Performance Analysis of long-distance WDM dispersion-managed transmission system using dispersion compensating fiber and FWM effects on optical communication system

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Submitted by:

Bhawna Utreja

Roll No. 800861021

Under the guidance of

Dr. Hardeep Singh

Assistant Professor

ECED, TU

Electronics and Communication Engineering Department

THAPAR UNIVERSITY, PATIALA

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CERTIFICATE

I hereby declare that work which is presented in the thesis entitled "**Performance Analysis of long-distance WDM dispersion-managed transmission system using dispersion compensating fiber and FWM effects on optical communication system**" is partial fulfillment of the requirement for the award of degree of Master of Engineering in Electronics and communication Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the guidance of Dr. Hardeep Singh.

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

Bhawna

Bhawna Utreja

(800861021)

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

Dr.Hardeep Singh
Assistant Professor
Electronics and Communication Engineering Department,
Thapar University,
Patiala-147004 (Punjab).

9.7.10

Dr. A. K. Chatterjee

Head, ECED

Thapar University, Patiala.

12.7.10

Dr. R. K. Sharma

Dean, Academic Affairs

Thapar University, Patiala.

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Bhawna Utreja
Roll No. 800861021

ABSTRACT

Telecommunication Network based on optical fiber technolgy have become a major information transmission system, with high capacity optical fiber links encircling the globe in both terrestial and undersea installations. In this dissertion fiber non-linearities have been studied, and analyzed the effect of various parameters of received power. The non-linearity in optical fibers fall into two categories: one is stimulated scattering (Raman and Brillouin), and the other is the optical Kerr effect due to changes in the refractive index i.e. self phase modulation, cross phase modulation and four wave mixing. The optical transmission is immune to electromagnetic interference and other environmental factors. In contrast the copper wire system and microwave links face a great reduction in transmission data due to these factors.

In the standard single mode fibers, the polarization mode dispersion is the phenomenon that cause the hurdles to reach the high bit-rate-distance product of amplified lightwave system. Non linearity effects arose as optical fiber data rates, transmission lengths, number of wavelengths, and optical power levels increased. Although fiber optics system excel in high bandwidth applications, optical fiber has been slow to achieve its goal to the premises or to solve the last mile problem. However, as bandwidth increases, more and more progress towards this goal can be observed.

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CHAPTER 1
INTRODUCTION

1.1 Optical Fiber Communication:

Now we are in twenty first century, the era of Information technology. There is no doubt that information technology has had an exponential growth throughout modern telecommunication system [1-5]. Particularly optical fiber communication plays a vital role in development of high quality and high-speed telecommunication system. Today, optical fiber are not only used in telecommunication but also used in internet and local area network (LAN) to achieve high signalling rates.

However, there is need for large capacities in long haul optical transmission, greater channel density has been achieved by WDM system and bit rate for each channel is also being increased. At 40 Gbits/s, which is in next generation of transmission rates, Polarization mode dispersion (PMD) which does not present a problem at bit rate of 10 Gbits/s and below can impose significant limitation on distance over which transmission is possible [6].

Transmission impairment, which are general not significant in regenerative system, accumulate along the transmission link when amplifier are used, so they cannot be simply ignored, and this put a new challenge to transmission design engineers. Non-Linear effects is significantly more complex, they generate not only dispersion on each channel, but also crosstalk between channels. Stimulated Raman Scattering (SRS), Four Wave Mixing (FWM), Self Phase Modulation (SPM), Cross Phase Modulation are examples of non-linear effects. Four Wave Mixing effect is due to third order electric susceptibility is called optical kerr effect and occur when light of two or more wavelengths is launched into fiber and it give rise to a new wavelength of which does not coincide with any of other wavelength.

Non-Linear effects such as self phase modulation and cross phase modulation combined with group velocity dispersion result in intensity distortion of the propagating signals in WDM link.

1.2 Historical Perspective of Optical Communication:

The use of light for transmitting information from one place to another place is a very old technique. In 800 BC., the Greeks used fire and smoke signals for sending information like victory in a war, alertting against enemy, call for help, etc. Mostly only one type of signal was conveyed. During the second century B.C. optical signals were encoded using signaling lamps so that any message could be sent. There was no development in optical communication till the end of the 18th century. The speed of the optical communication link was limited due to the requirement of line of sight transmission paths, the human eye as the receiver and unreliable nature of transmission paths affected by atmospheric effects such as fog and rain. In 1791, Chappe from France developed the semaphore for telecommunication on land. But that was also with limited information transfer [7].

In 1835, Samuel Morse invented the telegraph and the era of electrical communications started throughout the world. The use of wire cables for the transmission of Morse coded signals was implemented in 1844. In 1872, Alexander Graham Bell proposed the photo phone with a diaphragm giving speech transmission over a distance of 200 m. But within four years, Graham Bell had changed the photophone into telephone using electrical current for transmission of speech signals. In 1878, the first telephone exchange was installed at New Haven. Meanwhile, Hertz discovered radio waves in 1887. Marconi demonstrated radio communication without using wires in 1895. Using modulation techniques, the signals were transmitted over a long distance using radio waves and microwaves as the carrier. During the middle of the twentieth century, it was realized that an increase of several orders of magnitude of bit rate distance product would be possible if optical waves were used as the carrier [8].

Table 1.1 shows the different communication systems and their bit rate distance product.Here the repeater spacing is mentioned as distance. In the old optical communication system, the bit rate distance product is only about 1 (bit/s)-km due to enormous transmission loss (105 to 107 dB/km). The information carrying capacity of telegraphy is about hundred times lesser than a telephony. Even though the high-speed coaxial systems were evaluated during 1975, they had smaller repeater spacing. Microwaves are used in modern communication systems with the increased bit rate distance product. However, a coherent optical carrier like laser will have more information carrying capacity.

So the communication engineers were interested in optical communication using lasers in an effective manner from 1960 onwards. A new era in optical communication started after the invention of in 1960 by Maiman. The light waves from the laser, a coherent source of light waves having high intensity, high monochromaticity and high directionality with less divergence, are used as carrier waves capable of carrying large amount of information compared with radio waves and microwaves. Subsequently H M Patel, an Indian electrical engineer designed and fabricated a CO2 laser.

1.2.1 Unguided Optical Communication:

The optical communication systems are different from microwave communication systems in many aspects. In the case of optical systems, the carrier frequency is about 100 THz and the bit rate is about 1T bit/s. Further the spreading of optical beams is always in the forward direction due to the short wavelengths. Even though it is not suitable for broadcasting applications, it may be suitable for free space communications above the earth's atmosphere like intersatellite communications. For the terrestrial applications, unguided optical communications are not suitable because of the scattering within the atmosphere, atmospheric turbulence, fog and rain. The unguided optical communication systems played important role in the research between 1960 and 1970. For longer range unguided optical communication systems the neodymium laser (1.06 mm) and the carbon dioxide laser (10.6 mm) were the most favorable sources. Using narrow bandgap compound semiconductors like indium sulphide (for neodymium laser) and cadmium mercury telluride (for CO2 laser) one can have better detection using heterodyne detection techniques.

Table 1.1 Bit rate distance product

System	**Bit rate distance product (bit/s) – km**
Old optical communication	1
Telegraph	10
Telephone	10^3
Coaxial cables	10^5
Microwaves	10^6
Laser light in open air	10^9

1.2.2 The Birth of Fiber Optic Systems:

To guide light in a waveguide, initially metallic and non-metallic wave guides were fabricated. But they have enormous losses. So they were not suitable for telecommunication.

Tyndall discovered that through optical fibers, light could be transmitted by the phenomenon of total internal reflection. During 1950s, the optical fibers with large diameters of about 1 or 2 millimetre were used in endoscopes to see the inner parts of the human body.

Optical fibers can provide a much more reliable and versatile optical channel than the atmosphere, Kao and Hockham published a paper about the optical fiber communication system in 1966. But the fibers produced an enormous loss of 1000 dB/km. But in the atmosphere, there is a loss of few dB/km. Immediately Kao and his fellow workers realized that these high losses were a result of impurities in the fiber material. Using a pure silica fiber these losses were reduced to 20 dB/km in 1970 by Kapron, Keck and Maurer. At this attenuation loss, repeater spacing for optical fiber links become comparable to those of copper cable systems. Thus the optical fiber communication system became an engineering reality.

1.3 Thesis Objective:

1. To investigate the length of fiber on WDM system
2. To investigate the channel spacing 0.1 nm to 3 nm in FWM system.
3. To investigate the bit rate 5 Gb/s to 40 Gb/s bit rate bit rate in FWM system.

1.4 Thesis Organisation:

In chapter 1, the basic introduction, history,thesis objectives have been discussed. In chapter 2, literature survey of FWM and WDM have been discussed. In chapter 3, we have been discussed the basics of fiber optics, Dispersion, Non-linearity effects, FWM. In chapter 4, effects of length of fiber on WDM system, effect of channel spacing and data rates on FWM have been studied.

CHAPTER 2

LITERATURE SURVEY

2.1 Literature Review of FWM Modeling:

The basic quantum mechanical theory relating the microscopic material properties to the macroscopic nonlinear polarization which can be used in the Maxwell's equations was developed in [9, 10]. The first observations of FWM in bulk crystals, rectangular and planar waveguides was made in the early 1960s soon after the advent of the laser [11]. This was followed by the observation of FWM in low loss multi-mode silica glass fibers soon after its invention in the early 1970s [12].

An analytic solution to the governing wave-equation including the various nonlinear effects is not possible for the general situation of dispersive fibers. In the simulation approach one can use complex numerical methods to solve the wave-equation and system performance is assessed for design. This approach offers accuracy at the expense of computational complexity and lack of insight into the physical effects at play. The other approach involves creating simplified analytic models for particular phenomena using reasonable assumptions and approximations. These analytic models are less general than the numerical solution based simulations but they offer the transmission designer insight into the physical mechanism and makes the task of balancing the numerous effects and design variables more manageable. Analytic models focusing on typical operating conditions found in practical optical links can be found for SPM [13-15], XPM [16-20], SRS [21-23], SBS [24].

An approximate analytic model for FWM noise power generated by continuous-wave (CW) pump channels propagating in low loss single mode fiber was first developed in [25] for a single span link. In [26] the FWM due to CW waves for a multiple span link was derived. The model was extended to non-return-to-zero on-off-keying (NRZ-OOK) modulated channels in [27,28] but FWM noise bandwidth was taken as infinitely narrow and group velocity dispersion (GVD) induced inter-channel pulse walk-off was neglected. In [29,30] a finite-band FWM noise theory without walk-off was introduced for non-return-to-zero on-off keying (NRZ-OOK) and return-to-zero on-off-keying (RZ-OOK) modulated channels.

In the FWM models mentioned thus far GVD is taken into account only with respect to the phase mismatch it produces amongst the channels participating in the FWM. The interchannel pulse walk-off due to GVD is not accounted for. Due to the GVD of the fiber, channels at different wavelengths have different group velocities. This means that the data pulse train on different channels will experience different delay as the pulses travel down the fiber. This relative delay between the data pulses on neighboring channels is called interchannel pulse walk-off. In itself the inter-channel walk-off poses no impairment to the transmission quality but it does play an important role when evaluating the interaction of the neighboring channels through fiber nonlinearity. It is seen that inter-channel walk-off plays a very important role for the other inter-channel nonlinearities mentioned above XPM and SRS. In an initial version of a finite-band noise model including walk-off was presented for degenerate FWM (D-FWM).

Recently there has been a lot of interest in using return-to-zero differential-phase-shiftkeying (RZ-DPSK) modulation format for high speed WDM transmission [8, 31-33]. RZ6 DPSK offers two main advantages over the conventional return-to-zero on-off-keying (RZOOK) modulation scheme. Firstly it has been demonstrated that with balanced detection the RZ-DPSK format requires approximately 3 dB lower OSNR for the same bit-error-ratio (BER) performance as compared to RZ-OOK [8, 34,35]. Secondly the RZ-DPSK format is also thought to be generally more resilient to the transmission impairments caused by fiber nonlinearities [8]. Part of this higher resilience is thought to come from the intrinsic structure of the RZ-DPSK format in which the intensity profile in each bit slot remains the same as compared to the RZ-OOK in which the intensity is modulated for each bit according to the logic data [8]. This results in XPM creating less impairment through the pulse timing jitter resulting from overlap of the probe pulse with pulses with varying intensity profiles. Also because of the lower OSNR requirement for the same BER performance the RZ-DPSK systems can be operated at lower launch powers which should result in the further reduction of nonlinear impairments. So far no analytic model has been presented in the literature for the inter-channel FWM for the RZ-DPSK modulation format.

2.2 Literature review of WDM:

2.2.1 Background in WDM Communication Networks:

In recent years, the tremendous growths in Internet activities such as multimedia communications and networking have created an ever-increasing demand on network capacity. The wavelength division multiplexing/dense wavelength division multiplexing (WDM/DWDM) based networks have emerged as a very attractive option to gradually upgrade network transport capacity without huge investment in laying new optical cables. In the WDM/DWDM scheme, the existing fiber cables are used to carry increasing number of wavelengths instead of single wavelength carried by the fiber cables in the early 1990's. Originally started at 4 wavelength channels per fiber in the mid 1990's, current systems transporting up to 128 wavelength channels in a single fiber are commercially available (for example DWDM systems by Cisco). However, more commonly deployed systems support 32 to 64 channels. Aggregate system capacity has reached Tera bits/second milestone in system demonstrations by major vendors in 1998 [36-38]. Wavelength multiplexing and demultiplexing is seen as one of the enabling technologies to implement a WDM network. It provides functions for components such as optical amplifiers, wavelength converters, and optical cross-connects that are crucial to the performance of an entire system.

2.2.2 Wavelength Demultiplexing in WDM Networks

As a result of intensive research and development effort, the WDM technology is advancing at a brisk pace. In terms of laser source and transmission technology, the current industry record is set in a system which generated 1,022 channels using a single laser, and transmitted all 1,022 wavelength channels on a single fiber [39]. Future systems that can generate and transmit 10,000 channels in one fiber are envisioned. Noteworthy is the channel wavelength spacing in the Lucent demonstration which shrank from common DWDM standard of 50 GHz to 10 GHz with the goal of below 5GHz for future experiments [39]. The current trend is to pack more channels on a single fiber, with the long term objective of creating a revolutionary all optical and more intelligent network providing benefits of improved network efficiency and quality of service (QoS) in addition to a quantum leap in system capacity. These developments have created a large demand for high performance and flexible devices such as Wavelength Add/Drop Multiplexer (WADM) and Optical Cross-Connect (OCC), which are able to manipulate data paths through wavelength channels by optical means. One of the core functions repeatedly used in these devices is wavelength multiplexing and demultiplexing. It is not surprising that research to develop high performance wavelength demultiplexers with low channel cross talk, flat transmission characteristics, polarization independence, high channel count, and the ability to integrate with active components such as detectors, modulators, optical amplifiers has attracted strong interest in both academia and industry. The objective of these efforts is to produce a wavelength demultiplexer with 1) very high channel count, 2) good filter characteristics for each channel such as low cross talk, flat passing band, low signal to noise ratio, and so on, 3) ability for miniaturization and monolithic fabrication with active devices.

CHAPTER 3

FIBER OPTICS BASICS

3.1 Introduction:

Fiber optic technology is simply the use of light to transmit data. The general use of fiber optics did not begin until 1970s. Robert Maurer of Corning Glass Works developed a fiber with a loss of 20 dB/km promoting the commercial use of optical fiber. Since that time the use of fiber optics has increased dramatically. Advances in fiber technology, lower product costs, and installation have all contributed to the wide use of fiber.

The heaviest use of fiber is in the telecommunications industry. Telephone companies initially used fiber to transport high volumes of voice traffic between central office locations. During the 1980s telephone companies began to deploy fiber throughout their networks. Fiber technology allows companies to "future proof" networks. We use the phrase "future proof" because fiber is theoretically unlimited in bandwidth. Bandwidth is a measurement of the data carrying capacity of the media (in this case,fiber). The greater the bandwidth, the more data or information that can be transmitted. Copper has a bandwidth and a distance limitation, making it less desirable.

Benefits of fiber include:

1. High bandwidth for voice, video and data applications.
2. Optical fiber can carry thousands of times more information than copper wire. For example, a single-strand fiber strand could carry all the telephone conversations in the United States at peak hour.
3. Fiber is more lightweight than copper. Copper cable equals approximately 80 lbs./1000 feet while fiber weighs about 9lbs./1000 feet.
4. Low loss. The higher frequency, the greater the signal loss using copper cabling. With fiber, the signal loss is the same across frequencies, except at the very highest frequencies.
5. Reliability - Fiber is more reliable than copper and has a longer life span.
6. Secure - Fiber does not emit electromagnetic interference and is difficult to tap

3.2 Types of optical fiber:

Single mode fiber has a very small core causing light to travel in a straight line and typically has a core size of 8 or 10 microns. It has unlimited bandwidth that can go unrepeated for over 80 km, depending on the type of transmitting equipment. Single mode fiber has enormous information capacity, more than multimode fiber.

Multimode fiber supports multiple paths of light and has a much larger core and has a core size of 50 or 62.5 microns. The light travels down a much larger path in multimode fiber, allowing the light to go down several paths or modes.

Multimode fiber can be manufactured in two ways: step-index or graded index. Step-index fiber has an abrupt change or step between the index of refraction of the core and the index of refraction of the cladding. Multimode step-index fibers have lower bandwidth than other fiber designs.

Graded index fiber was designed to reduce modal dispersion inherent in step index fiber. Modal dispersion occurs as light pulses travel through the core along higher and lower order modes. Graded index fiber is made up of multiple layers with the highest index of refraction at the core. Each succeeding layer has a gradually decreasing index of refraction as the layers move away from the center. High order modes enter the outer layers of the cladding and are reflected back towards the core. Multimode graded index fibers have less attenuation (loss) of the output pulse and have higher bandwidth than multimode step-index fibers. We know that the light or the optical signals are guided through the silica glass fibers by total internal reflection. A typical glass fiber consists of a central core glass (50 mm) surrounded by a cladding made of a glass of slightly lower refractive index than the core's refractive index. The overall diameter of the fiber is about 125 to 200 mm. Cladding is necessary to provide proper light guidance i.e. to retain the light energy within the core as well as to provide high mechanical strength and safety to the core from scratches.

Based on the refractive index profile we have two types of fibers

(a) Step index fiber

(b) Graded index fiber.

(a) Step index fiber: In the step index fiber, the refractive index of the core is uniform throughout and undergoes an abrupt or step change at the core cladding boundary. The light rays propagating through the fiber are in the form of meridional rays which will cross the fiber axis during every reflection at the core cladding boundary and are propagating in a zig-zag manner as shown in figure 3.1a.

(b) Graded index fiber: In the graded index fiber, the refractive index of the core is made to vary in the parabolic manner such that the maximum value of refractive index is at the centre of the core. The light rays propagating through it are in the form of skew rays or helical rays which will not cross the fiber axis at any time and are propagating around the fiber axis in a helical (or) spiral manner as shown in figure 3.1b.

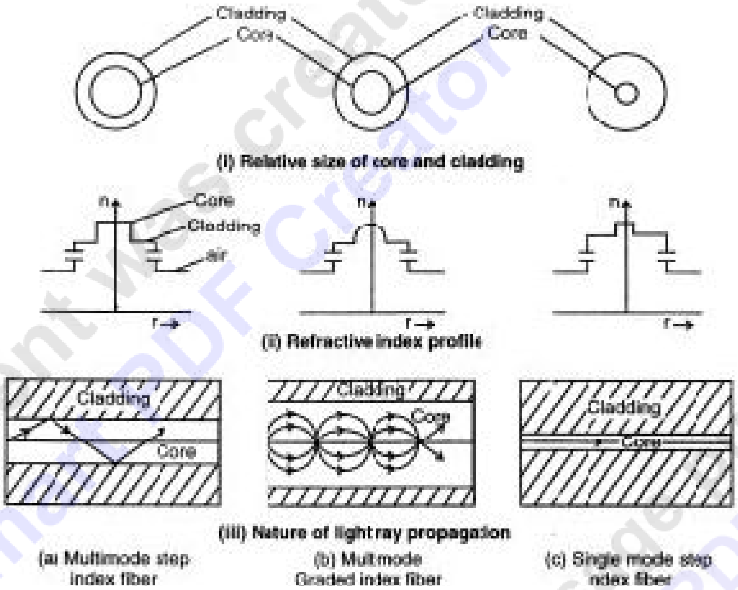


Figure3.1 : Different types of fiber

Based on the number of modes propagating through the fiber, there are multimode fibers and single mode fibers. Mode is the mathematical concept of describing the nature of propagation of electromagnetic waves in a waveguide. Mode means the nature of the electromagnetic field pattern (or) configuration along the light path inside the fiber. In metallic wave-guides there are transverse electric (TE) modes for which Ez = 0 but Hz ≠ 0 and transverse magnetic (TM) modes for which Hz = 0 but Ez ≠ 0 when the propagation of microwaves is along the *z*-axis. In optical fibers, along with TE and TM modes, there are also hybrid modes which have both axial electric and magnetic fields Ez and Hz. The hybrid modes are further classified into EH and HE modes. In EH modes, the axial magnetic field Hz is relatively strong whereas in HE modes, the axial electric field E*z* is relatively strong.

Based on the linearly polarized nature of light, today these modes are designated as linearly polarized (LP) modes. For example LP01 mode corresponds to HE11 mode. LP11 mode is the combination of HE21, TE01 and TM01 modes.

(c) Single mode fibers: In a single mode fiber, only one mode (LP01 mode) can propagate through the fiber (figure 3.1c). Normally the number of modes propagating through the fiber is proportional to its V-number.

In the case of single mode fiber, V-number 2.405. The single mode fiber has a smaller core diameter (10 mm) and the difference between the refractive indices of the core and the cladding is very small. Fabrication of single mode fibers is very difficult and so the fiber is expensive. Further the launching of light into single mode fibers is also difficult. Generally in the single mode fibers, the transmission loss and dispersion or degradation of the signal are very small. So the single mode fibers are very useful in long distance communication.

(d) Multimode fibers*:* For a multimode graded index fiber having parabolic refractive index profile core,

$N = V^2/4$

which is half the number supported by a multimode step index fiber. Generally in multimode fibers, the core diameter and the relative refractive index difference are larger than in the single mode fiber. In the case of multimode graded index fiber, signal distortion is very low because of self-focusing effects. Here the light rays travel at different speeds in different paths of the fiber because of the parabolic variation of refractive index of the core. As a result, light rays near the outer edge travel faster than the light rays near the centre of the core. In effect, light rays are continuously refocused as they travel down the fiber and almost all the rays reach the exit end of the fiber at the same time due to the helical path of the light propagation. Launching of light into the fiber and fabrication of the fiber are easy. These fibers are generally used in local area networks.

3.3 Dispersion and Losses in Fiber:

Dispersion in the fiber means the broadening of the signal pulse width due to dependence of the refractive index of the material of the fiber on the wavelength of the carrier. If we send digitized signal pulses in the form of square pulses, they are converted into broadened gaussian pulses due to dispersion. The dispersion leads to the distortion (or) degradation of the signal quality at the output end due to overlapping of the pulses. There are two kinds of dispersion mechanisms in the fiber: (i) Intramodal dispersion and (ii) Intermodal dispersion[40].

The dispersion effects can be explained on the basis of behaviour of group velocities of the guided modes in the optical fiber. Group velocity is the velocity at which the energy in particular mode travels along fiber. The propagation constant and group velocity is given by:

$\beta \; = \; n_1 \frac{2\Pi}{\lambda} = \frac{n_1 \omega}{C}$

$V_g = \frac{d\omega}{d\beta} \; = \frac{d\lambda}{d\beta}\frac{d\omega}{d\lambda}$

Since $\beta \; = \; n_1 \frac{2\Pi}{\lambda}$,

$\frac{d\beta}{d\lambda} = \frac{2\Pi}{\lambda}\frac{dn_1}{d\lambda} - n_1\frac{2\Pi}{\lambda^2}$

$Using \; \omega = \frac{2\Pi \; C}{\lambda}$

$\frac{d\omega}{d\lambda} = \frac{2\Pi \; C}{\lambda^2}$

Therefore , $V_g = \frac{d\lambda}{d\beta}\frac{d\omega}{d\lambda} = - \frac{\frac{2\Pi \; C}{\lambda^2}}{\frac{2\Pi}{\lambda}\frac{dn_1}{d\lambda} - n_1\frac{2\Pi}{\lambda^2}} = \frac{C}{n_1 - \lambda\frac{dn_1}{d\lambda}} = \frac{C}{N_g}$

where *Ng* is called the group index of the fiber. Thus the group velocity and phase velocity (*vp* =) are different in the optical fiber. Otherwise an optical fiber is a dispersive medium. Intramodal dispersion arises due to the dependence of group velocity on the wavelength. Further it increases with the increase in spectral width of the optical source. This spectral width is the range of wavelengths emitted by the optical source. For example in the case of LED, it has a large spectral width about 40 nm since it emits wavelengths from 830– 870 nm with the peak emission wavelength at 850 nm. In the case of laser diode which has a very narrow spectral width, the spectral width is about 1 or 2 nm only. Thus the intramodal dispersion can be reduced in an optical fiber using single mode laser diode as an optical source. Intramodal dispersion arises due to the dispersive properties of the optical fiber material (material dispersion) and the guidance effects of the optical fiber (waveguide dispersion).

(a) Material Dispersion (or) Chromatic Dispersion:

This dispersion arises due to the variation of the refractive index of the core material with the wavelength or frequency of light. It is directly proportional to the frequency bandwidth of the transmitted pulse. A material exhibits material dispersion when $\frac{d^2 n_1}{d\lambda^2} \neq 0$ For pure silica, the material dispersion tends to zero at the wavelength of 1.3 mm. Further by using an optical source with a narrow spectral width, the material dispersion can be reduced. For shorter wavelengths around 0.6 mm to 0.8 mm, the material dispersion exponentially rises to a higher value.

(b)Waveguide dispersion: This dispersion arises due to the finite frequency bandwidth and the dependence of the mode group velocity on the frequency of light. Higher the frequency bandwidth of the transmitted pulse, higher will be the waveguide dispersion. The amount of waveguide dispersion depends on the fiber design like core radius, since the propagation constant β is a function of $\frac{a}{\lambda}$ In the case of single mode fibers, waveguide dispersion arises when $\frac{d^2\beta}{d\lambda^2} \neq 0$. In the case of multimode fibers, most of the modes propagate far from the cutoff value. Therefore then all are almost free from waveguide dispersion.

Among the two dispersions,

material dispersion > waveguide dispersion.

3.4 Wavelength Division Multiplexing (WDM):

With wavelength division multiplexing different communication links share the same fiber on the basis of wavelength. Information associated with each link first goes through a modulation process . The result is the generation of light modulated by the information [41]. The light from the links can be coupled into a single fiber optic and then transmitted together down the fiber. At the receiving end different links can be separated on the basis of wavelength using demultiplexing operation. The resulting received information is then directed to the appropriate data device destination.

In the figure different wavelengths carrying separate signals are multiplexed by the multiplexer and then they are transmitted through a single fiber. At the receiver end, the separate signals at different wavelengths are demultiplexed by the demultiplexer and are given to separate receivers. From the receiver side also the signals can be transmitted in the same manner through the same fiber. Thus instead of handling a single channel with single wavelength and limited bit rate (10 Gb/s), the bit rate is raised to about 10 Tb/s, hence the information capacity of the fiber is increased by WDM technique. In principle any optical wavelength demultiplexer can be also used as a multiplexer. Thus for simplicity the word ‘multiplexer’ is often used as a general term to refer to both multiplexers and demultiplexers, except when it is necessary to distinguish the two devices or functions. There are two types of wavelength division multiplexers:

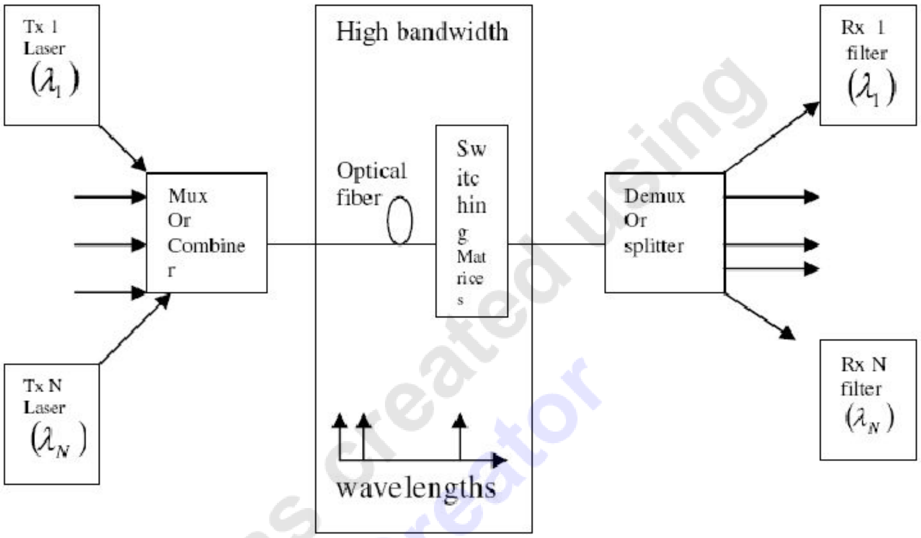


Figure 2.2 WDM architecture

1. Angularly dispensive devices such as **prisms** or **gratings.**

2. Interference filter based devices such as **multilayer thin film interference filters** or single mode integrated optical devices [42].

1. Grating as a multiplexer: A plane diffraction grating can be taken as a wavelength division multiplexer. Taking θ as the angle of diffracted beam,the dispersive power of the grating is given by

$$\frac{d\theta}{d\lambda}=2\,\frac{\tan\theta}{\lambda}$$

The combination of different wavelengths (multiplexing) or separation of different wavelengths (demultiplexing) is directly proportional to the dispersive power of grating i.e. directly proportional to tanθ and inversely proportional to λ. The different signals carried by different wavelengths $\lambda_{1,}$ $\lambda_{2,}$ λ_3 are collimated by a convex lens and then are incident on a reflection grating. The reflected light is a composite light or multiplexed light. The same grating multiplexer can also act as demultiplexer if we change the direction of the light beam.

(ii) Interference filter as a multiplexer: There are reflection interference filter type and absorption interference filter type multiplexers. Among these, absorption filter type is not used widely due to their higher absorption of signals. In the reflection type filter, there is a flat glass substrate upon which multiple layers of different dielectric films are deposited for wavelength sensitivity. These filters can be used in series to separate additional wavelength channels.

3.5 Non-Linearities:

In optical communication systems the term nonlinearity refers to the dependence of the system on power of the optical beam/s being launched into the fiber cable. Nonlinear effects in optical fibers have become an area of academic research and of great importance in the optical fiber based systems. Several experiments in the past have shown that the deployment of high-bit-rate multiwavelength systems together with optical amplifiers creates major non linear effects such as SRS, SBS, SPM, XPM and FWM.

The system design engineers should not deploy high-bit-rate (>10 Gbit/s per channel) multiwavelength systems without considering the nonlinear effects and their impact on these systems. We will also see various advantages and disadvantages of the above mentioned nonlinear effects in order to decide whether they affect the performance of these systems in a positive way or a negative way .

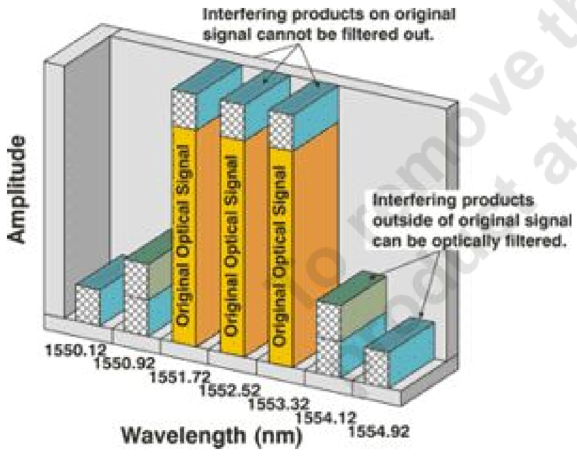
Nonlinearities in optical fibers originate due to the third order susceptibility (X^3). The real part of the equation gives us SPM, XPM and FWM while the imaginary part of the equation gives us SBS and SRS[43]. The nonlinear effects depend on the transmission length of the optical fiber. The longer the optical fiber, the more the light interacts with the fiber material and the greater the nonlinear effects.

When the optical power of the signal being transmitted through the fiber cable is increased then nonlinear scattering or stimulated scattering takes place. Stimulated scattering is transferring energy from the incident wave to another. In this case scattered wave at lower frequency (longer wavelength) with small energy difference is released in the form of phonons. Phonons are analogous to photons but only differ from it in terms of quantum properties. These scattered waves are also referred to as stokes waves. We can also say that stimulated scattering is another form of attenuation mechanism since the incident wave loses its energy during this process .

3.6 Four Wave Mixing:

Usually only systems that carry a number of simultaneous wavelengths, such as DWDM systems, exhibit four wave mixing (FWM). Caused by the nonlinear nature of the refractive index of the optical fiber itself, the FWM effect is similar to composite triple beat (CTB) distortion observed in CATV systems. CTB is also caused by nonlinearity, this time in the electrical amplifier chain or one of the optical components, usually the laser. CTB, like FWM, is classified as a third-order distortion phenomenon. Third-order distortion mechanisms generate third-order harmonics in systems with one channel. In multichannel systems, third-order mechanisms generate third-order harmonics and a gamut of cross products. These cross products cause the most problems since they often fall near or on top of the desired signals. Consider a simple three-wavelength (l_1, l_2, and l_3) system that is experiencing FWM distortion. In this simple system, nine cross products are generated near l_1, l_2, and l_3 that involve two or more of the original wavelengths. Note that there are additional products generated, but they fall well away from the original input wavelengths. Let us assume that the input wavelengths are l_1 = 1551.72 nm, l_2 = 1552.52 nm, and l_3 = 1553.32 nm. The interfering wavelengths that are of most concern in our hypothetical three wavelength system are: $l_1 + l_2 - l_3$= 1550.92 nm, $l_1 - l_2 + l_3$= 1552.52 nm, $l_2 + l_3 - l_1$= 1554.12 nm, $l_1 - l_2 + l_3$=1552.52 nm, $2l_1 - l_3$= 1550.12 nm, $2l_3 - l_1$1554.92 nm, $l_2 + l_3 - l_1$= 1554.12 nm, $2l_2 - l_1$= 1553.32 nm, $2l_3 - l_2$= 1554.12 nm It can be seen that three of the interfering products fall right on top of the original three signals. The remaining six products fall outside of the original three signals. These six can be optically filtered out. Because the three interfering products that fall on top of the original signals are mixed together, they cannot be removed by any means. Figure 3.3 shows the results graphically. The three tall solid bars are the three original signals. The shorter cross-hatched bars represent the nine interfering products. The number of interfering products increases as ½ • (N^3-N^2) where N is the number of signals.

Figure 3.3- FWM products for a three wavelength system



CHAPTER 4

PERFORMANCE LIMIT OF LONG DISTANCE WDM DISPERSION MANAGED TRANSMISSION SYSTEM USING DISPERSION COMPENSATING FIBER

In conventional long-distance wavelength-division multiplexed (WDM) dispersion-managed transmission systems, since both the dispersion-shifted fiber (DSF) and the standard single-mode fiber (SMF) have positive dispersion slope, perfect dispersion compensation can be achieved only for a single wavelength channel. In contrast, WDM dispersion managed systems comprised of a SMF followed by a higher order dispersion compensation fiber (DCF)[39]. In this chapter, We investigate the performance limit of WDM systems at different length if single mode fiber by employing the higher order DCF.

4.1 Introduction:

The system model shown in Fig. 4.1 is used for succeeding numerical simulations. Intensities of light sources are modulated by 32-bit pseudorandom electrical binary pulses in the sinusoidal return-to-zero (RZ) format (duty cycle)[44]. At the next stage, optical pulses pass through phase modulators driven synchronously by the inverted sinusoidal waveform to partially cancel out the SPM. The prechirped optical signals are then multiplexed and launched into the SMF. Chromatic dispersion of the SMF is periodically compensated by a relatively short piece of DCF's placed at the end of the compensation interval. At the receiving side, WDM signals are demultiplexed and pass through optical channel selecting filters (CSF's). We used Lorentzian bandpass filters for this purpose. An ideal square-law detector converts the intensity of incoming optical pulses to the electric current followed by a Bessel–Thompson low-pass filter.

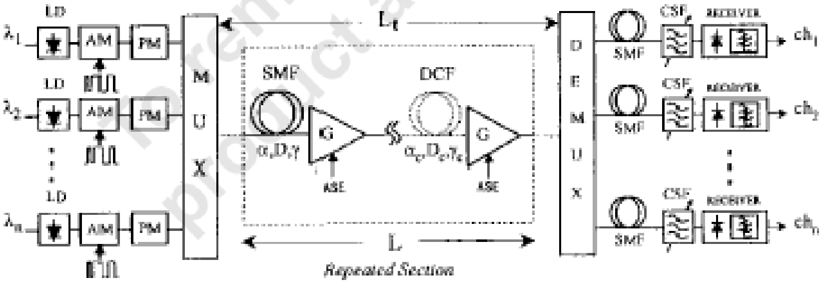


Figure 4.1 Configuration of WDM dispersion managed transmission system

4.2 Simulation setup for the effect of length of fiber on WDM system:

The figure shows the structure for the analysis of length variation on WDM system. The length is varied in five steps 50 to 250 km. The WDM transmitter consist of 16 channels, which are separated from receiver (16 channels) by a single mode fiber of varying lengths followed by a dispersion compensating fiber. In transmitter 16 channels are spaced from each other by 0.1nm. Each transmission section consist of data source, modulator driver (NRZ), Laser source and modulator (sin2). Data source produces a pseudo-random sequence of bits at a rate of 2.5 Gb/s. The output of data source is given to modulator driver which produces a NRZ (Non return to zero) format pulse train. The transmitted signal is formed by modulating the light carrier by the NRZ data source. The light carrier is generated by Lorentzian laser source at the center frequency of 192.65 THz.

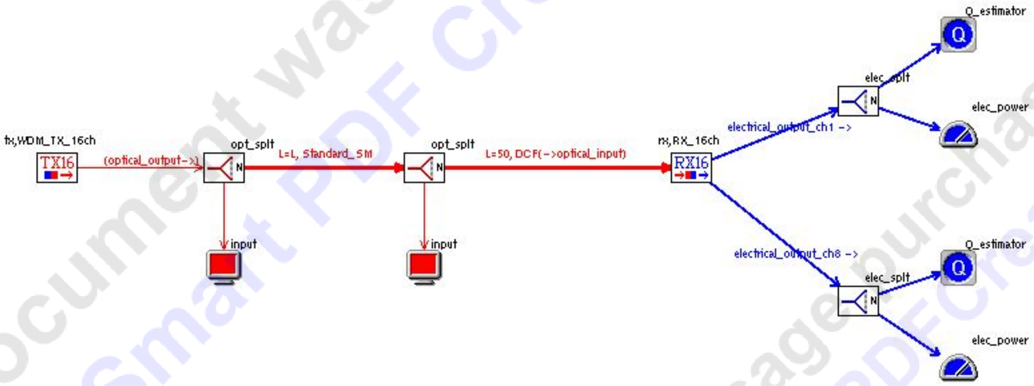
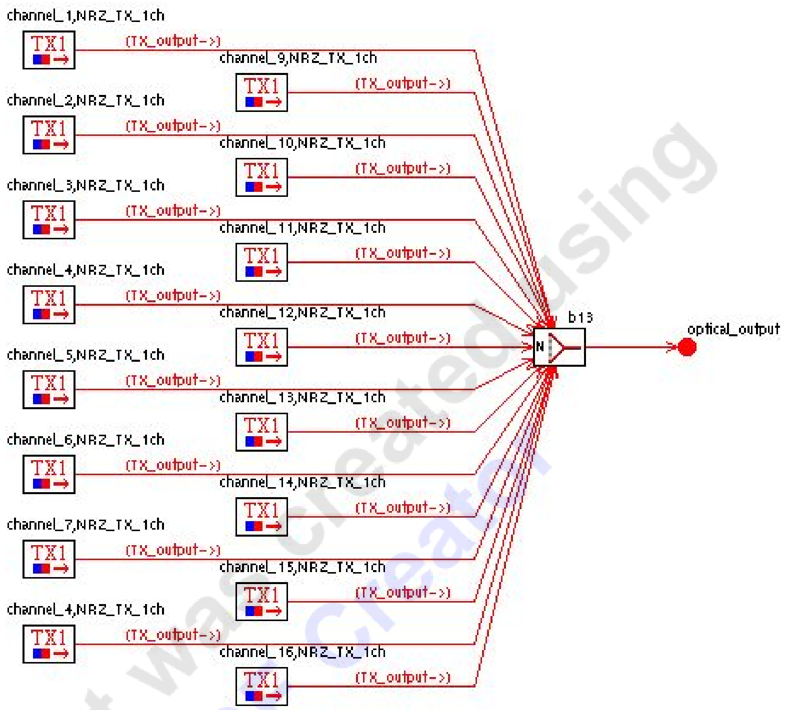


Figure 4.2 simulation structure of WDM system

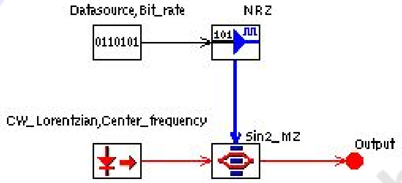
The transmission medium used is a standard single mode fiber (D=16) of varying length. The properties of standard single mode are shown in table .The receiver used is the system is the PIN (Receiver, PIN) receiver, which uses the PIN (p-intrinsic-n) diode as a detector. The pin photodiode simulated had 79% quantum efficiency. The output of the receiver is given to the measurement devices which are fed through the electrical splitter (elec_splt), the electrical power meter (elec_power) and the Q estimator (Q_Received). The optical spectrum of the signal is observed from optical spectrum before DCF fiber.



This compound component simulates a WDM 16–channel NRZ transmitter,
based on a CW lasers and external Mach–Zehnder modulators

Figure 4.3 Simulation diagram of 16 channel WDM transmitter

Single Channel Transmitter



This compound component simulates a single channel NRZ transmitter,
based on a CW lasers and external Mach–Zehnder modulators

Figure 4.4 diagram of single channel WDM transmitter

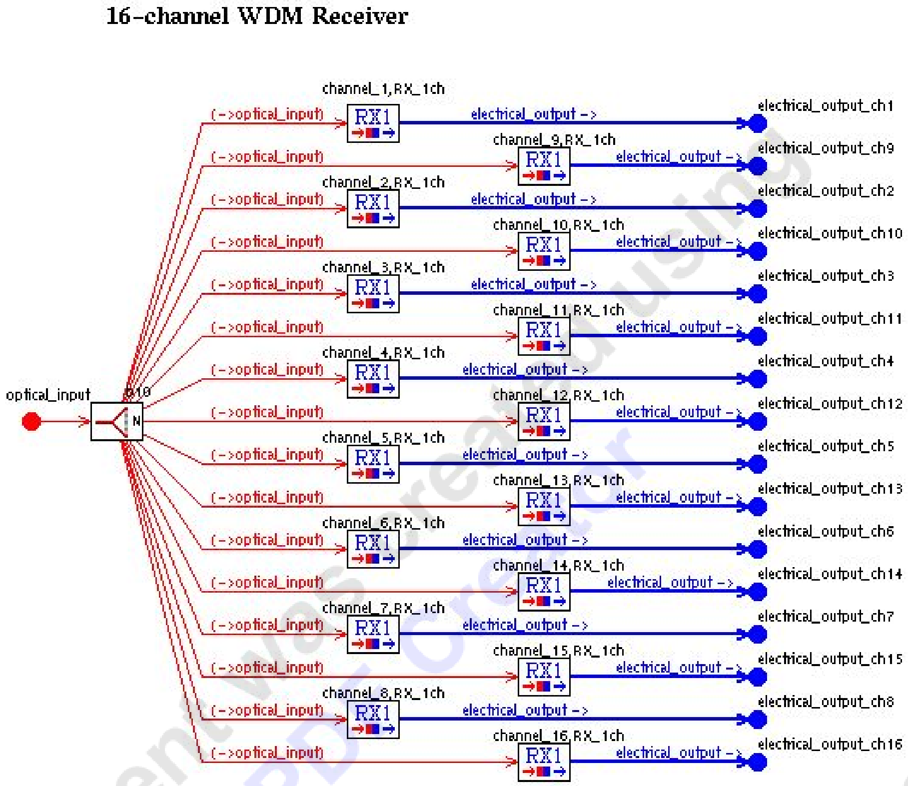
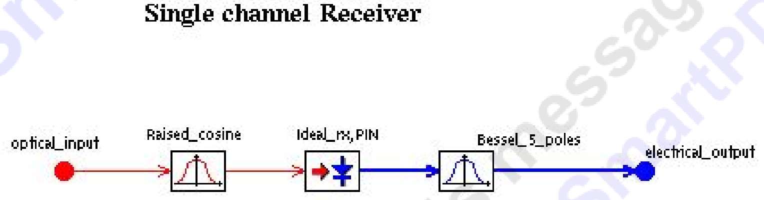


Figure 4.5 Diagram of 16-channel receiver



This compound component simulates a single channel receiver composed of:
- an optical Raised Cosine shape filter, with selectable roll-off and 3 dB bandwidth
- an ideal photodiode PIN (no noise, responsivity 1 A/W at 193 THz)
- a 5th order lowpass Besel filter, with selectable 3 dB bandwidth

Figure 4.6 Diagram of single channel receiver

Bit rate (Gb/s)	10
Center frequency(THz)	192.65
Channel spacing	0.1

4.1 Properties of WDM 16 channels

Type	NRZ rectangular
Low level	-2.5
High level	2.5

4.2 Properties of driver

Type	Sin^2
Excess loss (dB)	3.0

4.3 Properties of amplitude modulator

Parameter	SSMF
Loss (dB/km)	0.2
Dispersion (ps/nm/km)	16
Wavelength for dispersion (nm)	1550
Dispersion correlation length (km)	20
PMD (ps/km^0.5)	0.1
Fiber birefringence	ON
Fiber non-linearity	ON
Length	L
Zero dispersion wavelength (nm)	1391.533
Non Linear refractive index	$2.5*10^{-20}$

4.4 Properties of fiber

Parameter	Value
Loss (dB/km)	0.55
Dispersion (ps/nm/km)	-80

4.5 Properties of DCF

Parameter	Value
Reference frequency (THz)	193
Quantum efficiency	0.79
Responsivity (A/W)	1

4.6 Properies of PIN diode

4.3 Simulation results:

The figures shown below are the results obtained for the different values of Length. The Length is varied from 50 to 250 km in five steps. After the simulation run, the results showing the impacts of the length variation on the system performance are discussed below. The results are obtained in the form of optical spectrum and Q estimator. The values of eye opening, eye closing and power evaluation are plotted against the specified values of Length.

Optical spectrum

Figure 4.7 show the optical spectrum before DCF fiber

Result based on eye diagram for different lengths

Figure 4.14 shows the result of eye opening on length of 50 km is 1.6e^{-005}, 75 km is 4e^{-005}, 150 km is 1.25e^{-005}, 200 km is 0.1 and 250 km is 0.

Figure 4.15 shows the result of eye closing on length of 50 km is 0.1 dB, 75 km is 1 dB, 100 km is 1 dB, 150 km is 4 dB, 200 km is 26 dB and 250 km is 20 dB

Figure 4.16 shows the result of BER value on length of 50 km is 1.0e^{-040}, 75 km is 1e^{-024}, 150 km is 1.0e^{-029}, 200 km is 1.0e^{-005} and 250 km is 1.0e^{-002}.

The eye diagram for different lengths have been seen. It is concluded that from figure 4.8 to 4.13, as we increasing the length of the fiber, the eye opening decreases.

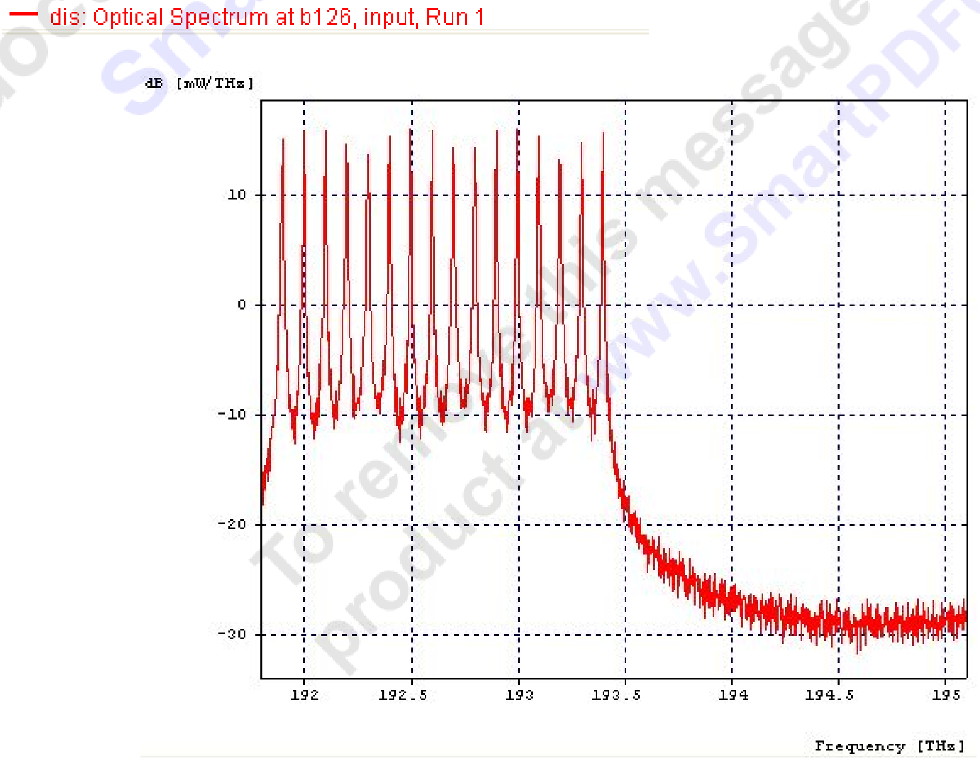


Figure 4.7 Optical spectrum

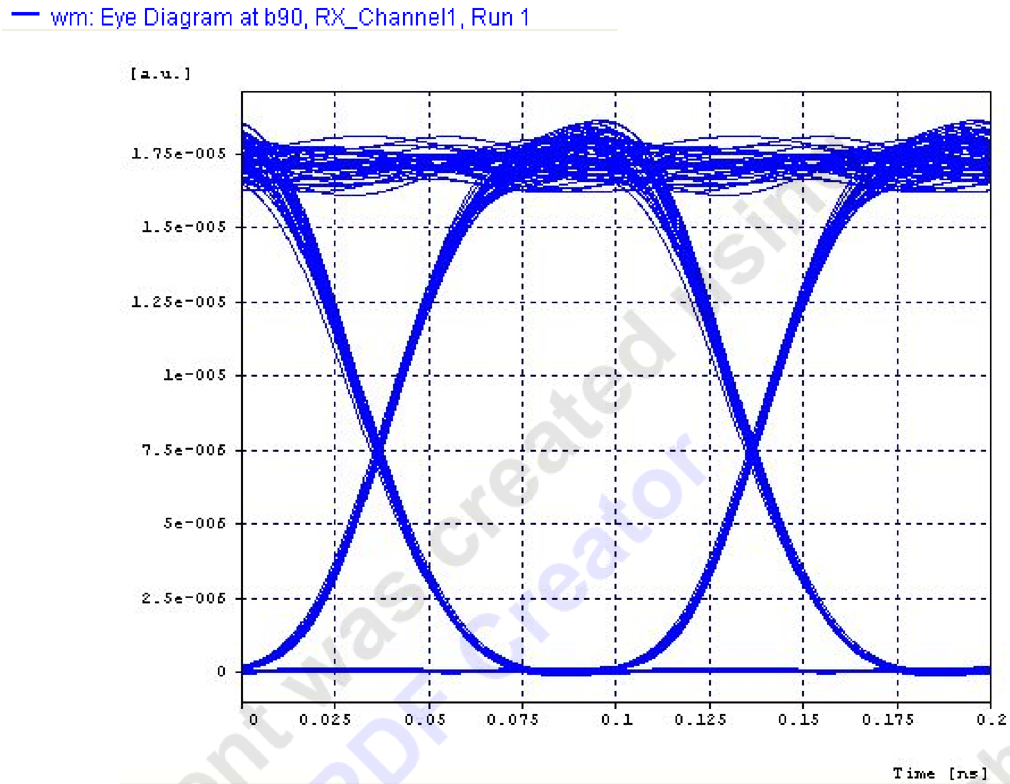


Figure 4.8 Eye diagram for fiber length of 50 km

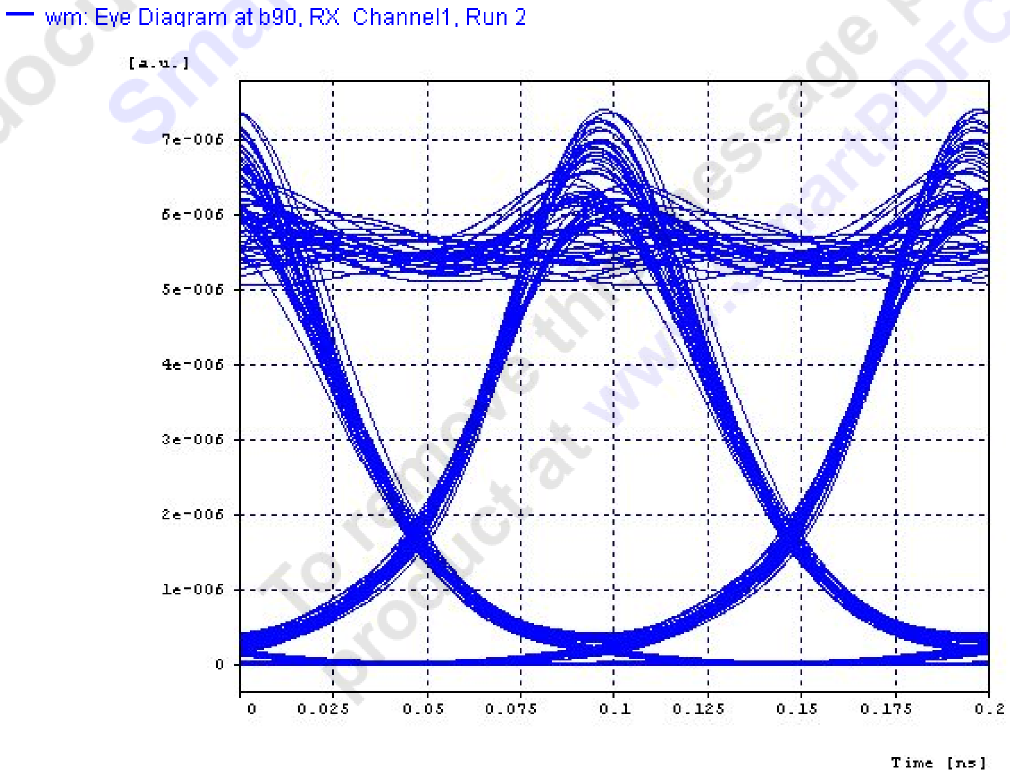


Figure 4.9 Eye diagram for fiber length of 75 km

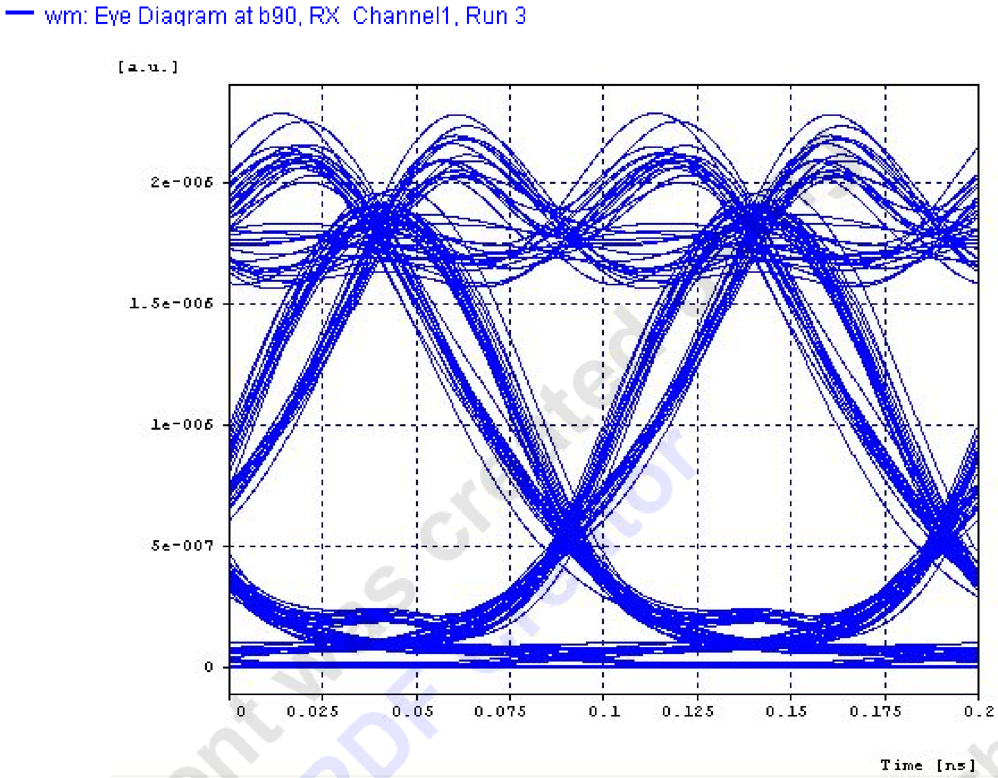


Figure 4.10 Eye diagram for fiber length of 100 km

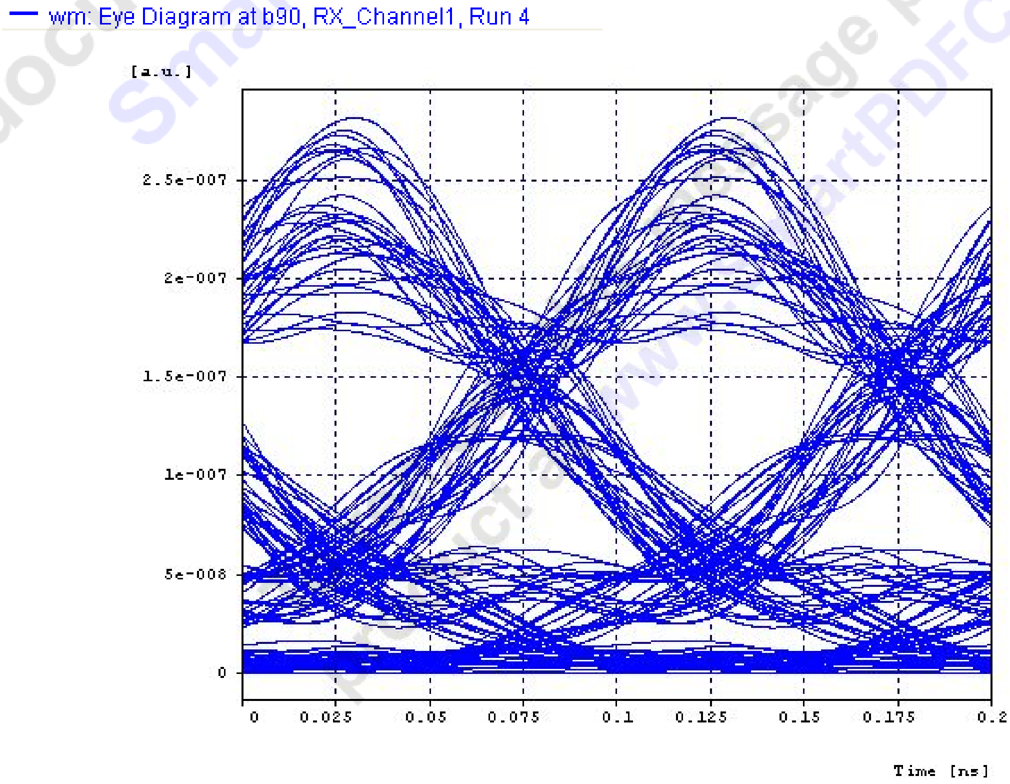


Figure 4.11 Eye diagram for fiber length of 150 km

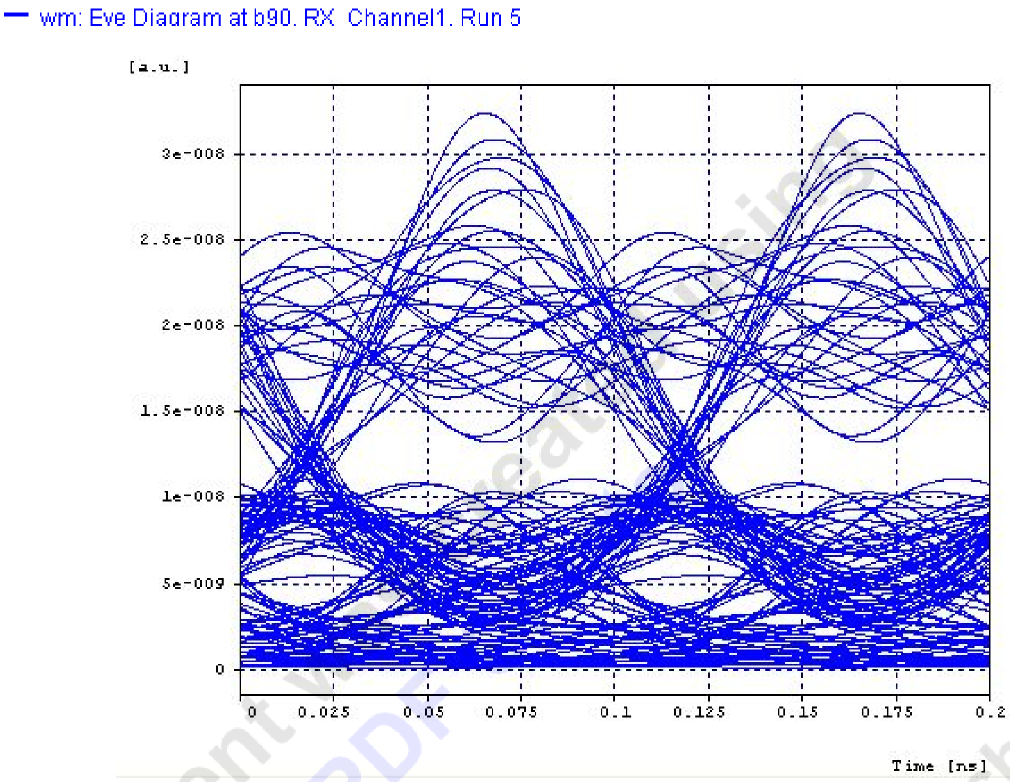


Figure 4.12 Eye diagram for fiber length of 200 km

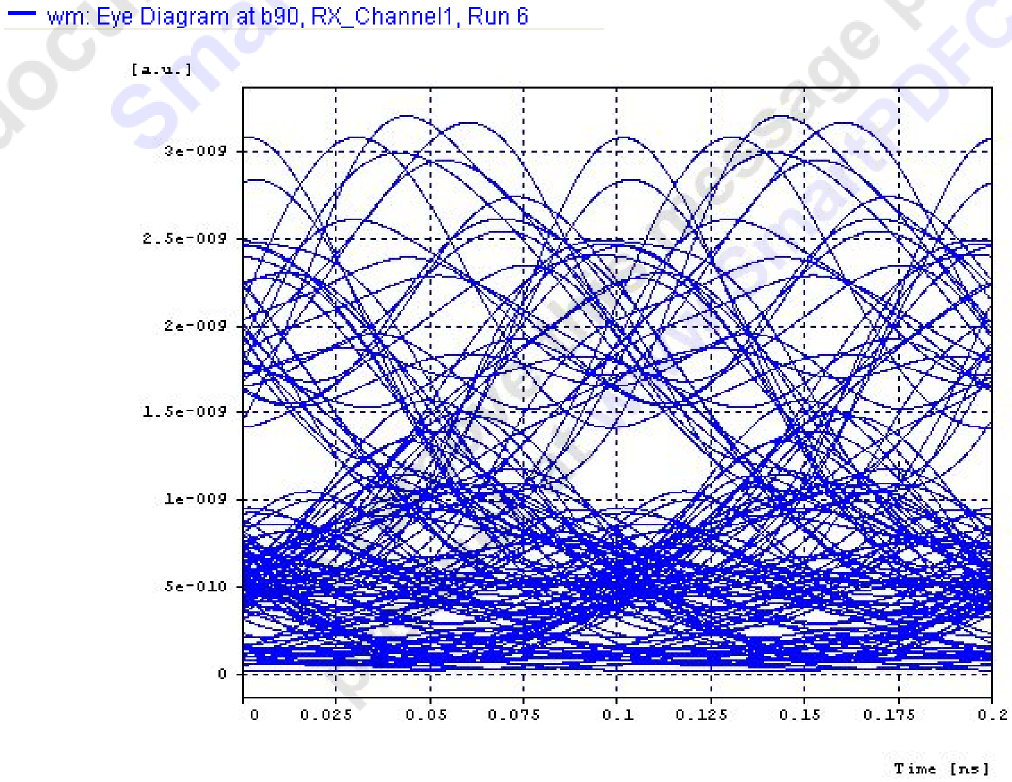


Figure 4.13 Eye diagram for fiber length of 250 km

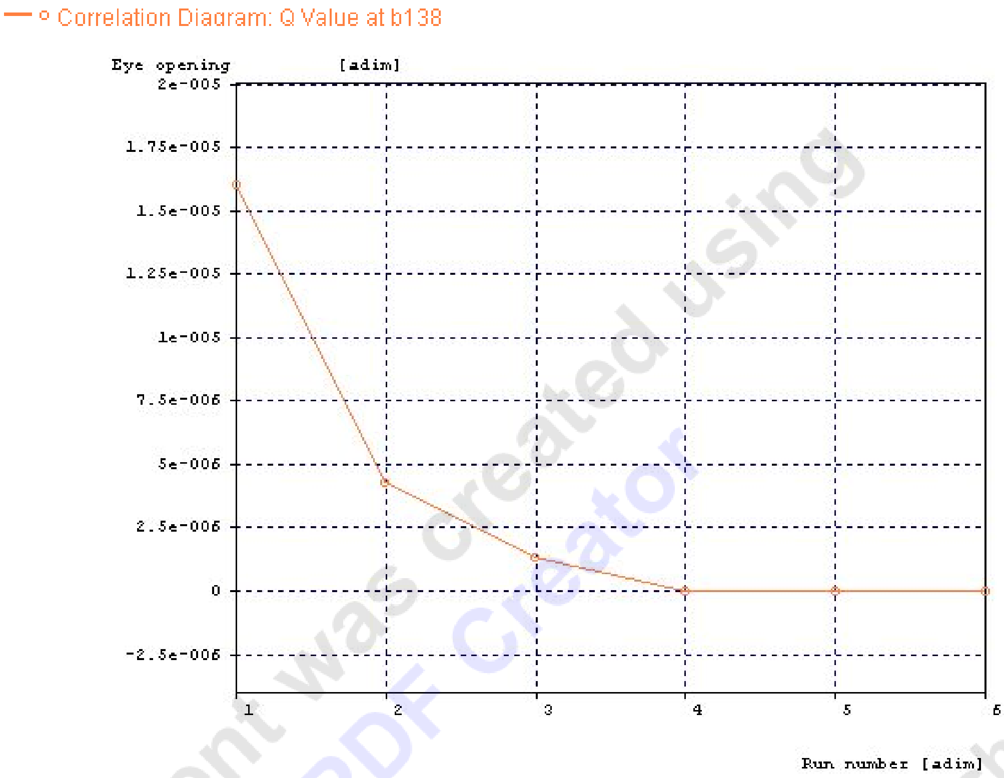


Figure 4.14 Eye opening diagram for fiber lengths

Figure 4.15 Eye closing diagram for fiber lengths

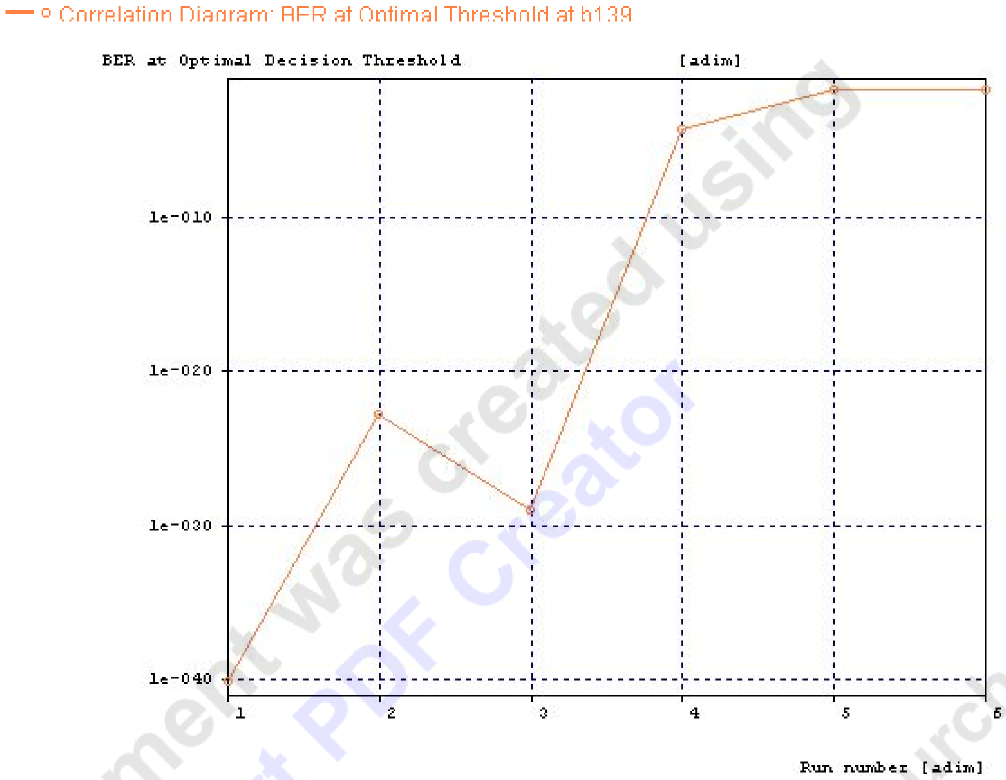


Figure 4.16 BER diagram for fiber lengths

CHAPTER 5

EFFECT OF FWM ON OPTICAL FIBER COMMUNICATION SYSTEM

This chapter simulates three - channel WDM optical communication system to investigate the effect of channel spacing, effect of data rate and the effect of dispersion.

The effect of FWM has been evaluated for different values of channel spacing and with increase of channel spacing, there is successful supression of FWM effects .

5.1 Introduction:

To observe and verify penalties induced by Four-Wave Mixing in the transmission systems working in the 1310 nm window with low dispersion value we used a set-up as depicted in Figure 5.1.

We can distinguish three parts: transmitter side, 100 km transmission link and an optically preamplified receiver end. The transmitter consists of the four DFB lasers operating in CW (continuous wave) condition at wavelengths 1309.275 nm, 1309.870 nm, 1310.435 nm, 1310.980 nm. The wavelength spacing is equal to 100 GHz. All four signals are combined in power coupler and amplified in SOA #1 to the power level 0 dBm per channel. Following SOA Mach-Zender modulator modulates simultaneously all four signals at the bit rate 10 Gbit/s with 231¡1 pseudo-random bit sequence (PRBS) pattern length. After second SOA #12 optical signals pass through 5 km of dispersion shifted fibre (DSF) to decorrelate bit pattern. The transmission link consists of the two 51 km SSMF spans and one, placed between them, in-line SOA amplifier to compensate the fibre losses. The average 51 km fibre span losses are 18 dB and an average dispersion at 1310 nm is equal to -2.5 ps/nm*km. The receiver contains SOA#12 acting as a preamplifier and two band-pass filters placed before and after SOA#12. The filter bandwidth is respectively 0.5 nm and 0.2 nm. Output of the second filter is connected using 90-10 power coupler to optical spectrum analyser (OSA) and NEL receiver module. The NEL receiver module consists of the 10 Gb/s O/E converter with post/limiting amplifier module and 10 Gb/s clock and data recovery module. The clock and the data output of the NEL receiver module are connected to the bit error rate (BER) test-set.

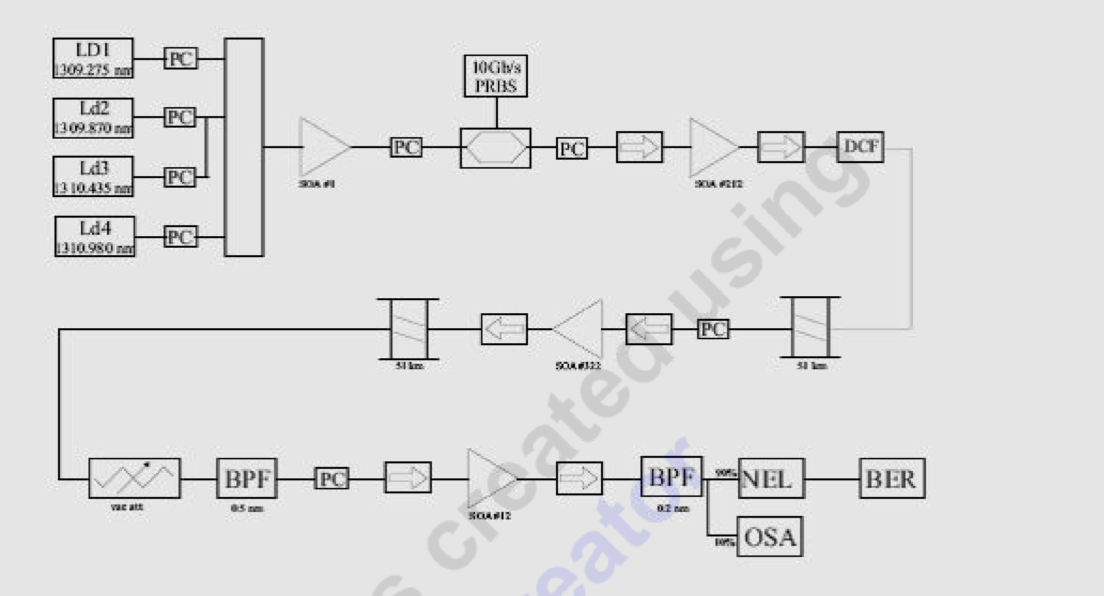
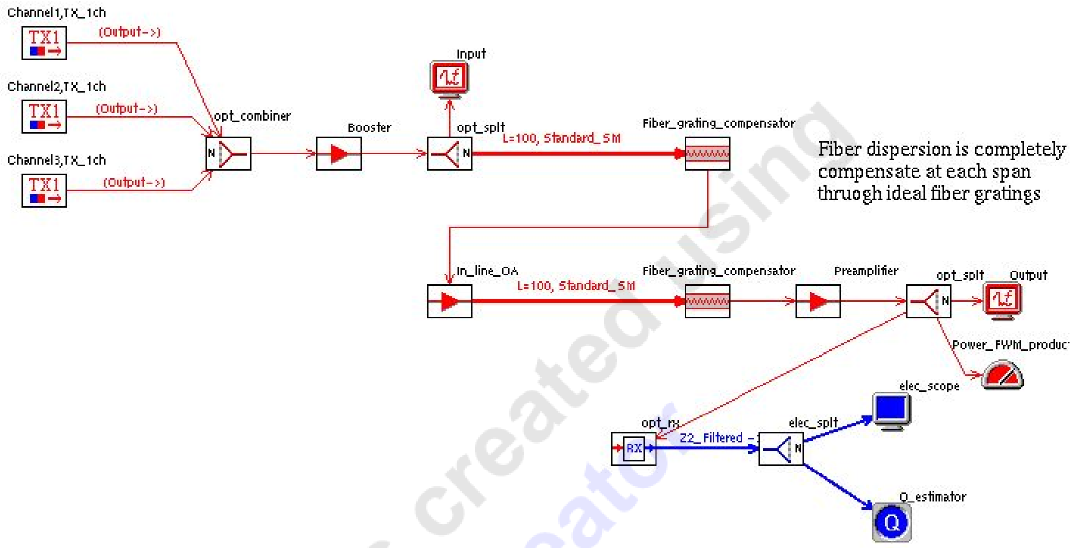


Figure 5.1 Experiment setup

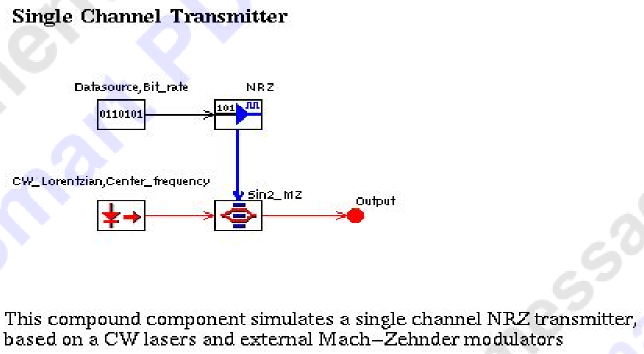
5.2 Simulation setup for the effect of channel spacing:

The three WDM transmitter channels are spaced from each other by unequal spacing. Each transmission section consist of data source, modulator driver (NRZ), Laser source and modulator ($\sin^2$). Data source produces a pseudo-random sequence of bits at a rate of 10 Gb/s. The output of data source is given to modulator driver which produces a NRZ (Non return to zero) format pulse train. The transmitted signal is formed by modulating the light carrier by the NRZ data source. The light carrier is generated by Lorentzian laser source at the center frequency of 192.65 THz.The output of three WDM transmitter are combined by a optical combiner and then amplified and is passed through single mode fiber of length 100 km and dispersion of 16 ps/nm/km. The output of fiber is passed to fiber grating to compensate the dispersion. The output of the PIN receiver is given to the measurement devices which are fed through the electrical splitter (elec_splt), the Q estimator (Q_Received) and signal measurement (eye diagram).



Fiber dispersion is completely compensate at each span thruogh ideal fiber gratings

Figure 5.2 simulation setup for channel spacing in FWM



This compound component simulates a single channel NRZ transmitter, based on a CW lasers and external Mach–Zehnder modulators

Figure 5.3 Diagram of single channel transmitter

Parameter	Value
Bit rate (Gb/s)	2.488
Center frequency	Center frequency-1.5*channel spacing
Modulator excess loss (dB)	4
PRBS sequence degree	7

Table 5.1 Properties of transmitter channel

Parameter	Value
Reference frequency (THz)	193.05
Compensating dispersion at ref. frequency	-5.937

Table 5.2 Properties of fiber grating

Parameter	Value
Sensitivity (dBm)	-29.96
Responsivity (A/W)	1

Table 5.3 Properties of optical receiver

5.2.1 Simulation results:

The figures shown below are the results obtained for the different values of channel spacing. It is varied from 0.1 to 3 nm in seven steps. After the simulation run, the results showing the impacts of the channel variation on the system performance are discussed below. The results are obtained in the form of optical spectrum and Q estimator. The values of eye opening, eye closing and power evaluation are plotted .

Optical spectrum

Figure 5.11 show the optical spectrum power at 0.1 nm is -43.5 dBm, 0.5 nm is -44.2 dBm, 1 nm is -43.5 dBm, 1.5 nm is -41.5 dBm, 2 nm is -42.5 dBm , 2.5 nm is -41.4 dBm, 3nm is -40 dBm .

Eye diagrams:

Figure 5.19 shows the result of eye opening on channel spacing of 0.1 nm is $1.5e^{-005}$, 0.5 nm is $2.5e^{-005}$, 1.0 nm is $5e^{-005}$, 1.5 nm is $9e^{-005}$, 2 nm is $3e^{-005}$, 2.5 nm is $4.5e^{-005}$ and 3 nm is $1e^{-005}$.

Figure 5.20 shows the result of eye closing on channel spacing of 0.1 nm is 23 dB, channel spacing of 0.5 nm is 21 dB, 1 nm is 17 dB, 1.5 nm is 15 dB, 2 nm is 19 dB,2.5 nm is 18 dB and 3 nm is 26 dB.

The eye diagram for different spacings have been seen. It is concluded that amongst figure 5.12 to 5.18, as we keep on increasing channel spacing, the eye opening is more, the non-linearity decreasing i.e. co-channel interference decreases.

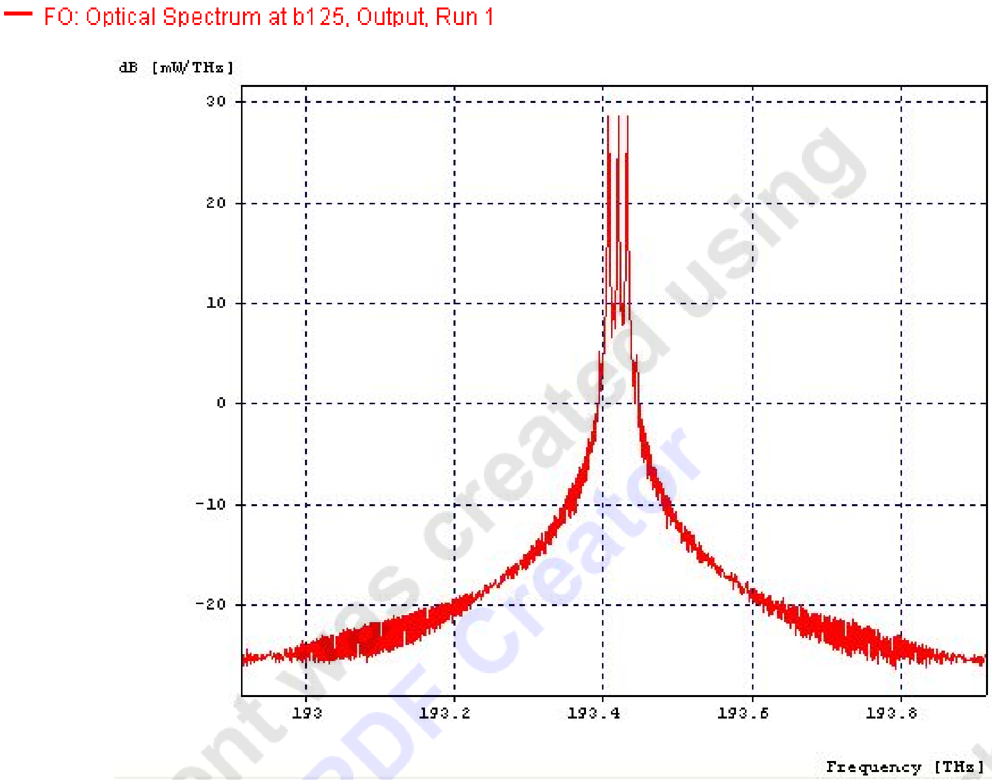


Figure 5.4 Optical spectrum with channel spacing of 0.1nm

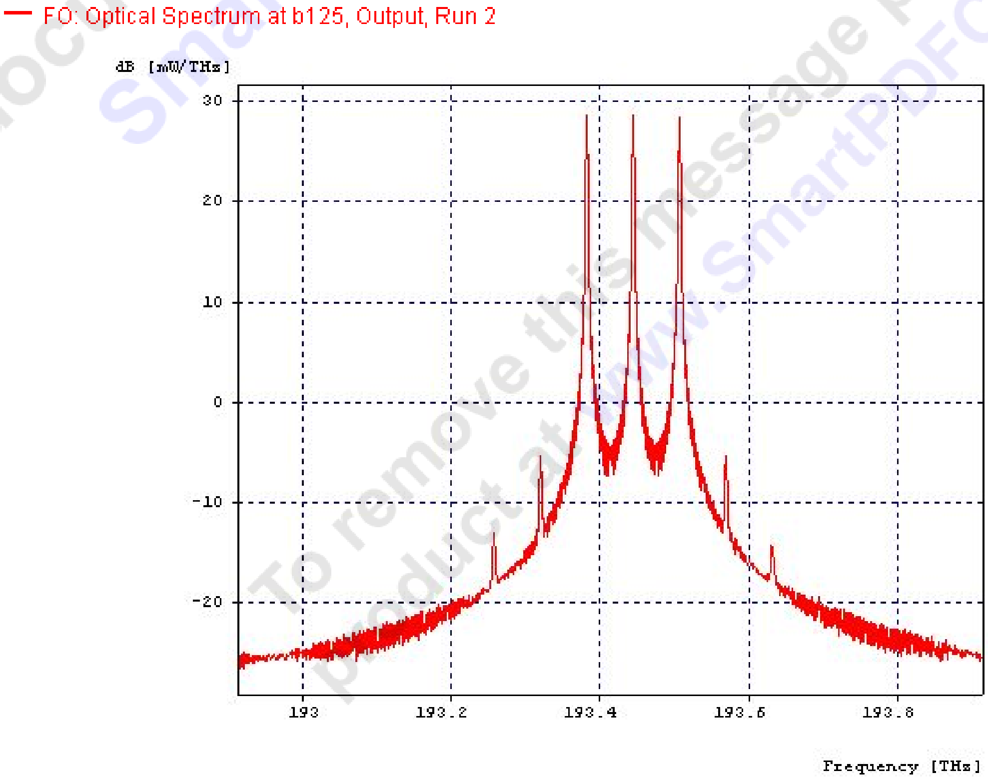


Figure 5.5 Optical spectrum with channel spacing of 0.5nm

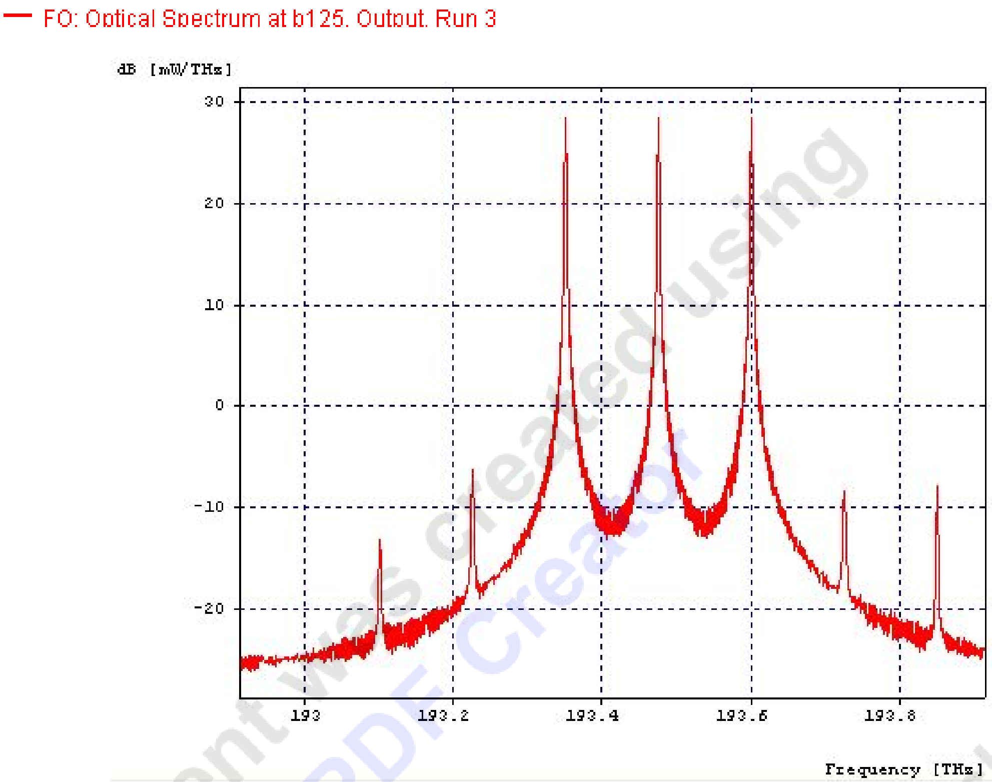


Figure 5.6 Optical spectrum with channel spacing of 1nm

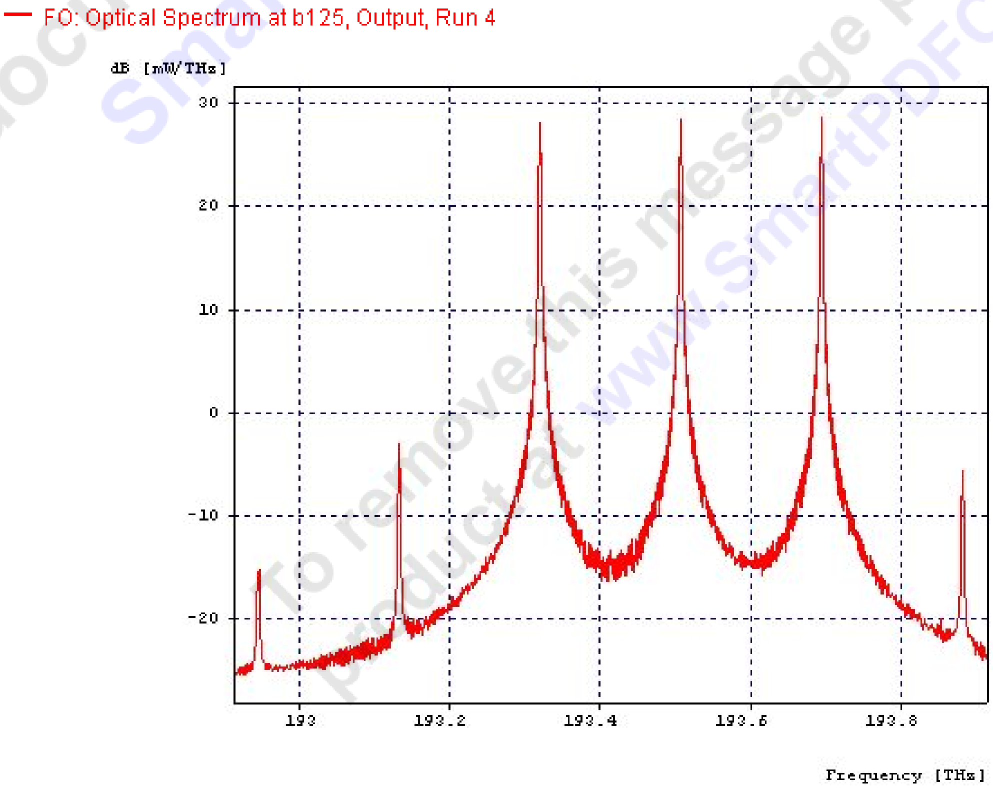


Figure 5.7 Optical spectrum with channel spacing of 1.5nm

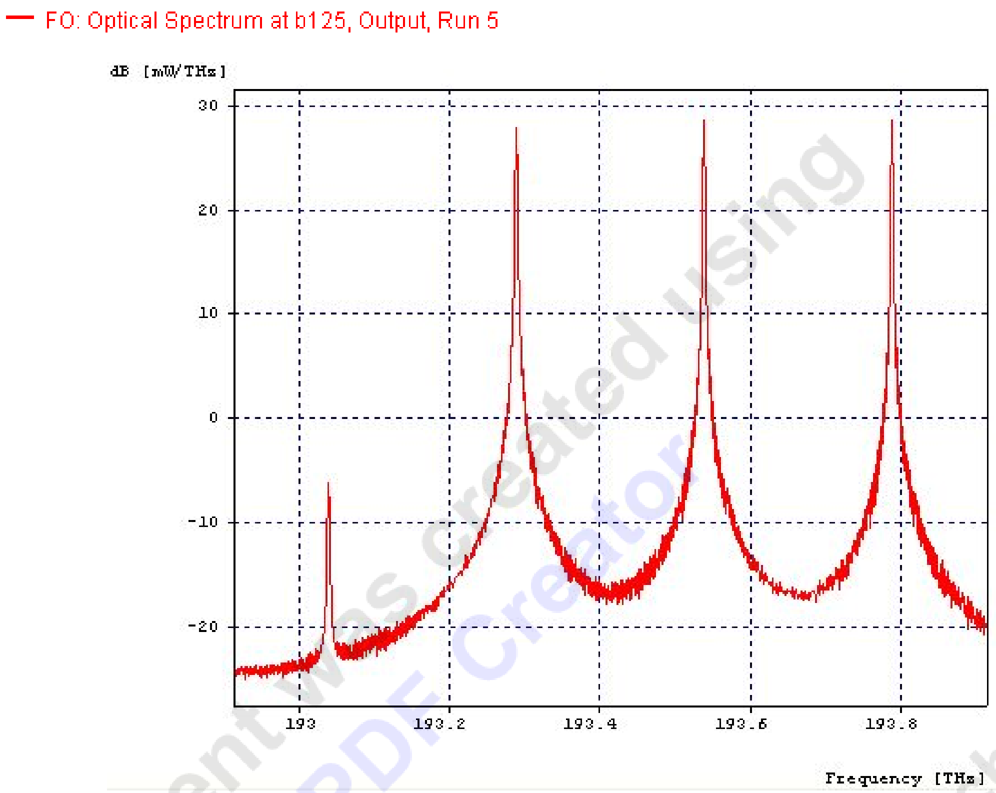


Figure 5.8 Optical spectrum with channel spacing of 2.0 nm

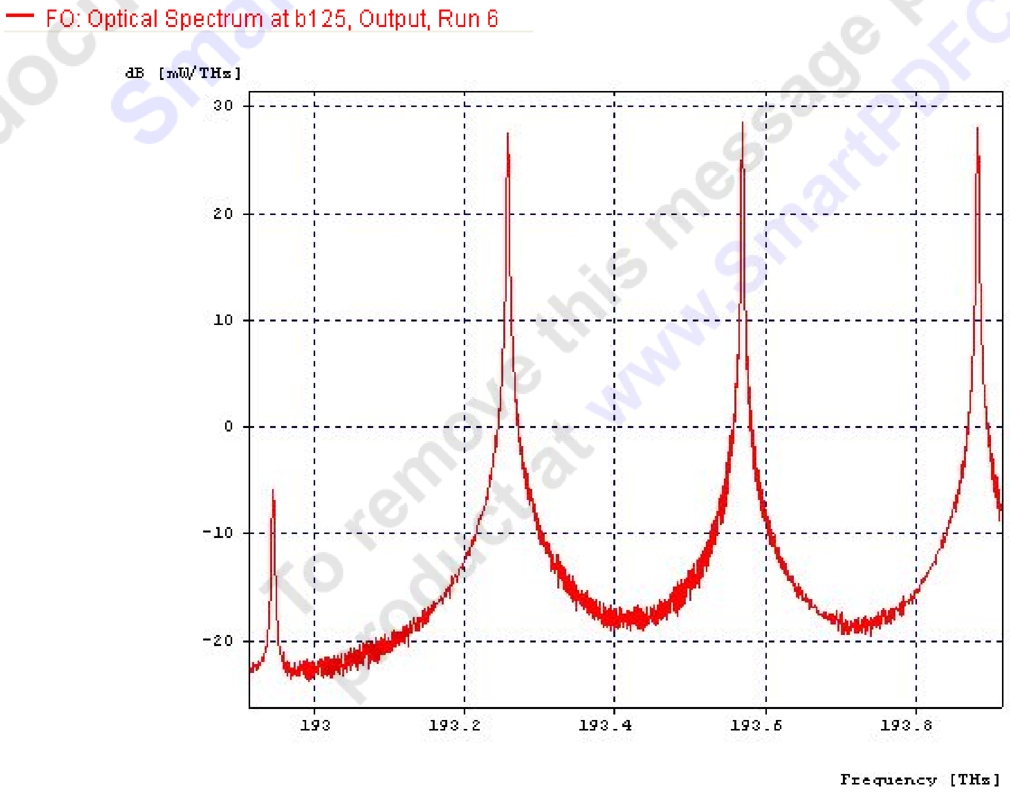


Figure 5.9 Optical spectrum with channel spacing of 2.5nm

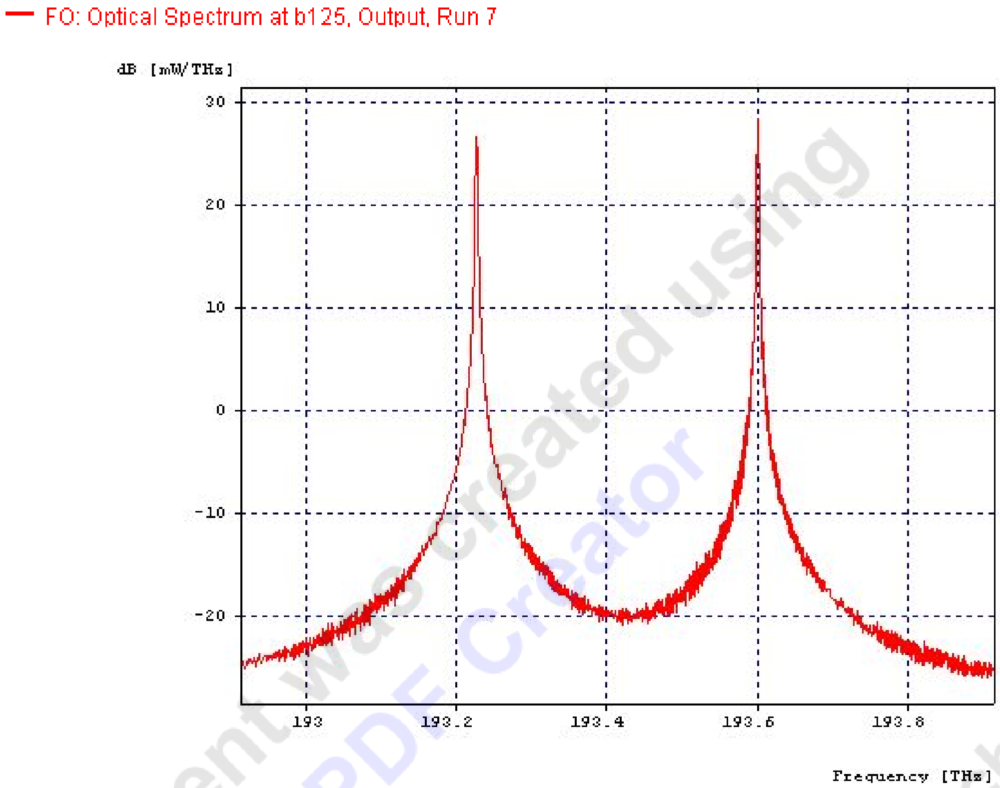


Figure 5.10 Optical spectrum with channel spacing of 3.0nm

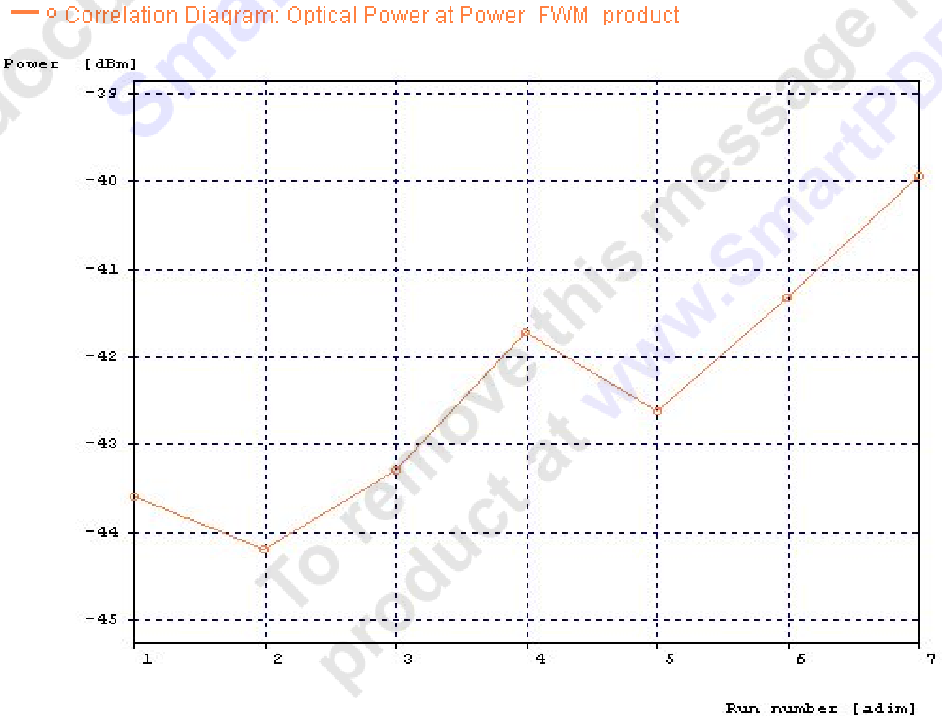


Figure 5.11 Correlation diagram of power of different channel spacing

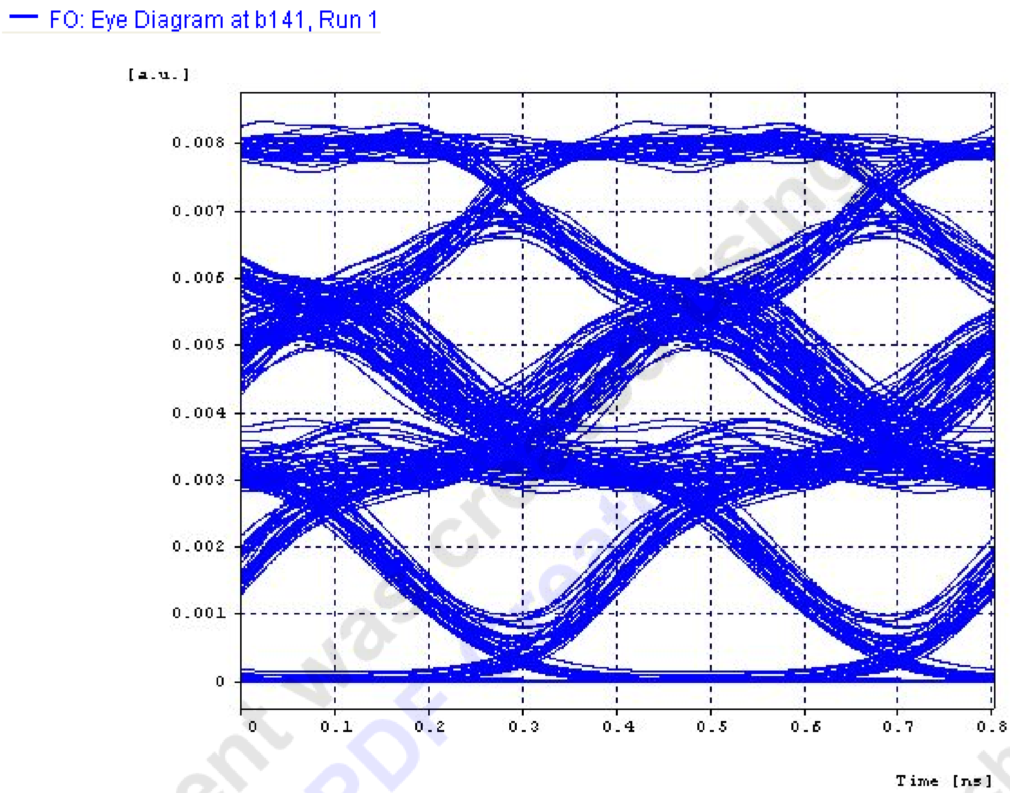


Figure 5.12 Eye diagram with channel spacing 0.1nm

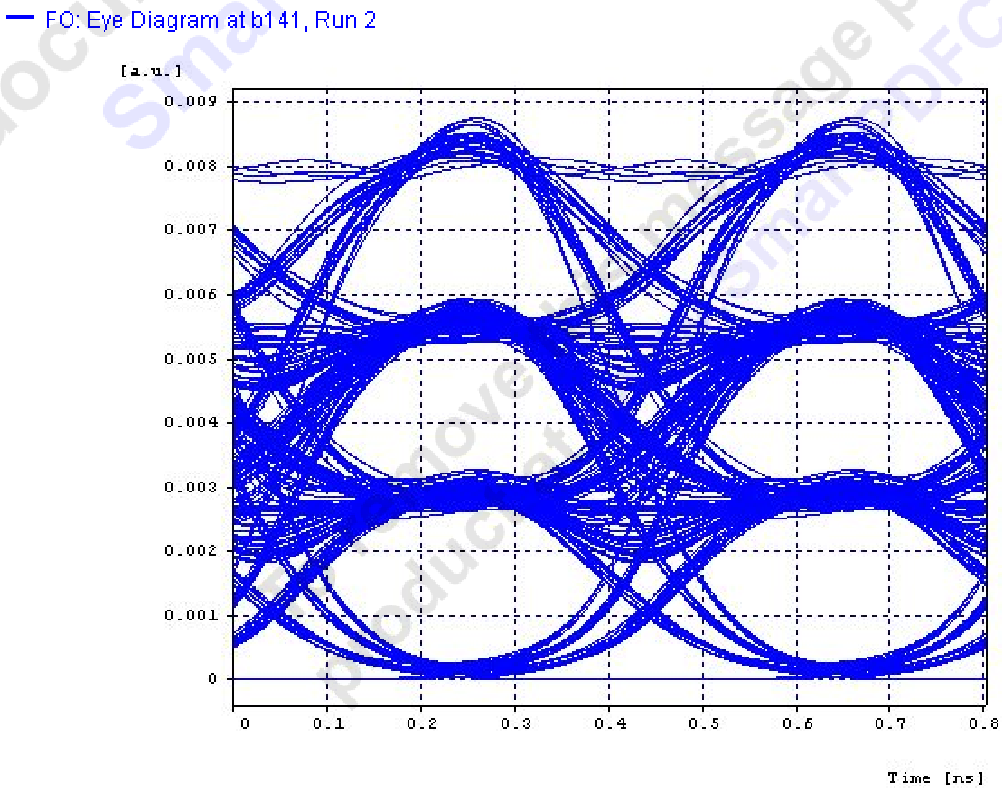


Figure 5.13 Eye diagram with channel spacing 0.5nm

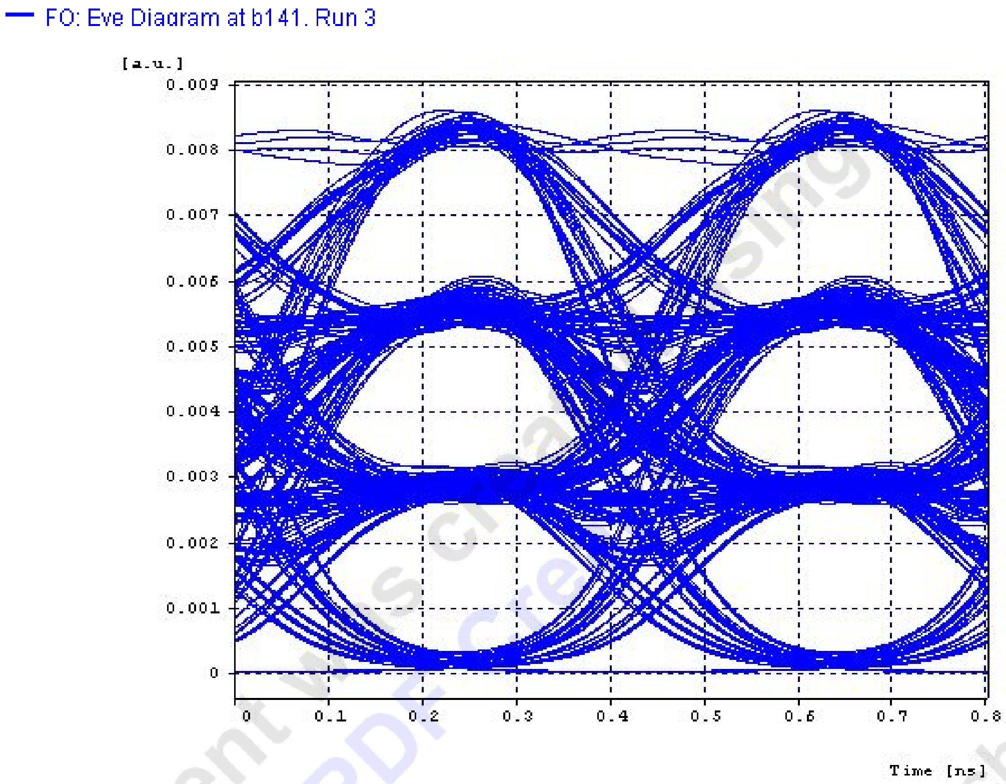


Figure 5.14 Eye diagram with channel spacing 1.0nm

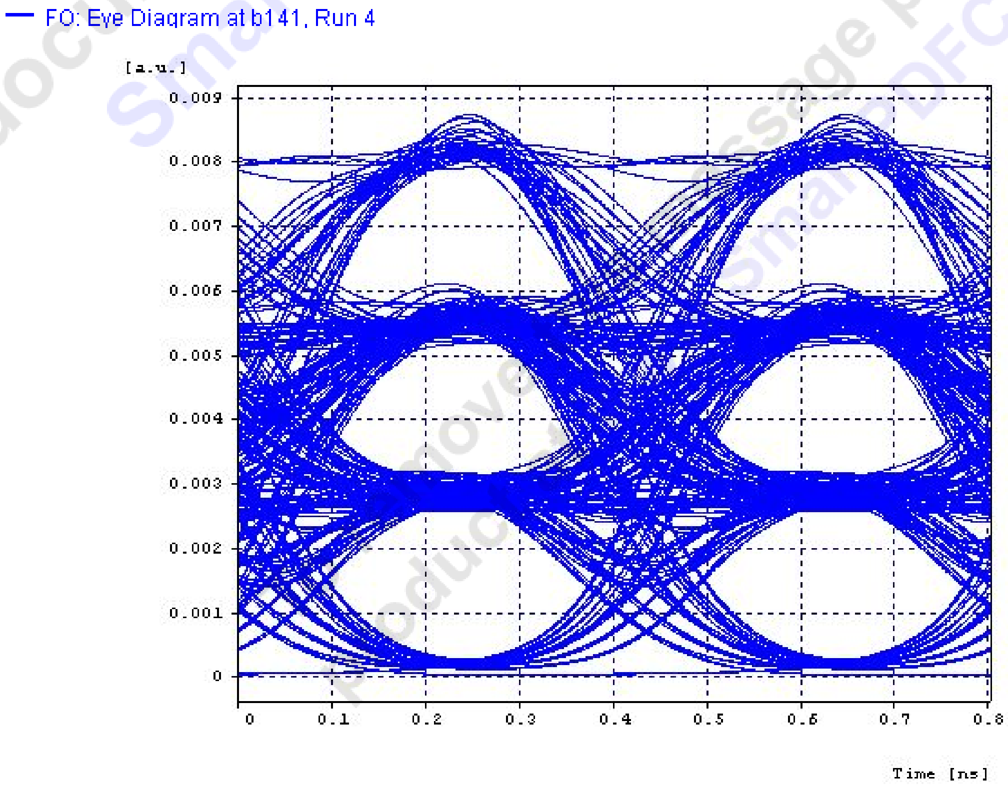


Figure 5.15 Eye diagram with channel spacing 1.5nm

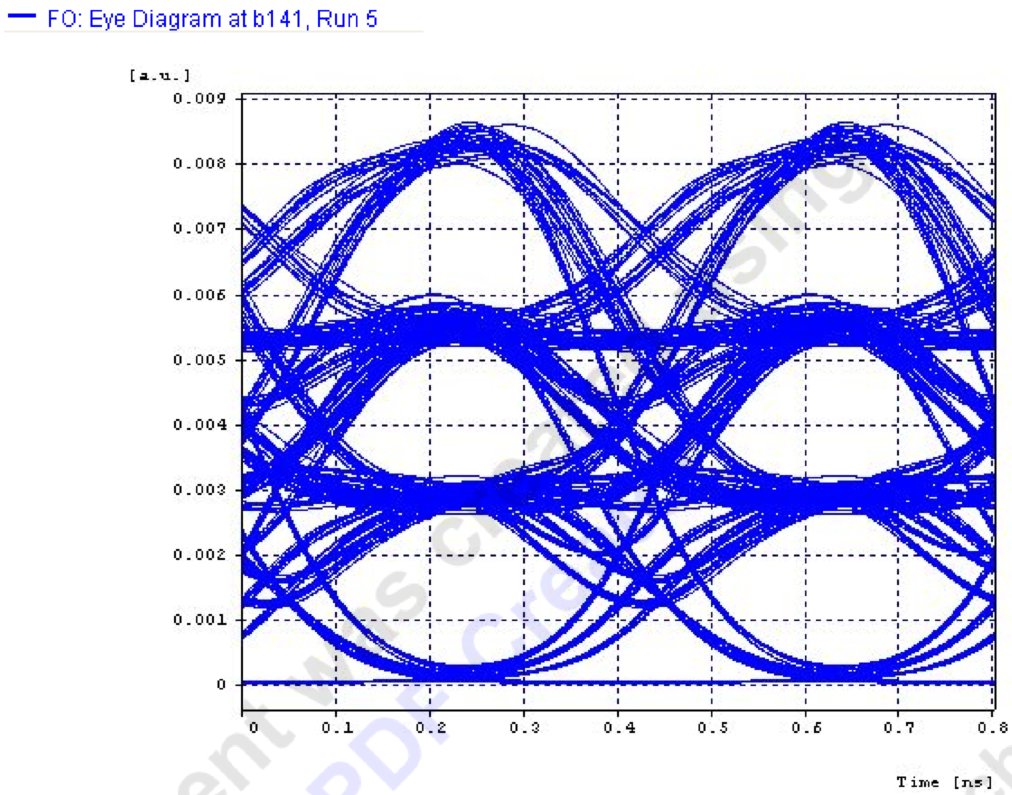


Figure 5.16 Eye diagram with channel spacing 2.0 nm

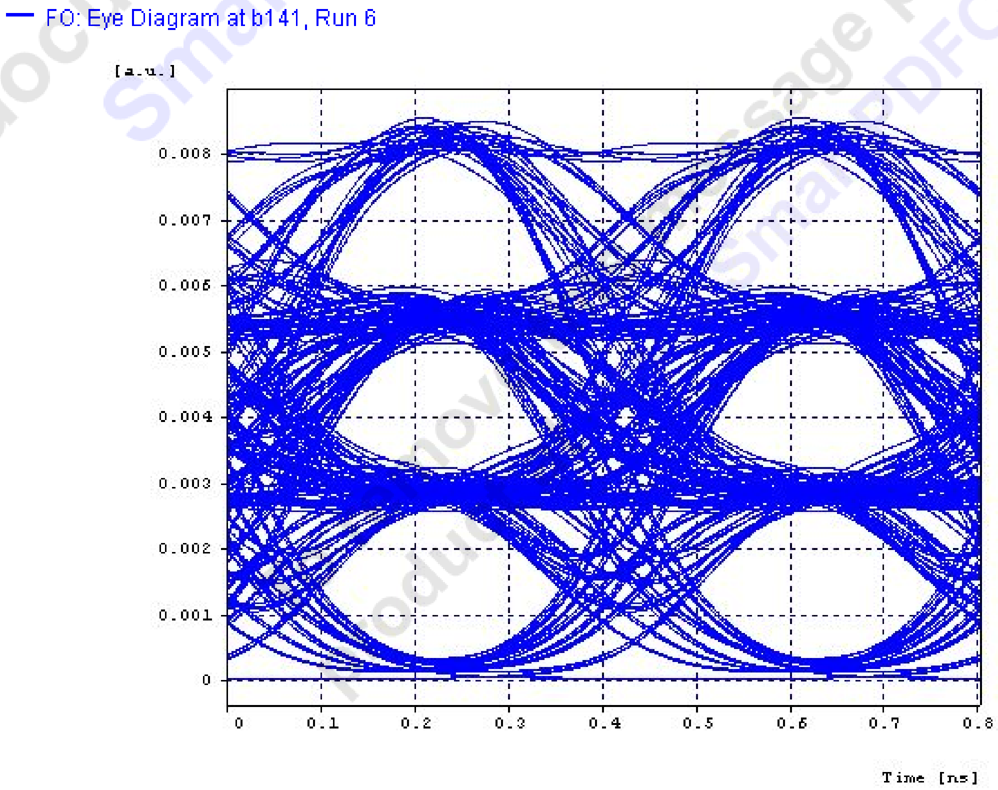


Figure 5.17 Eye diagram with channel spacing 2.5 nm

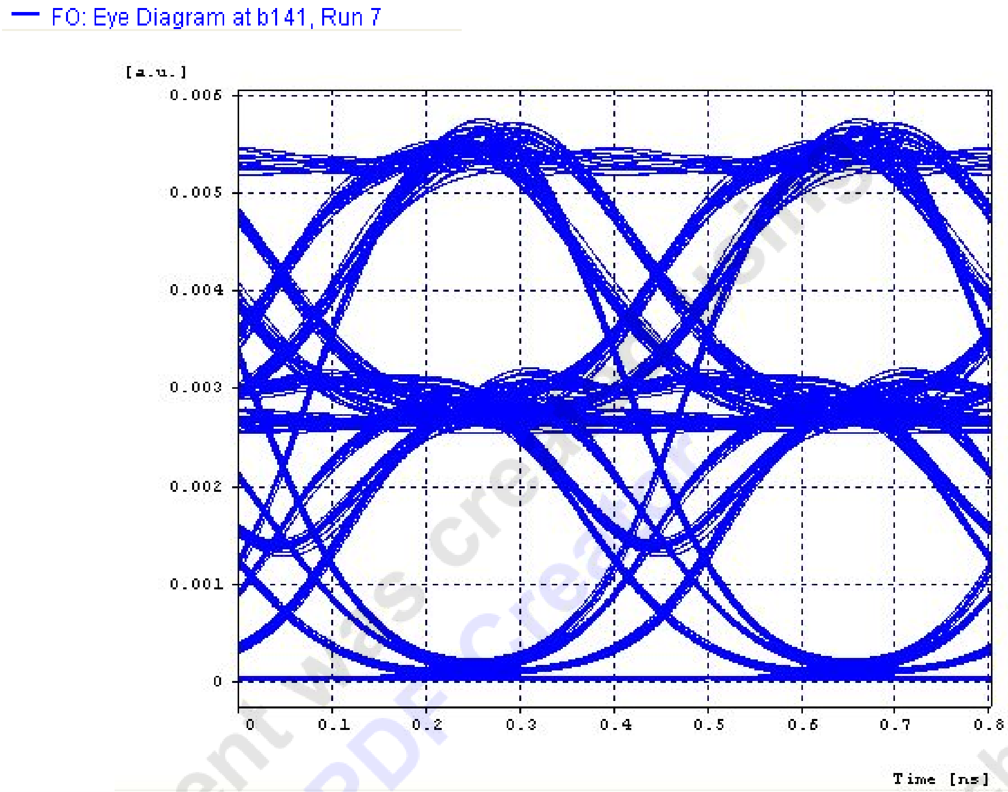


Figure 5.18 Eye diagram with channel spacing 3.0 nm

Figure 5.19 Correlation diagram of eye opening value at different channel spacing

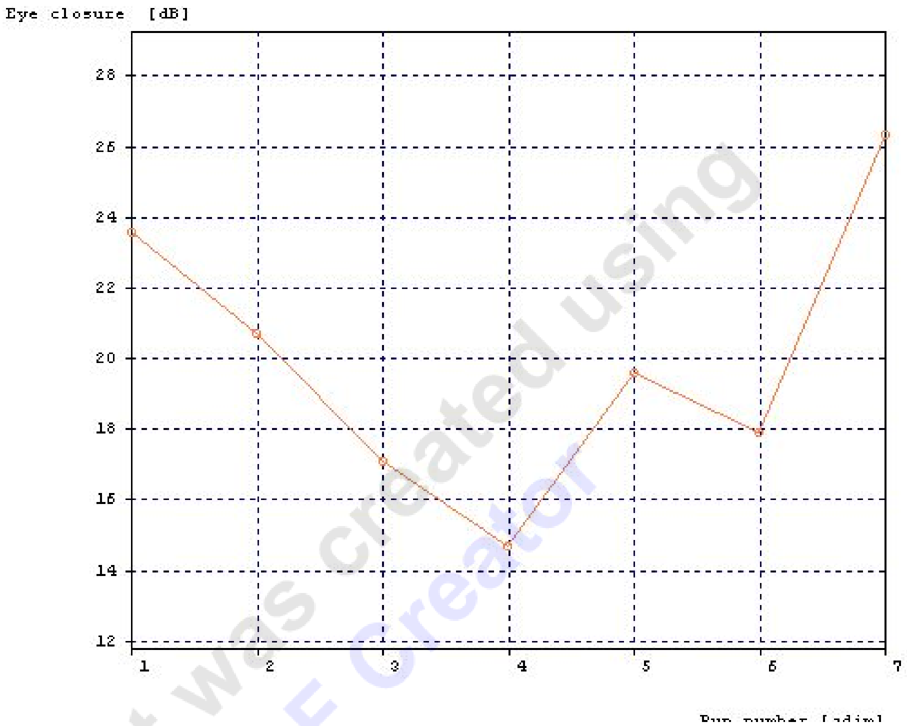


Figure 5.20 Correlation diagram of eye closing value at different channel spacing

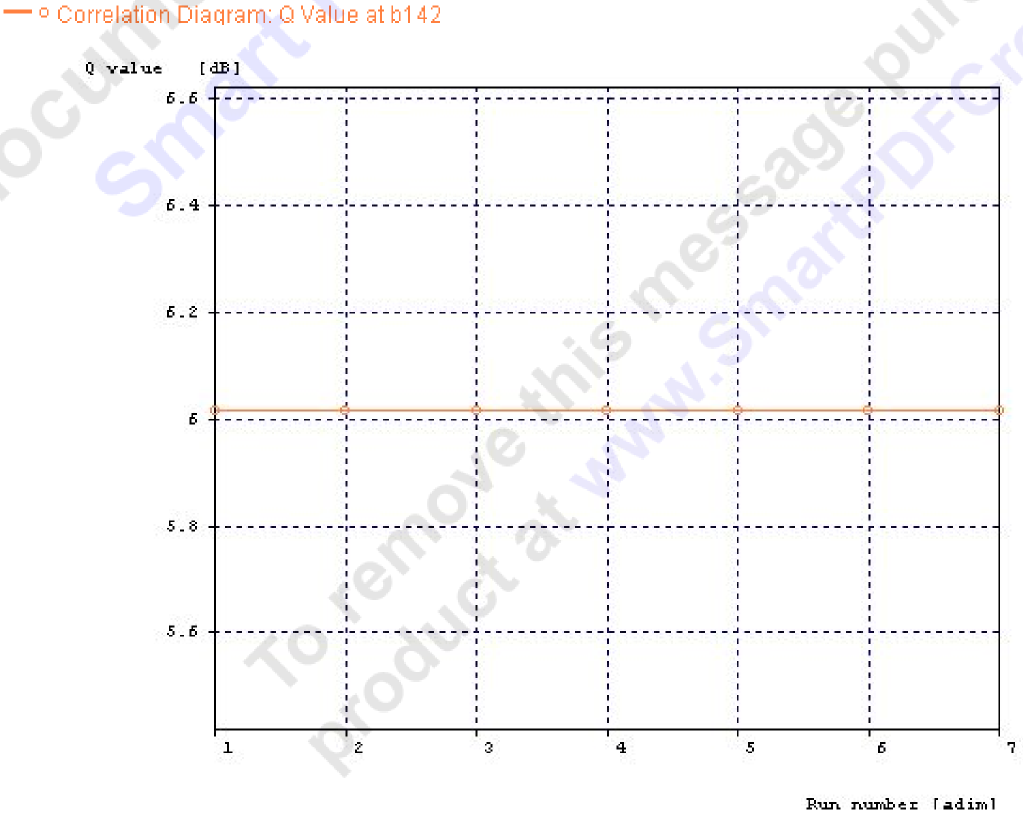


Figure 5.21 Q value

5.3 Effect of data rate on FWM:

Figure 5.22 shows the three WDM transmitter, with different data sources which are modulated by different laser frequencies by the modulator $\sin^2$ and the optical combiner is used to combine the outputs. At receiver side different measurement devices are used to study the effect of different data rates on output in terms of eye opening, closing, Q value.

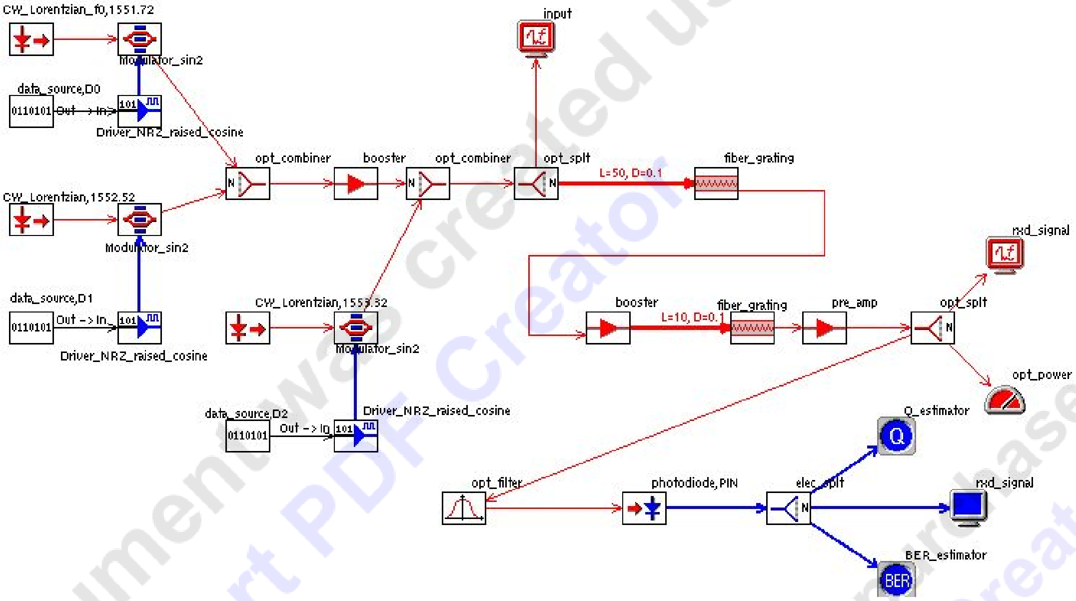


Figure 5.22 Simulation setup for the effect of data rates on FWM

Parameter	Value
Type	Lorentzian
Center frequency f0, f1,f2(THz)	193.20, 193.10, 193.00

Table 5.4 Properties of laser

Parameter	Value
Dispersion (ps/nm/km)	0.1
PMD (ps/km^0.5)	0.1
Length (km)	50

Table 5.5 Properties of fiber

Figure 5.23 Optical spectrum at 5 Gb/s

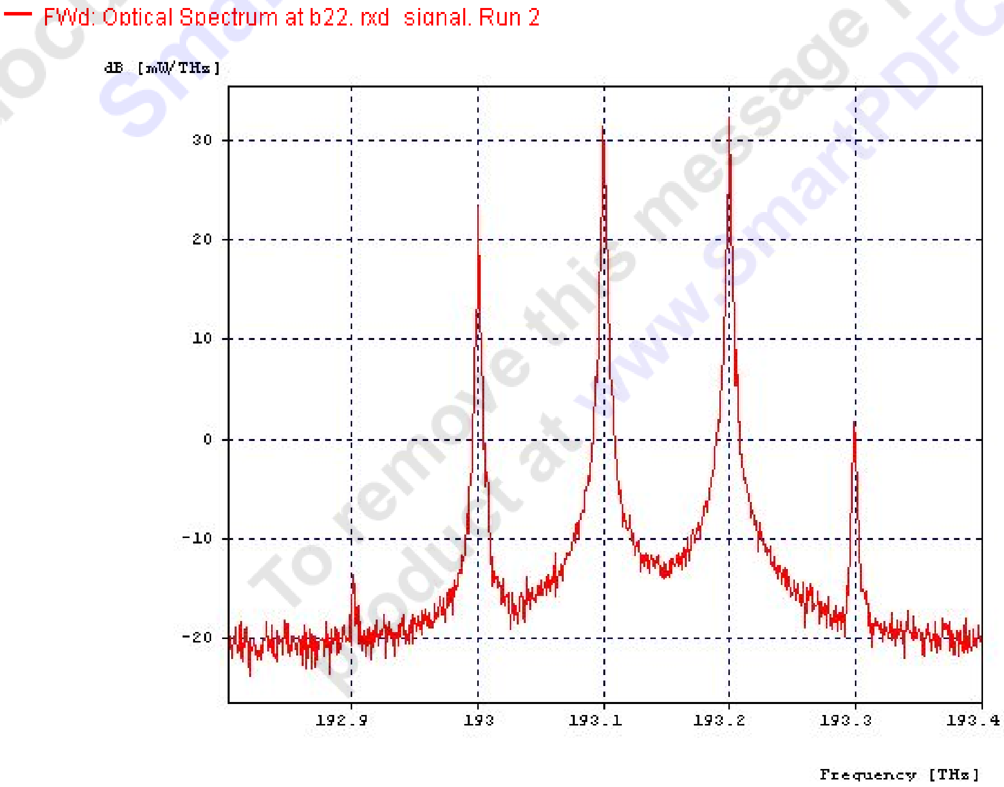


Figure 5.24 Optical spectrum at 10 Gb/s

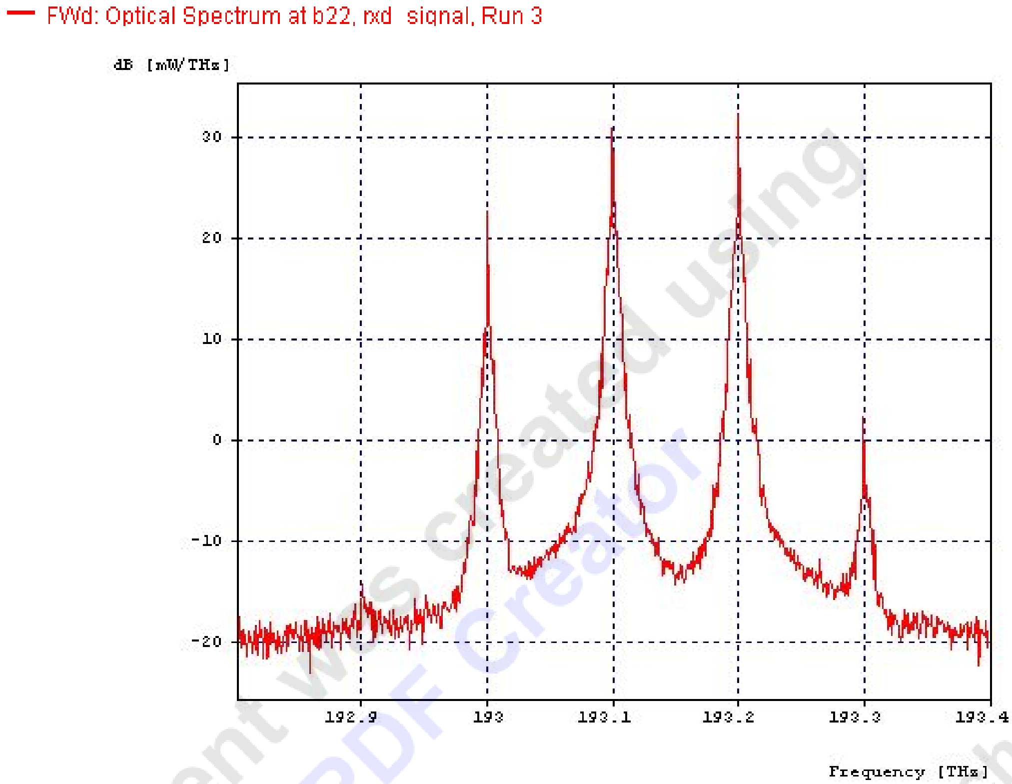


Figure 5.25 Optical spectrum at 20 Gb/s

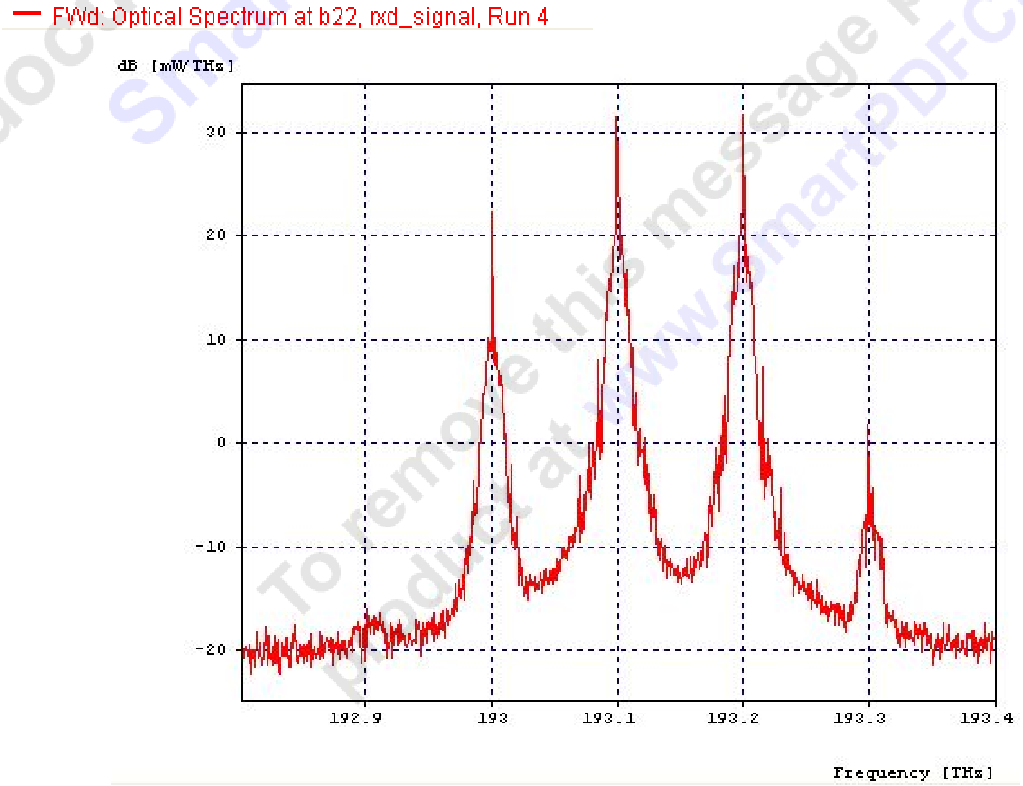


Figure 5.26 Optical spectrum at 30 Gb/s

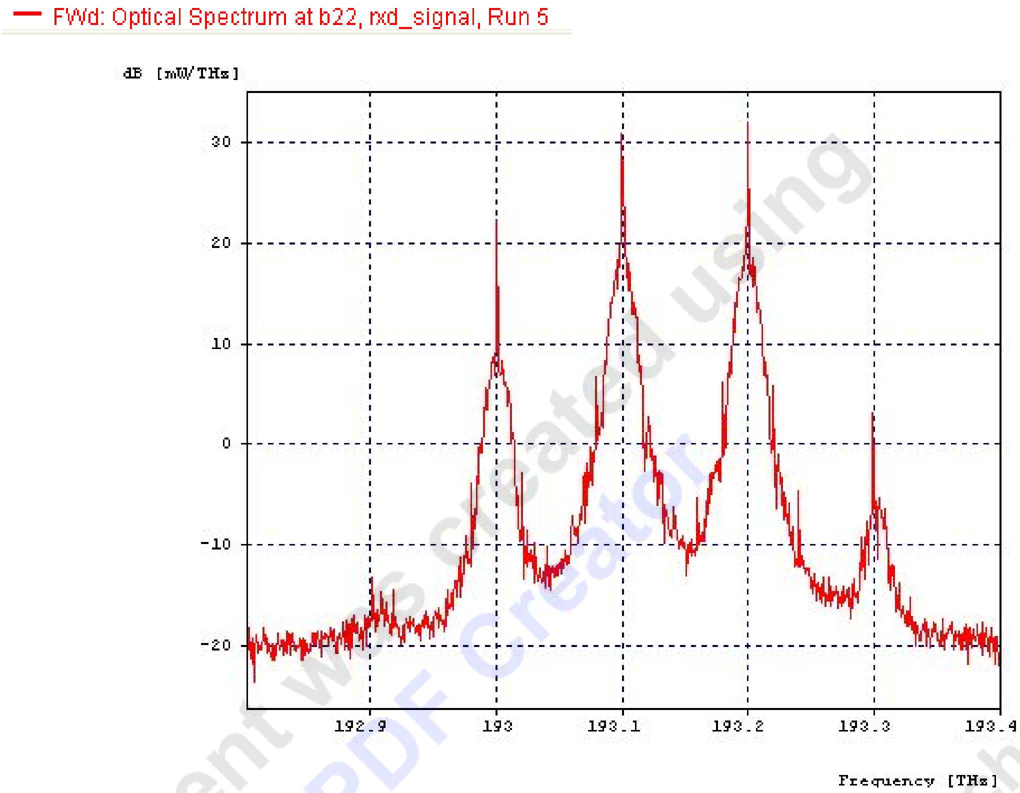


Figure 5.28 Optical spectrum at 40 Gb/s

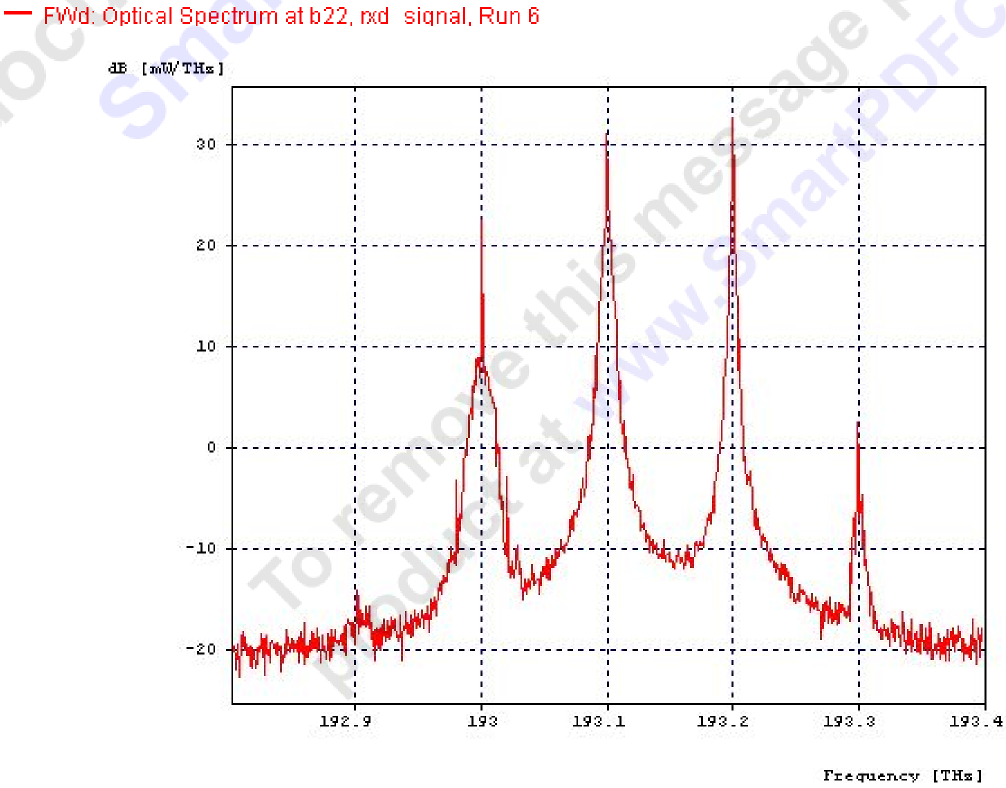


Figure 5.29 Optical spectrum at 5,10,20 Gb/s

5.3.1 Simulation results:

Optical spectrum:

Figure 5.30 shows the power value at 5 Gb/s is 3.5 dBm , 10 Gb/s is 2.75 dBm, 20 Gb/s is 4.12 dBm , 30 Gb/s is 4 dBm , 40Gb/s is 3.5 dBm and at different data rates 5, 10, 20 Gb/s is 4.15dBm .

Q values:

Figure 5.37 shows the value of eye opening at 5 Gb/s is 0.0015, 10 Gb/s is 0.00075, 20 Gb/s is 0.00375, 30 Gb/s is 0.00275, 40 Gb/s is 0.0006 and at different data rates 5, 10, 20 Gb/s is 0.0035 a. u.

Figure 5.38 shows the value of eye closing at 5 Gb/s is 3dB , 10 Gb/s is 6.5 dB , 20 Gb/s is 1dB, 30 Gb/s is 1.5 dB, 40 Gb/s is 8 dB and at different data rates 5, 10, 20 Gb/s is 1 dB.

Figure 5.39 shows the value of Q at 5 Gb/s is 15 dB, 10 Gb/s is 12 dB ,20 Gb/s is 20 dB, 30 Gb/s is 18 dB, 40 Gb/s is 11dB and at different data rates 5, 10, 20 Gb/s is 21 dB.

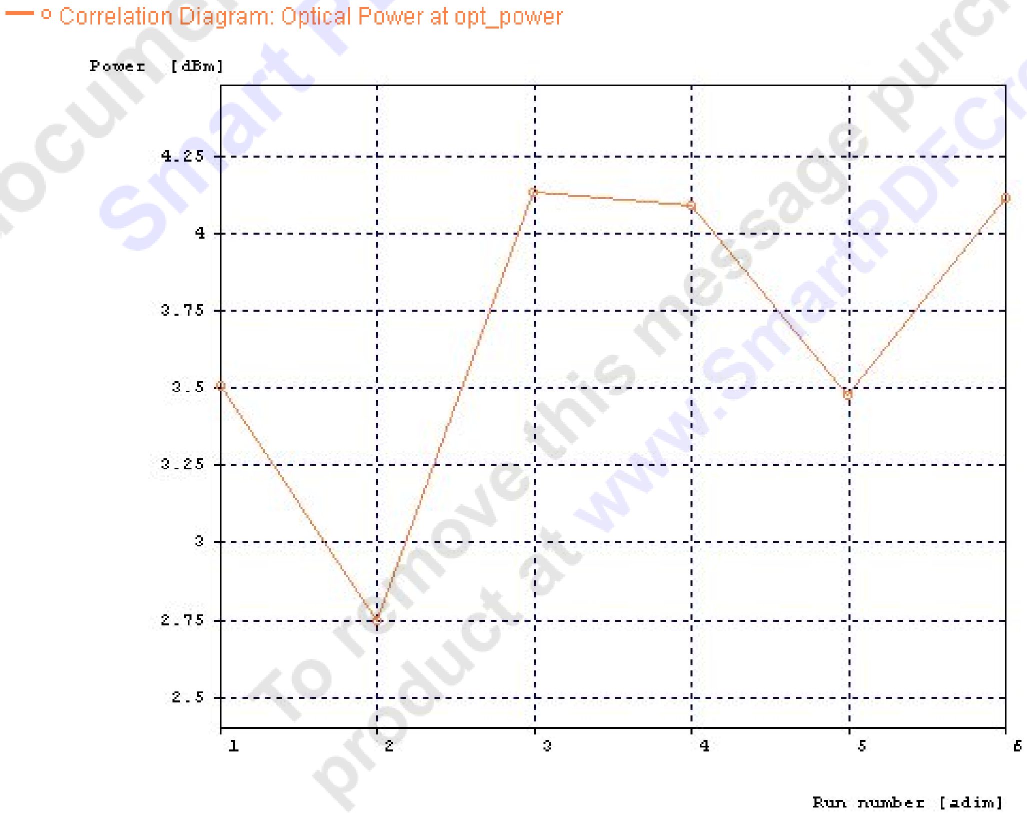


Figure 5.30 Correlation diagram of power

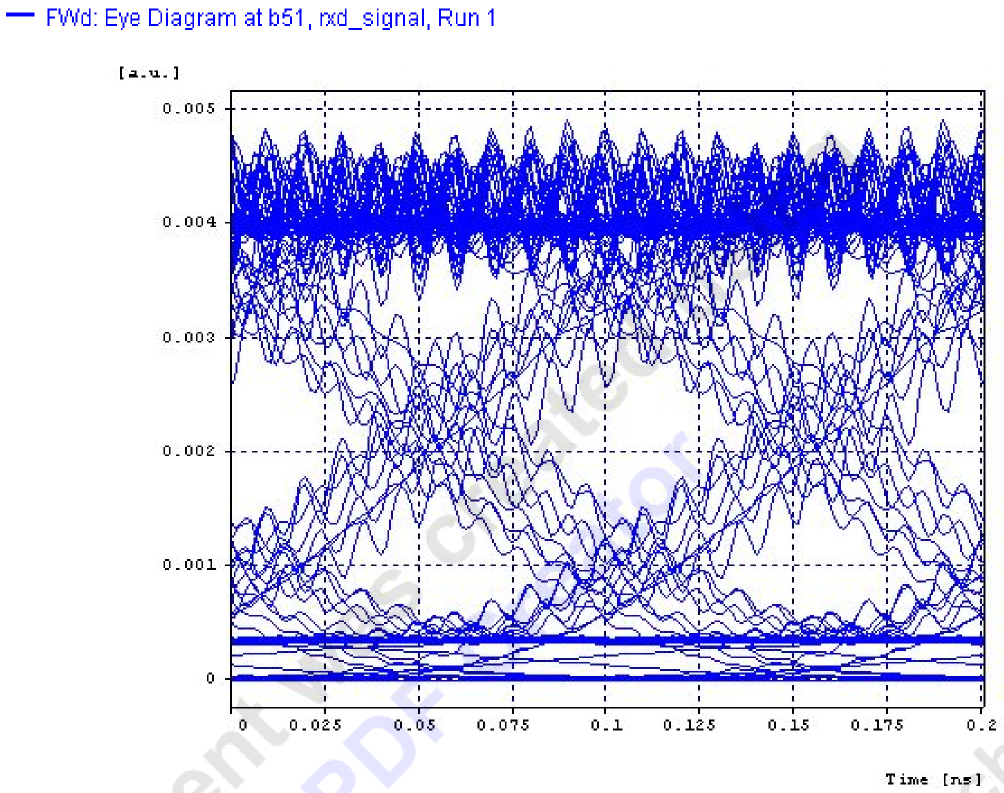


Figure 5.31 Eye diagram at 5 Gb/s

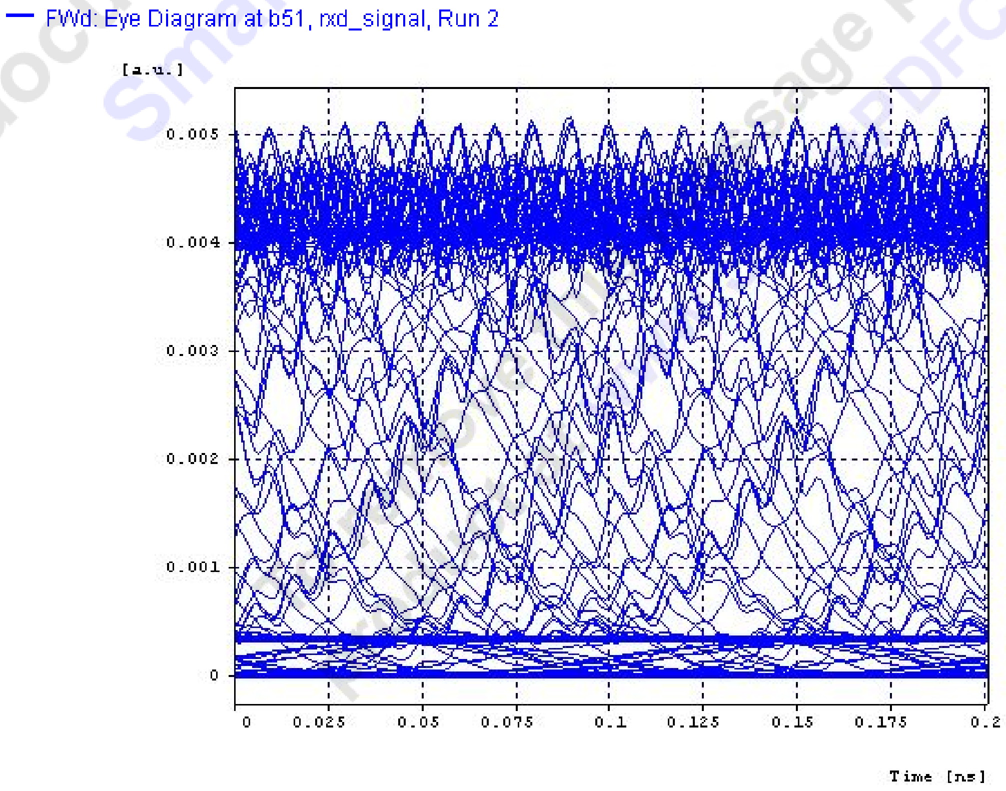


Figure 5.32 Eye diagram at 10Gb/s

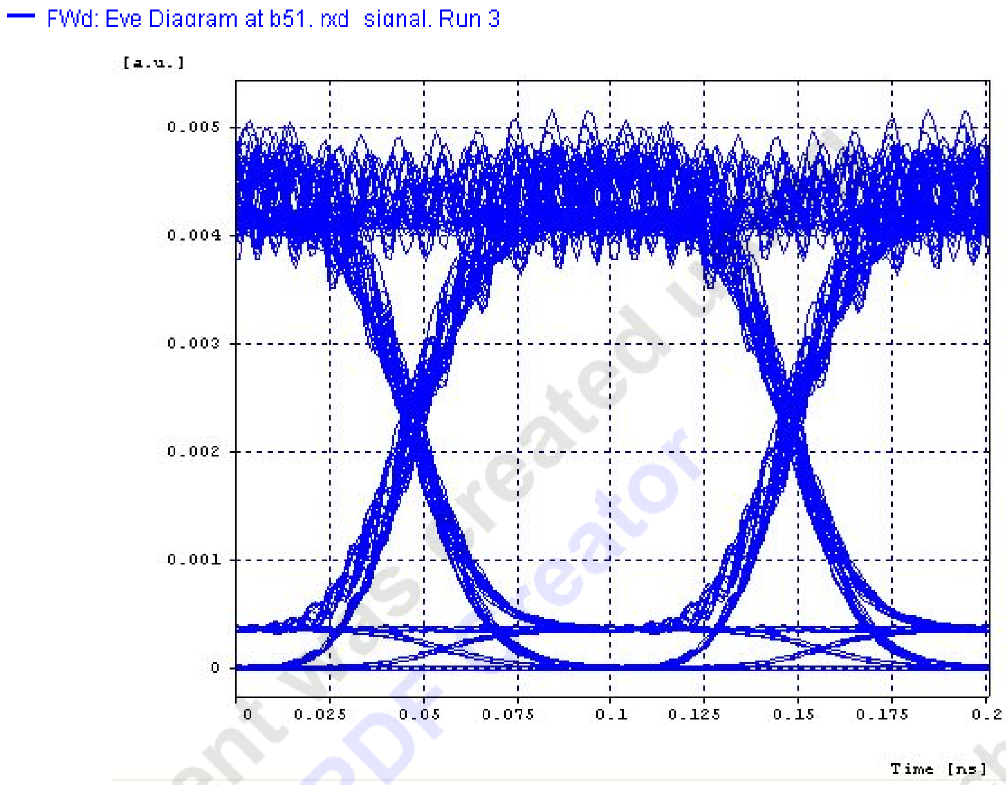


Figure 5.33 eye diagram at 20 Gb/s

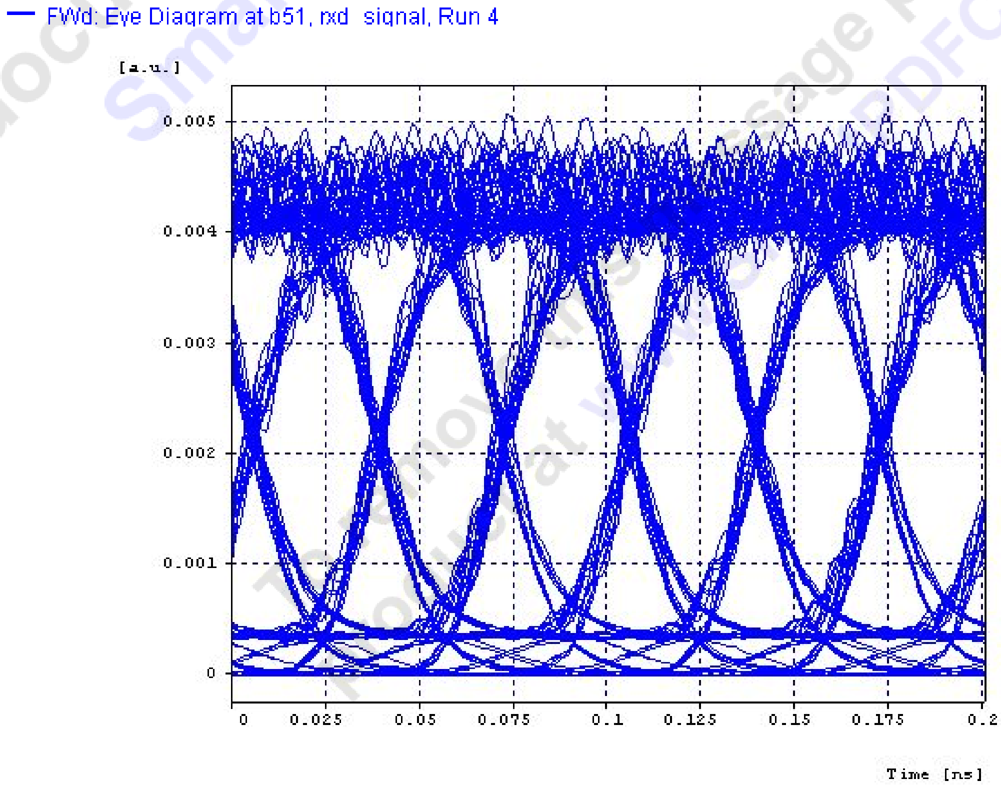


Figure 5.34 Eye diagram at 30 Gb/s

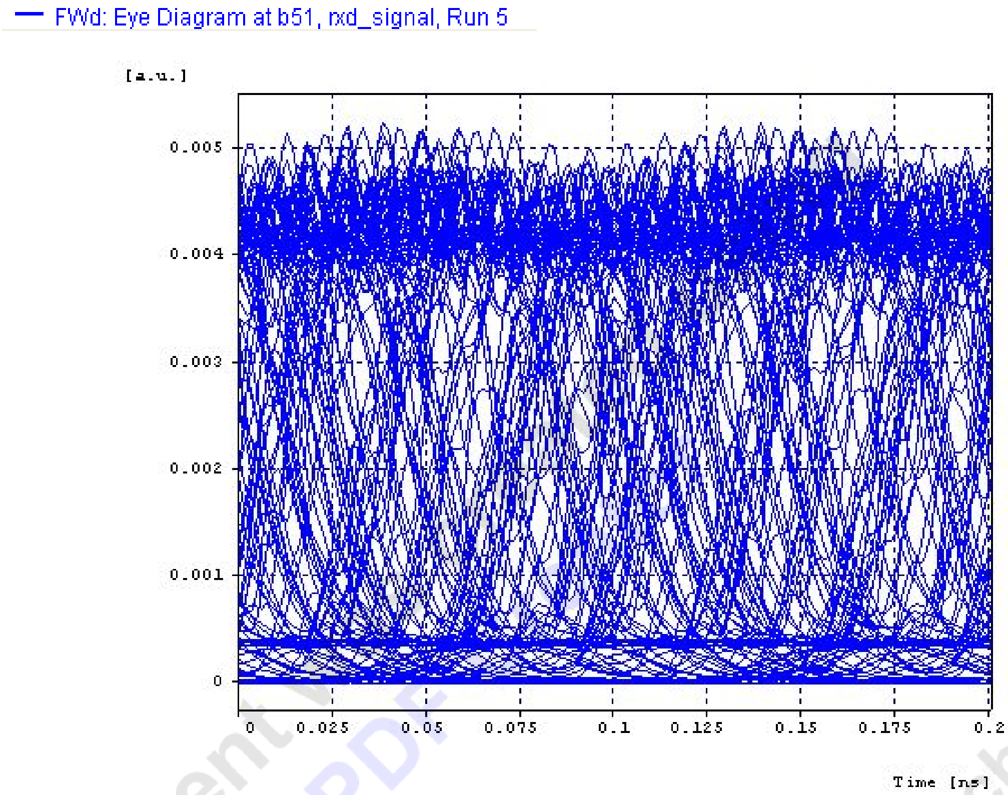


Figure 5.35 Eye diagram at40 Gb/s

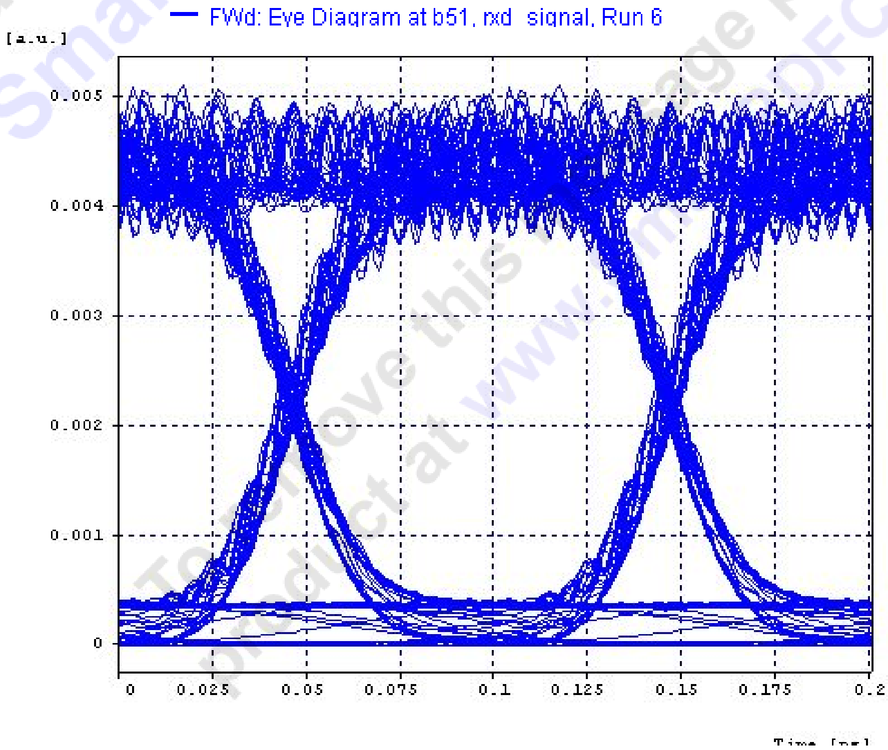


Figure 5.36 Eye diagram at 5,10, 20 Gb/s

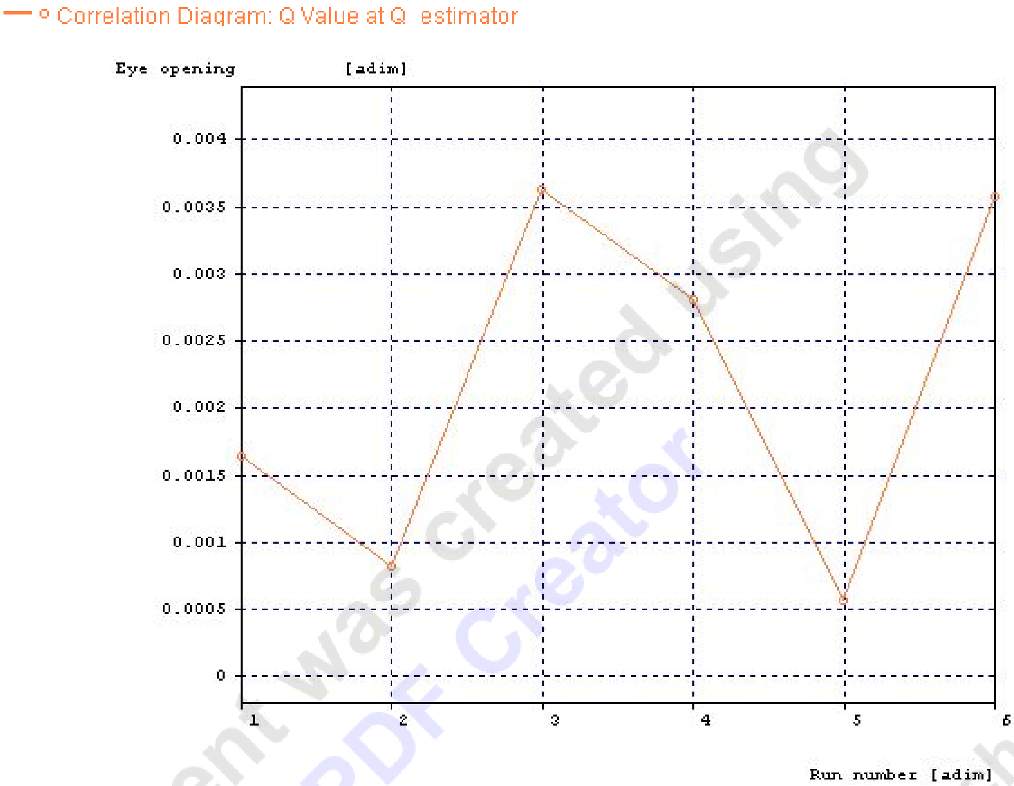


Figure 5.37 Eye opening at different data rates

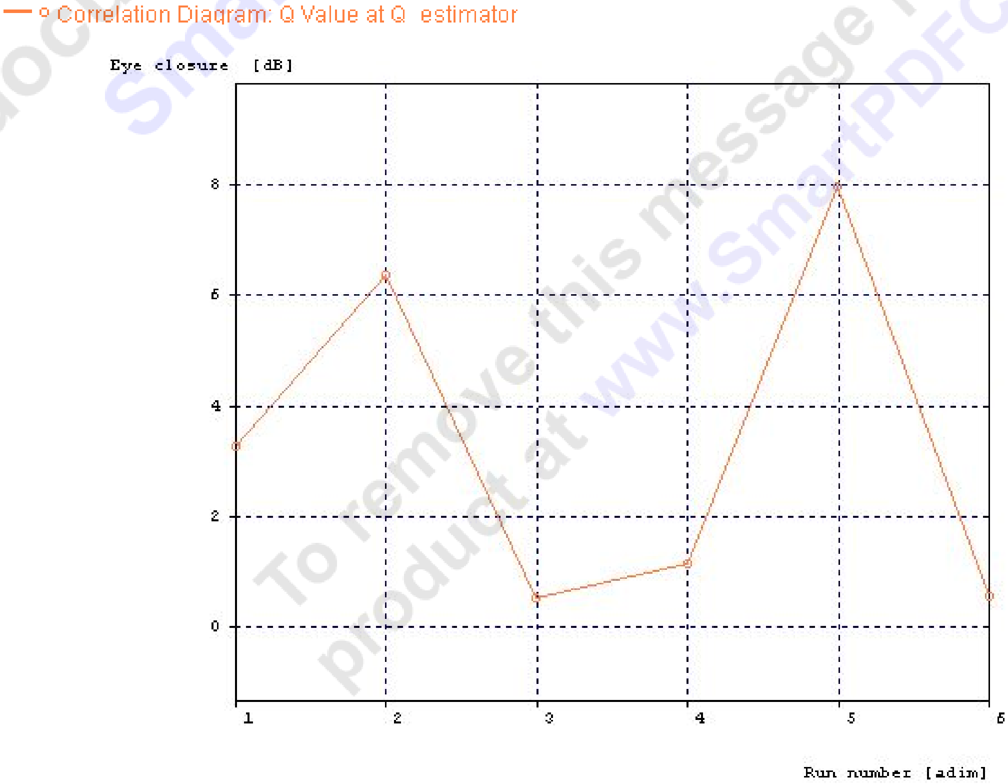


Figure 5.38 Eye closing at different data rates

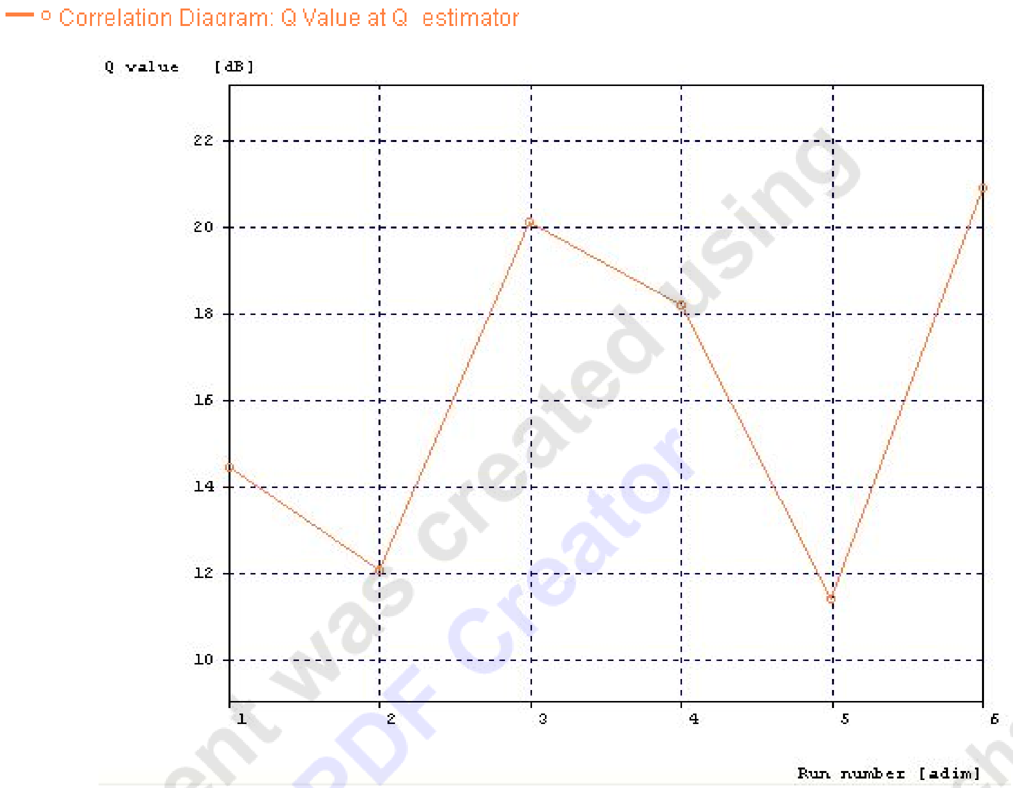


Figure 5.39 Q value

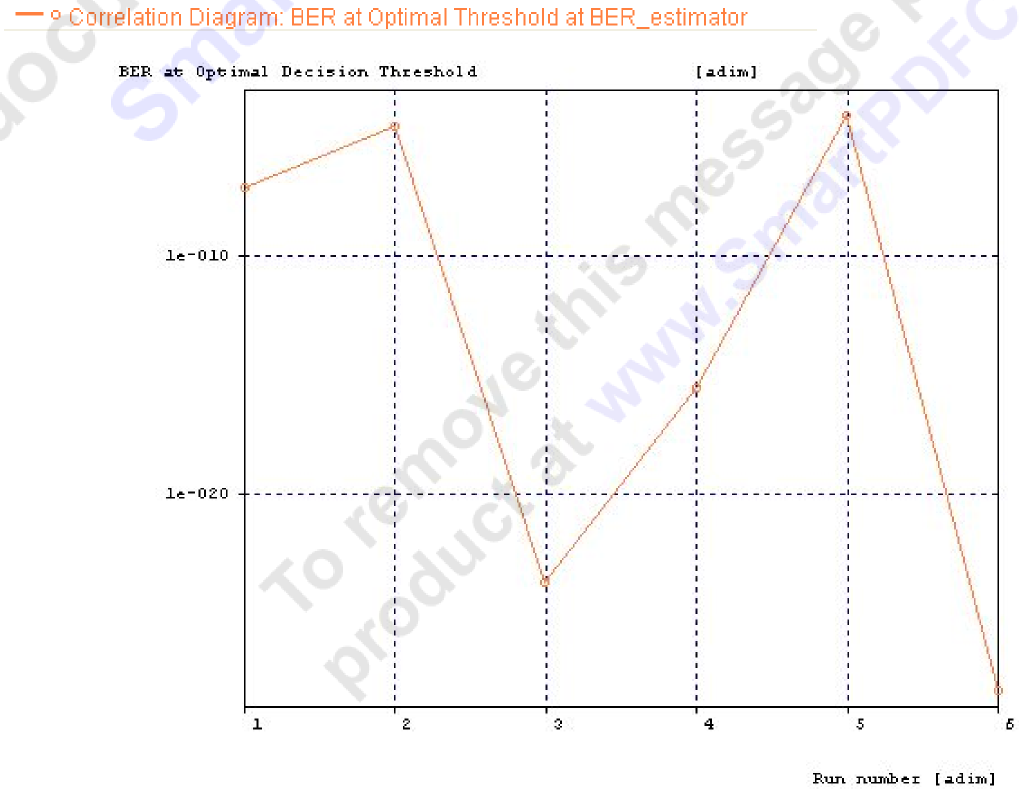


Figure 5.40 BER at different data rates

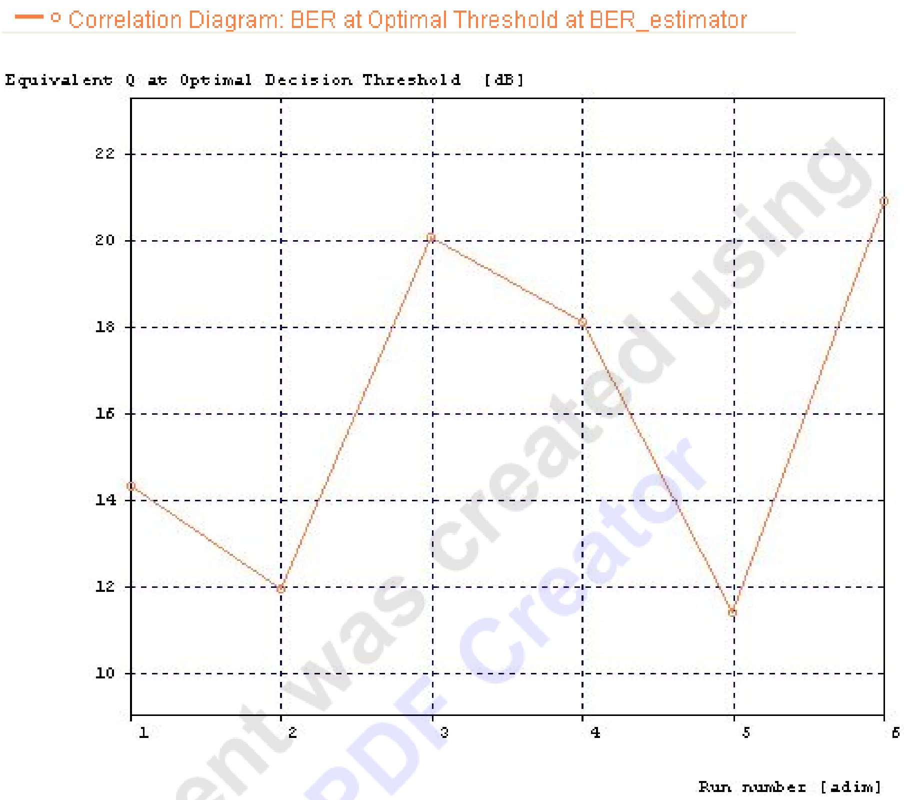


Figure 5.41 Q at optimum threshold

CHAPTER 6

CONCLUSION AND FUTURE SCOPE OF WORK

6.1 Conclusion

The main purpose of this research work is to investigate the effects of length of fiber on WDM system and limitation imposed by FWM on optical communication system. In WDM system we investigate the variation of length from 50 to 250 km, 75 km is best length for maximum eye opening i.e better performance.

In FWM at different channel spacing is varied from 0.1 to 3 nm , we investigate 1.5 nm is best for optical communication system. With increase in channel spacing the non linearity effects decrease. In FWM as we increase different data rates the performance decreases as we compared with analytical method.

6.2 Future scope of work:

In this thesis, the work is reported on WDM system and non-linear effect FWM. The nonlinear effects such as self phase modulation and cross phase modulation (XPM) are not included in this work. In future can be included self and cross phase modulation. Further, the crosstalk due to other fiber nonlinearities like stimulated Brillouin scattering and stimulated Raman scattering can be studied. In this research work, the polarization effects have been ignored. These effects along with dispersion and the fiber nonlinearities may be treated in analytical forms and result can be compared with present analytical method.

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