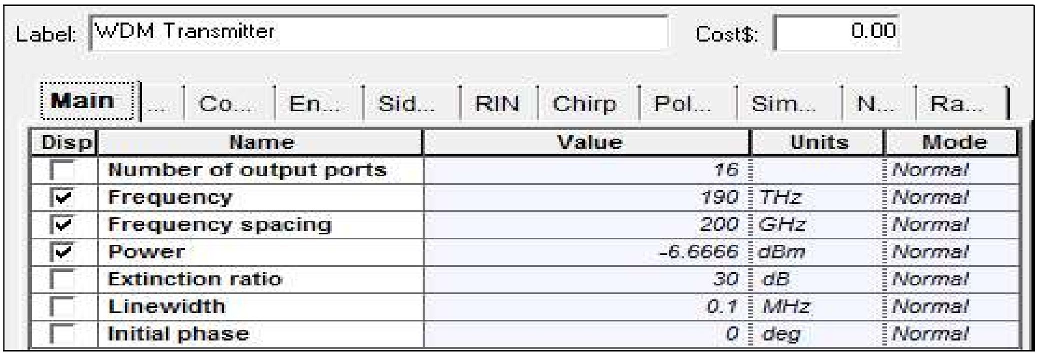
Figure (4-13):- The block diagram for each WDM channel transmitter.

The first stage is the PRBS. The same engine used in the Pseudo-Random Bit Sequence Generator component is used in this stage. Parameters bit rate, order, number of leading and trailing zeros are used in the internal PRBS. A different seed will be used for each bit sequence for each WDM channel. The operation and parameters of the PRBS component are described in the technical background of the Pseudo-Random Bit Sequence Generator.

The second stage is the Coding/Modulation. The parameter Modulation type has three options: RZ, NRZ and Off. RZ, and NRZ. Coding is generated by the engines of the RZ Pulse Generator and NRZ Pulse Generator respectively. A CW operation of the transmitter is possible by selecting Off as modulation type. The Duty cycle (ordering the PRBS generator) parameter is used when modulation type RZ is selected.

The last stage is the optical source and modulation scheme. By using the parameter transmitter type, the user can select between an external modulated laser schemes (EML) or a directly modulated laser scheme (DML). The laser engine used in this stage is the same used in the Directly Modulated Laser Measured component. The multiplexer output is connected to the loop control components in the second stage of regime.WDM transmitter properties are (frequency is 190THz, frequency spacing is 200GHz, power with -6.6666dBm (0.2154mW), Bitrate=Bitrate

(Bit/s), and NRZ modulation format). Figure 4.14 show the main properties of WDM transmitter.



Label: WDM Transmitter
Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Number of output ports	16		Normal
☑	Frequency	190	THz	Normal
☑	Frequency spacing	200	GHz	Normal
☑	Power	-6.6666	dBm	Normal
☐	Extinction ratio	30	dB	Normal
☐	Linewidth	0.1	MHz	Normal
☐	Initial phase	0	deg	Normal

Figure (4-14):- Main properties for the WDM optical transmitter.

4.5.2. Transmission Link:-

The next step is to design the transmission span. The transmission span that consists of "cells" i.e. it is periodic. The "Loop control" component will actually perform the multiplication of cells the necessary number of times. The use of cells stems from the necessity of dispersion compensation. At bit rates as high as 40Gbps, the design of the cell is crucial. This means that during the propagation, within one cell, not only is there a strong overlap between the adjacent pulses, but the original bit stream will be totally scrambled due to the dispersion-induced pulse broadening.

This regime of propagation, known as "pulse-overlapped", is of very high practical importance, since in this case the impact of the nonlinear effects taking place due to the interaction of the overlapping pulses that belong to one and same information channel (known as intra-channel nonlinearities) are reduced. Then, signals entered to the loop control are launched into the fiber link SSMF (100km), and split it into two cells (50km) for each. Which has properties such as, dispersion of (17ps/nm/km), and attenuation with (0.2dB/km); Figure 4.15 and 4.16 show the subsystem transmission link and its main properties, and then amplified with four EDFA with gain, and noise figure are (10, 5, 10, and 5 dB), and (6, 6, 6, and 6) respectively. There are two cells of DCF with some properties of length (10km), attenuation (0.5dB/km), dispersion (-85ps/nm/km), and dispersion slope (-0.3ps/nm^2/km) for each cell. After that, the signal round trip rewards to the loop control and then enters to the receiver side.

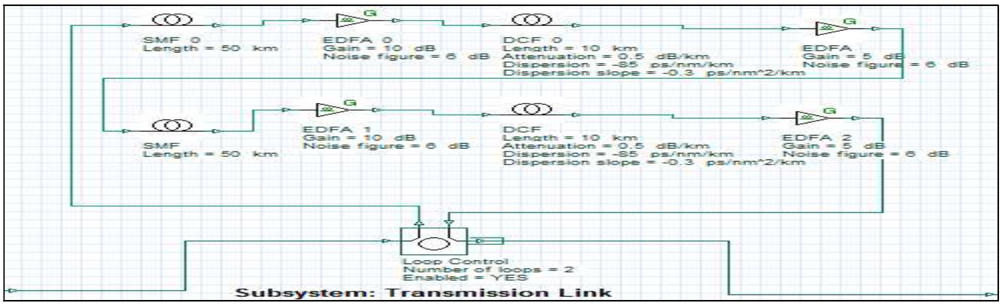
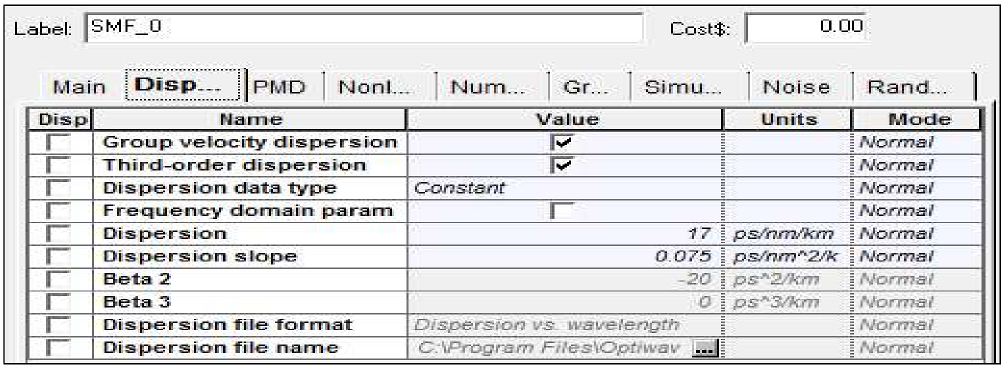


Figure (4-15):- Transmission link Subsystem.

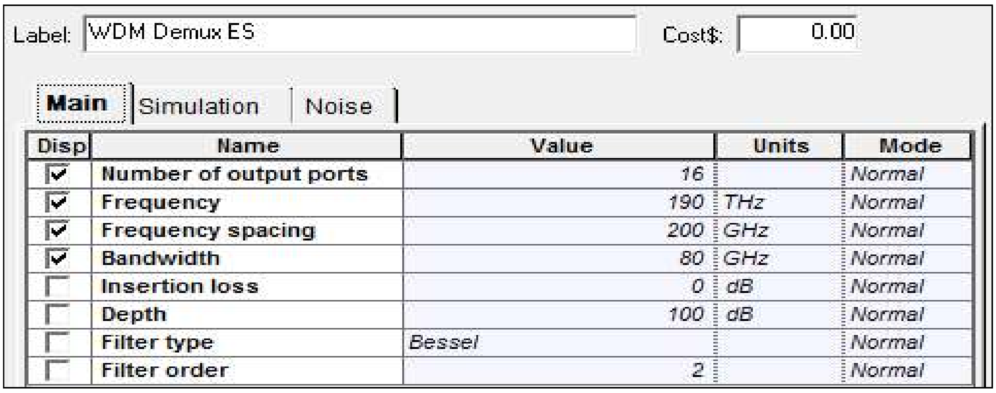

Label: SMF_0 Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Group velocity dispersion	☑		Normal
☐	Third-order dispersion	☑		Normal
☐	Dispersion data type	Constant		Normal
☐	Frequency domain param	☐		Normal
☐	Dispersion	17	ps/nm/km	Normal
☐	Dispersion slope	0.075	ps/nm^2/k	Normal
☐	Beta 2	-20	ps^2/km	Normal
☐	Beta 3	0	ps^3/km	Normal
☐	Dispersion file format	Dispersion vs. wavelength		Normal
☐	Dispersion file name	C:\Program Files\Optiwav		Normal

Figure (4-16):- The main properties for the SSMF.

4.5.3. WDM Receiver:-

The WDM receiver design consists of (1 to 16) Demultiplexer and “single-channel” receiver connected to each output port. The WDM Demultiplexer has equal spacing with frequency (190GHz), frequency spacing (200GHz), bandwidth (80GHz), depth (100dB), and second order Bessel filter to filtering each channel optically. Figure 4.17 views the main properties of WDM Demultiplexer. Each Demultiplexer output is connected to optical receiver subsystem as viewed in Figure 4.18. The subsystem was built using two different types of photodetectors; one Bessel filter and the 3R regenerator. The component properties allow the user to select the internal component parameters. Depending on the choice between PIN and APD, the Switch/Select components will redirect the signal into the proper photodetector type. Then, each subsystem outputs connected to the BER analyzer to be monitored the output signals by BER eye diagram and Q-Factor. Figures 4.19a and 4.19b illustrate the optical receiver and BER analyzer for output channels (1-16) subsystems. For more details about other components properties (See Appendix B).



Label: WDM Demux ES

Cost$: 0.00

Disp	Name	Value	Units	Mode
☑	Number of output ports	16		Normal
☑	Frequency	190	THz	Normal
☑	Frequency spacing	200	GHz	Normal
☑	Bandwidth	80	GHz	Normal
☐	Insertion loss	0	dB	Normal
☐	Depth	100	dB	Normal
☐	Filter type	Bessel		Normal
☐	Filter order	2		Normal

Figure (4-17):- The main properties of the WDM Demultiplexer.

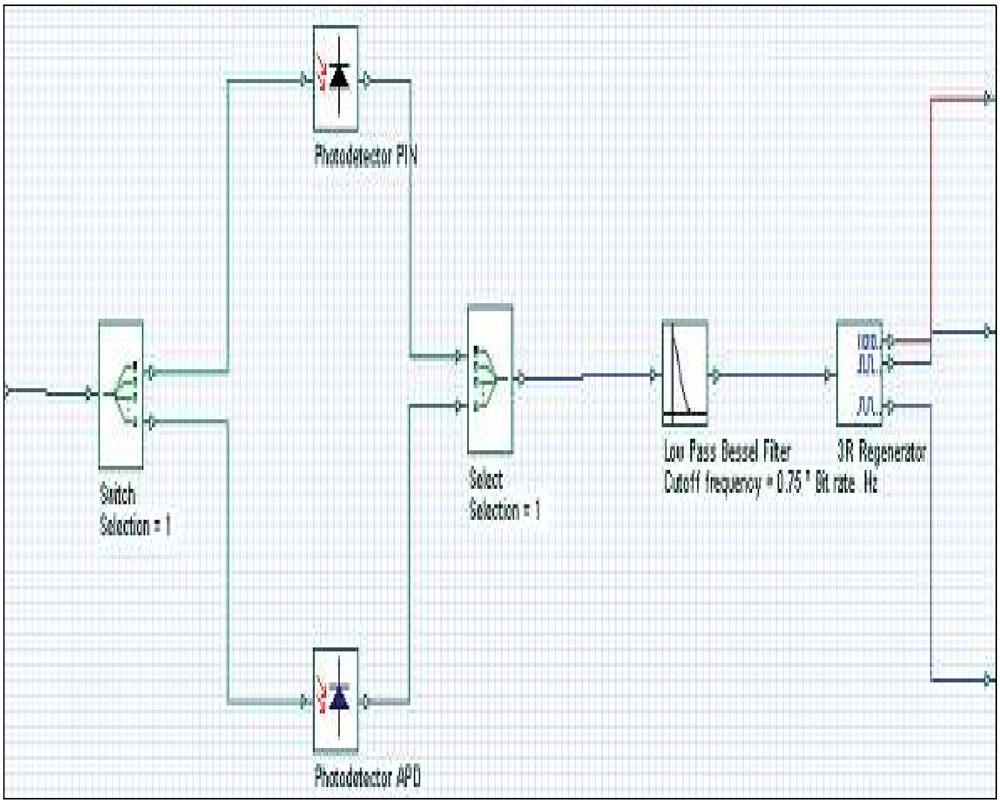


Figure (4-18):- The optical receiver subsystem (Green Lines means optical signal, Blue means electrical signal, and Red means digital signal).

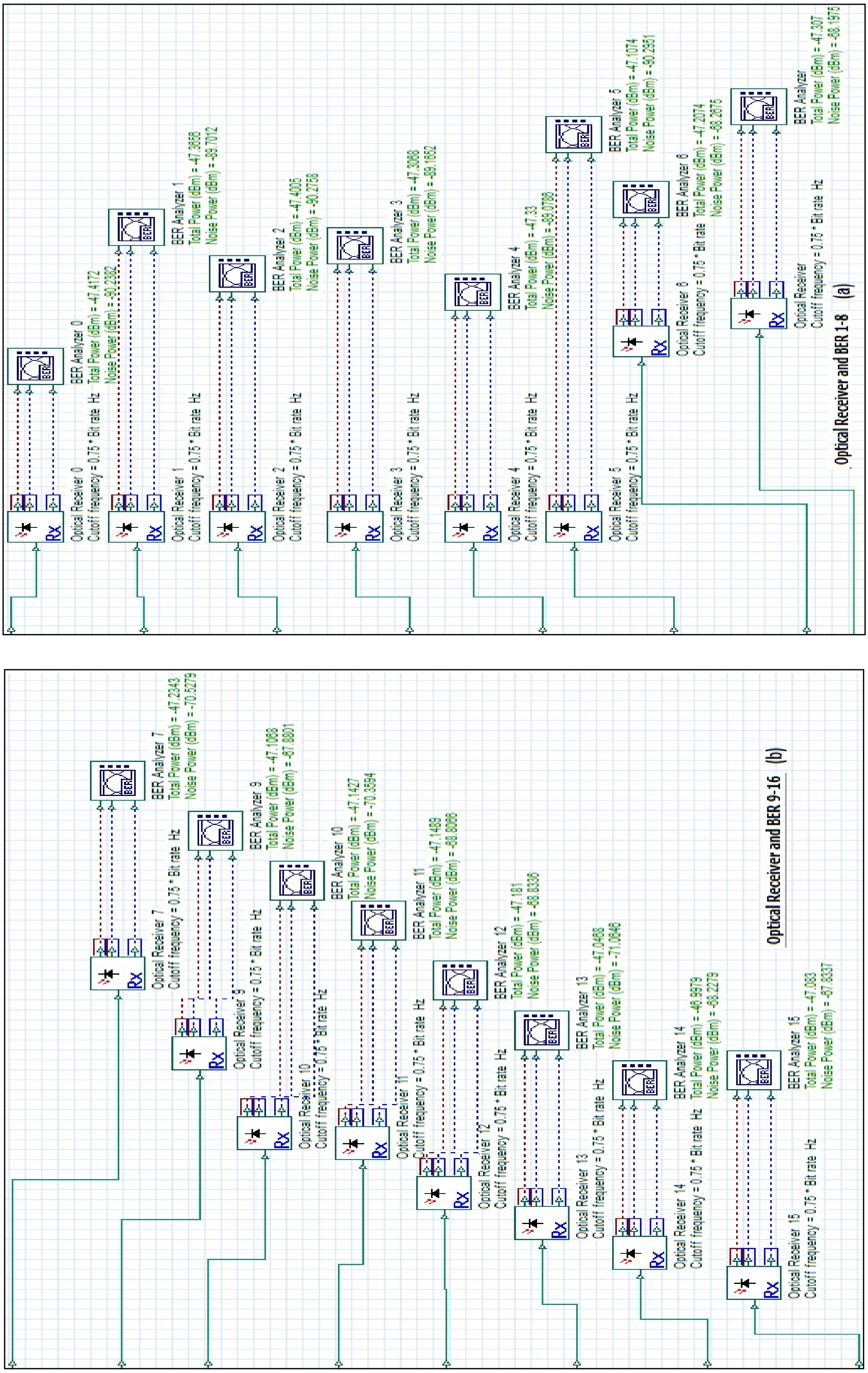


Figure (4-19):- Optical receiver for the 40Gbps (a): The optical receiver and BER analyzer for output channels (1-8) subsystem, and (b): The optical receiver and BER analyzer for output channels (9-16).

4.6. An AWG Multiplexer/De-Multiplexer with 8×40Gbps:-

To demonstrate the MEMS and SOI capabilities; here will be use the AWG as multiplexer/demultiplexer. Figures (4.20, and 4.21) show a block diagram and layout properties of the AWG architecture. This layout consists of three main parts: the first one is an optical transmitter with its components, the second one is the optical transmission link, and the last one is the receiver with its components.

4.6.1. Transmitter:-

This side is responsible for generating the optical signal and launching them into the optical fiber. 8-CW laser with wavelength (193.1-193.8THz, See Table (4.1)), and power is (0dBm), (8) NRZ format generator (40Gbps) in external (8) Mach-Zender (MZ) modulator. The signal data patterns are generated by pseudorandom bit sequences (PRBS), as sequence length equal to (64bits), sample per bit is (256), and number of samples is (16384). Each output signal is connected to each input port of an AWG (8×8) multiplexer to multiplexing them and the output of AWG is connected to the (8×1) power combiner. Figure 4.21 illustrates the main properties of an AWG as multiplexer.

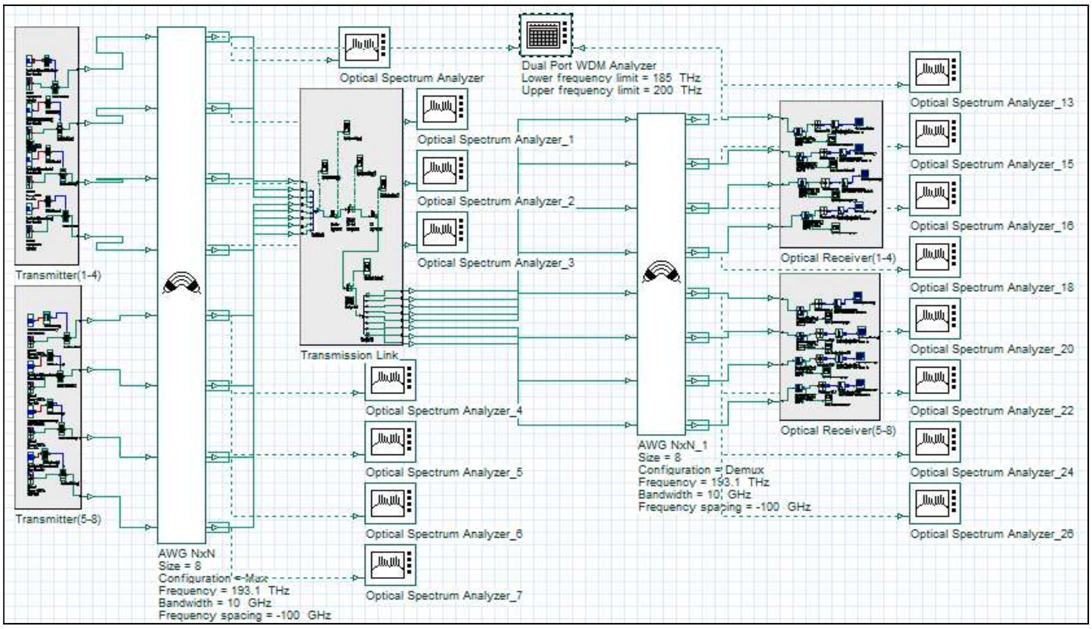
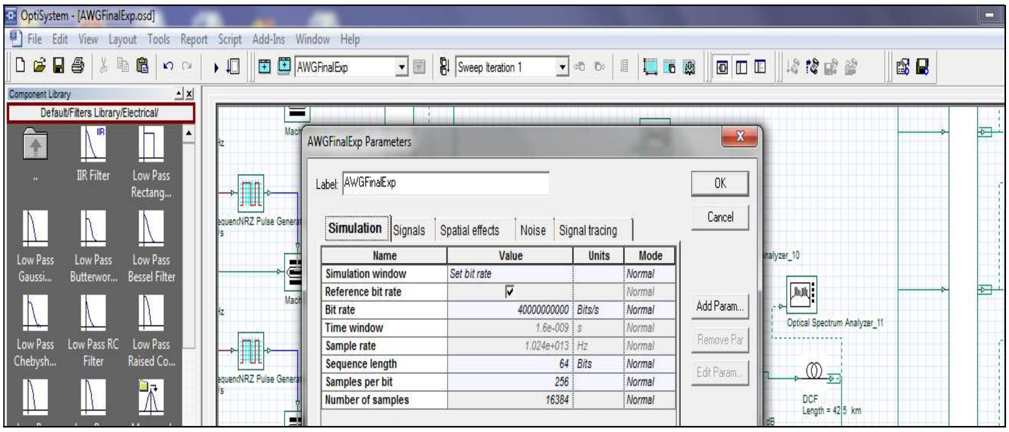


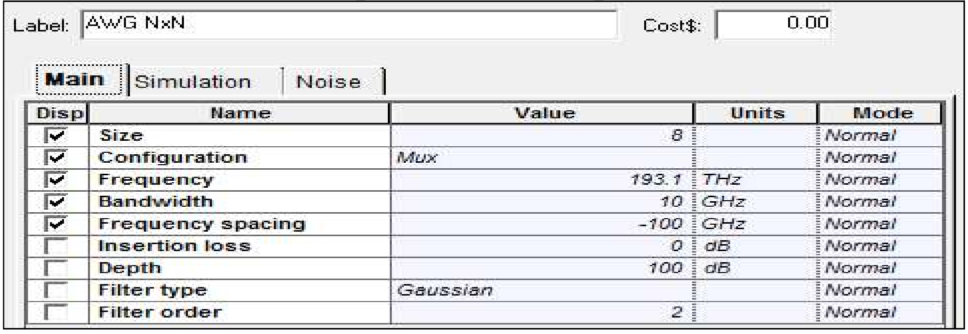
Figure (4-20):- The Block Diagram of AWG architecture.



Label: AWGFinalExp

Name	Value	Units	Mode
Simulation window	Set bit rate		Normal
Reference bit rate	☑		Normal
Bit rate	40000000000	Bits/s	Normal
Time window	1.6e-009	s	Normal
Sample rate	1.024e+013	Hz	Normal
Sequence length	64	Bits	Normal
Samples per bit	256		Normal
Number of samples	16384		Normal

Figure (4-21):- The main Layout Properties of the AWG Multiplexer/Demultiplexer.



Label: AWG NxN   Cost$: 0.00

Disp	Name	Value	Units	Mode
☑	Size	8		Normal
☑	Configuration	Mux		Normal
☑	Frequency	193.1	THz	Normal
☑	Bandwidth	10	GHz	Normal
☑	Frequency spacing	-100	GHz	Normal
☐	Insertion loss	0	dB	Normal
☐	Depth	100	dB	Normal
☐	Filter type	Gaussian		Normal
☐	Filter order	2		Normal

Figure (4-22):- The main AWG 8×8 Multiplexer Properties.

4.6.2. Transmission Link:-

After the power combiner output, all signals are launched into the transmission line. The first cell is a SSMF with length (200km). The dispersion is equal to (17ps/nm/km), attenuation loss is (0.2dB/km), and effective area ($80\mu m^2$). To compensate the degrading in the signal power, two components of EDFA (Gain=40dB, and Noise Figure =6dB) are used. After signal propagates, the dispersion is accumulated. This can be compensated by DCF with length (42.5km), and a dispersion slope ($0.21 ps/\mu m^2/km$). At the end side, all signals entered to the (1×8) power splitter. Figure 4.23 shows the transmission link, and Figures (4.24 – 4.27) show the main properties of these components. Then, each output signal is connected to the corresponding port of an (8×8) AWG to de-multiplex them.

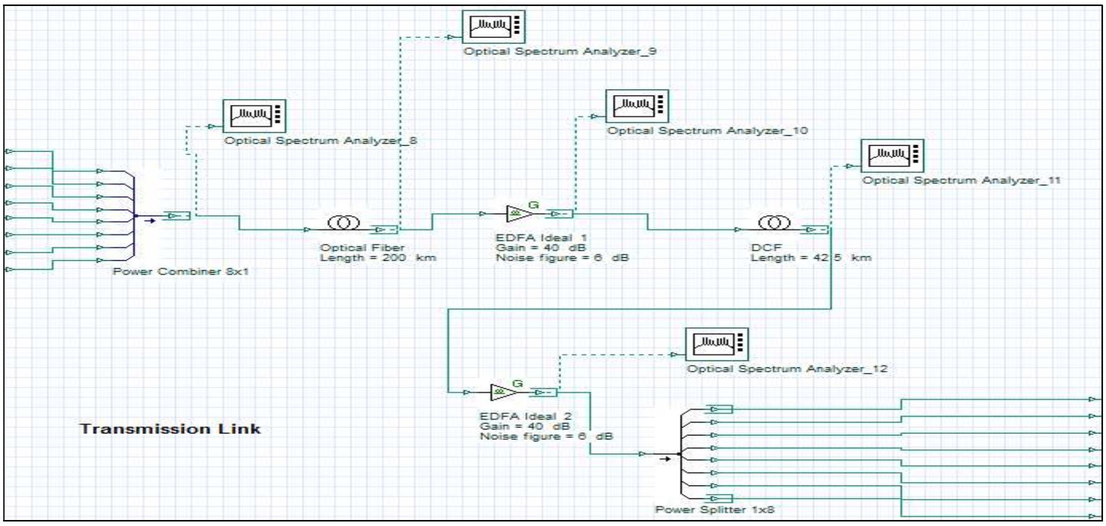
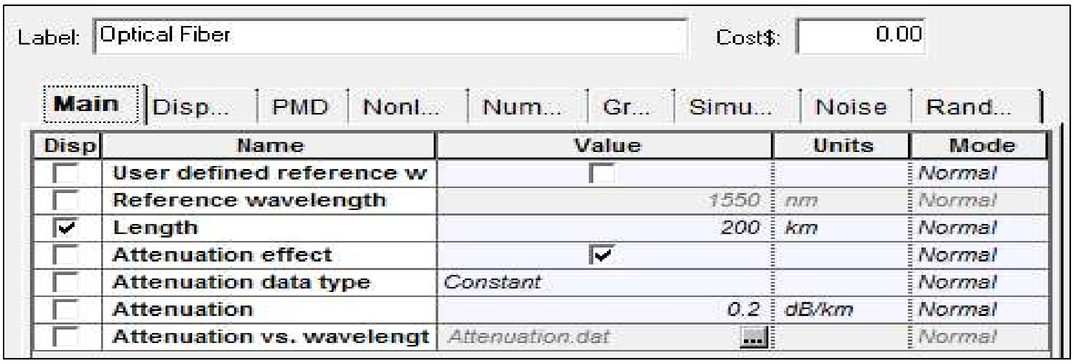


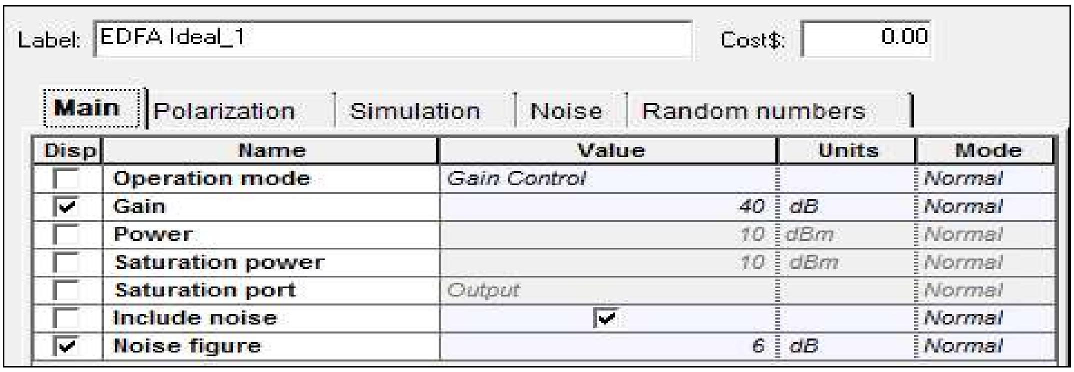
Figure (4-23):- The transmission link subsystem.



Label: Optical Fiber   Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	User defined reference w	☐		Normal
☐	Reference wavelength	1550	nm	Normal
☑	Length	200	km	Normal
☐	Attenuation effect	☑		Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.2	dB/km	Normal
☐	Attenuation vs. wavelengt	Attenuation.dat ...		Normal

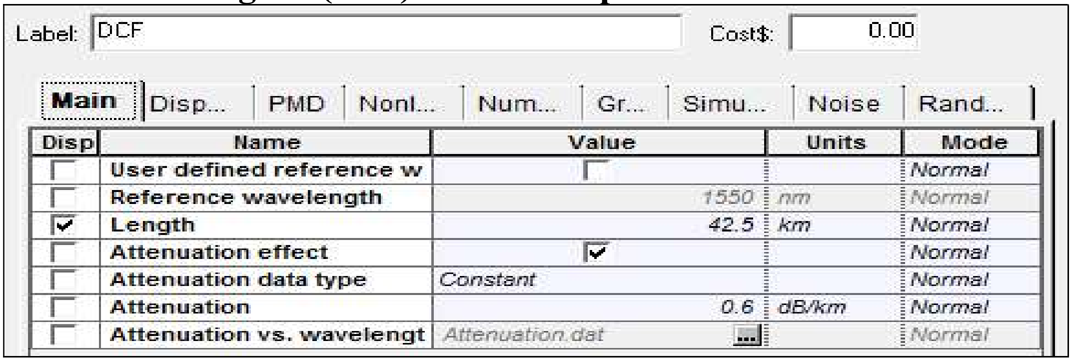
Figure (4-24):- The main SSMF Properties.



Label: EDFA Ideal_1   Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Operation mode	Gain Control		Normal
☑	Gain	40	dB	Normal
☐	Power	10	dBm	Normal
☐	Saturation power	10	dBm	Normal
☐	Saturation port	Output		Normal
☐	Include noise	☑		Normal
☑	Noise figure	6	dB	Normal

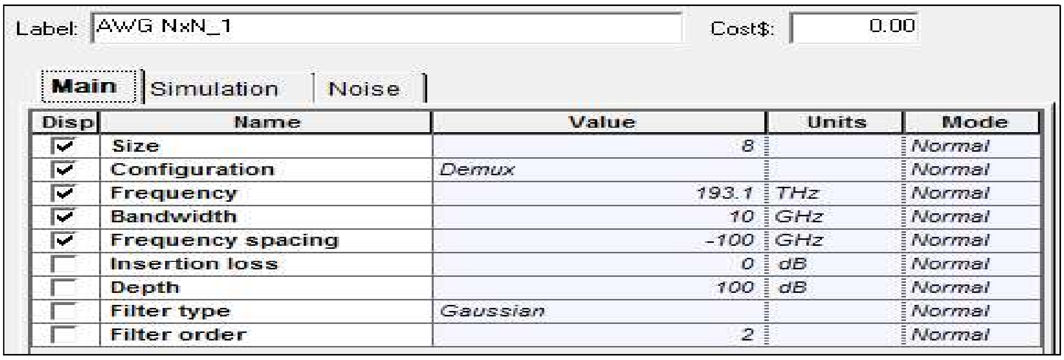
Figure (4-25):- Main Properties of EDFA.



Label: DCF   Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	User defined reference w	☐		Normal
☐	Reference wavelength	1550	nm	Normal
☑	Length	42.5	km	Normal
☐	Attenuation effect	☑		Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.6	dB/km	Normal
☐	Attenuation vs. wavelengt	Attenuation.dat ...		Normal

Figure (4-26):- Main Properties of DCF.



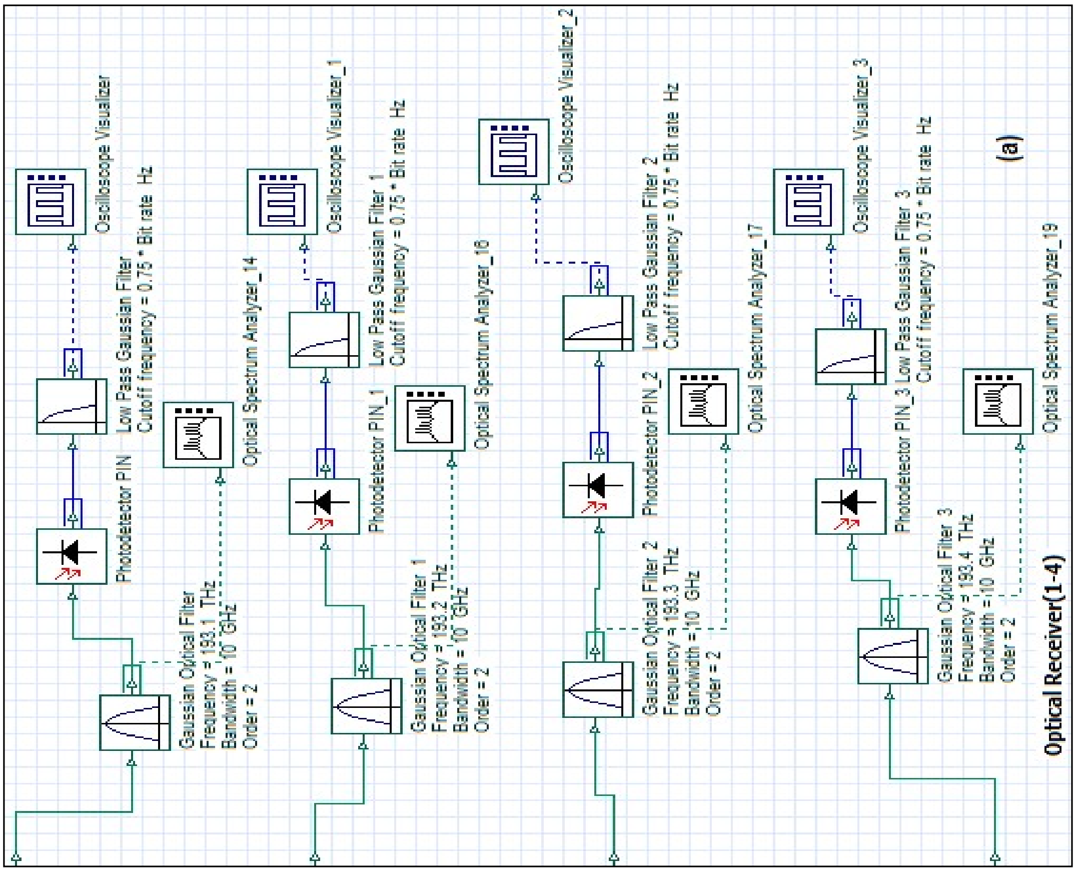
Label: AWG NxN_1 Cost$: 0.00

Disp	Name	Value	Units	Mode
☑	Size	8		Normal
☑	Configuration	Demux		Normal
☑	Frequency	193.1	THz	Normal
☑	Bandwidth	10	GHz	Normal
☑	Frequency spacing	-100	GHz	Normal
☐	Insertion loss	0	dB	Normal
☐	Depth	100	dB	Normal
☐	Filter type	Gaussian		Normal
☐	Filter order	2		Normal

Figure (4-27):- Main AWG Demultiplexer Properties.

4.6.3. End Front Side Receiver:-

At the end side of regime, each signal is filtered by the optical Gaussian filter with bandwidth (10GHz), and order with (2), and detected by the PIN photodetector, to reshape each electrical signal entered to the low pass Gaussian filter with cutoff frequency (0.75×Bitrate Hz). Figures (4.28a - 4.28b) show the optical receiver subsystems for the channels (1-4), and (5-8) respectively. Figures (4.29-4.31) show the main properties of these components. The output signals were monitored by the oscilloscope visualizer.



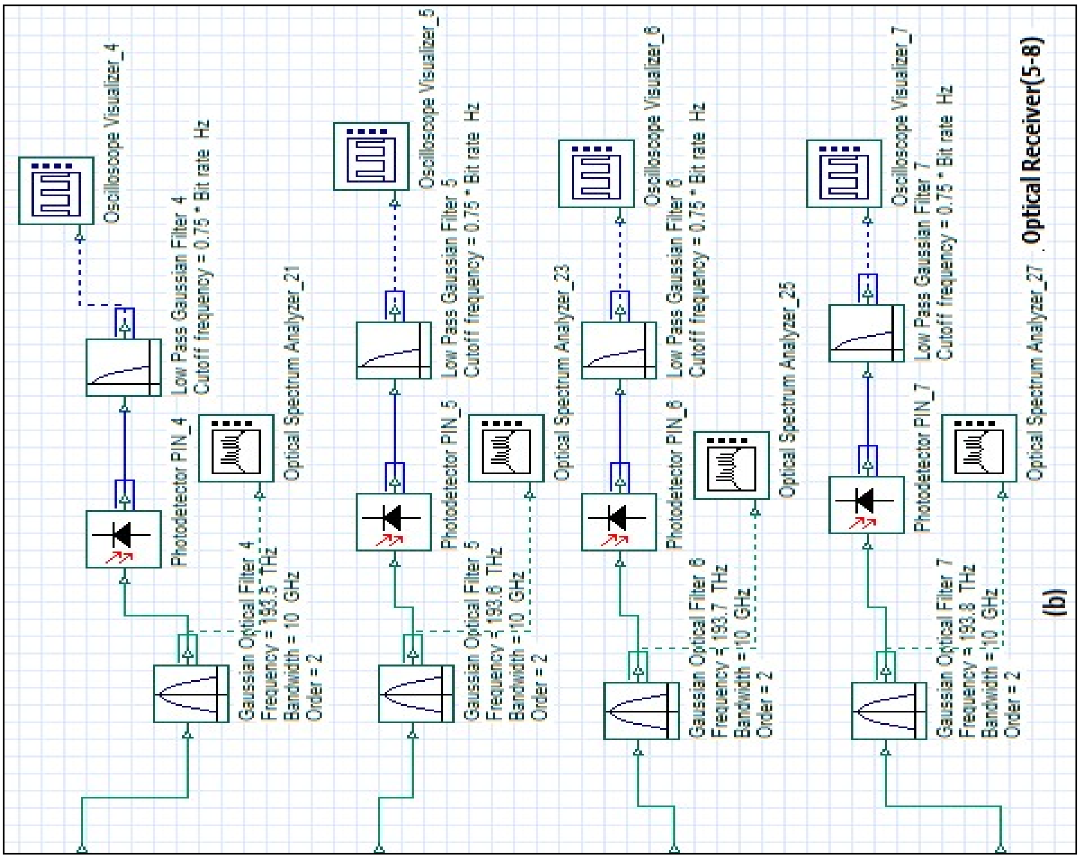
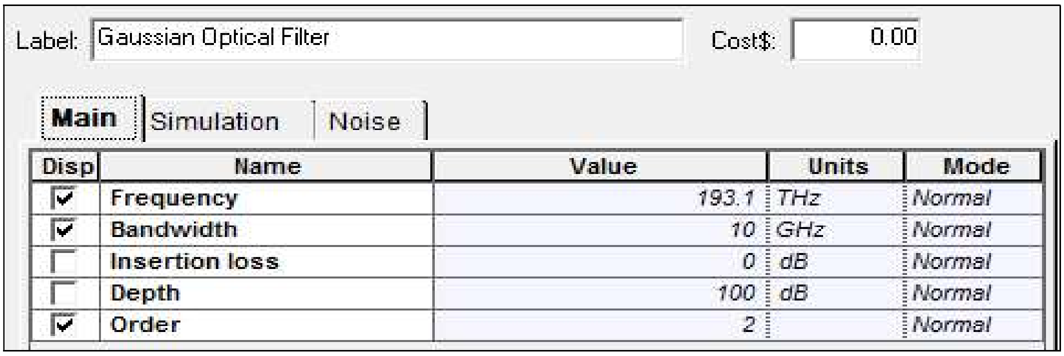


Figure (4-28):- The optical receiver for the AWG (a): the (1-4) channels subsystems, and (b): the (5-8) channels subsystem.

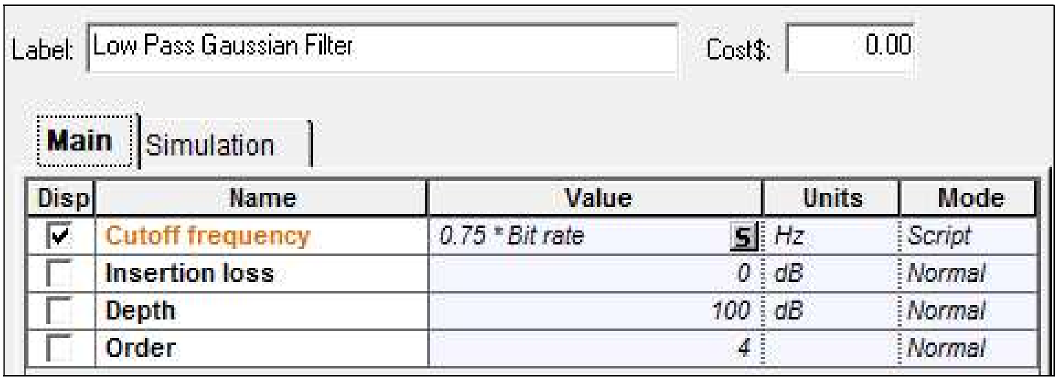


Label: Gaussian Optical Filter

Cost$: 0.00

Disp	Name	Value	Units	Mode
☑	Frequency	193.1	THz	Normal
☑	Bandwidth	10	GHz	Normal
☐	Insertion loss	0	dB	Normal
☐	Depth	100	dB	Normal
☑	Order	2		Normal

Figure (4-29):- The main Gaussian Optical Filter Properties.

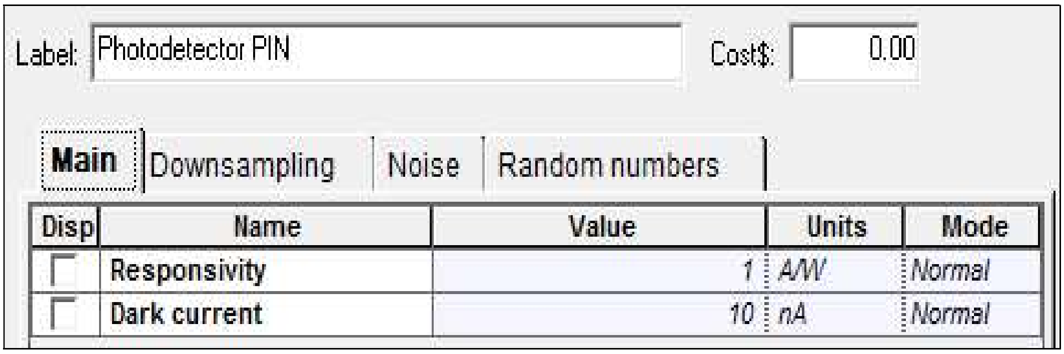


Label: Low Pass Gaussian Filter

Cost$: 0.00

Disp	Name	Value	Units	Mode
☑	Cutoff frequency	0.75 * Bit rate	Hz	Script
☐	Insertion loss	0	dB	Normal
☐	Depth	100	dB	Normal
☐	Order	4		Normal

Figure (4-30):- The main low Pass Gaussian Filter Properties.



Label: Photodetector PIN

Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Responsivity	1	A/W	Normal
☐	Dark current	10	nA	Normal

Figure (4-31):- The main Photodetector PIN Properties.

4.7. Simulation Results and Discussions:-

In this chapter, will be introduce the simulation results and discussion for three experiments (10Gbps WDM, 40Gbps WDM, and AWG multiplexing). Each of them has many graphs to explain the relationship between parameters. The output power, gain, and noise figures are calculated through OptiSystem package (see Appendix A), as function of input wavelength. So, the system performance is evaluated from the Q-Factor, and BER pattern. In the next sections, some figures will be demonstrated, but the others will be listed in Appendix C.

4.7.1. Results for the 10Gbps WDM Network System without Nonlinearities Problems Management:-

Based on the WDM network simulation analysis many features for the series of Figures (4-32 to 4-39) are described below:

1) Figure 4.32: demonstrate the sampled input signals before launched into the optical fiber, all signal shape seem good and have no degradation.
2) Figure 4.33: show sampled signal after span with (150km), it seem not good in shaping and generate another new signals this is due to the nonlinearities problem presence such as (SPM, and FWM) in WDM systems.

3) Figure (4.34, and 4.35): illustrates the output signals after demultiplexer for the channel_1, and channel_8 respectively. Also can be see the other new signals generated by nonlinearities problem.
4) Figures (4.36-4.39): illustrates the Q-Factors and the Min BER for chaneels_1 and channel_8, respectively, from BER analyzer cannot see the eye opening this mean the ISI is high, and the system performance are not good, because the nonlinearities problems in WDM systems.

The 8×10Gbps WDM system demonstrated over optical link with 150km. The dispersion not managed by DCF, and no optical amplifier was be used. There are no received powers at the end side receiver, also this due to nonlinearities problems.

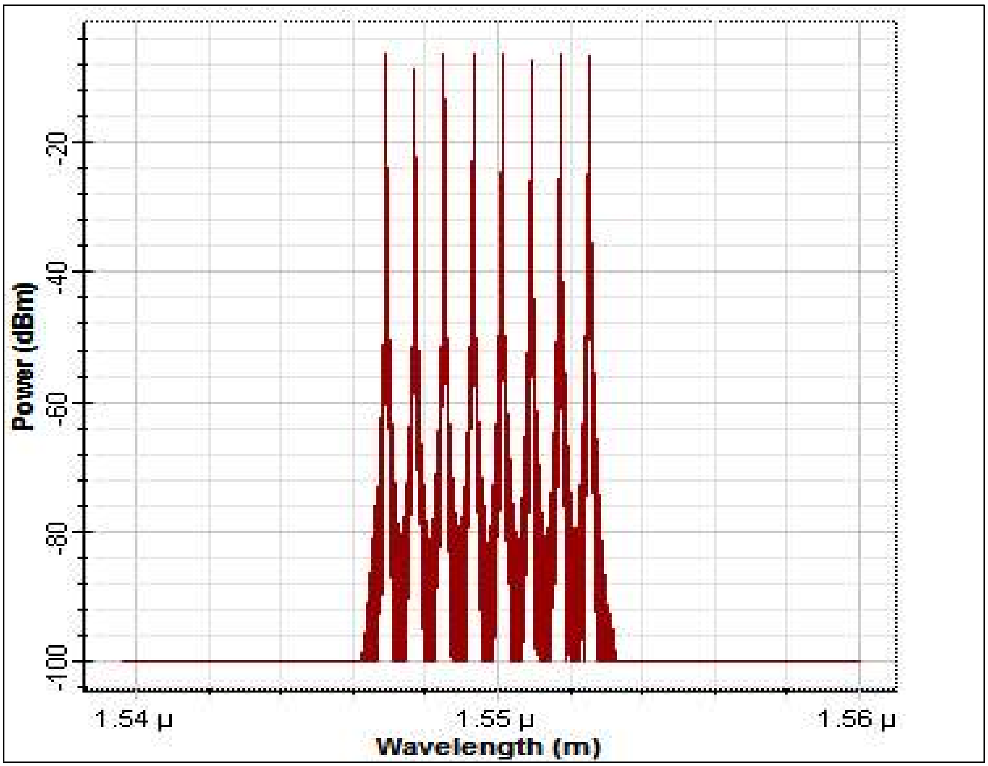


Figure (4-32):- Sampled Input signals before launched into the optical fiber.

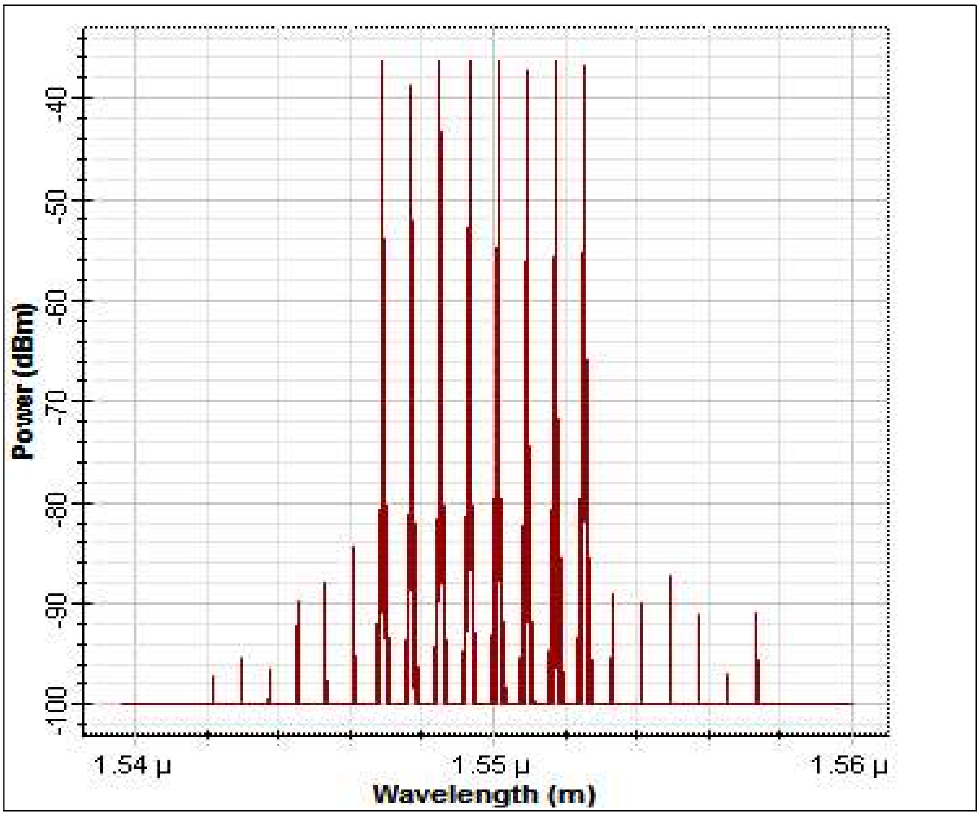


Figure (4-33):- Sampled signal after span with (150km).

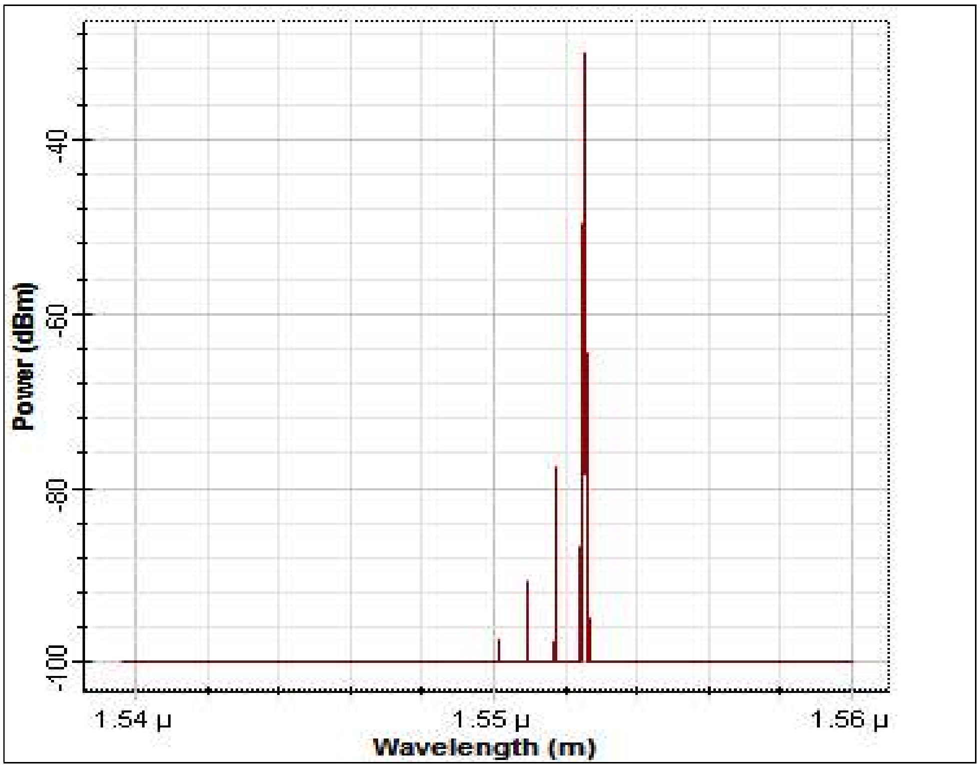


Figure (4-34):- Output signal after demultiplexer for the channel_1 after span with 150km.

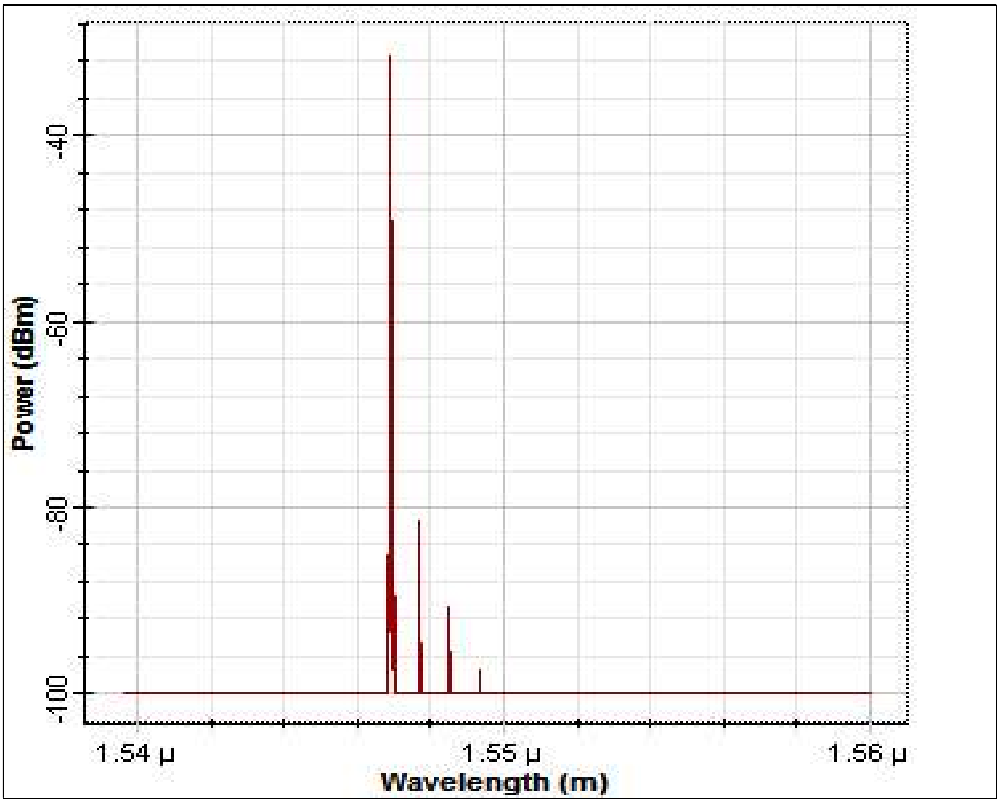


Figure (4-35):- Output signal after demultiplexer for the channel_8 after span with 150km.

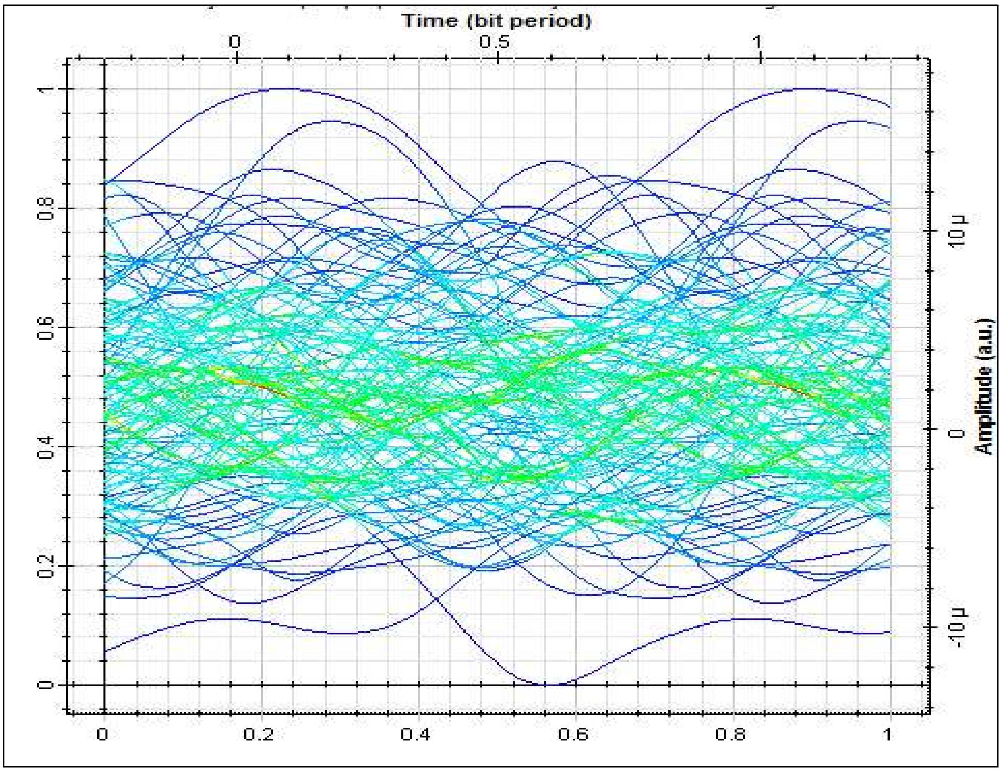


Figure (4-36):- Q-Factor for the channel_1.

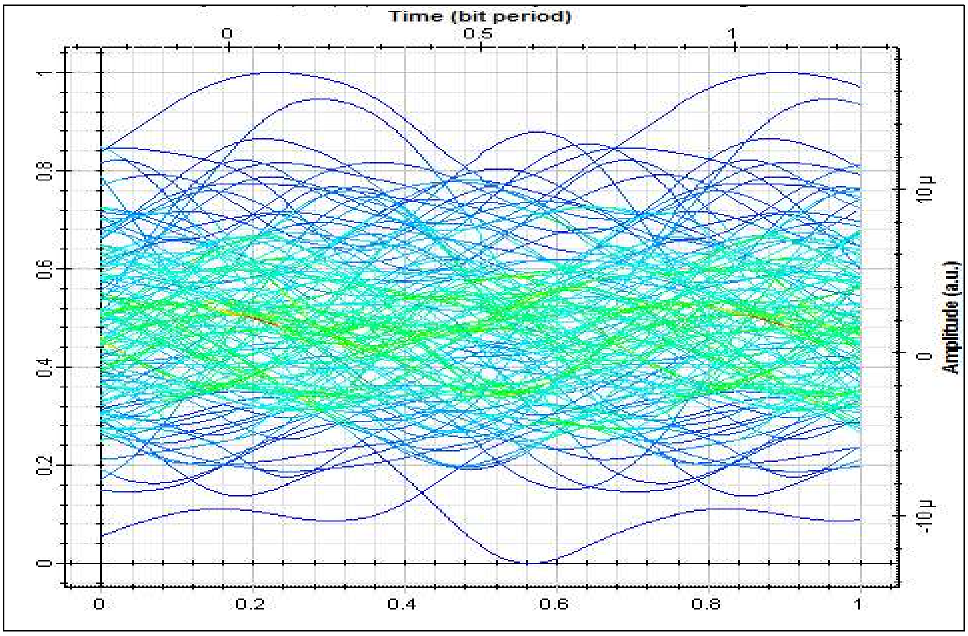


Figure (4-37):- Min BER for the Channel_1.

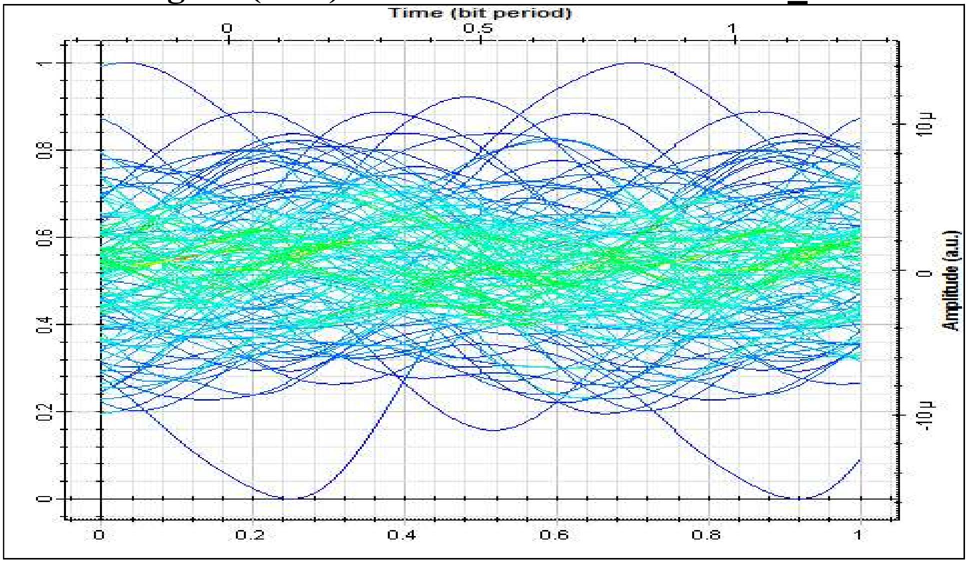


Figure (4-38):- Q-Factor for the output channel_8.

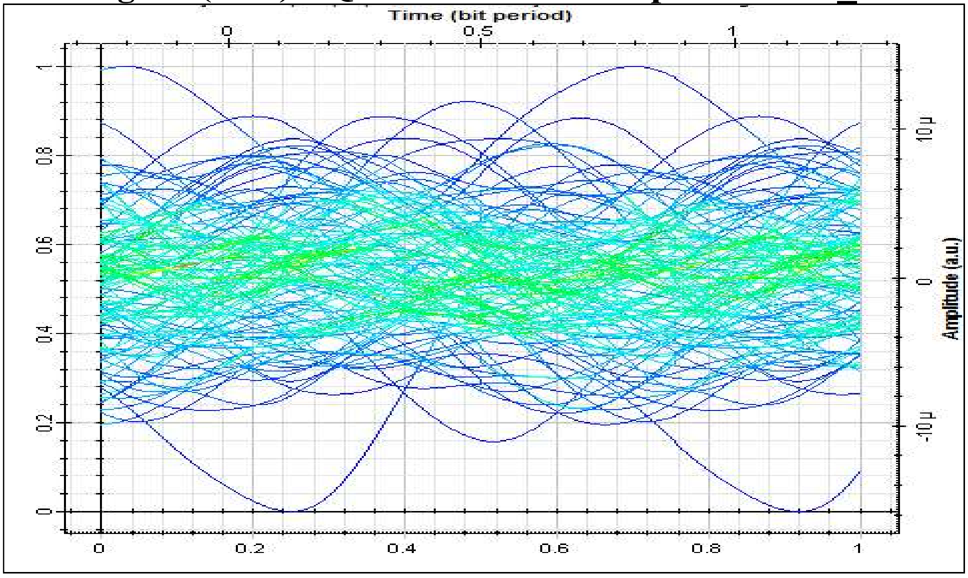


Figure (4-39):- Min BER for the output channel_8.

4.7.2. Results for the 8×10Gbps WDM Network System:-

Based on the WDM optical network simulation analysis, many features for the series of Figures (4.40 to 4.48) are described below:-

1) Figure 4.40: indicate that the gain (dB) versus wavelength (nm), increasing in wavelength follows increasing in gain.
2) Figure 4.41: illustrate the input noise (white noise) for all wavelengths. All CW lasers have the same power (0dBm).
3) Figure 4.42: shows the input signal spectrum for all 8- channels.
4) Figure 4.43: views the noise figure (NF) iteration for wavelength versus noise figure, meanwhile the NF decreases while wavelengths increase.
5) Figure 4.44: illustrates the output noise spectrum iteration. When wavelength increases, the output power (dBm) also increases.
6) Figure 4.45: demonstrates the output signal spectrum iteration. The power versus the wavelength, violation in signals refers to nonlinearities effects due to length fiber. But this is acceptable for this architecture.
7) Figure 4.46: shows the power (dBm) versus wavelength (nm) at gain flatness for the pump power (23mw). A large input signal power is considered in this case since high signal input power helps to produce high output power. The dynamic range has good values (40-50dBm).
8) Figures (4.47, and 4.48): illustrate the eye diagram for channels_1, and channel_8. Based on these figures, the performance of the system was analyzed using BER; the eye pattern for wavelength (1), (1552.52nm) gives a large opening, which means that the intersymbol interference (ISI) is low. The width of the opening indicates the time over which sampling for detecting is performed. The maximum eye opening yields greatest protection against noise. The BER has an average of ((1.7520×10^{-6}) to (6.4221×10^{-6})). (For

more details about other eye diagrams, and Q-factors from output channels, see Appendix C).

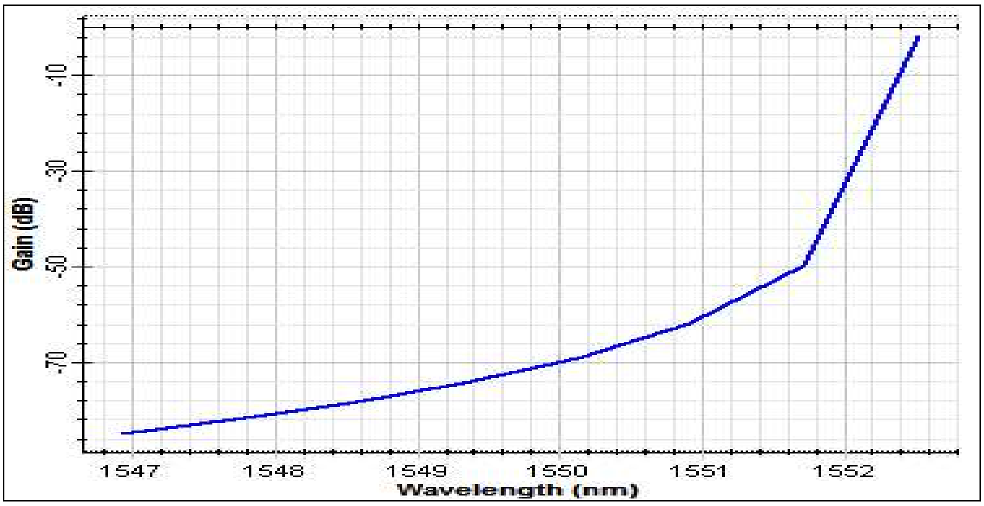


Figure (4-40):- Gain versus wavelength iteration.

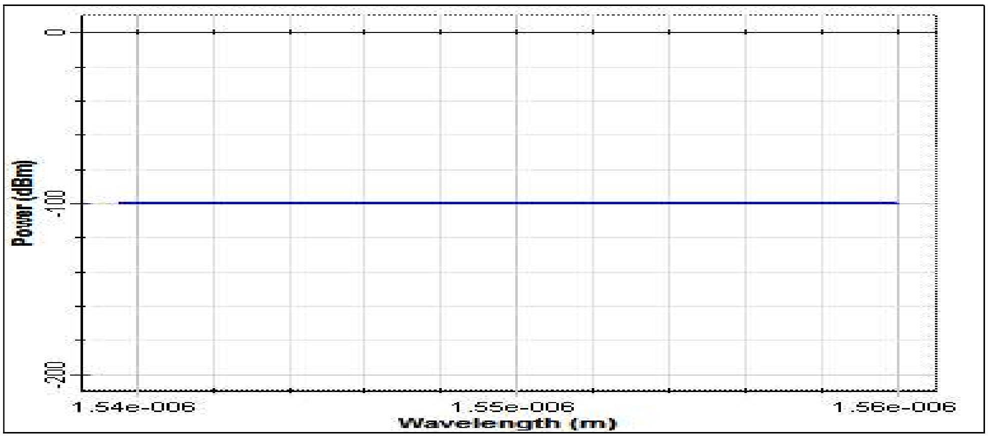


Figure (4-41):- Input Noise (white noise) Spectrum Iteration.

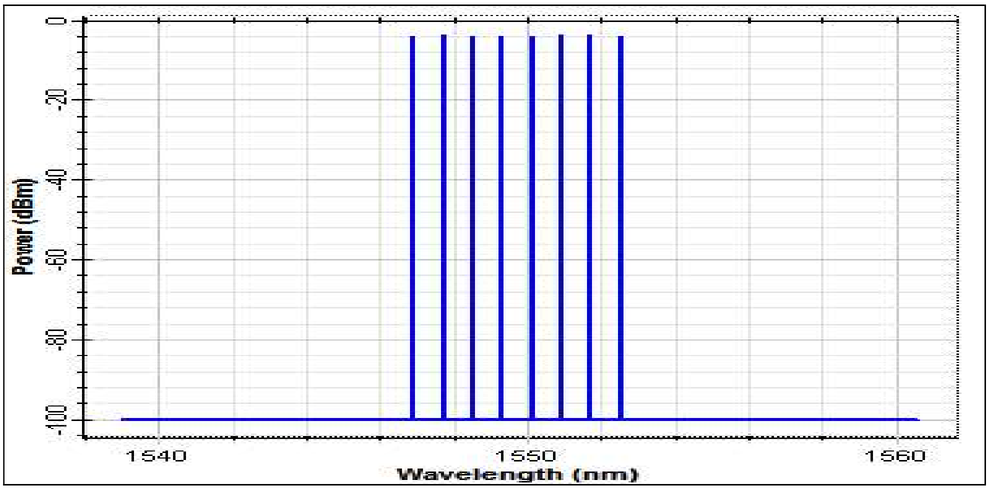


Figure (4-42):- Input Signal Spectrum Iteration.

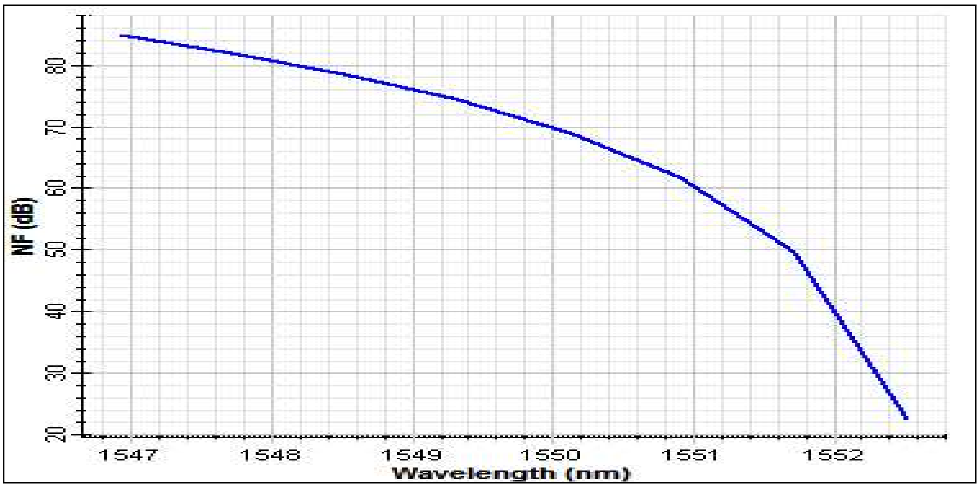


Figure (4-43):- Noise Figure versus wavelength Iteration.

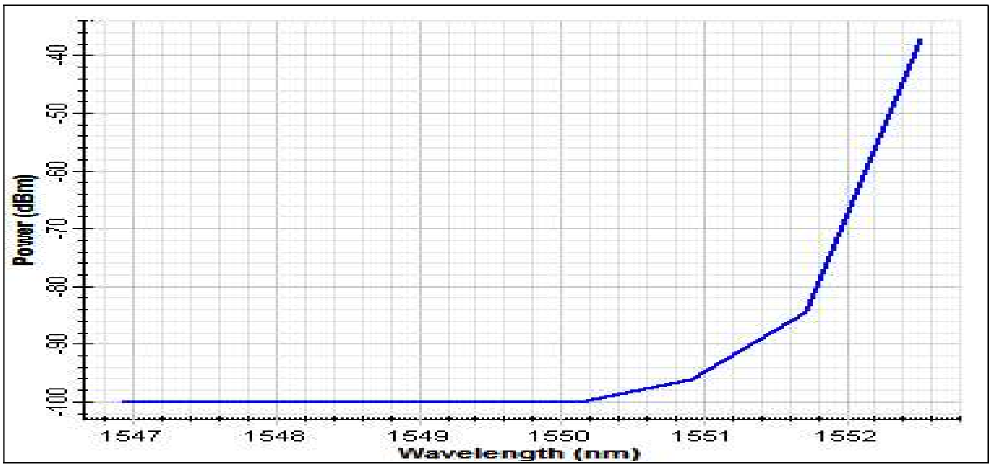


Figure (4-44):- Output Noise Spectrum Iteration.

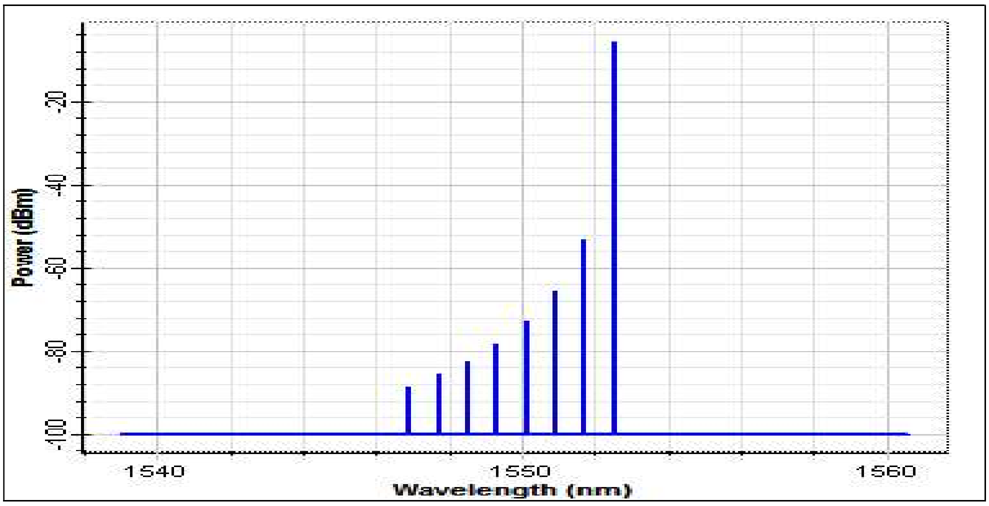


Figure (4-45):- Output Signal Spectrum Iteration.

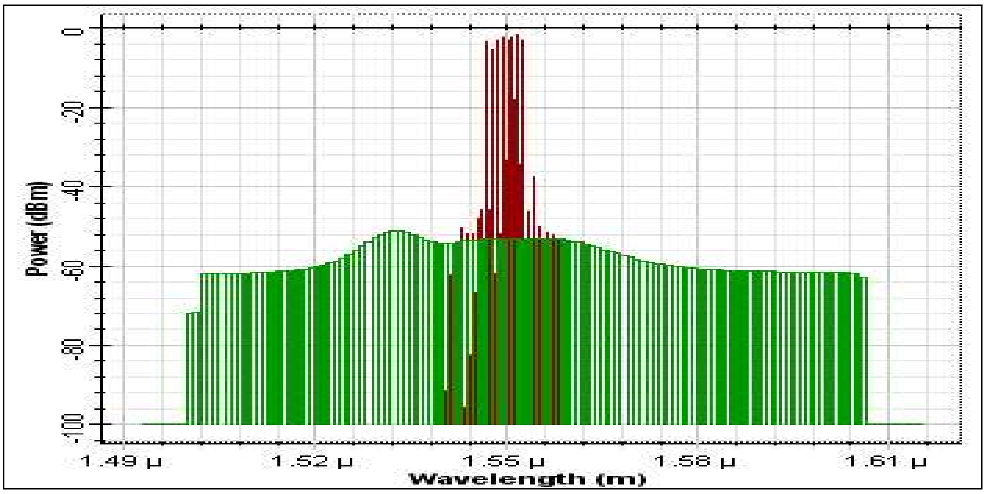


Figure (4-46):- Output power (red), and noise spectrum (green).

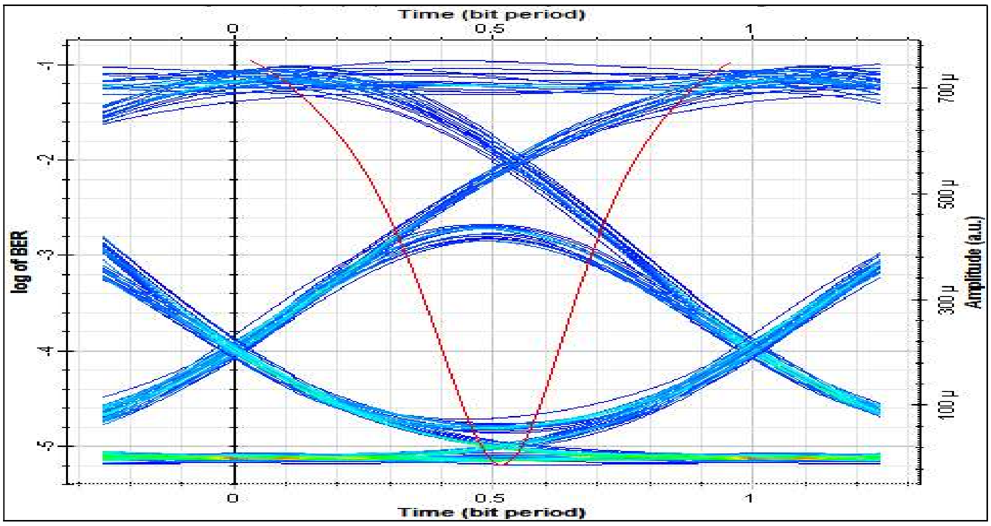


Figure (4-47):- Eye diagram from BER analyzer for (Channel_1(193.1THz)).

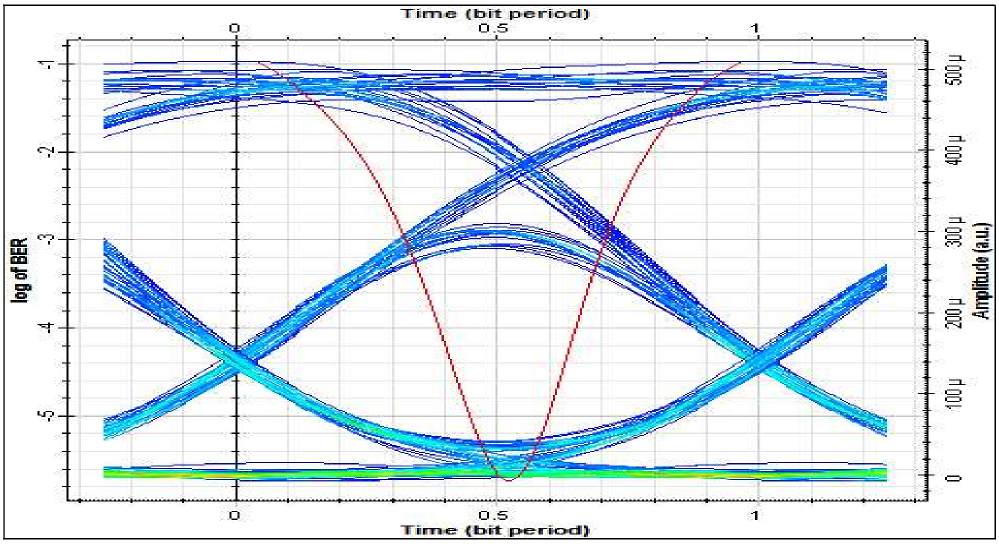


Figure (4-48):- Eye diagram from BER analyzer for (Channel _8(193.8THz)).

The 8×10Gbps WDM system demonstrated an error free transmission, channel spacing (100GHz) with distance of (150km) based on WDM/EDFA signals; NRZ external modulation format of optical signal was used. The dispersion management is fully treated by DCF as a compensator with the in-line optical amplifiers such as EDFA to improve the optical signal-to-noise-ratio (OSNR), and reduce the nonlinear effects in transmission system. Polarization mode dispersion is not a significant problem for 10Gbps systems.

The optimum fiber length to this system is (150km) transmission distance with ($BER< 10^{-15}$), the average total power is (-5dBm), and the average noise power is (-37dBm) for all 8-channels that were listed in Table (4.2) in the previous chapter.

4.7.3. Results for the 16×40Gbps WDM Network System:-

Figures (4.49 to 4.63) clearly demonstrate the performance in a 40Gbps for 16-channels WDM optical system with 100GHz channel spacing and the fiber spans for SSMF is (100km), and the (20km) of DCF. Figures (4.49 to 4.63) will be subsequently described and discussed:

1) Figure 4.49: optical spectral analyzer for all 16-channels after WDM multiplexer (i.e., span link=0km).
2) Figure 4.50: optical spectral analyzer for all 16-channels, (red color) power, and (green color) noise after (100km) of SSMF, and the (20km) of DCF.
3) Figure 4.51: shows the attenuation (dB/km) versus the wavelength (nm) the optimum value of attenuation is 0.2dBm/km.
4) Figure 4.52: shows the Dispersion (ps/nm/km) versus wavelength (nm) for the DCF.
5) Figure 4.53: Input power channel (dBm) versus wavelength (m) from the optical spectrum analyzer (OSA).

6) Figure 4.54: Dispersion (ps/nm/km) versus wavelength (nm) for the SSMF. The optimum value is (17ps/nm/km) at the (1554nm).
7) Figure 4.55: The effective area (μm^2) with the wavelength (nm).
8) Figures (4.56 to 4.59): BER analyzer for output channels (1, 8, 9, and 16), i.e., (1577.85nm, 1572.04nm, 1571.21nm, and 1565.4nm) respectively, after (100km) of SSMF, and the (20km) of DCF, from the BER analyzers.
9) Figures (4.60 to 4.63): Q-Factor for the output channels (1, 8, 9, and 16), i.e., (190THz, 191.4THz, 191.6THz, and 193THz) respectively, after (100km) of SSMF, and the (20km) of DCF, from the BER analyzers.

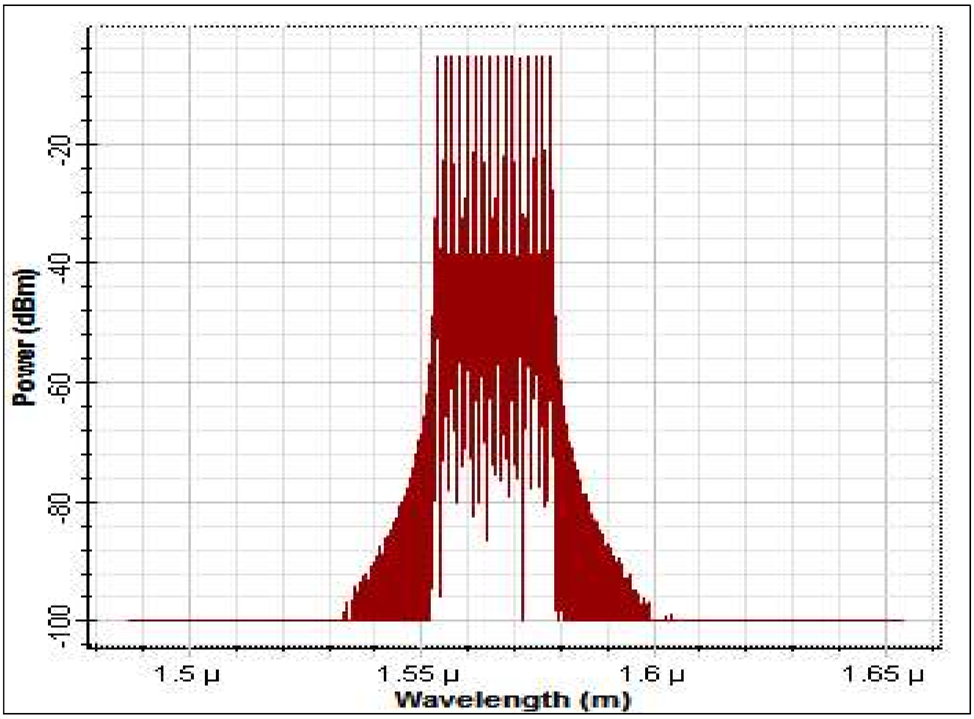


Figure (4-49):- Optical spectral analyzer for all 16-channels when span link=0km.

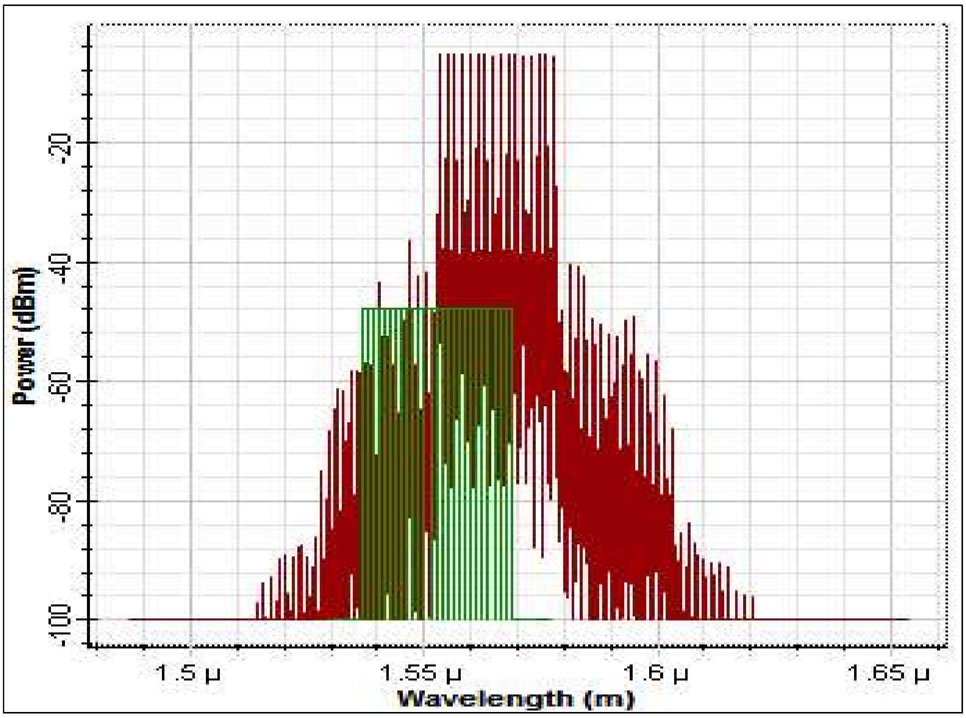


Figure (4-50):- Optical spectral analyzer for all channels when span link=100km.

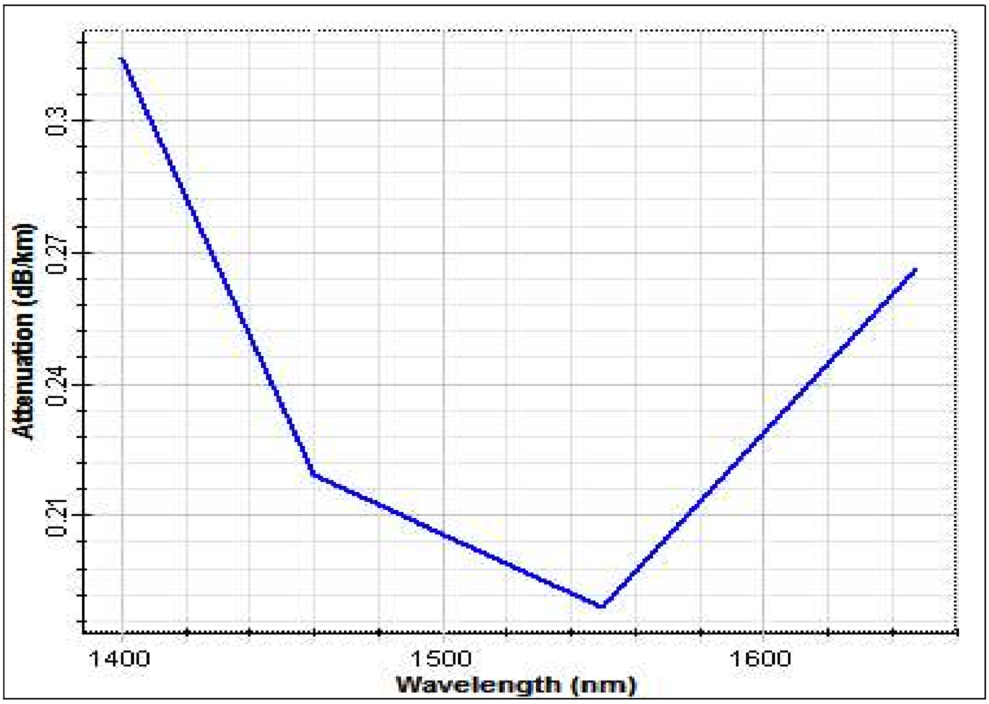


Figure (4-51):- Attenuation iteration.

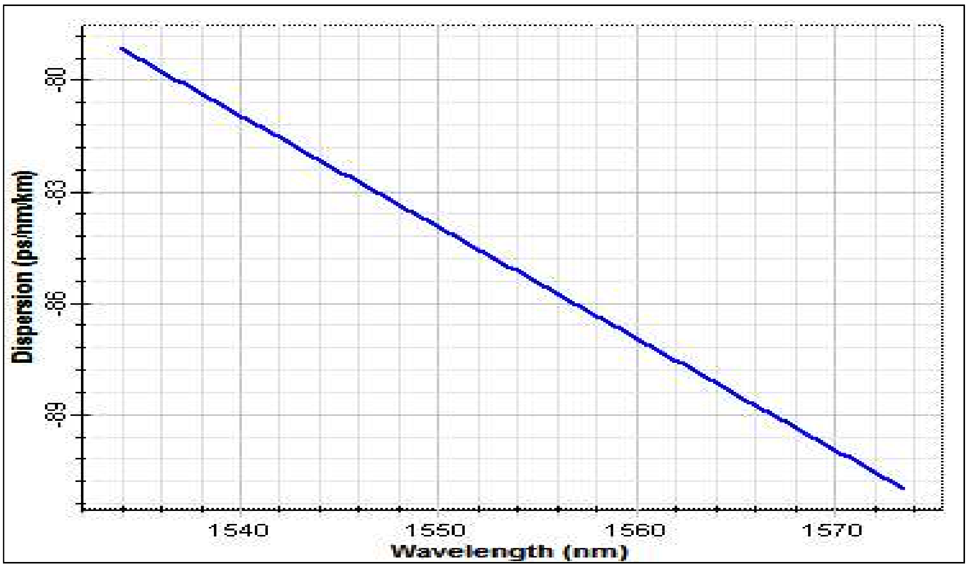


Figure (4-52):- Dispersion iteration for DCF.

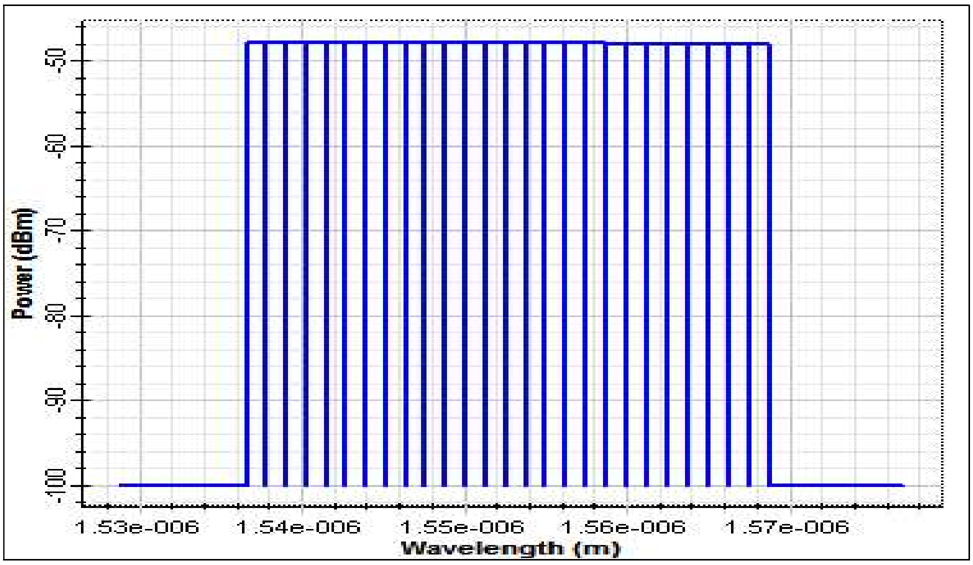


Figure (4-53):- Input power level for all channels.

Figure (4-54):- Dispersion iteration for the SSMF.

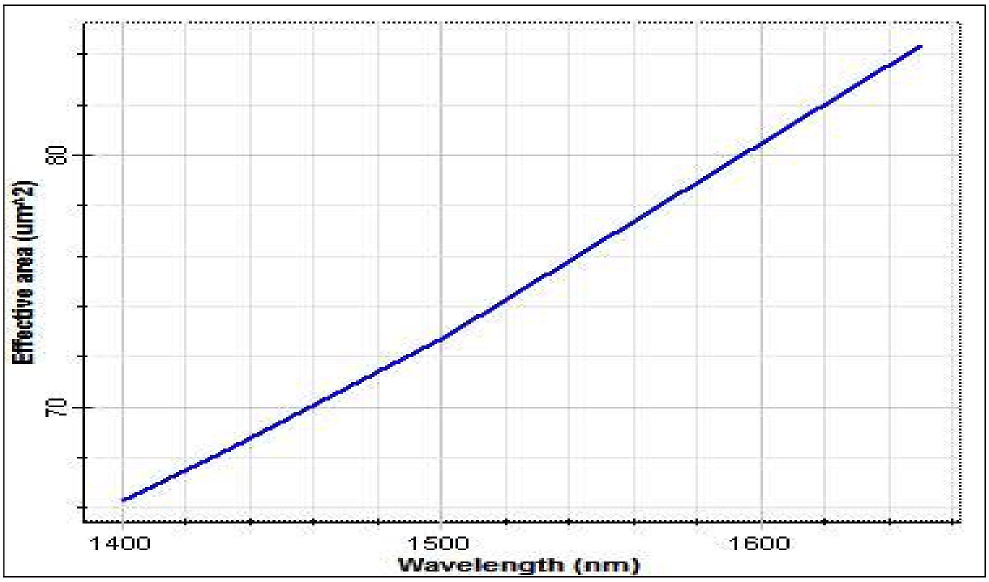


Figure (4-55):- Effective area iteration.

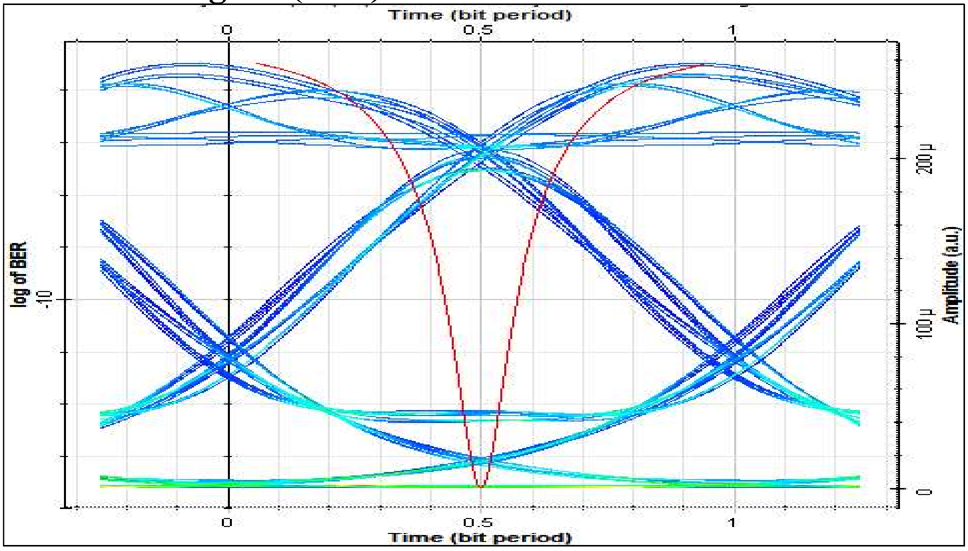


Figure (4-56):- BER analyzer for output channel_1 (190THz) when span=120km.

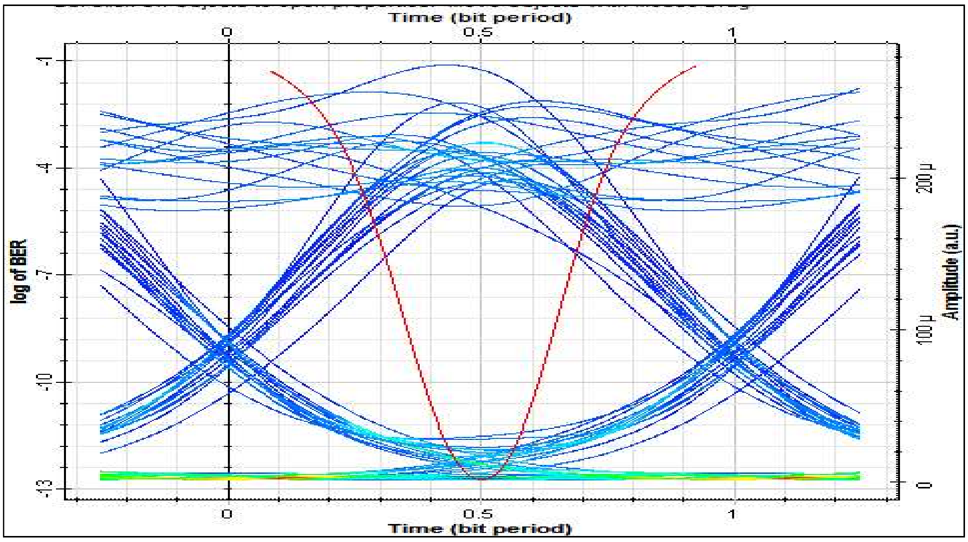


Figure (4-57):- BER analyzer for output channel_8 (191.4THz) when span=120km.

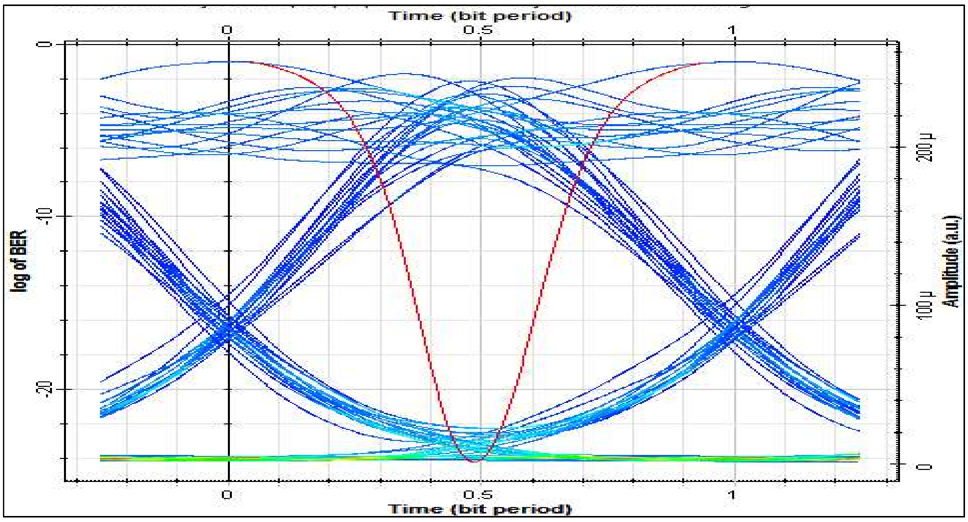


Figure (4-58):- BER analyzer for output channel_9 (191.6THz) when span=120km.

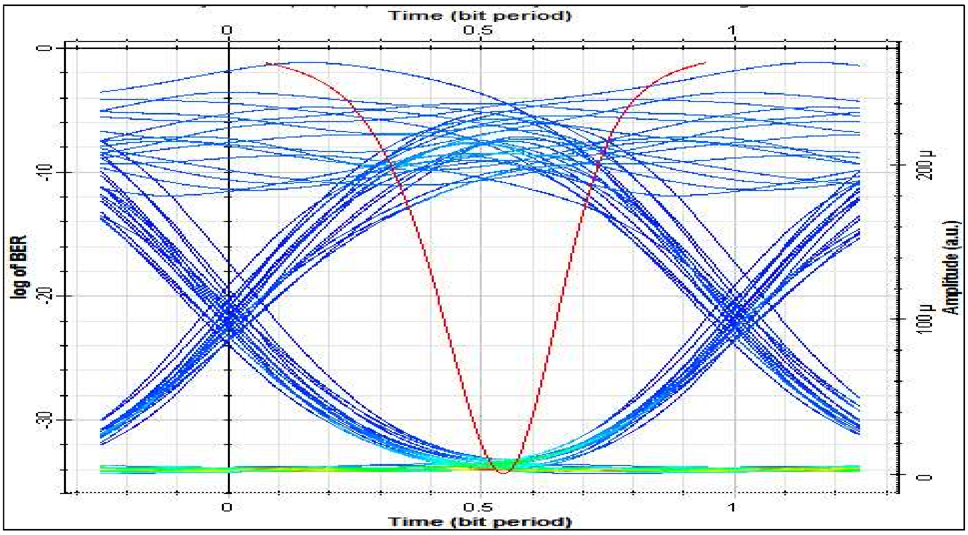


Figure (4-59):- BER analyzer for output channel_16 (193THz) when span=120km.

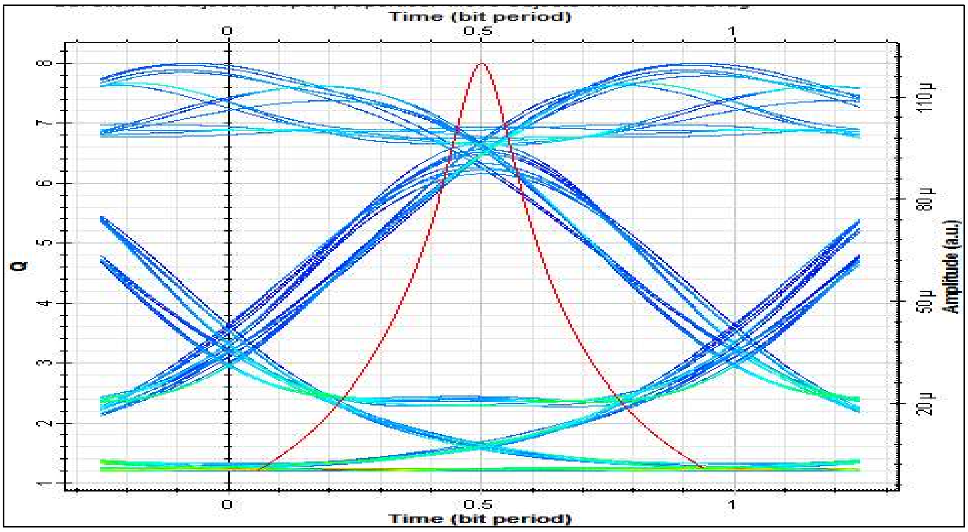


Figure (4-60):- Q-Factor for the output channel_1 (190THz) when span=120km.

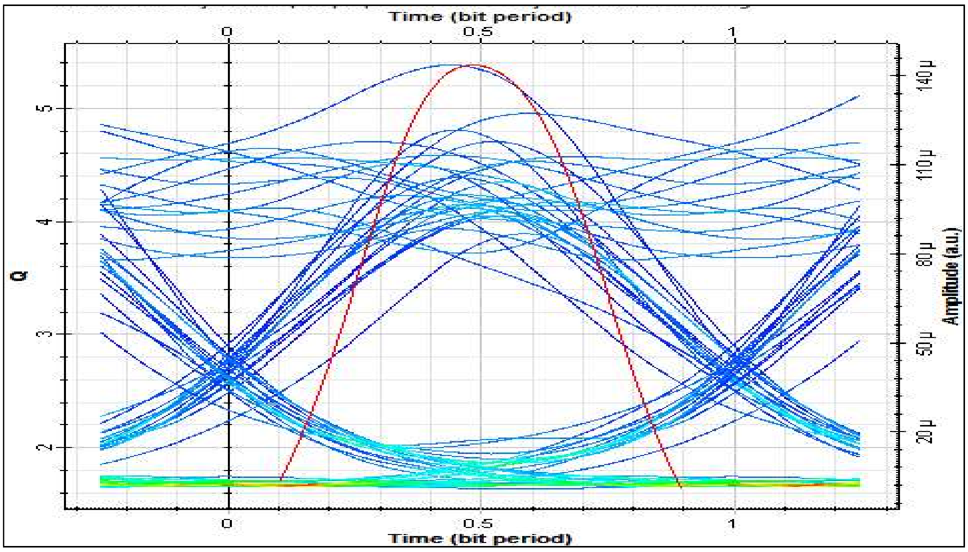


Figure (4-61):- Q-Factor for the output channel_8 (191.4THz) when span=120km.

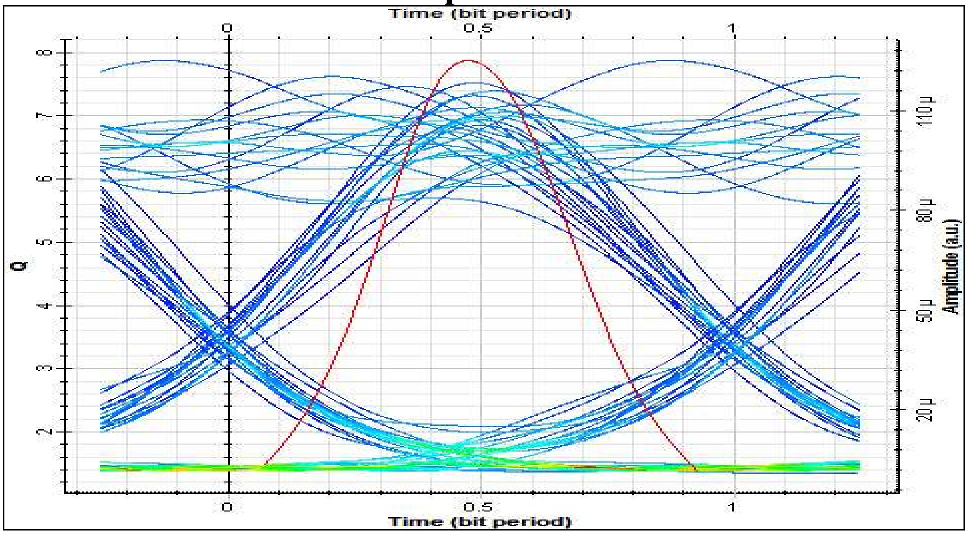


Figure (4-62):- Q-Factor for the output channel_9 (191.6THz) when span=120km.

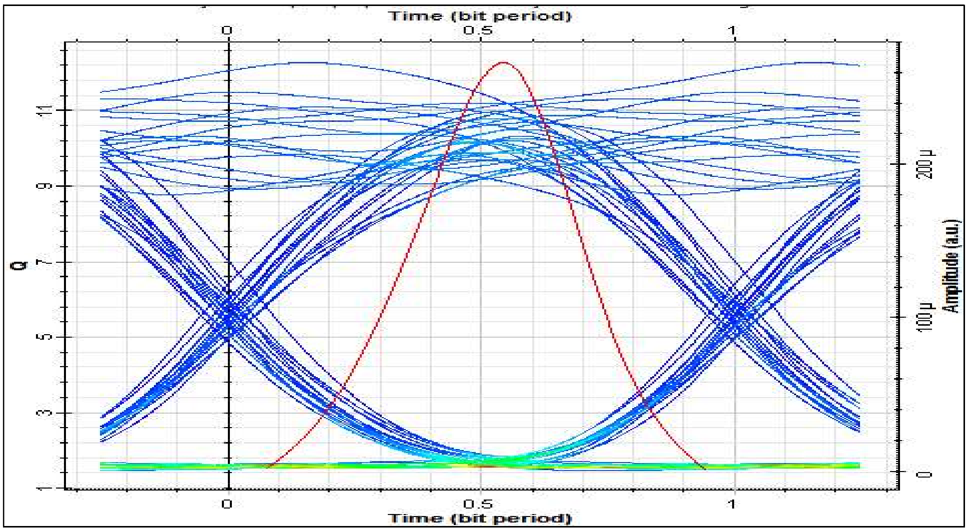


Figure (4-63):- Q-Factor for the output channel_16 (193THz) when span=120km.

Dispersion is fully managed through compensating by DCF, and to improve degradation in signal, EDFA was be used.

Based on the above figures, the evaluating performance of the system was analyzed using BER; the eye pattern gives a large opening. This means the intersymbol interference (ISI) is low. The width of the opening indicates the time over which sampling for detecting is performed. The maximum eye opening yields greatest protection against noise. The (BER $<10^{-30}$). From the BER analyzer, the average optical power level for all channels is (-47.5dBm), while the average maximum Q-factors for all 16-channels are (10.4875). (For more details about other eye diagrams, and Q-Factors from output channels, see Appendix C).

4.4. Results for the AWG 8×40Gbps Network system:-

In this experiment, the oscilloscope will determine if any waveform samples fall on the mask. A larger population of waveform samples should provide a more accurate assessment of the transmitter performance. However, every graph will have random characteristics in both amplitude (noise) and time (jitter). There needs to be enough minimum samples allow the oscilloscope in having sufficient data to align the mask the waveform for avoid slight change in the results and failure. The input and output signal behaviors for this regime are listed as follows:

1) Figure (4.64): shows the power versus wavelength for all channels after combiner and span link is (0km).
2) Figure (4.65): power versus wavelength from OSA after 242.5km of SSMF.
3) Figure (4.66): shows 8- signal from OSA, red color (power) and green color (noise) after amplification process through EDFA.
4) Figure (4.67): shows all signals from OSA, red color (power) and green color (noise) after management dispersion by DCF. The noise shape is uniform.

5) Figure (4.68): show power versus wavelength for the input optical signal for channel_1.
6) Figure (4.69): the output channel_1 (193.1THz) after reshaping by Gaussian optical filter.
7) Figure (4.70): oscilloscope visualizer shows the amplitude versus time for the output channel_1 after direct detection by PIN.
8) Figure (4.71): oscilloscope visualizer shows the amplitude versus time for the channel_8 (193.8THz) output after direct detection by PIN.

The violation in signals refers to the collecting data at the receiver side. There are many factors influencing the output signal such (modulation format, sampling, filter, and bandwidth). However, the oscilloscope is a reference receiver. The high-frequency content of the signal is suppressed. The signal appears to be very well behaved, and the waveform easily passes the mask test. (See Appendix C for other output results).

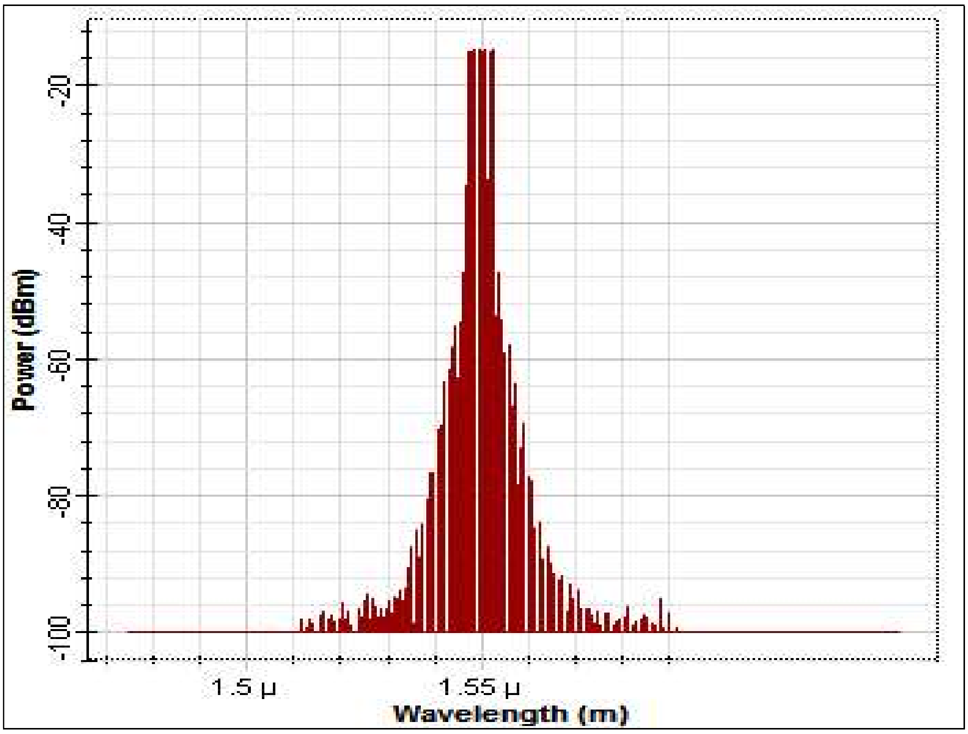


Figure (4-64):- The power versus wavelength for all channels after combiner when span=0km.

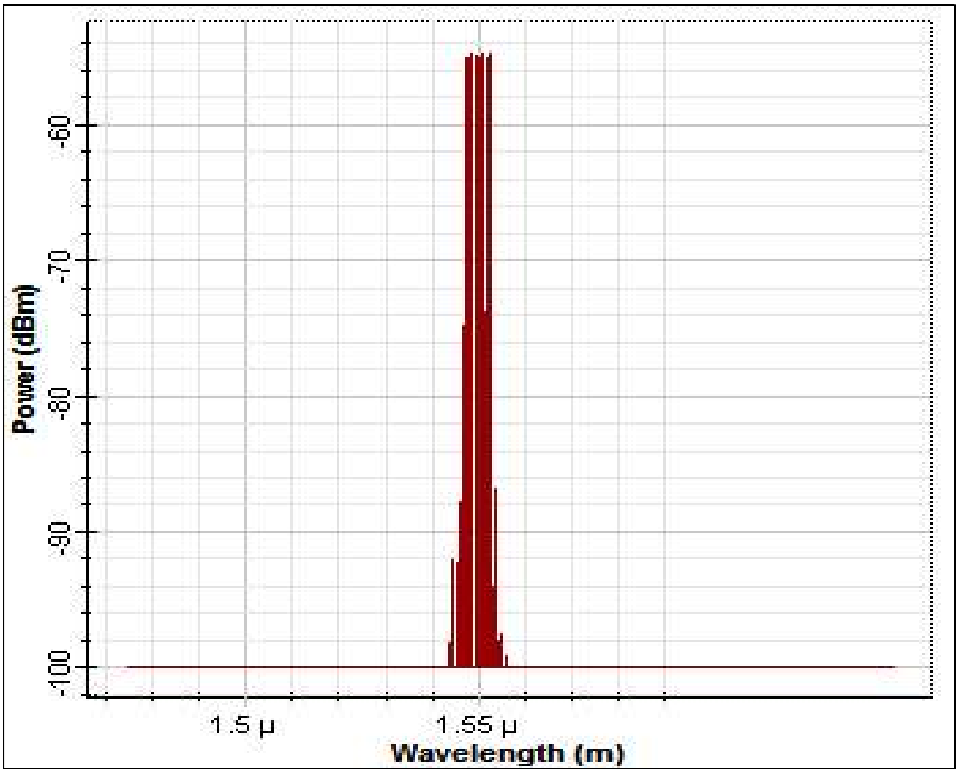


Figure (4-65):- Power versus wavelength from OSA when span=242.5km.

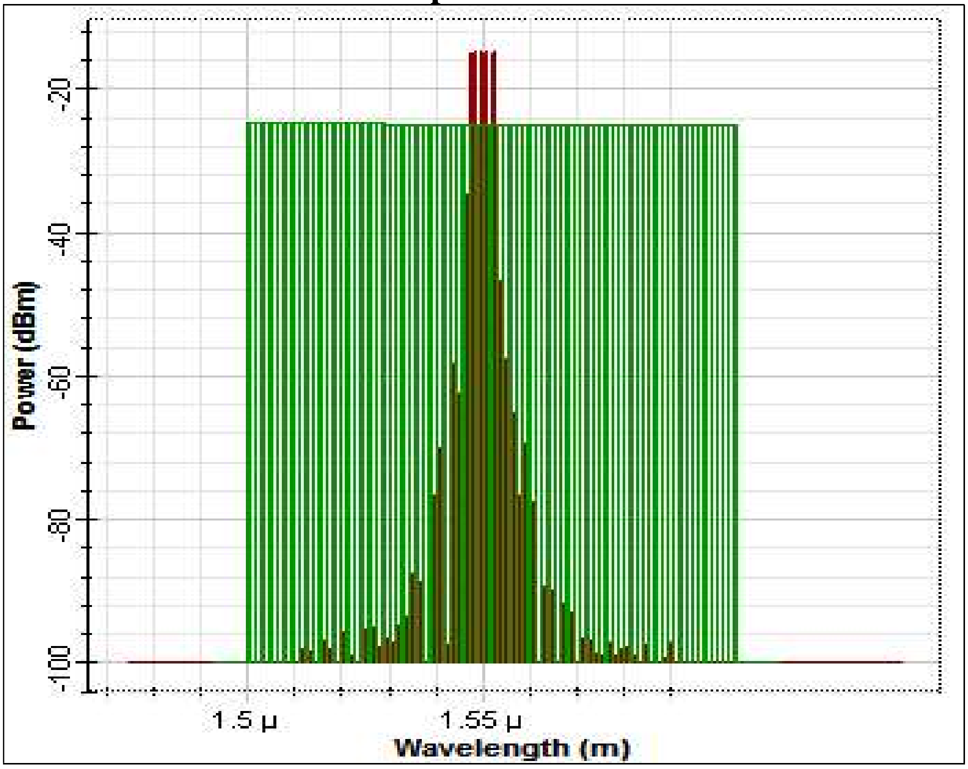


Figure (4-66):- All signal from OSA, red color (power) and green color (noise(uniform)) after EDFA.

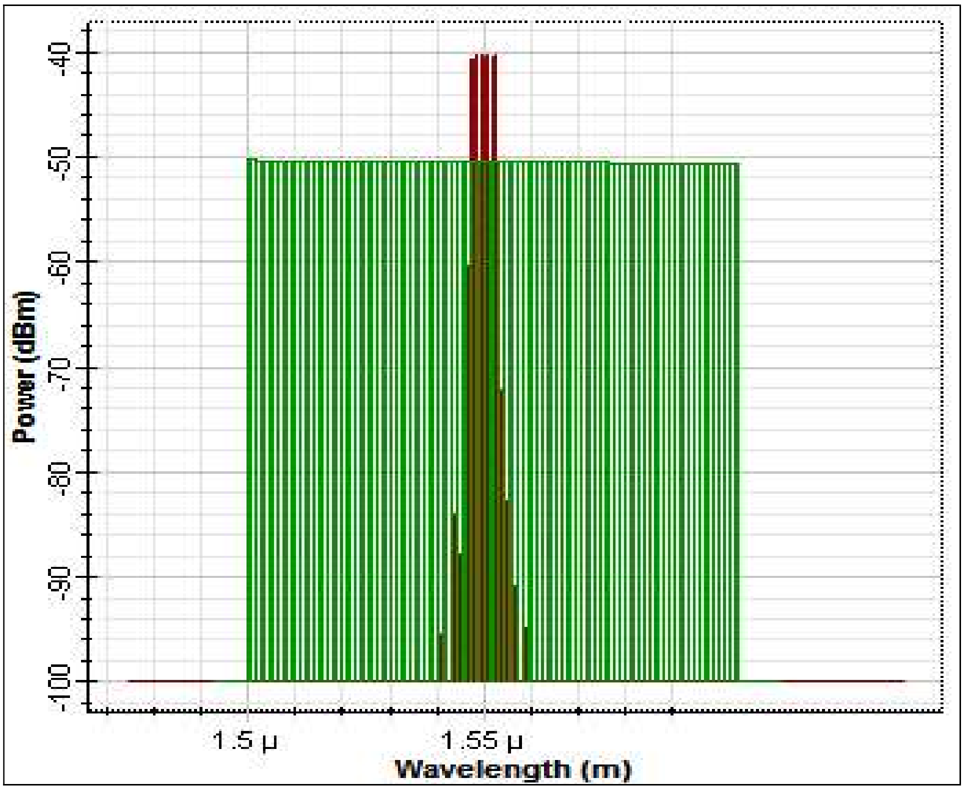


Figure (4-67):- All signal from OSA, red color (power) and green color (noise) after DCF.

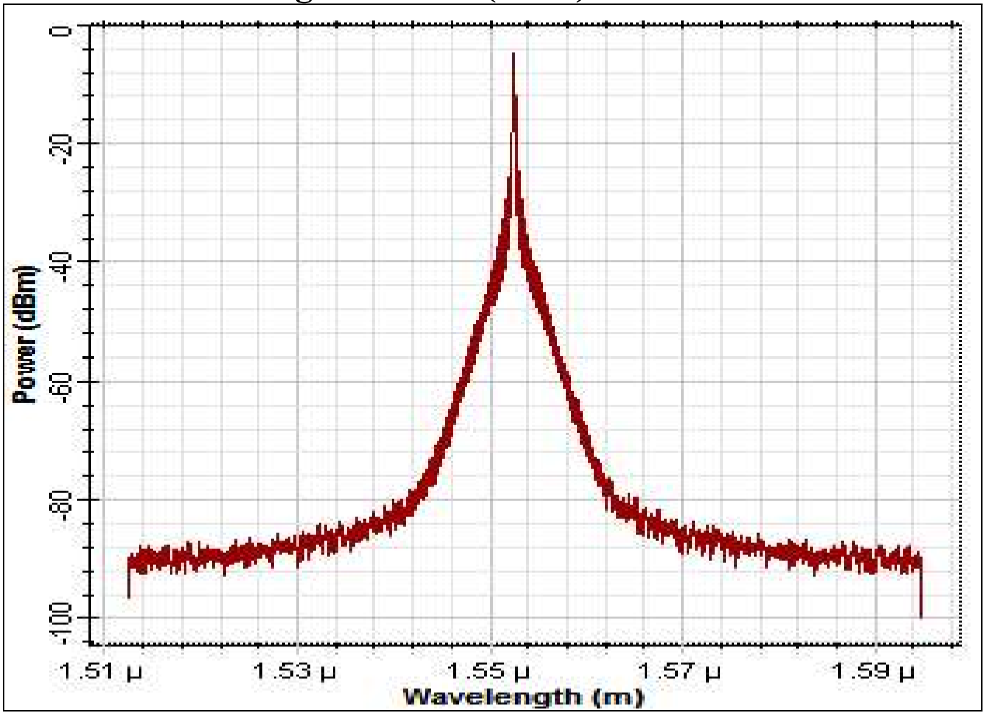


Figure (4-68):- Input optical signal for the channel_1(1552.52nm).

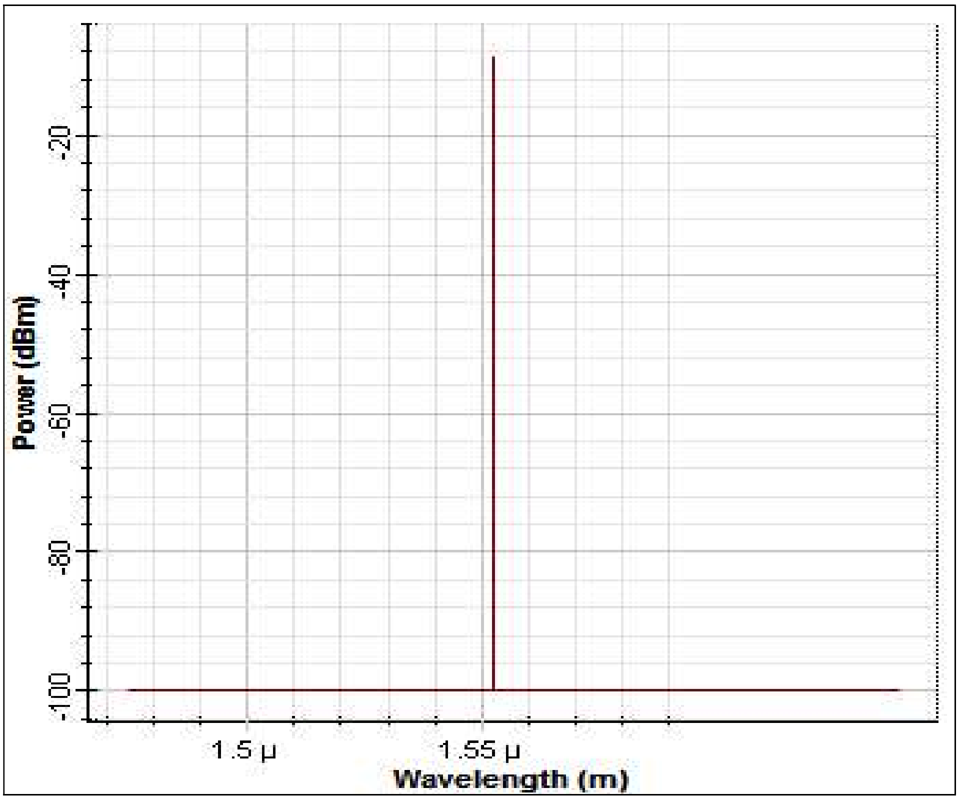


Figure (4-69):- The output channel_1(1552.52nm) after optical filter.

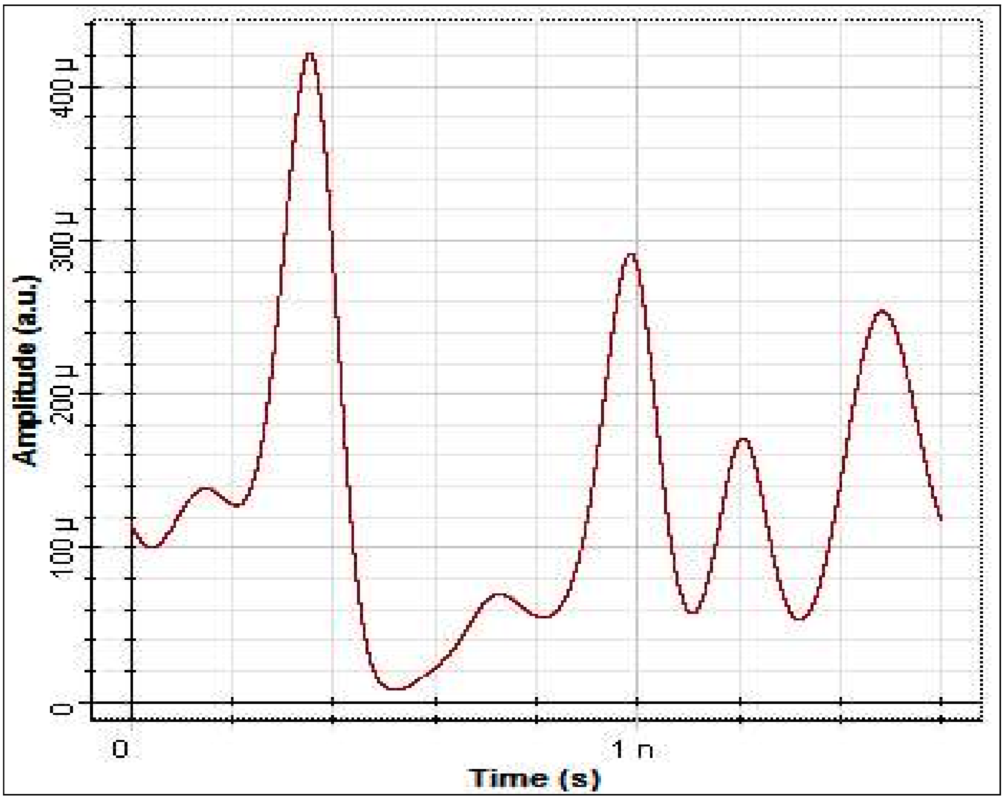


Figure (4-70):- The amplitude versus time for the channel_1(1552.52nm) output after PIN from the oscilloscope visualizer.

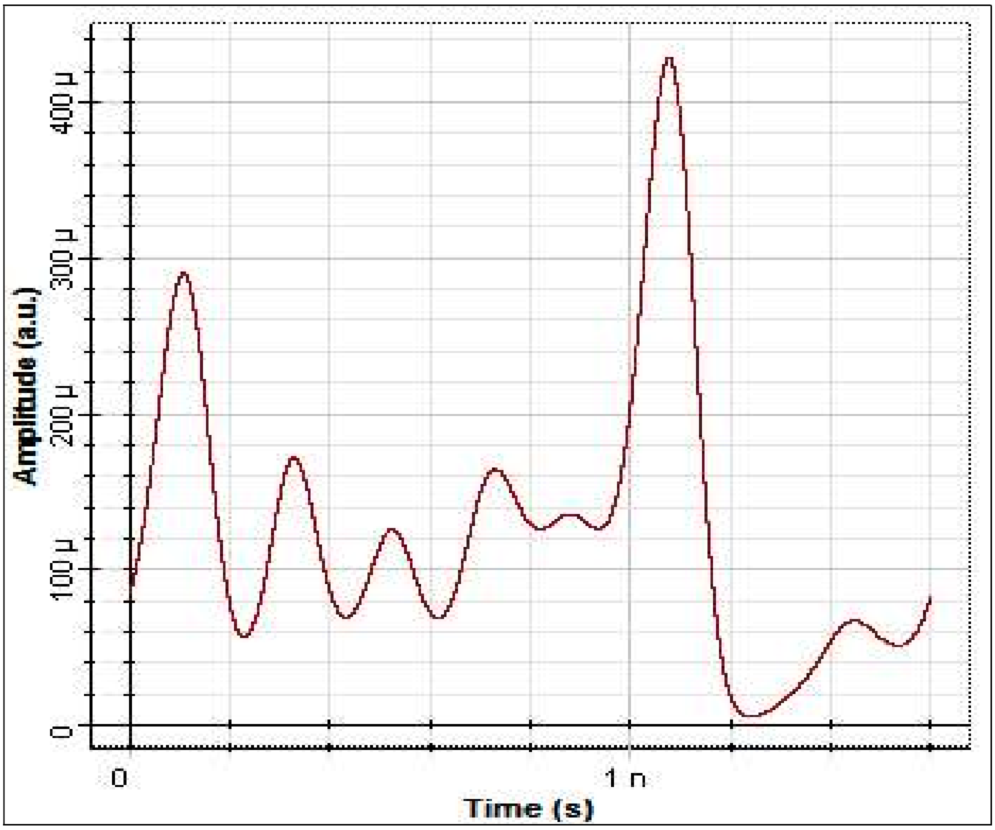


Figure (4-71):- The amplitude versus time for the channel_8(1546.92nm) output after PIN from the oscilloscope visualizer.

From the dual port WDM analyzer, the total (gain is -3.6856dbm, input signal is 4.0402dBm, output signal is 0.3545dBm, and output noise is 1.4248dBm). So, from the optical power meter, the average power is (-6.4255dBm).

Based on the details of the investigations performed by AWG multiplexer, by choose an architecture that matches the specification applications. The capability of this architecture is shown to be enhanced by the addition of small scale optical switches which yield flexibility in bandwidth setting. This is an attractive characteristic that allows cost-effective evolution of system throughput.

5.1. Conclusions:-

Evaluating performance at data rates of (8×10Gb/s WDM, 16×40Gb/s WDM and 8×40Gb/s AWG over 150km, 120km, and 242.5km) respectively optical link with minimum system impairments, the presence of (Passive/Active) components should be taken into considerations. The nonlinearities problem and dispersion compensation do not managed by optical amplifier and DCF in experiment (1), there are no received powers at the end side receiver, also this due to nonlinearities problems. To overcome the problems that appear in experiment (1), the dispersion management is fully treated by DCF as a compensator with the in-line optical amplifiers such as EDFA to improve the optical signal-to-noise-ratio (OSNR), and reduce the nonlinear effects in transmission system in experiments (2, 3, and 4). The simulation results show that a data transmission rates can be successfully transmitted and deliver a cost effective infrastructure, and:

1) The WDM systems have good performance, and fully exploit the high speed, low error rate, availability of multiple channels on a single fiber, and the major contribution is the development of the multi-destination communication over the lightwave WDM system.
2) The scheme is very attractive for the upgrading currently optical networks, and saving expenditures by adding more bandwidth to the WDM systems. By doing so, they can also keep increasing capacity of existing systems.
3) By comparing results in chapter 4 for 8×10Gb/s WDM system with those for 16×40Gb/s WDM systems, it is quite clear that at fiber spans, the performance of 8×10Gb/s systems are better than those of the 40Gb/s systems. So far, the AWG multiplexer has clear advantages for relatively data rate WDM systems.
4) Nonlinear crosstalk originated from XPM and FWM are major sources of system performance degradation. The high local

dispersion of SSMF-28 creates a strong walk-off between WDM channels during transmission and minimizes the nonlinear crosstalk between them.

5) The AWG plays a key role in current and future WDM optical network solutions due to its modular upgradability, transparency, flexibility, efficiency, reliability, and protection.
6) Furthermore, this architecture is truly scalable in terms of handling additional wavelengths or nodes in an efficient manner. This simulation can be applied to the existing optical fiber communication network with ultimate reduction of the cost, and operational expenditure for overall network system. It also provides valuable features such elimination of optical-electrical-optical (O-E-O) operations.
7) By using the WDM optical network, the majority of the people who live in urban and rural areas can use the (Internet access, E-education, E-governance, E-banking, E-health, E-commerce, E-tourism, E-agriculture, E-manufacturing, E-business, E-society, and telemedicine) in an easy way with minimum costs. This will help close the digital divide with other countries, and enhance sustainable socio-economic development and accelerate poverty reduction in the country.

5.2. Suggestions for Further Research:-

Due to the increasing demand for more bandwidth, optical networks are becoming more and more complex. Minimizing the probability of error for the whole network is of interest, and the system performance is optimized for all users and channels in the network, and:-

a) Using another modulation formats such as (carrier suppressed-return to zero (CS-RZ) or non return to zero-digital phase shift keying (NRZ-DPSK)) to provide optimum suppression to nonlinear effects (SPM and IM).

b) Using the hybrid AWG and WDM as a central wavelength routing hub, to reuse the capability of the AWG.

c) To support any-to-any traffic, or one hub station or more with OADM nodes, or other devices, at any node traffic can be terminated, managed, and connected with other networks.

d) Deploying WDM systems as Dense-WDM (DWDM).

e) Further progress on the AWG is expected to contribute greatly to the construction of the future photonic networks including OADM systems and OXC systems.

f) Applying this work to the metropolitan (metro) or ring network in all towns.

g) Using Wavelet, Fuzzy Logic, Multiwavelet, or Genetic Algorithm to study behavior of optical signal propagation in optical systems to try to reduce the nonlinearities effects..

h) Applying the results of the current research by the Ministries of Communications, and Sciences and Technology.

i) Finally, by WDM, no architecture changes are needed for the existing infrastructure in this field. This work can be modified to include network reconfiguration by adding optical add-drop multiplexer (OADM).

A.1. Computer Simulation Model [77]:-

Optical communication systems are increasing in complexity on an almost daily basis. The design and analysis of these systems, which normally include nonlinear devices and non-Gaussian noise sources, are highly complex and extremely time-intensive. As a result, these tasks can now only be performed efficiently and effectively with the help of advanced new software tools.

OptiSystem is an innovative optical communication system simulation package that designs, tests, and optimizes virtually any type of optical link in the physical layer of a broad spectrum of optical networks, from analog video broadcasting systems to intercontinental backbones.

OptiSystem is a stand-alone product that does not rely on other simulation frameworks. It is a system level simulator based on the realistic modeling of fiber optic communication systems. It possesses a powerful new simulation environment and a truly hierarchical definition of components and systems. Its capabilities can be extended easily with the addition of user components, and can be seamlessly interfaced to a wide range of tools.

"OptiSystem 7.0" package it is a license product of Optiwave Corporation (Canadian based company) used tested, and verified to an implemented network simulation. This package has many features as listed below:-

1. Rapid, low-cost prototyping,
2. Global insight into system performance,
3. Straightforward access to extensive sets of system characterization data,
4. Automatic parameter scanning and optimization,
5. Assessment of parameter sensitivities aiding design tolerance specifications,
6. Dramatic reduction of investment risk and time-to-market, and

7. Visual representation of design options and scenarios to present to prospective customers.

OptiSystem allows for the design automation of virtually any type of optical link in the physical layer, and the analysis of optical networks, from long haul systems to MANs and LANs. OptiSystem's have wide range of applications and as follows:

1. Optical communication system design from component to system level/enhancement on components level at the physical layer,
2. Cable TV or TDM/WDM network design,
3. Passive optical networks (PON) based FTTx,
4. Free space optic (FSO) systems,
5. Radio over fiber (ROF) systems,
6. SONET/SDH ring design,
7. Transmitter, channel, amplifier, and receiver design,
8. Dispersion map design,
9. Documentation and sample files,
10. Covering broadband optical system based on a passive optical network,
11. Electronic equalization,
12. New modulation formats,
13. Optical CDMA,
14. Coherent optical transmission,
15. Estimation of BER and system penalties with different receiver models, and
16. Amplified system BER and link budget calculations.

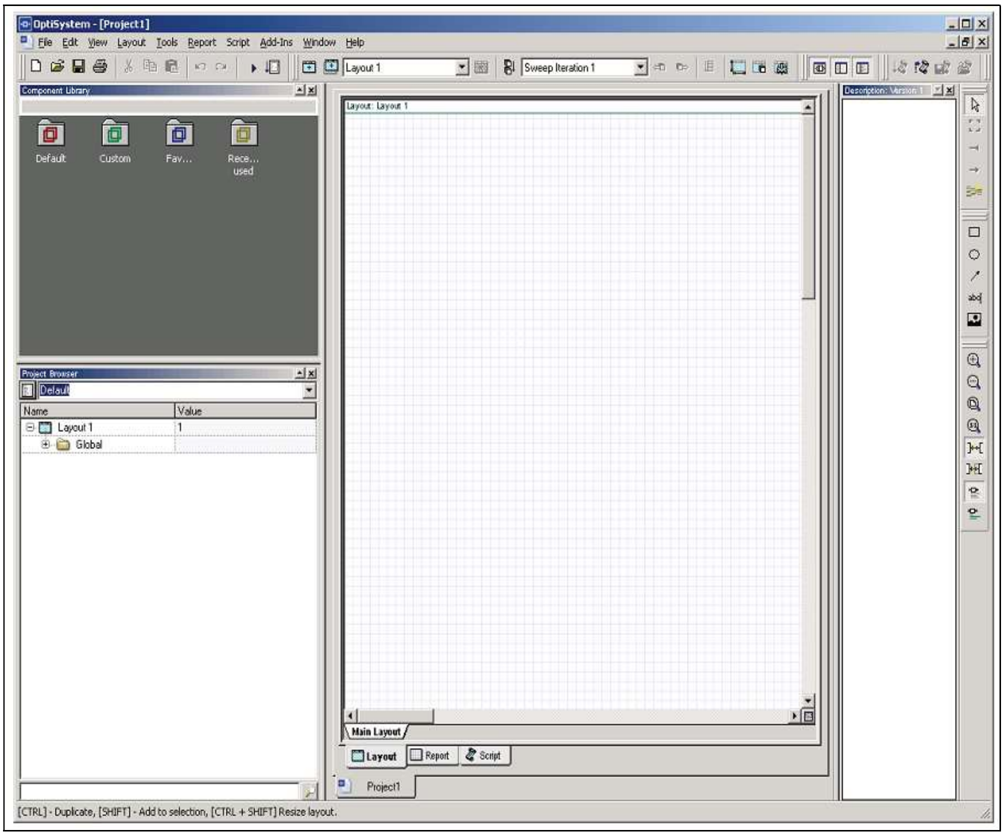
So, this package applied in many international research centers, and universitie.

A comprehensive Graphical User Interface (GUI) controls the optical component layout and netlist, A-2 ent models, and presentation graphics (See Figure A.1).

A.2. Hardware and Software Requirements [77]:-

OptiSystem requires the following minimum system configuration:

1) Personal computer with Pentium 3 processor or equivalent,
2) Microsoft Windows XP (Vista) or Windows 7 Home Premium (32-bit or 64-bit),
3) 400 Mega Byte (MB) free hard disk space,
4) 1024 x 768 graphic resolution, minimum 65536 colors,
5) 128 MB of Read and write memory (RAM) (recommended),
6) Internet Explorer 5.5 or higher, and
7) DirectX 8.1 or higher.



[CTRL] - Duplicate, [SHIFT] - Add to selection, [CTRL + SHIFT] Resize layout.

Figure (A-1):- OptiSystem Graphical User Interface (GUI).

A.3. Project Structure Overview:-

The OptiSystem project consists of a maximum of fifteen layouts. Within the same project file you can have multiple layouts with different components and component properties (see Figure A.2).

1. Sweep iterations:

   Each layout can have certain component parameters assigned to be in sweep mode. You can define the number of sweep iterations to be performed on the selected parameters. The parameter value changes through each sweep iteration; this produces a series of different calculation results based on the changing parameter values. The parameter sweep dependent elements of a layout are: Parameters and Results.

2. Optimizations:

   Each layout has optimizations. Use optimizations to change the values of certain parameters during calculation so your system can reach the desired state. Optimizations are independent of parameter sweeps, but can be performed this for each individual parameter sweep iteration.

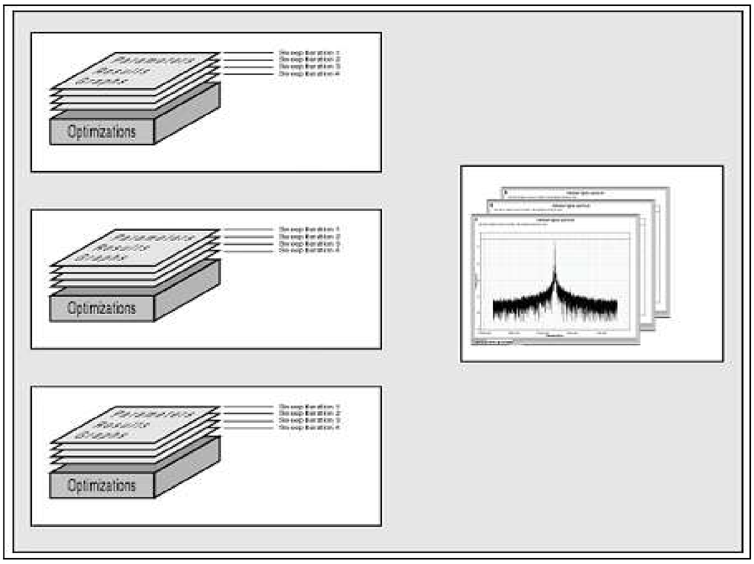


Figure (A-2):- Project structure.

3. Main parts of the GUI:-

The OptiSystem GUI contains the following main windows:

I. Project layout:-

The main working area where you insert components into the layout, edit components, and create connections between components (see Figure A.3).

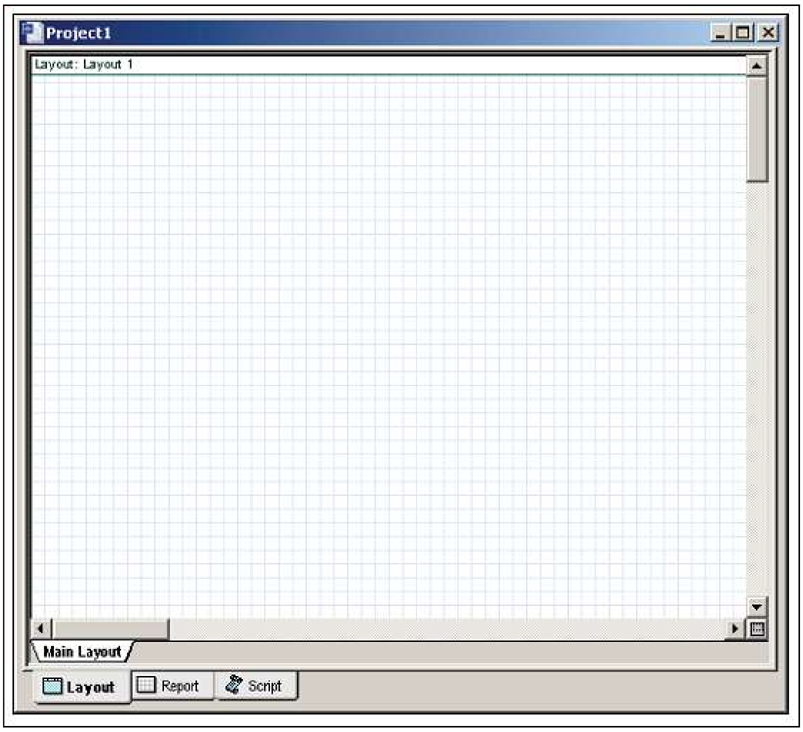


Figure (A-3):- Project layout window.

II. Dockers:-

Use dockers, located in the main layout, to display information about the active (current) project:

a. Component Library,

b. Project Browser, and

c. Description.

III. Component Library:-

Access components to create the system design (see Figure A.4).

Figure (A-4):- Component library window.

IV. Placing components in the Main layout:-

To place components into the Main layout, drag the component from the Component Library to the Main layout (see Figure A.5).

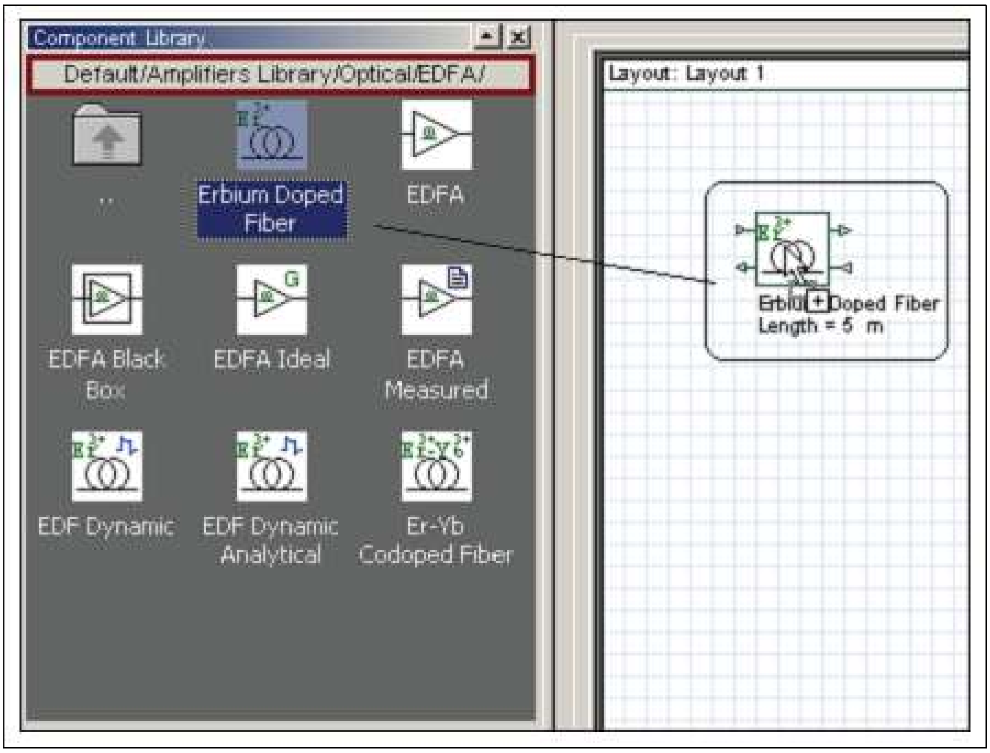


Figure (A-5):- Placing components in the main layout.

V. Visual Basic Script:-

You can control many of the objects that you use when you create the layout using Visual Basic Script (VB Script). You can create components, assign parameters and results and run simulations. This powerful feature eliminates many lengthy, repetitive manual tasks. This manual describes how to use VBScript with OptiSystem, and includes examples and tutorials.

VI. Quick Visual Basic references:-

The following is a basic description of a selected part of the VB Script language. For more information and a complete reference, refer to Microsoft online documentation at: **http://msdn.microsoft.com/scripting/** .In Visual Basic, every variable type is variant. Variants are tagged unions.

A variant stores a value and information on the value type. Variants support the following types:

a) 2-byte and 4-byte integer
b) 4-byte and 8-byte floating points
c) Strings
d) Booleans
e) HRESULT
f) Pointers to IUnknown and IDispatch interfaces

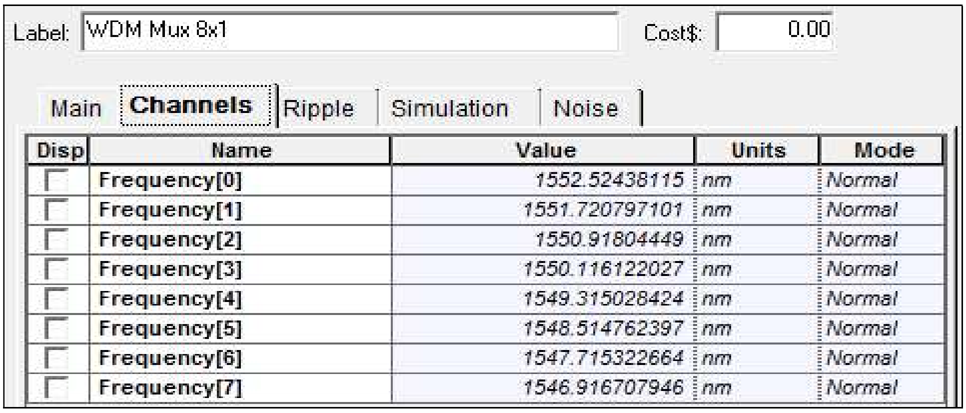
You must be aware of the type of data required by the OptiSystem VB Script programming interface. For example, consider the number 80. The number 80 can be stored as a 2-byte integer, a 4-byte integer, a 4-byte float, an 8-byte float, or even as a string. When calling the application programming interface (API), you must ensure that you are passing the proper type. Otherwise, the API will not behave properly. You must convert to the proper type.

B.1. Other Component Properties:-

In the following subsection, we will illustrate the main global parameters for the layouts and their components.

B.1.1. Properties of the component of the 8×10Gb/s:-

Figures below show the main global parameters for the test layout that was illustrated in Figure 4.4, each component in this layout.

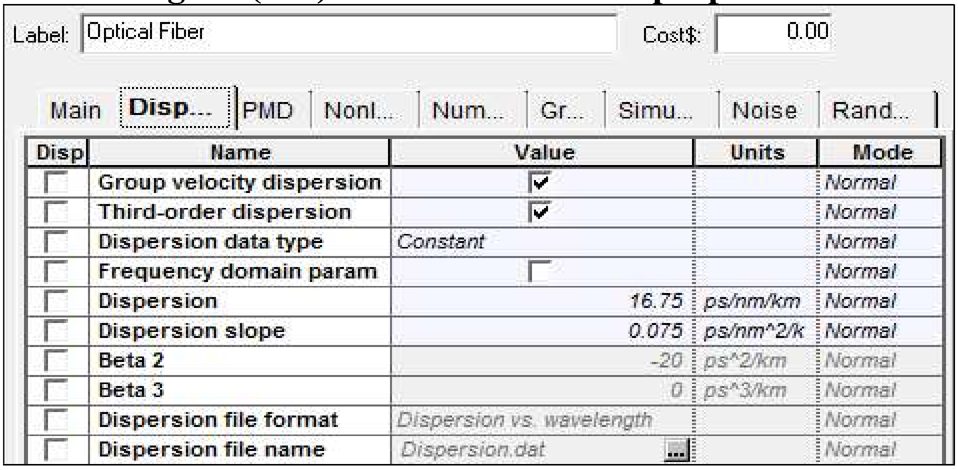


Label: WDM Mux 8x1

Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Frequency[0]	1552.52438115	nm	Normal
☐	Frequency[1]	1551.720797101	nm	Normal
☐	Frequency[2]	1550.91804449	nm	Normal
☐	Frequency[3]	1550.116122027	nm	Normal
☐	Frequency[4]	1549.315028424	nm	Normal
☐	Frequency[5]	1548.514762397	nm	Normal
☐	Frequency[6]	1547.715322664	nm	Normal
☐	Frequency[7]	1546.916707946	nm	Normal

Figure (B-1):- WDM 8-channels properties.

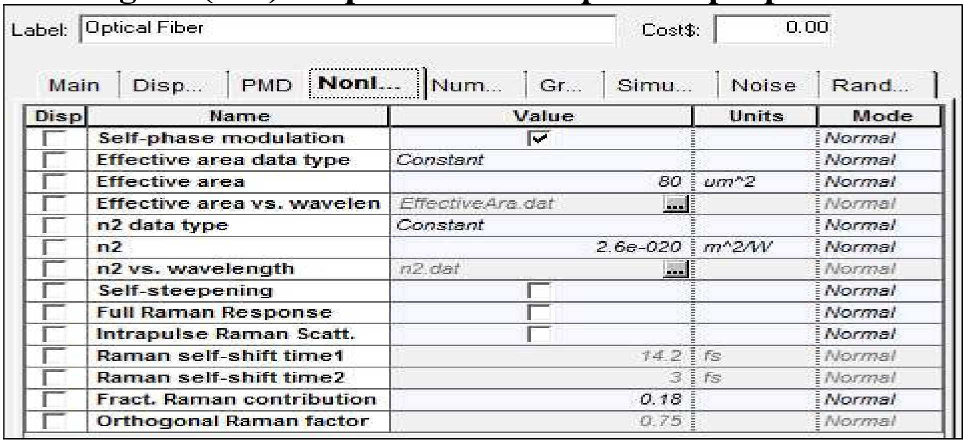


Label: Optical Fiber

Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Group velocity dispersion	☑		Normal
☐	Third-order dispersion	☑		Normal
☐	Dispersion data type	Constant		Normal
☐	Frequency domain param	☐		Normal
☐	Dispersion	16.75	ps/nm/km	Normal
☐	Dispersion slope	0.075	ps/nm^2/k	Normal
☐	Beta 2	-20	ps^2/km	Normal
☐	Beta 3	0	ps^3/km	Normal
☐	Dispersion file format	Dispersion vs. wavelength		Normal
☐	Dispersion file name	Dispersion.dat		Normal

Figure (B-2):- Optical fiber Dispersion properties.

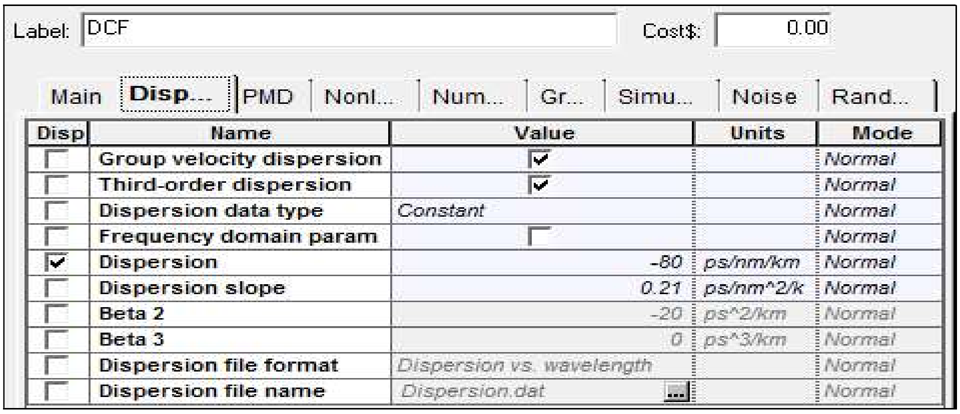


Label: Optical Fiber

Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Self-phase modulation	☑		Normal
☐	Effective area data type	Constant		Normal
☐	Effective area	80	um^2	Normal
☐	Effective area vs. wavelen	EffectiveAra.dat		Normal
☐	n2 data type	Constant		Normal
☐	n2	2.6e-020	m^2/W	Normal
☐	n2 vs. wavelength	n2.dat		Normal
☐	Self-steepening	☐		Normal
☐	Full Raman Response	☐		Normal
☐	Intrapulse Raman Scatt.	☐		Normal
☐	Raman self-shift time1	14.2	fs	Normal
☐	Raman self-shift time2	3	fs	Normal
☐	Fract. Raman contribution	0.18		Normal
☐	Orthogonal Raman factor	0.75		Normal

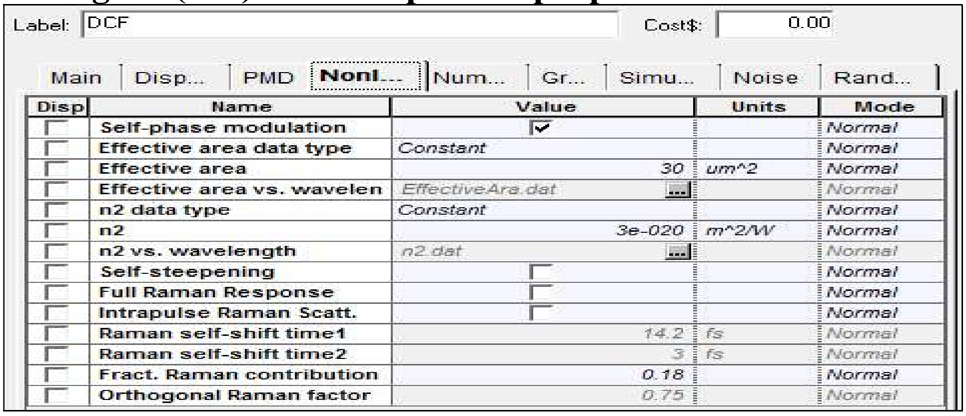
Figure (B-3):- The nonlinearities properties for the SSMF.



Label: DCF   Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Group velocity dispersion	☑		Normal
☐	Third-order dispersion	☑		Normal
☐	Dispersion data type	Constant		Normal
☐	Frequency domain param	☐		Normal
☑	Dispersion	-80	ps/nm/km	Normal
☐	Dispersion slope	0.21	ps/nm^2/k	Normal
☐	Beta 2	-20	ps^2/km	Normal
☐	Beta 3	0	ps^3/km	Normal
☐	Dispersion file format	Dispersion vs. wavelength		Normal
☐	Dispersion file name	Dispersion.dat ...		Normal

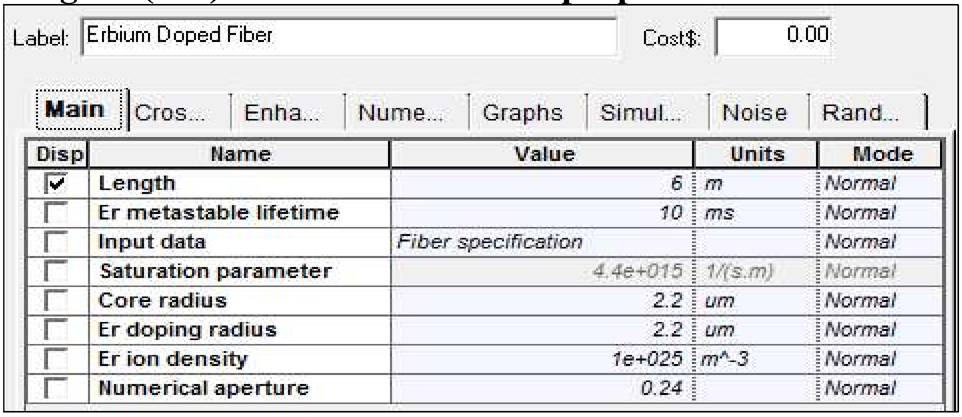
Figure (B-4):- The dispersion properties for the DCF.



Label: DCF   Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Self-phase modulation	☑		Normal
☐	Effective area data type	Constant		Normal
☐	Effective area	30	um^2	Normal
☐	Effective area vs. wavelen	EffectiveAra.dat ...		Normal
☐	n2 data type	Constant		Normal
☐	n2	3e-020	m^2/W	Normal
☐	n2 vs. wavelength	n2.dat ...		Normal
☐	Self-steepening	☐		Normal
☐	Full Raman Response	☐		Normal
☐	Intrapulse Raman Scatt.	☐		Normal
☐	Raman self-shift time1	14.2	fs	Normal
☐	Raman self-shift time2	3	fs	Normal
☐	Fract. Raman contribution	0.18		Normal
☐	Orthogonal Raman factor	0.75		Normal

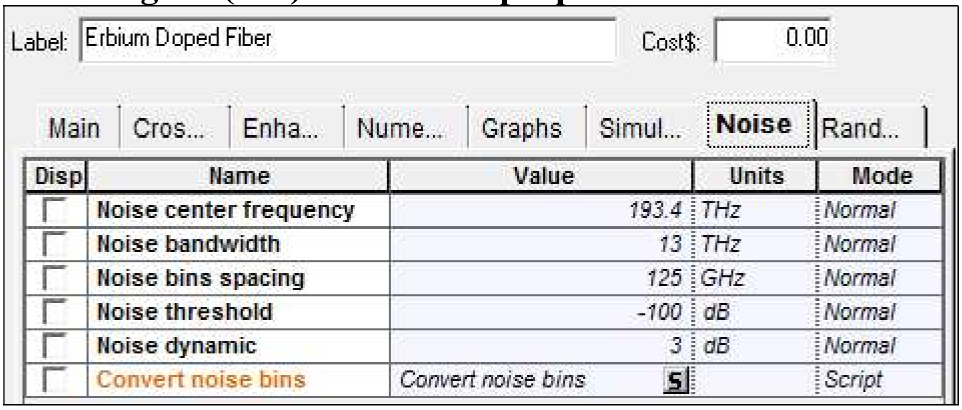
Figure (B-5):- The Nonlinearities properties for the DCF.



Label: Erbium Doped Fiber   Cost$: 0.00

Disp	Name	Value	Units	Mode
☑	Length	6	m	Normal
☐	Er metastable lifetime	10	ms	Normal
☐	Input data	Fiber specification		Normal
☐	Saturation parameter	4.4e+015	1/(s.m)	Normal
☐	Core radius	2.2	um	Normal
☐	Er doping radius	2.2	um	Normal
☐	Er ion density	1e+025	m^-3	Normal
☐	Numerical aperture	0.24		Normal

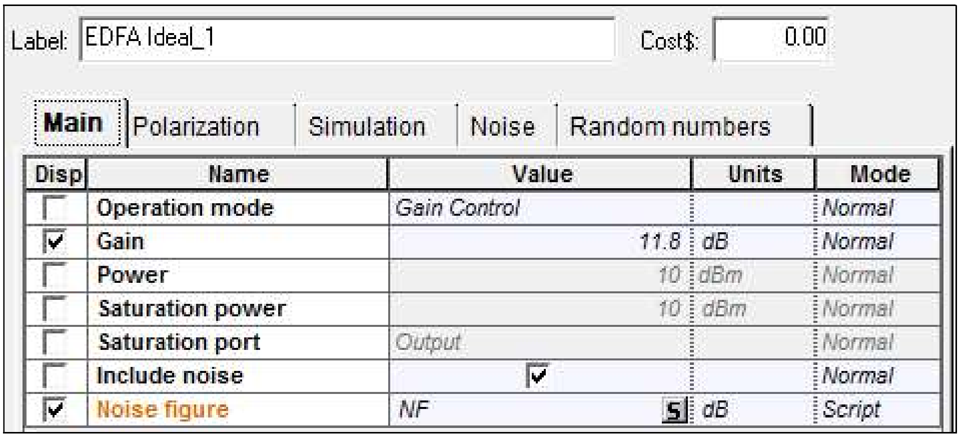
Figure (B-6):- The main properties of the EDF.



Label: Erbium Doped Fiber   Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Noise center frequency	193.4	THz	Normal
☐	Noise bandwidth	13	THz	Normal
☐	Noise bins spacing	125	GHz	Normal
☐	Noise threshold	-100	dB	Normal
☐	Noise dynamic	3	dB	Normal
☐	Convert noise bins	Convert noise bins S		Script

Figure (B-7):- The noise properties for EDF.

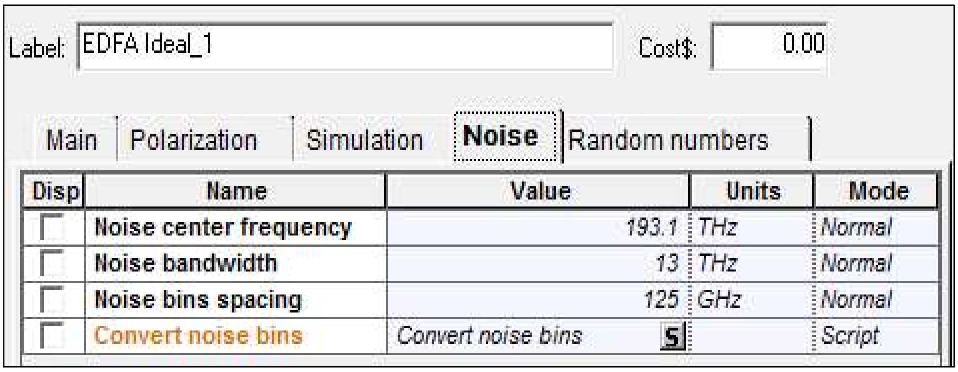


Label: EDFA Ideal_1 Cost$: 0.00

Main | Polarization | Simulation | Noise | Random numbers

Disp	Name	Value	Units	Mode
☐	Operation mode	Gain Control		Normal
☑	Gain	11.8	dB	Normal
☐	Power	10	dBm	Normal
☐	Saturation power	10	dBm	Normal
☐	Saturation port	Output		Normal
☐	Include noise	☑		Normal
☑	Noise figure	NF	dB	Script

Figure (B-8):- The main properties for EDFA.



Label: EDFA Ideal_1 Cost$: 0.00

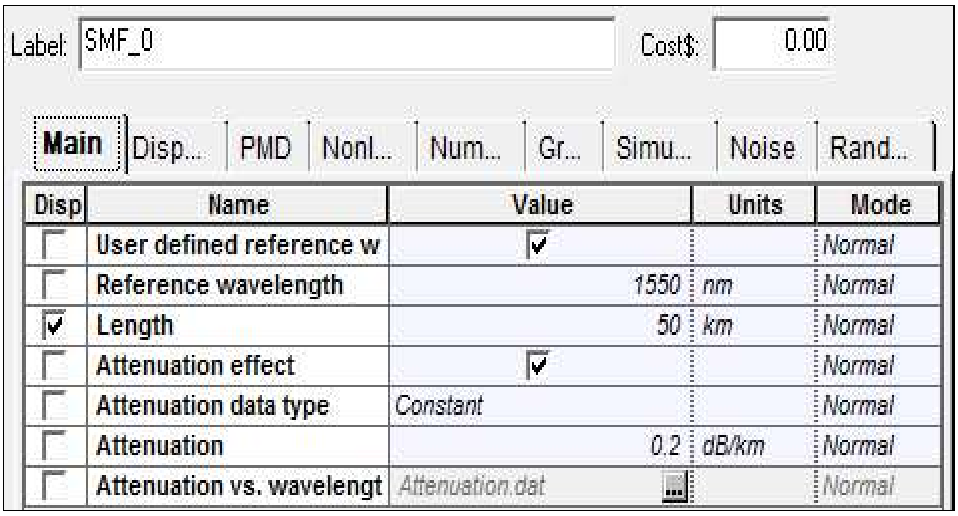
Main | Polarization | Simulation | Noise | Random numbers

Disp	Name	Value	Units	Mode
☐	Noise center frequency	193.1	THz	Normal
☐	Noise bandwidth	13	THz	Normal
☐	Noise bins spacing	125	GHz	Normal
☐	Convert noise bins	Convert noise bins		Script

Figure (B-9):- The noise properties for EDFA.

B.1.2. Properties of the component of the 16×40Gb/s:-

Figures below show the main global parameters for the test layout Figure 4.11, and each component in layout.

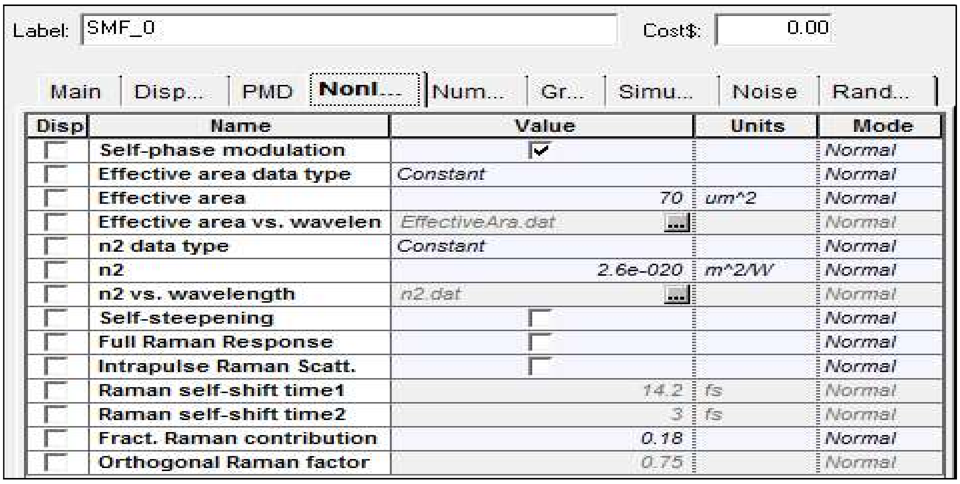


Label: SMF_0 Cost$: 0.00

Main | Disp... | PMD | Nonl... | Num... | Gr... | Simu... | Noise | Rand...

Disp	Name	Value	Units	Mode
☐	User defined reference w	☑		Normal
☐	Reference wavelength	1550	nm	Normal
☑	Length	50	km	Normal
☐	Attenuation effect	☑		Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.2	dB/km	Normal
☐	Attenuation vs. wavelengt	Attenuation.dat		Normal

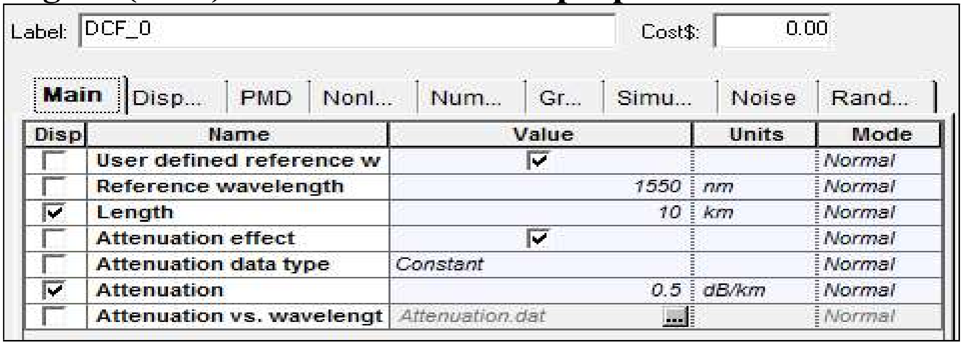
Figure (B-10):- The main properties for the SSMF.



Label: SMF_0 Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Self-phase modulation	☑		Normal
☐	Effective area data type	Constant		Normal
☐	Effective area	70	um^2	Normal
☐	Effective area vs. wavelen	EffectiveAra.dat		Normal
☐	n2 data type	Constant		Normal
☐	n2	2.6e-020	m^2/W	Normal
☐	n2 vs. wavelength	n2.dat		Normal
☐	Self-steepening	☐		Normal
☐	Full Raman Response	☐		Normal
☐	Intrapulse Raman Scatt.	☐		Normal
☐	Raman self-shift time1	14.2	fs	Normal
☐	Raman self-shift time2	3	fs	Normal
☐	Fract. Raman contribution	0.18		Normal
☐	Orthogonal Raman factor	0.75		Normal

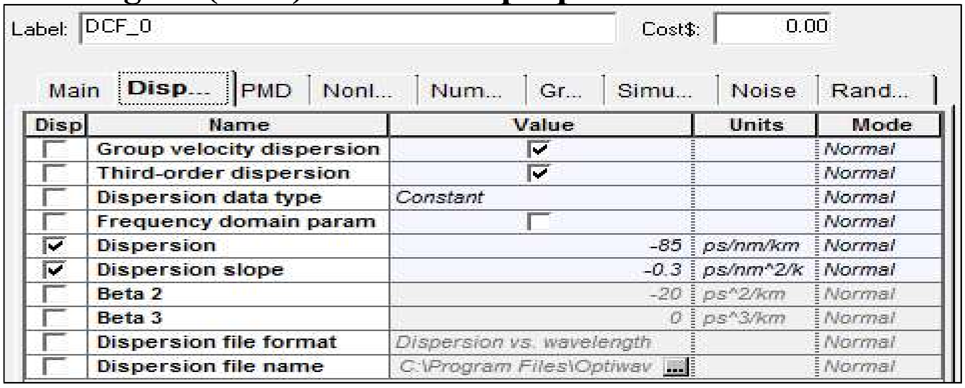
Figure (B-11):- The nonlinearities properties for the SSMF.



Label: DCF_0 Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	User defined reference w	☑		Normal
☐	Reference wavelength	1550	nm	Normal
☑	Length	10	km	Normal
☐	Attenuation effect	☑		Normal
☐	Attenuation data type	Constant		Normal
☑	Attenuation	0.5	dB/km	Normal
☐	Attenuation vs. wavelengt	Attenuation.dat		Normal

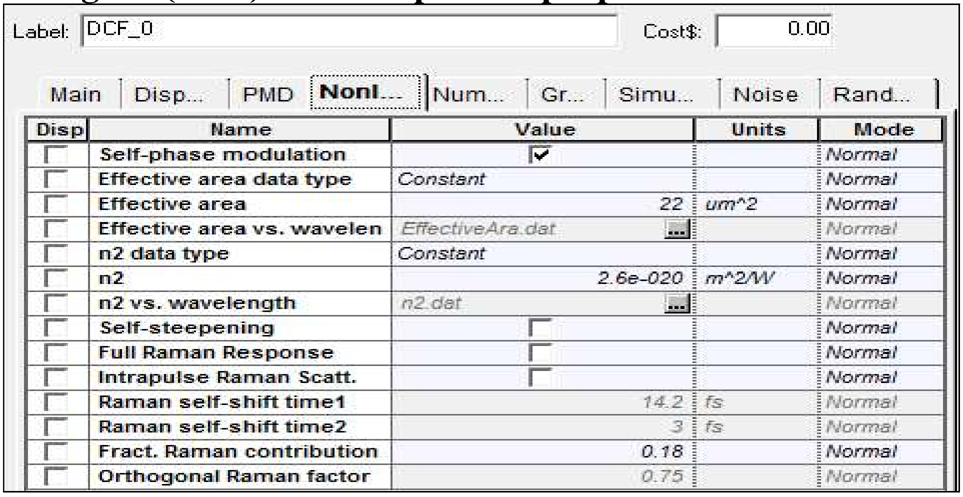
Figure (B-12):- The main properties for the DCF.



Label: DCF_0 Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Group velocity dispersion	☑		Normal
☐	Third-order dispersion	☑		Normal
☐	Dispersion data type	Constant		Normal
☐	Frequency domain param	☐		Normal
☑	Dispersion	-85	ps/nm/km	Normal
☑	Dispersion slope	-0.3	ps/nm^2/k	Normal
☐	Beta 2	-20	ps^2/km	Normal
☐	Beta 3	0	ps^3/km	Normal
☐	Dispersion file format	Dispersion vs. wavelength		Normal
☐	Dispersion file name	C:\Program Files\Optiwav		Normal

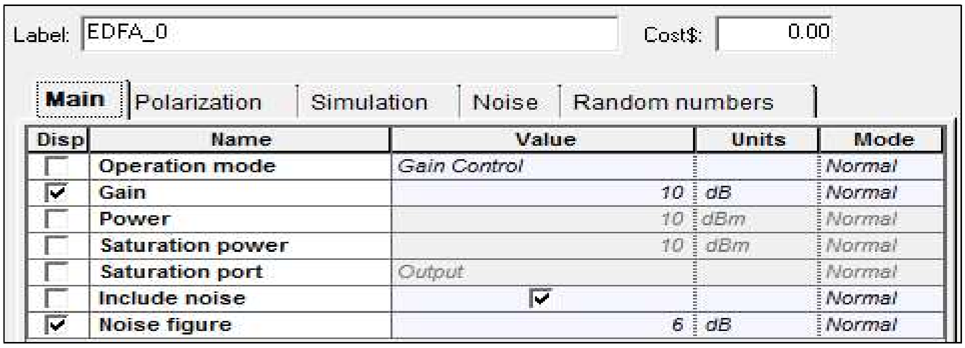
Figure (B-13):- The dispersion properties for the DCF.



Label: DCF_0 Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Self-phase modulation	☑		Normal
☐	Effective area data type	Constant		Normal
☐	Effective area	22	um^2	Normal
☐	Effective area vs. wavelen	EffectiveAra.dat		Normal
☐	n2 data type	Constant		Normal
☐	n2	2.6e-020	m^2/W	Normal
☐	n2 vs. wavelength	n2.dat		Normal
☐	Self-steepening	☐		Normal
☐	Full Raman Response	☐		Normal
☐	Intrapulse Raman Scatt.	☐		Normal
☐	Raman self-shift time1	14.2	fs	Normal
☐	Raman self-shift time2	3	fs	Normal
☐	Fract. Raman contribution	0.18		Normal
☐	Orthogonal Raman factor	0.75		Normal

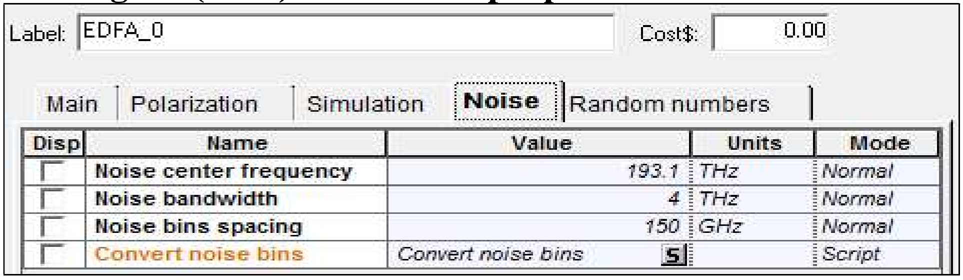
Figure (B-14):- The nonlinearities properties for the DCF.



Label: EDFA_0 Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Operation mode	Gain Control		Normal
☑	Gain	10	dB	Normal
☐	Power	10	dBm	Normal
☐	Saturation power	10	dBm	Normal
☐	Saturation port	Output		Normal
☐	Include noise	☑		Normal
☑	Noise figure	6	dB	Normal

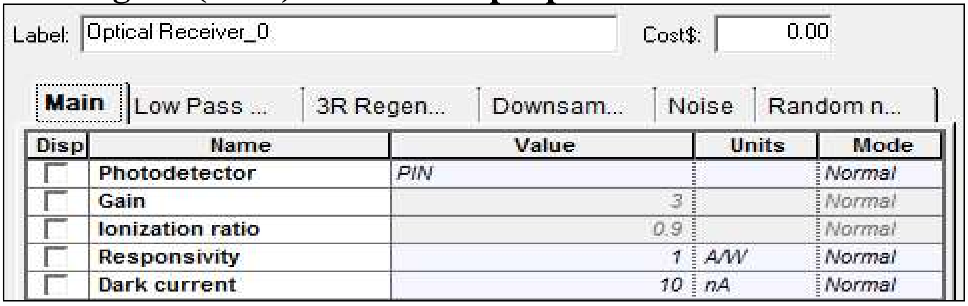
Figure (B-15):- The main properties for the EDFA.



Label: EDFA_0 Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Noise center frequency	193.1	THz	Normal
☐	Noise bandwidth	4	THz	Normal
☐	Noise bins spacing	150	GHz	Normal
☐	Convert noise bins	Convert noise bins S		Script

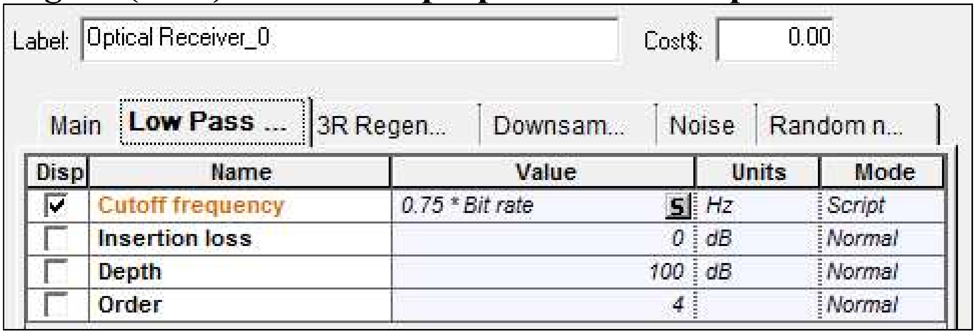
Figure (B-16):- The noise properties for the EDFA.



Label: Optical Receiver_0 Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Photodetector	PIN		Normal
☐	Gain	3		Normal
☐	Ionization ratio	0.9		Normal
☐	Responsivity	1	A/W	Normal
☐	Dark current	10	nA	Normal

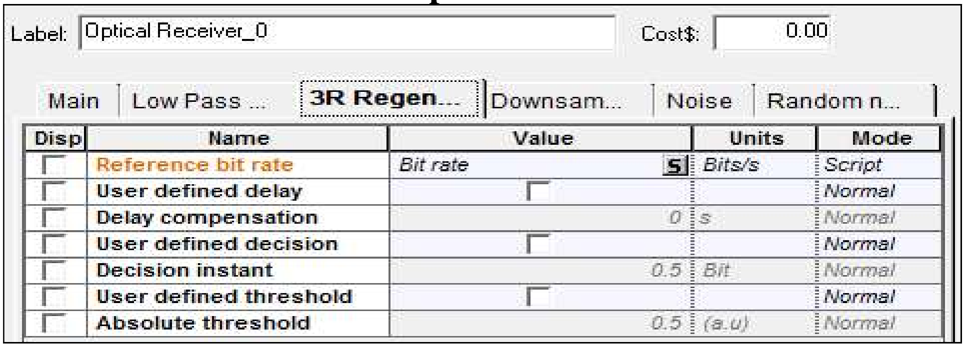
Figure (B-17):- The main properties for the optical receiver.



Label: Optical Receiver_0 Cost$: 0.00

Disp	Name	Value	Units	Mode
☑	Cutoff frequency	0.75 * Bit rate S	Hz	Script
☐	Insertion loss	0	dB	Normal
☐	Depth	100	dB	Normal
☐	Order	4		Normal

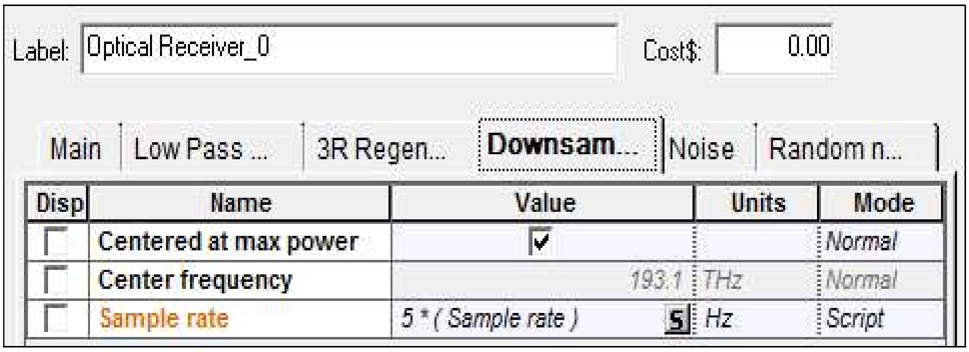
Figure (B-18):- The low pass filter properties in the optical receiver.



Label: Optical Receiver_0 Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Reference bit rate	Bit rate S	Bits/s	Script
☐	User defined delay	☐		Normal
☐	Delay compensation	0	s	Normal
☐	User defined decision	☐		Normal
☐	Decision instant	0.5	Bit	Normal
☐	User defined threshold	☐		Normal
☐	Absolute threshold	0.5	(a.u)	Normal

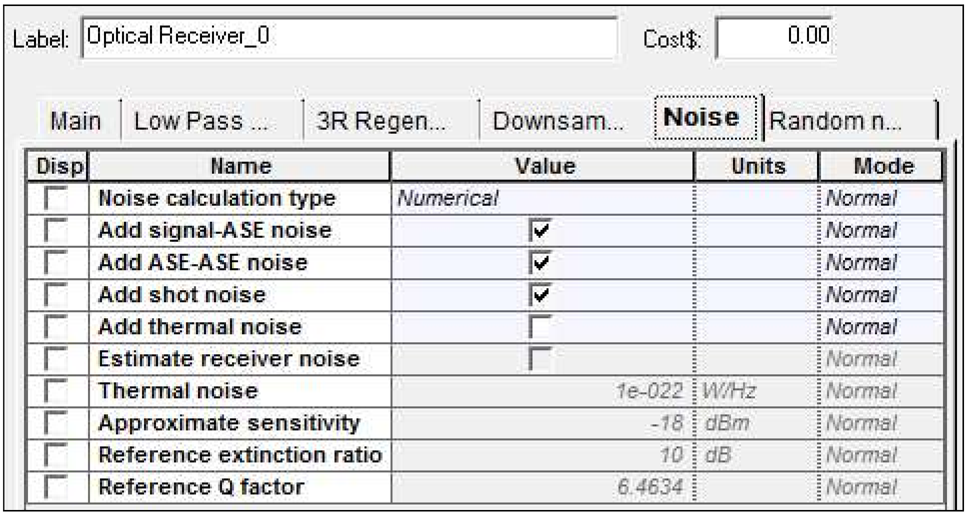
Figure (B-19):- The 3R regeneration properties in the optical receiver.



Label: Optical Receiver_0 Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Centered at max power	☑		Normal
☐	Center frequency	193.1	THz	Normal
☐	Sample rate	5 * (Sample rate)	Hz	Script

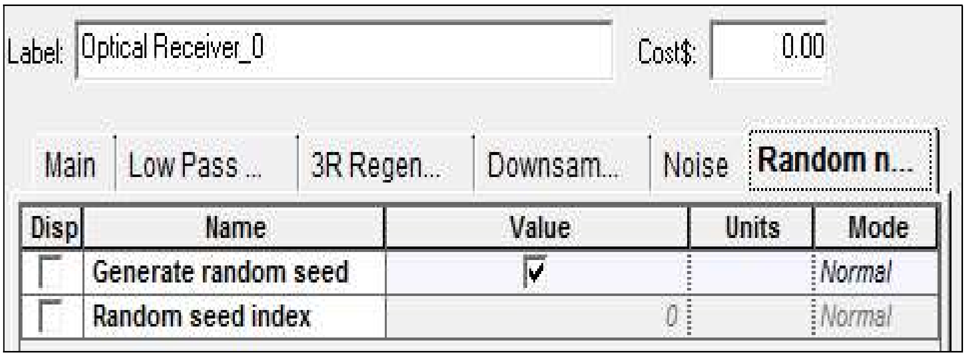
Figure (B-20):- The downsampling properties in the optical receiver.



Label: Optical Receiver_0 Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Noise calculation type	Numerical		Normal
☐	Add signal-ASE noise	☑		Normal
☐	Add ASE-ASE noise	☑		Normal
☐	Add shot noise	☑		Normal
☐	Add thermal noise	☐		Normal
☐	Estimate receiver noise	☐		Normal
☐	Thermal noise	1e-022	W/Hz	Normal
☐	Approximate sensitivity	-18	dBm	Normal
☐	Reference extinction ratio	10	dB	Normal
☐	Reference Q factor	6.4634		Normal

Figure (B-21):- The noise properties in the optical receiver.



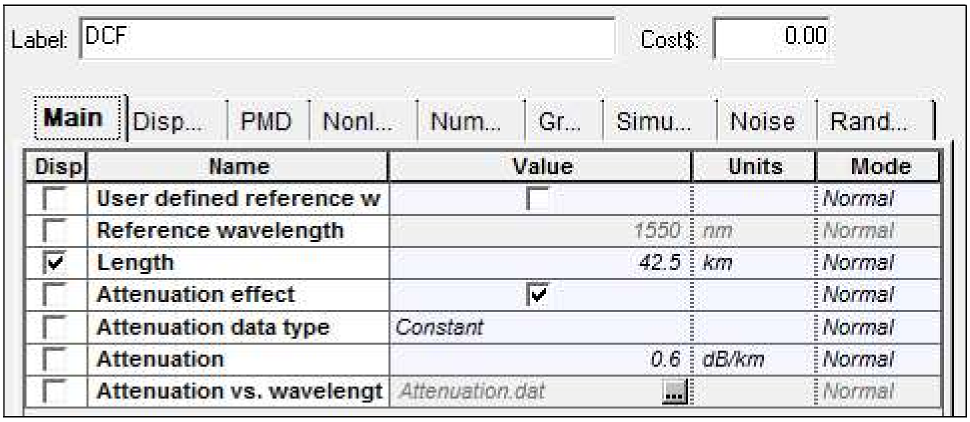
Label: Optical Receiver_0 Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	Generate random seed	☑		Normal
☐	Random seed index	0		Normal

Figure (B-22):- The random seed properties in the optical receiver.

B.1.3. Properties of the component of the 8×40Gb/s AWG:-

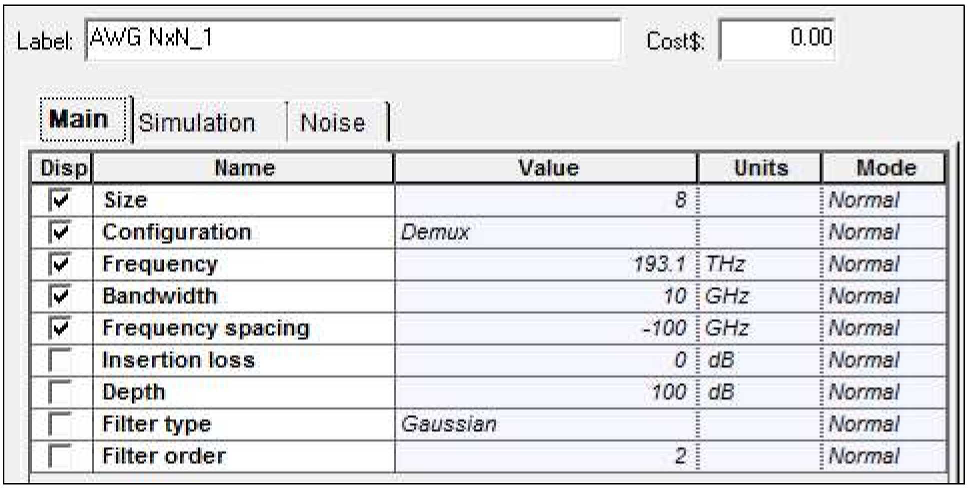
Figures below show the main global parameters for the DCF and AWG N×N DEMUX at the layout in Figure 4.20.



Label: DCF
Cost$: 0.00

Disp	Name	Value	Units	Mode
☐	User defined reference w	☐		Normal
☐	Reference wavelength	1550	nm	Normal
☑	Length	42.5	km	Normal
☐	Attenuation effect	☑		Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.6	dB/km	Normal
☐	Attenuation vs. wavelengt	Attenuation.dat		Normal

Figure (B-23):- The main properties for the DCF.



Label: AWG NxN_1
Cost$: 0.00

Disp	Name	Value	Units	Mode
☑	Size	8		Normal
☑	Configuration	Demux		Normal
☑	Frequency	193.1	THz	Normal
☑	Bandwidth	10	GHz	Normal
☑	Frequency spacing	-100	GHz	Normal
☐	Insertion loss	0	dB	Normal
☐	Depth	100	dB	Normal
☐	Filter type	Gaussian		Normal
☐	Filter order	2		Normal

Figure (B-24):- The main properties for the AWG N×N DEMUX.

C.1. Other System Results:-

In the following subsection, we will illustrate the remainder results for the three test beds demonstrated in this thesis.

C.1.1. Other Output Results for the 8×10Gb/s WDM System:-

Figures below show other results obtained from the experiment 10Gb/s WDM.

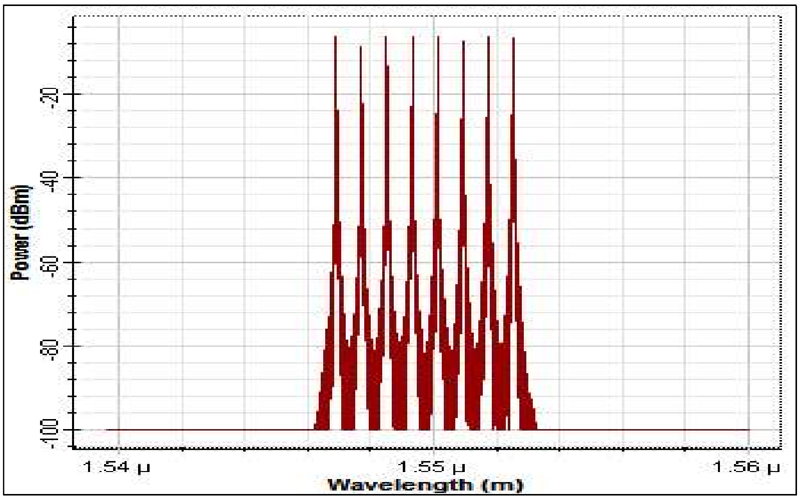


Figure (C-1):- Power versus Wavelength for 8-channels after multiplexer from the OSA.

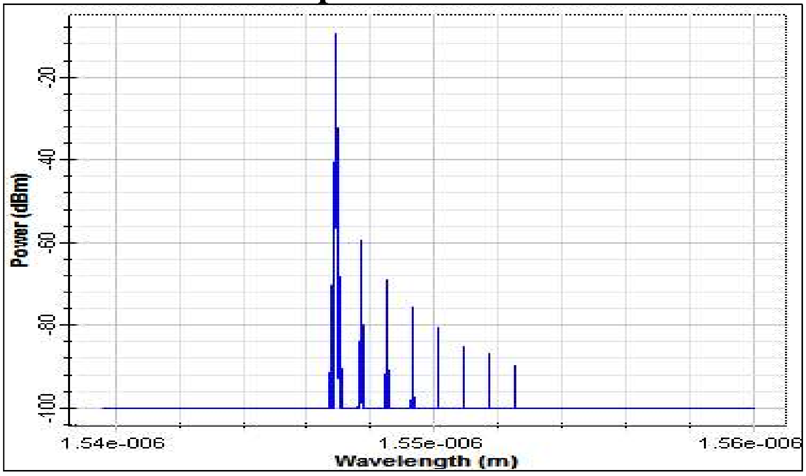
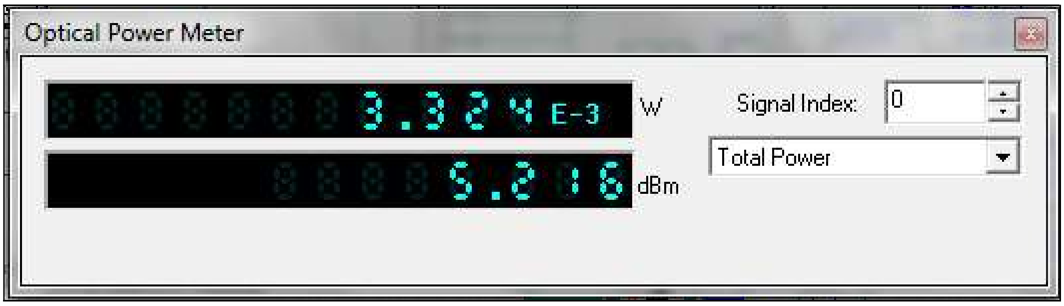


Figure (C-2):- Sampled signal spectrum iteration from the OSA.



Optical Power Meter

3.324 E-3 W

5.216 dBm

Signal Index: 0

Total Power

Figure (C-3):- Optical Power Meter after transmission Link.

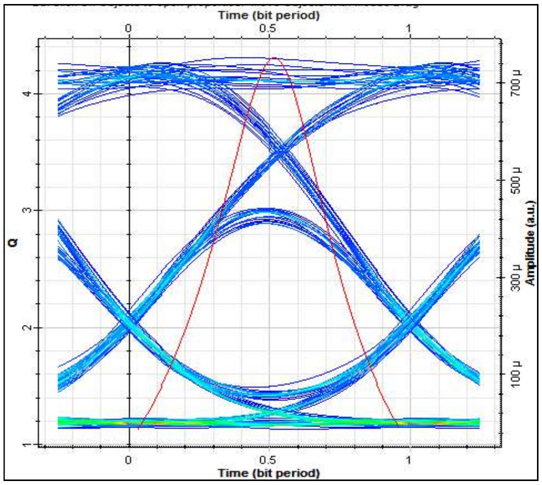


Figure (C-4):- Q-Factor for the output channel_1(1552.52nm).

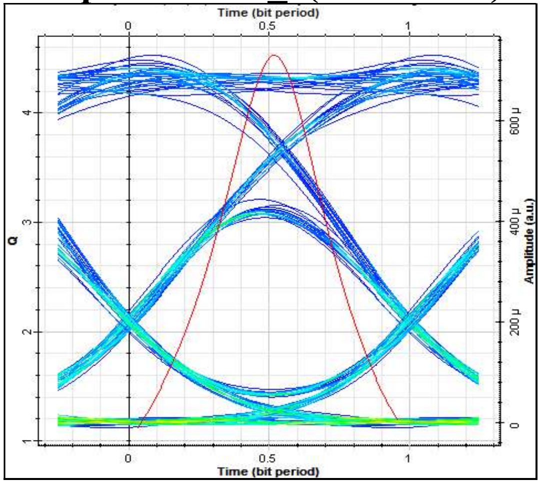


Figure (C-5):- Q-Factor for the output channel_2(1551.72nm).

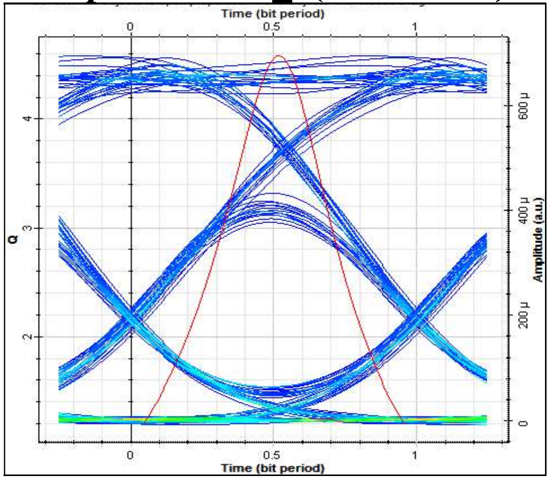


Figure (C-6):- Q-Factor for the output channel_3(1550.92nm).

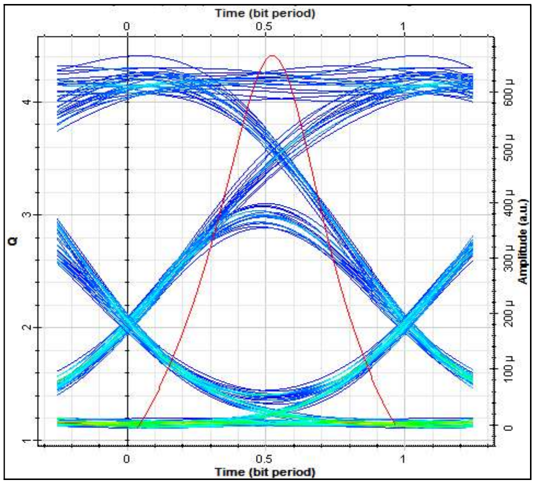


Figure (C-7):- Q-Factor for the output channel_4(1550.12nm).

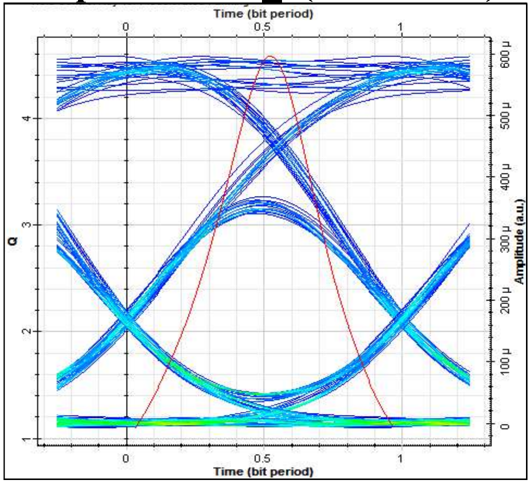


Figure (C-8):- Q-Factor for the output channel_5(1549.32nm).

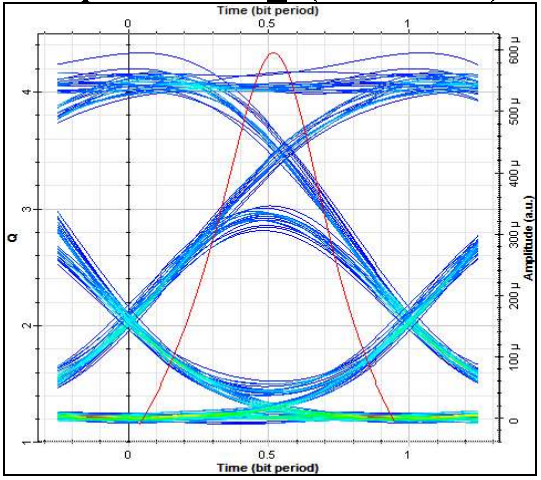


Figure (C-9):- Q-Factor for the output channel_6(1548.51nm).

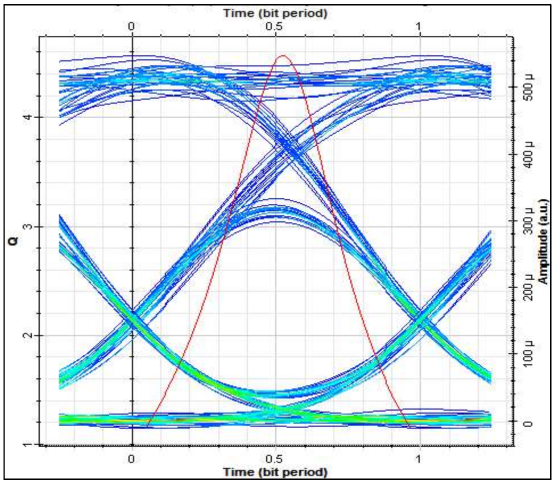


Figure (C-10):- Q-Factor for the output channel_7(1547.72nm).

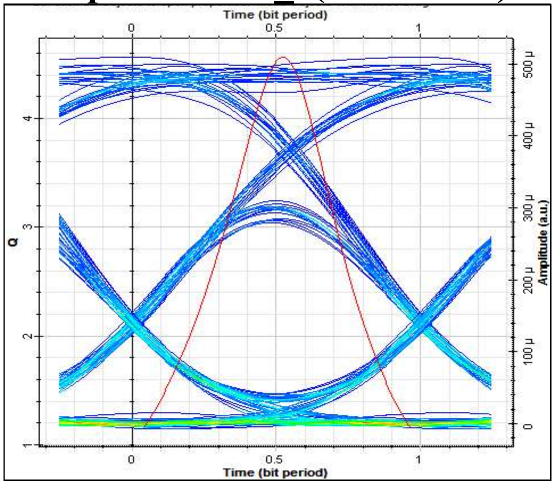


Figure (C-11):- Q-Factor for the output channel_8(1456.92nm).

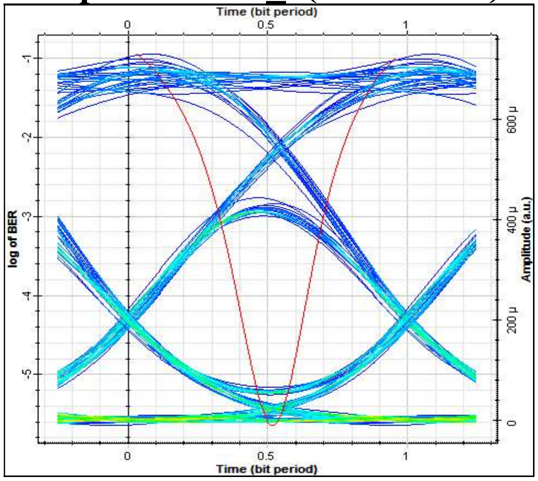


Figure (C-12):- BER analyzer for the output channel_2(1551.72nm).

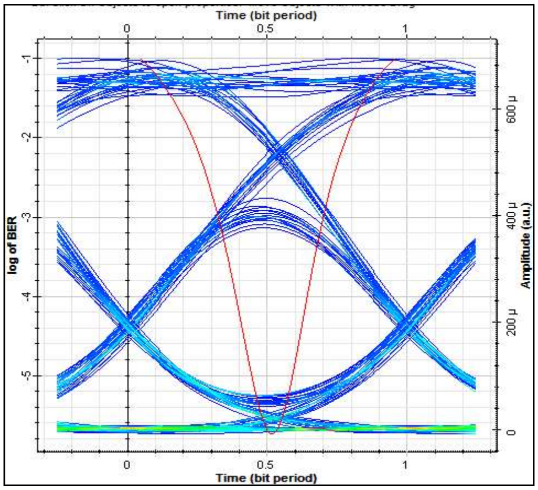


Figure (C-13):- BER analyzer for the output channel_3(1550.92nm).

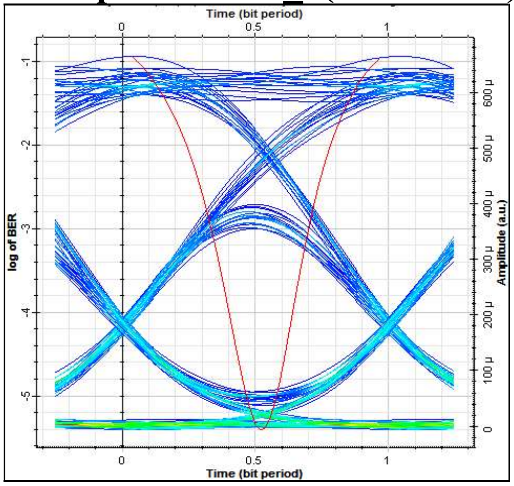


Figure (C-14):- BER analyzer for the output channel_4(1550.12nm).

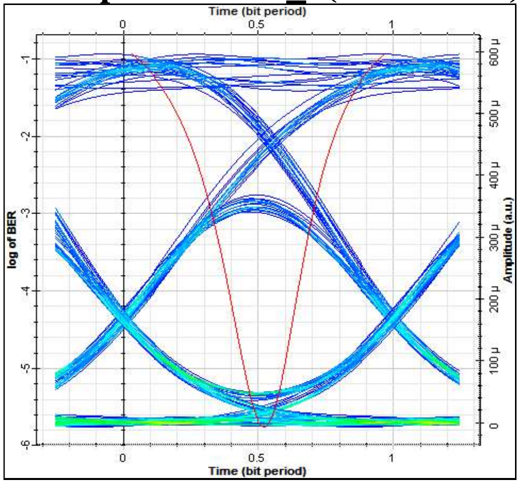


Figure (C-15):- BER analyzer for the output channel_5(1549.32nm).

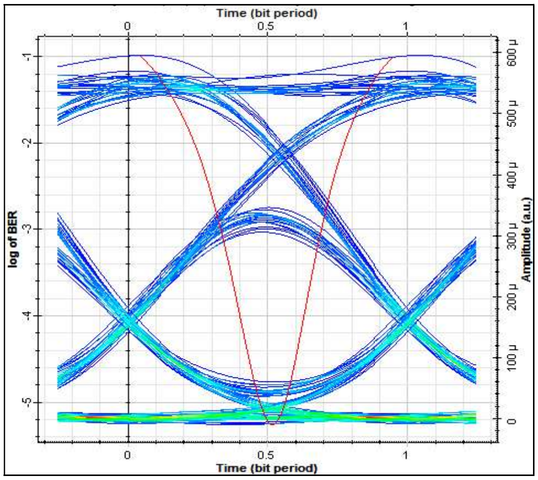


Figure (C-16):- BER analyzer for the output channel_6(1548.51nm).

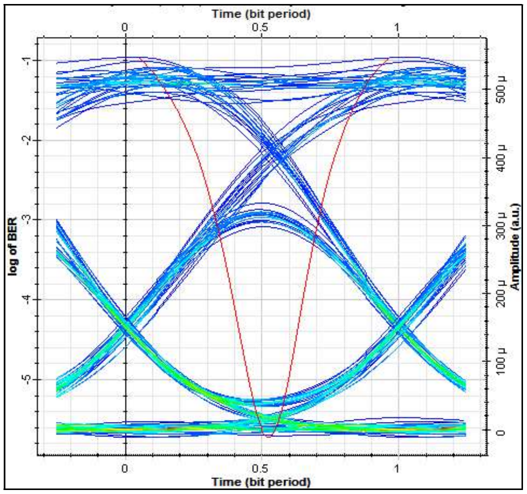


Figure (C-17):- BER analyzer for the output channel_7(1547.72nm).

C. 1. 2. Other Output Results for the 16×40Gb/s WDM System:-

Figures below show other results obtained from the experiment 40Gb/s WDM.

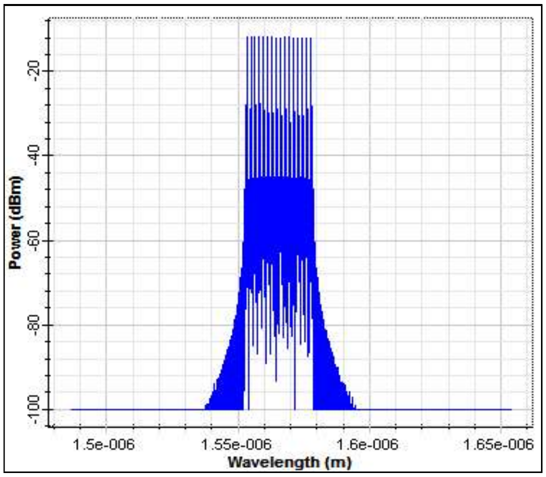


Figure (C-18):- Sampled Signal Spectrum Iteration for 16-channels from the OSA.

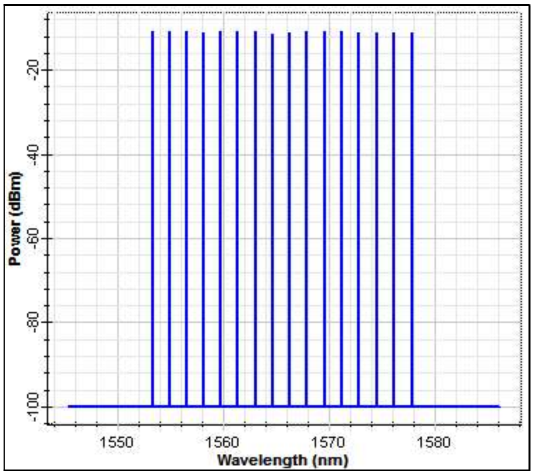


Figure (C-19):- Signal Spectrum Iteration for 16-channels from the OSA.

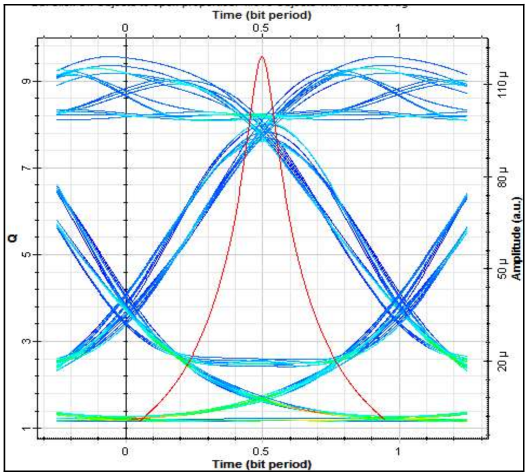


Figure (C-20):- Q-Factor for the output channel_2(1577.02nm).

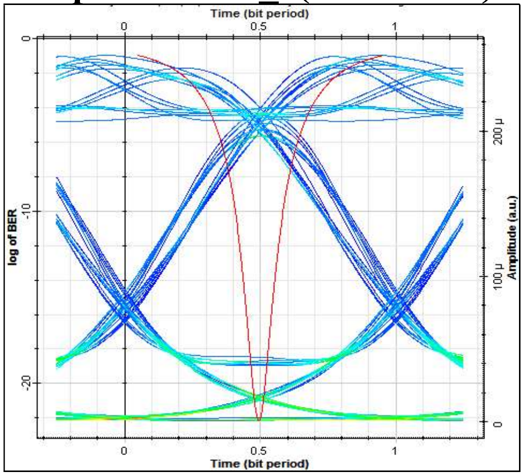


Figure (C-21):- BER analyzer for the output channel_2(1577.02nm).

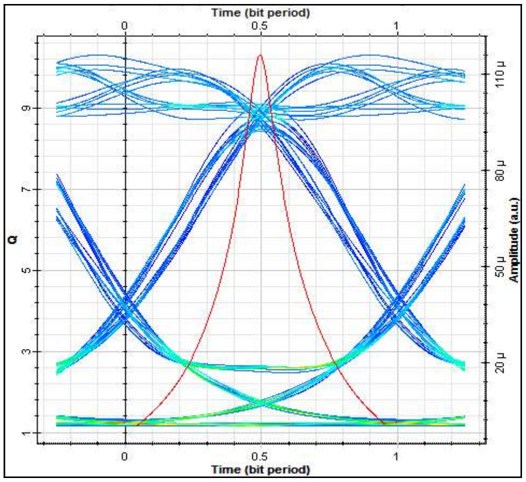


Figure (C-22):- Q-Factor for the output channel_3(1576.19nm).

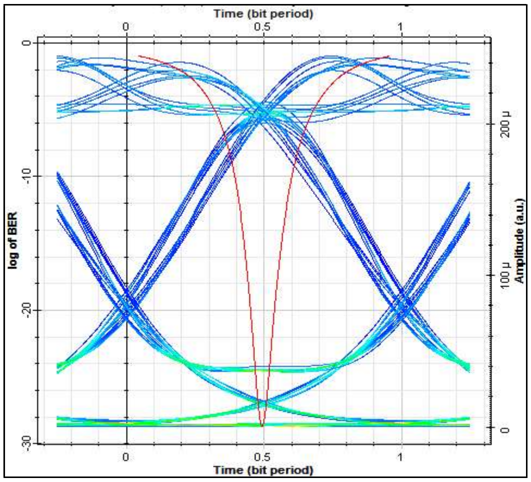


Figure (C-23):- BER analyzer for the output channel_3(1576.19nm).

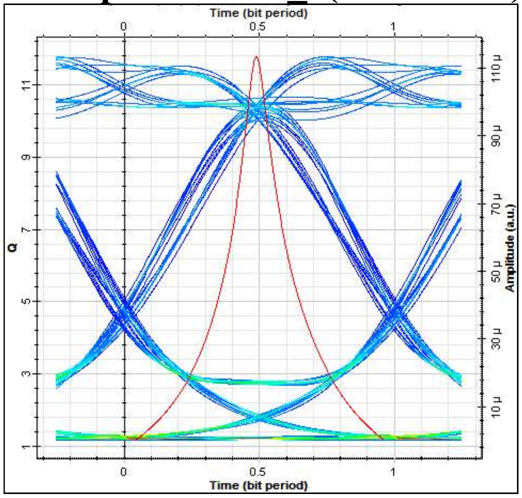


Figure (C-24):- Q-Factor for the output channel_4(1575.36nm).

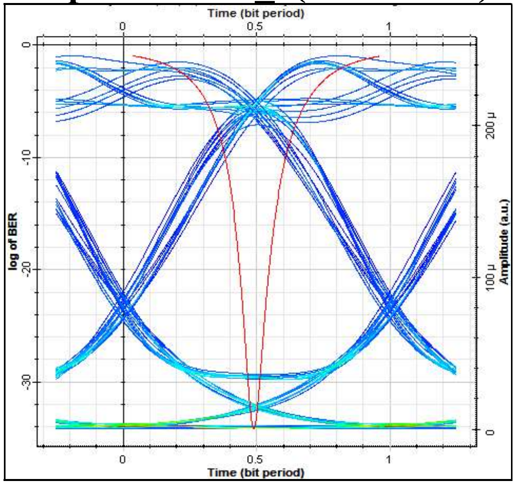


Figure (C-25):- BER analyzer for the output channel_4(1575.36nm).

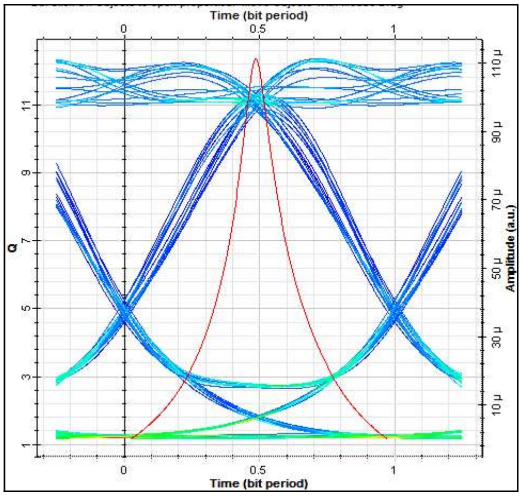


Figure (C-26):- Q-Factor for the output channel_5(1574.53nm).

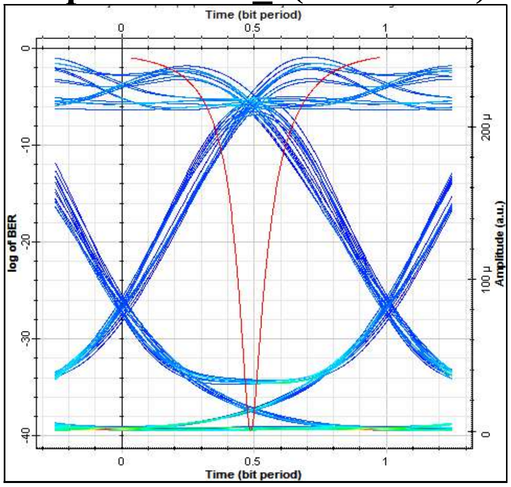


Figure (C-27):- BER analyzer for the output channel_5(1574.53nm).

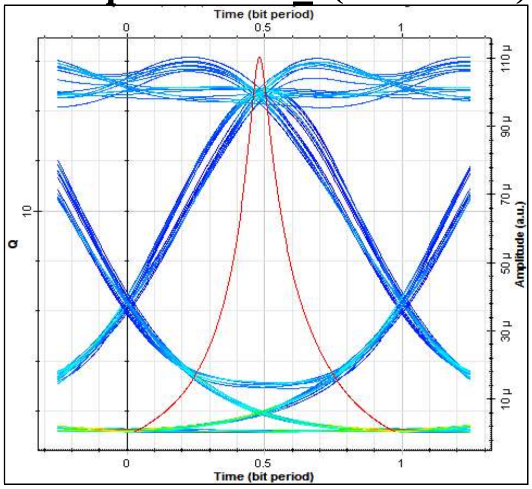


Figure (C-28):- Q-Factor for the output channel_6(1573.7nm).

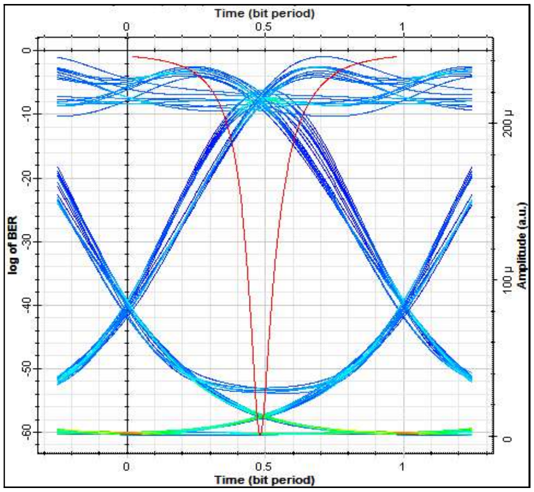


Figure (C-29):- BER analyzer for the output channel_6(1573.7nm).

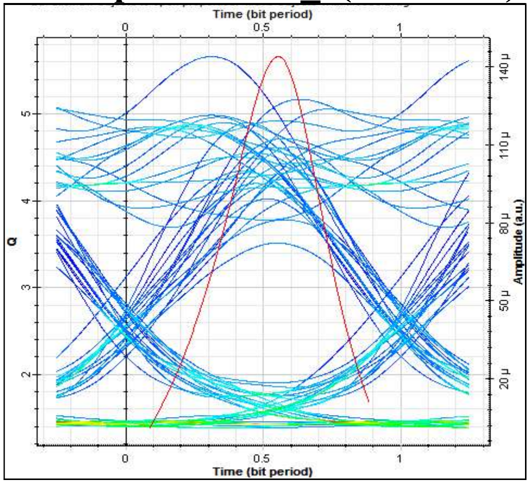


Figure (C-30):- Q-Factor for the output channel_7(1572.87nm).

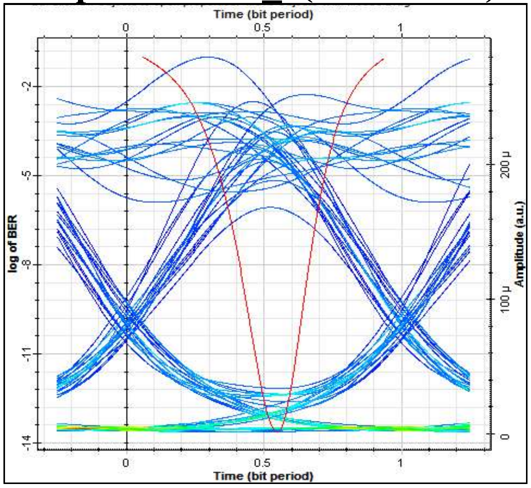


Figure (C-31):- BER analyzer for the output channel_7(1572.87nm).

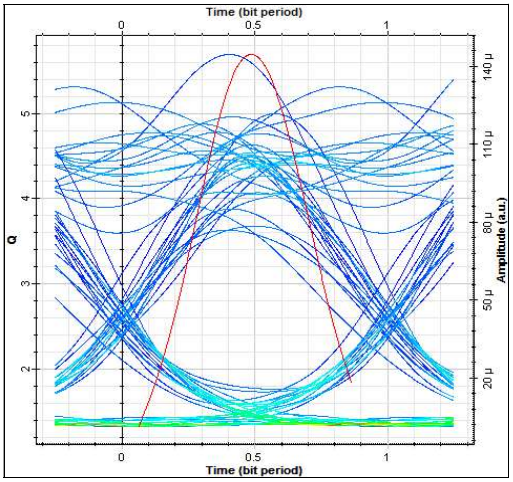
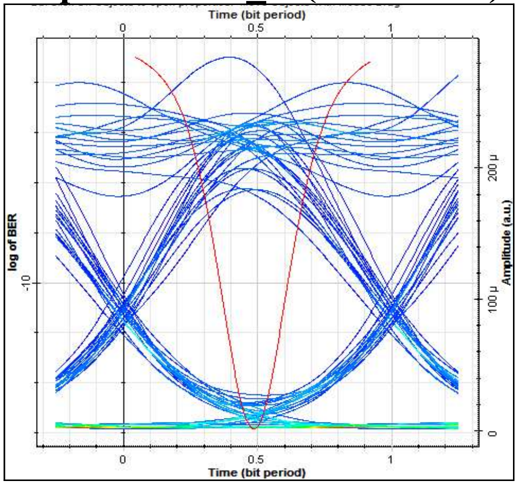


Figure (C-32):- Q-Factor for the output channel_10(1570.38nm).



Figure(C-33):-BER analyzer for the output channel_10(1570.38nm)

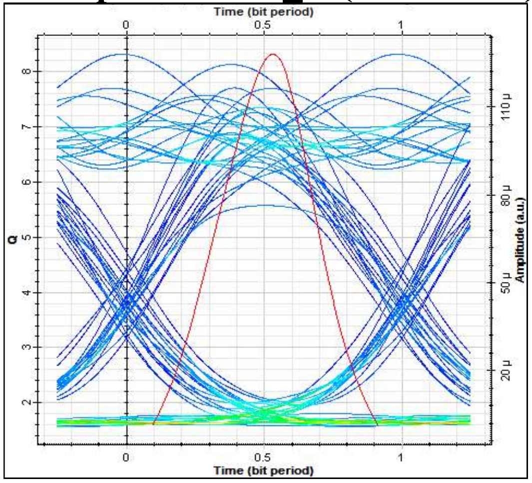
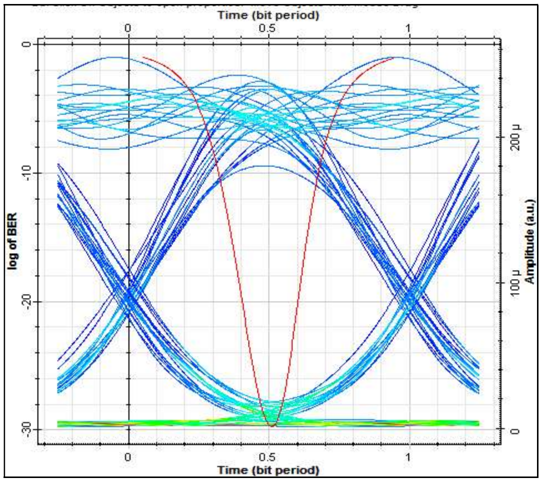


Figure (C-34):-Q-Factor for the output channel_11(1569.55nm).



Figure(C-35):-BER analyzer for the output channel_11(1569.55nm)

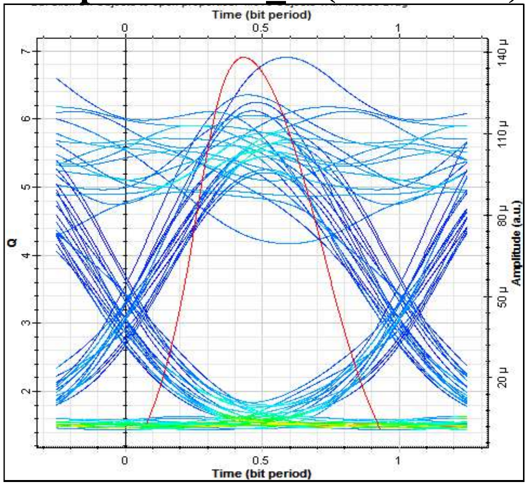
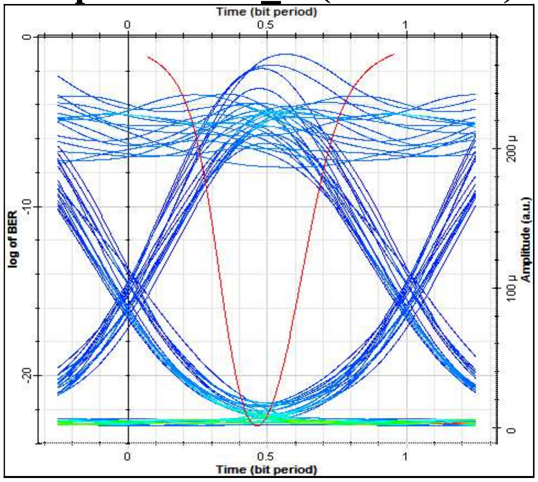
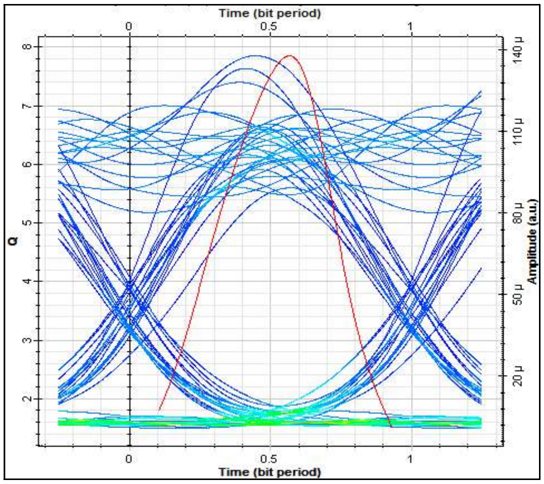


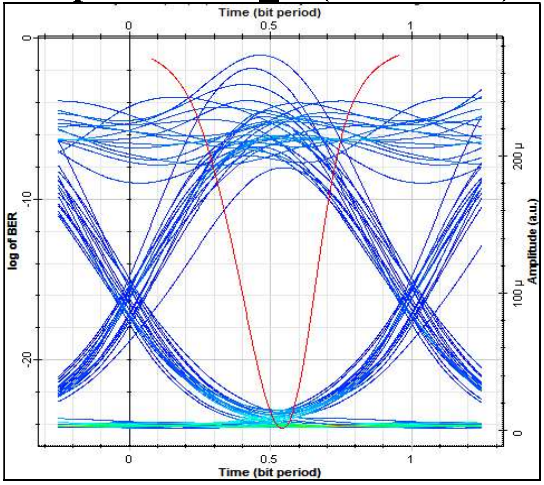
Figure (C-36):-Q-Factor for the output channel_12(1568.72nm)



Figure(C-37):-BER analyzer for the output channel_12(1568.72nm).



Figure(C-38):-Q-Factor for the output channel_13(1567.89nm).



Figure(C-39):-BER analyzer for the output channel_13(1567.89nm).

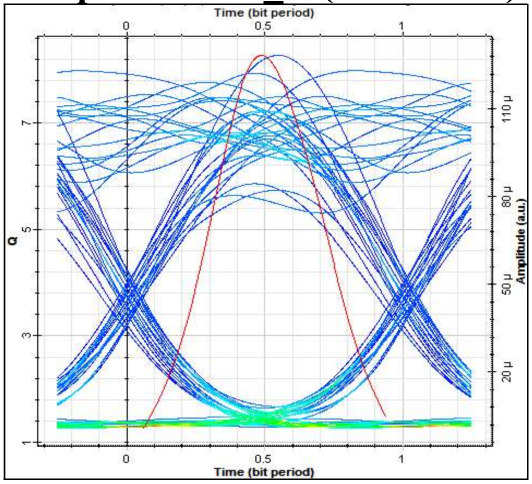
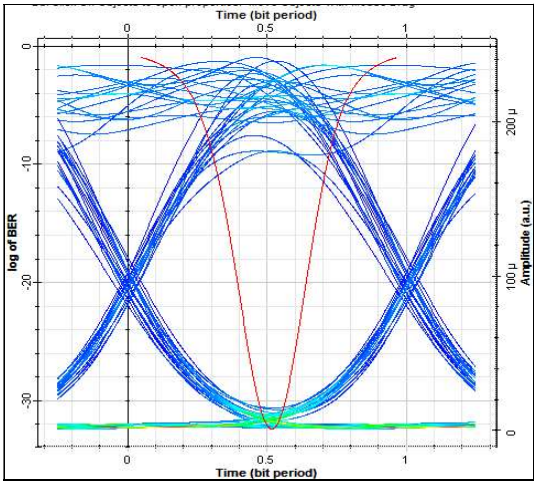
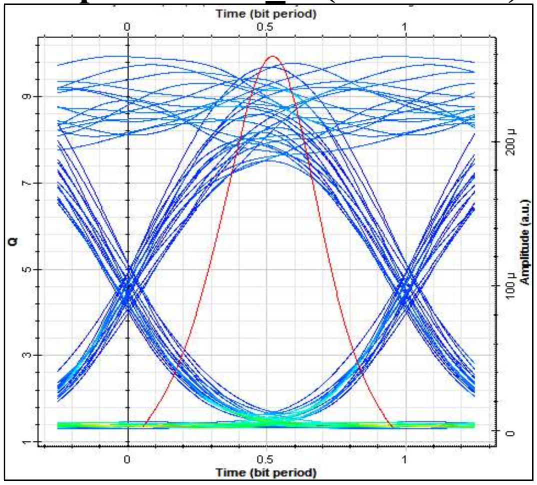


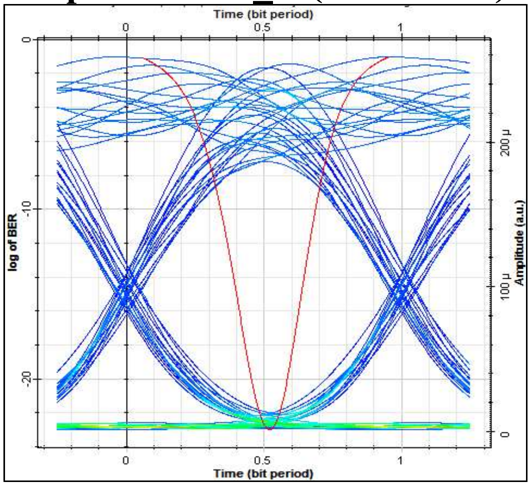
Figure (C-40):- Q-Factor for the output channel_14(1567.06nm).



Figure(C-41):-BER analyzer for the output channel_14(1567.06nm).



Figure(C-42):-Q-Factor for the output channel_15(1566.23nm).



Figure(C-43):-BER analyzer for the output channel_15(1566.23nm).

C. 1. 3. Other Output Results for the 8×40Gb/s AWG System:-

Figures below show other results obtained from the experiment 40Gb/s AWG MUX/De-MUX.

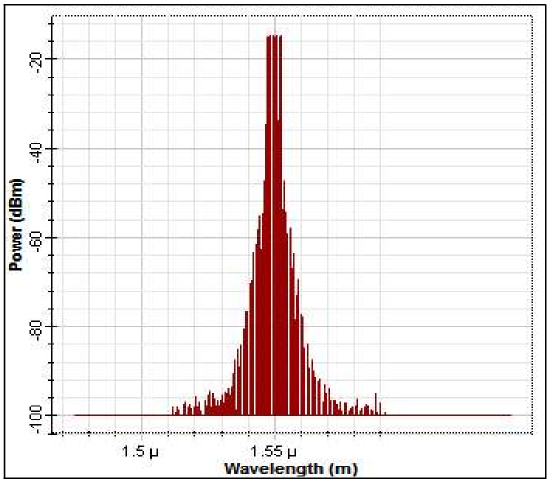


Figure (C-44):- All signals after combiner from the OSA.

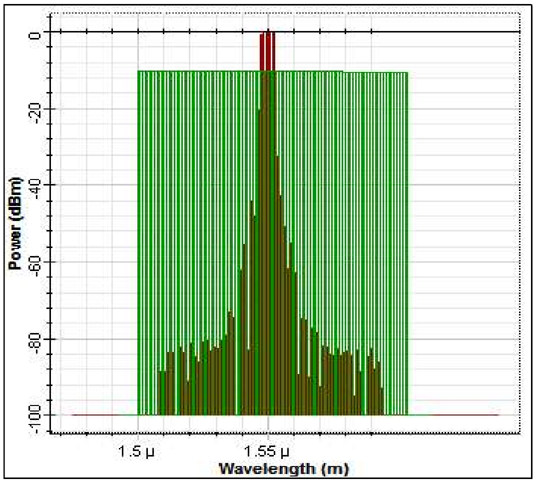


Figure (C-46):- Power versus wavelength after EDFA_2 (red color mean power, and green color mean noise from the OSA.

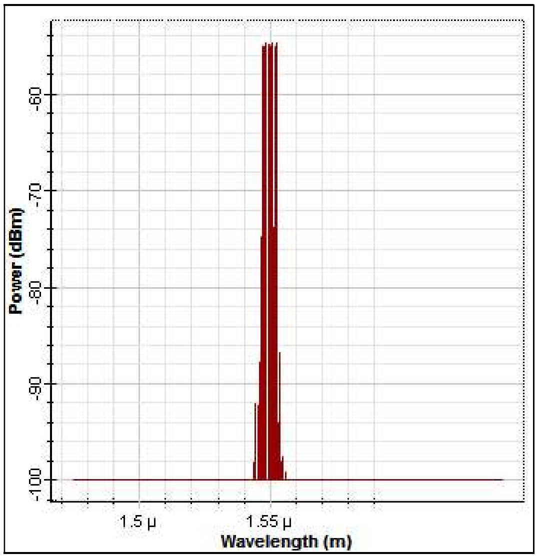


Figure (C-45):- All 8-channels after 242.5km transmission link.

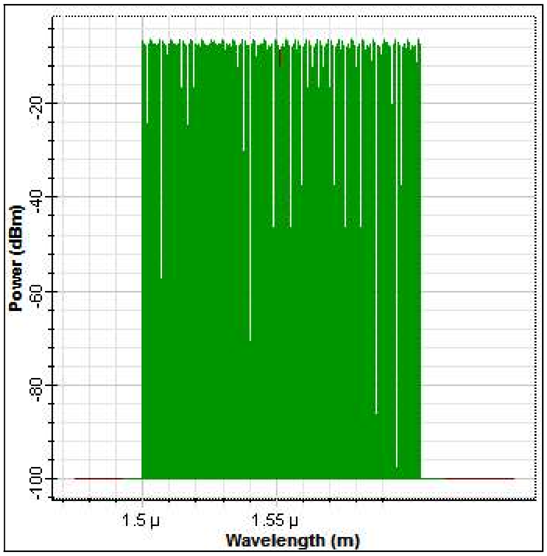


Figure (C-47):- Output Signal 1 after AWG-DE-MUX.

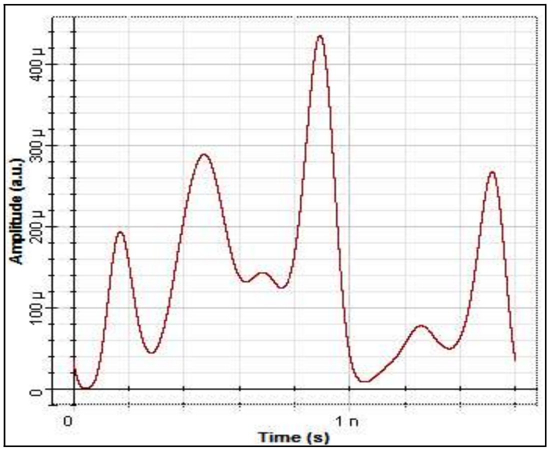


Figure (C-48):- Output Signal_ 2(193.2THz), after PIN from oscilloscope visualizer.

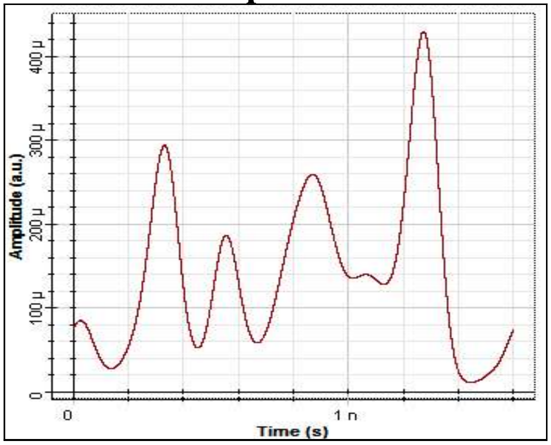


Figure (C-49):- Output Signal_ 3(193.3THz), after PIN from oscilloscope visualizer.

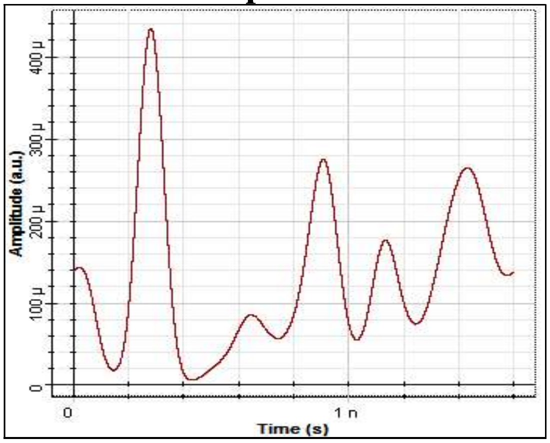


Figure (C-50):- Output Signal_ 4(193.4THz), after PIN from oscilloscope visualizer.

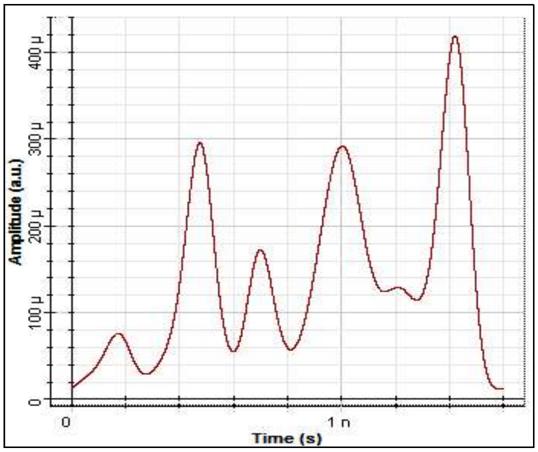


Figure (C-51):- Output Signal_ 5(193.5THz), after PIN from oscilloscope visualizer.

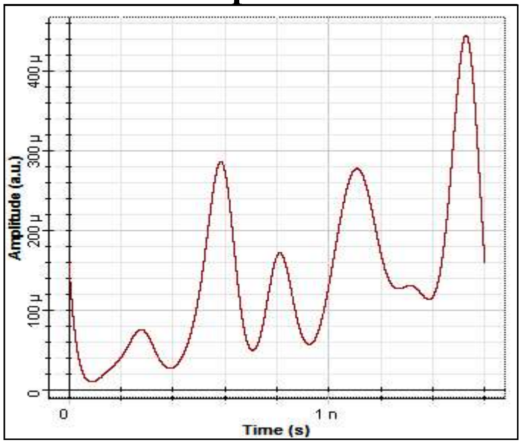


Figure (C-52):- Output Signal_ 6(193.6THz), after PIN from oscilloscope visualizer.

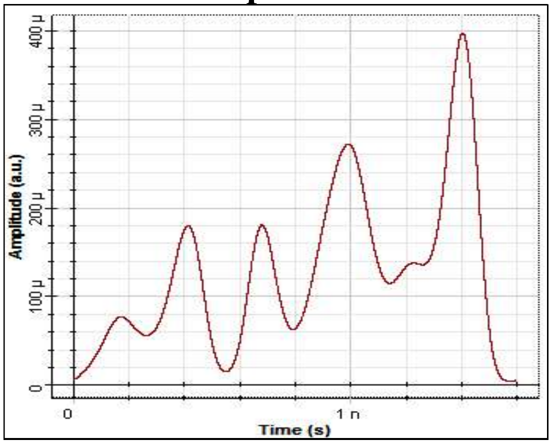


Figure (C-53):- Output Signal_ 7(193.7THz) after PIN from oscilloscope visualizer.

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إقرار المشرف

أشهد بأن إعداد الأطروحة الموسومة بـ "**تقييم (WDM)وتطبيقاته على شبكة ضوئية**" قد جرى تحت إشرافي في جامعة الموصل / كلية علوم الحاسوب والرياضيات وهي جزء من متطلبات نيل شهادة دكتوراه فلسفة في علوم الحاسوب.

التوقيع:
الاسم: **أ.م.د. خليل أبراهيم السيف**
التاريخ: / / ٢٠١١

إقرار المقيم اللغوي

أشهد بأن إعداد الأطروحة الموسومة بـ " **تقييم (WDM)وتطبيقاته على شبكة ضوئية** " قد تمت مراجعتها من الناحية اللغوية وتصحيح ما ورد فيها من أخطاء لغوية وتعبيرية وبذلك أصبحت الأطروحة مؤهلة للمناقشة بقدر تعلق الأمر بسلامة الأسلوب وصحة التعبير.

التوقيع:
الاسم: **أ.م.د. حسين علي أحمد**
التاريخ: / / ٢٠١١

إقرار رئيس لجنة الدراسات العليا

بناءاً على التوصيات التي تقدم بها المشرف والمقيم اللغوي أرشح هذه الأطروحة للمناقشة.

التوقيع:
الاسم: **أ.م.د. نجلاء بديع الدباغ**
التاريخ: / / ٢٠١١

إقرار رئيس القسم

بناءاً على التوصيات التي تقدم بها المشرف والمقيم اللغوي ورئيس لجنة الدراسات العليا أرشح هذه الأطروحة للمناقشة.

التوقيع:
الاسم: **أ.م.د. خليل أبراهيم السيف**
التاريخ: / / ٢٠١١

قرار لجنة آلمناقشه

نشهد إننا أعضاء لجنة التقويم آلمناقشه قد إطلعنا على الأطروحه آلموسومه

" تقييم المازج ألمقسم للأطوال الموجيه الضوئيه وتطبيقاتها على شبكه ضوئيه"

وناقشنا الطالب **عيسى إبراهيم عيسى آلجبوري** في محتوياتها وفيما له علاقه بها بتأريخ ٢٠١١/٩/٢١ وإنها جديرة لنيل شهادة دكتوراه فلسفه في علوم الحاسوب .

التوقيع:

الأسم: **د. باسل يونس ذنون**

المرتبه العلميه: **أستاذ**

التاريخ : / /٢٠١١

رئيس اللجنه

التوقيع:

الأسم: **د. عبدالمنعم صالح رحمه**

المرتبه العلميه: **أستاذ**

التاريخ : / /٢٠١١

عضو اللجنه

التوقيع:

الأسم: **د. عبدالآله عبدالجبار عبدالله**

المرتبه العلميه: **أستاذ مساعد**

التاريخ : / /٢٠١١

عضو اللجنه

التوقيع:

الأسم: **د. إبتسام رحيمه كريخي السعيدي**

المرتبه العلميه: **أستاذ مساعد**

التاريخ : / /٢٠١١

عضو اللجنه

التوقيع:

الأسم: **د. منار يونس كشموله**

المرتبه العلميه: **أستاذ مساعد**

التاريخ : / /٢٠١١

عضو اللجنه

التوقيع:

الأسم: **د. خليل إبراهيم آلسيف**

المرتبه العلميه: **أستاذ مساعد**

التاريخ : / /٢٠١١

عضو اللجنه (آلمشرف)

قرار مجلس الكليه

إجتمع مجلس كلية علوم الحاسوب والرياضيات بجلسته ( ) ألمنعقده بتأريخ / /٢٠١١ وقرر منحه شهادة دكتوراه فلسفه في علوم الحاسوب.

التوقيع:

الأسم: **د.احمد محمد جمعة**

مقرر مجلس كلية علوم الحاسوب والرياضيات

التاريخ: / /٢٠١١

التوقيع:

الأسم: **أ. د. ظافر رمضان مطر**

عميد كلية علوم الحاسوب والرياضيات

التاريخ: / /٢٠١١

المستخلص

تم تصميمِ ومحاكاة شبكة مازج الاطوال الموجية المقسمة ضوئيا" وتطبيقاتها بإسْتِعْمال مكبرات الاشارة الضوئيه الحاوية على عنصر الايربيوم، الذي يستخدم في تكبير الإشاراتِ الواهنه خلال رحلتها في الليف البصري، واستخدام وصلة ليف لتَعويض التفرّقِ في الإشاراتِ البصريةِ، اعتمد في هذا التصميم على ليف قياسيٍ أحادي النمط نوع ٢٨ الذي يُستَعملُ حالياً كعمود فقري للبنية التحتية للأتصالات الضوئية في جمهورية العراق.

ولتقييم اداء الشبكة الضوئية استخدم في هذة المحاكاة أربعة لوحات عمل متعددة القنوات مع معدل بيانات (٨×١٠ جيجا بت لكل ثانية و ١٦×٤٠ جيجا بت لكل ثانية و ×١٠ جيجا بت لكل ثانية كمازج موجّه المصفوفه)على وصلةِ الإرسالِ البصريةِ (١٥٠ كيلومتر، ١٢٠ كيلومتر، و٢٤٢.٥ كيلومتر) على التوالي مع أقل ضرر للنظام والأخذ بنظر الإعتبار وجود المكونات (سلبية / نشيطة). وتبين نَتائِجَ المحاكاةَ بأنّ معدل ارسال البيانات أرسل وجهز بنجاح مع كلّفَ بنى تحتيه قليلة- فعالة وحققت أداءا" جيدا" للنظام. وبمراقبة (معامل النوعية واقل معدل خطأ في البيانات المرسله وطاقة الاشارة الخارجة) خلال النظامِ المرئي ،ظهرت نَتائِج مقبولة. وتم اختبار وتحقيق النتائج من خلال المنتج البرمجي (نظام-ضوئي-٧) المرخص لنا بالعمل به من قبل الشركة الكندية المنتجة.

ومن خلال نتائج التجربة الاولى التي لم تعالج فيها مشاكل اللاخطية لم نحصل على طاقة اشارة خارجة ولم نحصل على عين المراقبة لمحلل معدل خطأ البيانات في جهة الاستلام, ولتجاوز المشكلة التي ظهرت في التجربة انفة الذكر, تم استخدام مكبرات الاشارة الضوئيه الحاوية على عنصر الايربيوم لتحسين الاشارة المستلمة وتقليل انحدارها وتم ادارة مشكلة التفرق في الاشارة باستخدام ليف بصري ذو مواصفات خاصة في التجارب الثانية والثالثة والرابعه. وان النتائج التي تحققت من التجربة الثانية عند طول الليف البصري ١٥٠ كيلومتر (معدل خطأ البيانات اقل من ١٠$^{\wedge-١٠}$ ومعدل طاقة الاشارة -٥ ديسبل متر ومعدل ضوضاء الطاقة -٣٧ ديسبل متر) وللتجربة الثالثة عند طول الليف البصري ١٢٠ كيلومتر(معدل خطأ البيانات اقل من ١٠$^{\wedge-٣٠}$ ومعدل طاقة الاشارة -٤٧.٥ ديسبل متر واعلى معدل لمعامل النوعية ١٠.٤٨٧٥) وللتجربة الرابعه بطول لليف البصري ٢٤٢.٥ كيلومتر(الكسب الكلي -٣.٦٨٥٦ ديسبل متر والاشارة الداخلة ٤.٠٤٠٢

ديسبل متر والشارة الخارجة ٠.٣٥٤٥ ديسبل متر وضوضاء الاشارة الخارجة ١.٤٢٤٨ ديسبل متر ومعدل الطاقة –٦.٤٢٥٥ ديسبل متر).

إن شبكة مازج الأطوال الموجية المقسمة ضوئيا" وتطبيقاته ، الذي يُمْكِنُهما المُسَاهَمَة في تَزويد عرض حزم غير محدود بكلف قليله, لكُلّ مديات خدمة أنظمةِ إتصالِ الألياف الضوئية التي تصلحُ مثلا للإتصال بالإنترنتِ، أعمال إلكترونية، مجتمع إلكتروني، ليف إلى البيتِ ، صوت على بروتوكول الإنترنتِ ، فيديو، وتفاعلات متعددة الأوساط. وبالتالي فان شبكة مازج الاطوال الموجية المقسمة ضوئيا" تقدم خصائص قيمة كقابلية التوسع والمرونة والشفافية والغاء الحاجة الى عمليات (بصري – كهربائي– بصري).

جامعة الموصل
كلية علوم الحاسوب والرياضيات

تقييم المازج المقسم للأطوال الموجيه الضوئية وتطبيقاتها على شبكه ضوئية

عيسى إبراهيم عيسى آلجبوري

أطروحة دكتوراه
علوم الحاسوب

بإشراف
الأستاذ المساعد الدكتور
خليل إبراهيم آلسيف

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