A Thesis Report

on

THEORETICAL AND SIMULATION STUDIES OF FIBER OPTICAL COMMUNICATION SYSTEMS WITH HIGHER ORDER DISPERSION, FIBER TYPE AND SELF PHASE MODULATION

Submitted In partial fulfillment of the requirement for the award of degree of

MASTER OF ENGINEERING
IN
ELECTRONICS & COMMUNICATION ENGINEERING

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Certificate

I hereby certify that the work which is being presented in the thesis entitled, ***"Theoretical and Simulation Studies of Fiber Optical Communication Systems with Higher Order Dispersion, Fiber Type and Self Phase Modulation"****, in partial fulfillment of the requirements for the award of degree of* ***Master of Engineering in Electronics & Communication Engineering*** *at* ***Thapar University****, Patiala, is an authentic record of my own work carried out under the supervision of* ***Dr.R. S. Kaler*** *and refers other researcher's works which are duly listed in the reference section.*

The matter embodied in this thesis has not been submitted for the award of any other degree of this or any other university.

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This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

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ABSTRACT

Focus on development of broadband optical communication systems is incredible since it offers combination of wide bandwidth and low losses unmatched by any other transmission medium but group velocity dispersion and fiber nonlinearities remain inherent limitations of such systems thereby degrading the performance. The main motivation of this work was to study theoretical and simulation studies of broadband optical communication systems due to dispersion and fiber nonlinearities. The GVD effect is the major factor that degrades the performance of high bit-rate long-distance optical communications systems. The studies on dispersion are very limited as far as the significance of higher order dispersion terms are concerned. Fiber nonlinearities have become one of most significant limiting factors of system performance since the advent of erbium-doped fiber amplifiers (EDFAs) because input power is increasing and the effects of fiber nonlinearities are accumulating with the use of EDFAs. In wavelength-division-multiplexing (WDM) systems, inter-channel interference due to fiber nonlinearities may limit the system performance significantly.

First, the FM-AM conversion with respect to binary intensity modulated PCM systems including higher order dispersion term are discussed using large signal analysis for dispersive optical fiber. The modified expression for power penalty has been derived and its impact on laser linewidth and bit rate has been investigated. For power penalty less than 0.5 dB, the plots between bit rate and transmission distance are plotted. It is seen that the transmission distance increases with decrease in linewidth over significant bit rates. The transmission distance with first order dispersion term for 150 KHz linewidth is approximately 900 km for 40Gb/s bit rate and 10^{-12} bit error rate. With proper first order dispersion compensation i.e. with second order dispersion only, the transmission distance can be enhanced to 10^6 km for this linewidth for the same bit rate. It is also seen that the linewidth requirement is narrow for larger bit rates and large transmission distances. For achieving transmission distance of 200 km, the linewidth requirement is 3 KHz, 60 KHz

and 5 MHz for bit rates 100 Gb/s, 40 Gb/s and 10 Gb/s respectively with bit error rate of 10^{-9}. For WDM systems, with acceptable bit error rate of 10^{-12}, the linewidth requirement reduces to 2KHz, 40 KHz and 2 MHz for bit rates 100 Gb/s, 40 Gb/s and 10 Gb/s respectively. Secondly, it has been shown that the bit error rate becomes deciding factor to select the fiber over long distance. From the results & discussion, it can be concluded that Dispersion shifted fibers anomalous & normal are performing better for long distances. Finally, we investigate power effects on simulation of 10 Gb/s NRZ optical communication systems with self phase modulation (SPM). In this, the behavior of SPM versus the optical power for a two spans amplified system has been investigated. A 10 Gb/s NRZ signal is launched over two DS fiber spans (D=0.4 ps/nm/km) of 50 km, each. The power at the input to each span is varied from 10 to 17.5 dBm by using the parametric run feature in OptSim. EDFA noise has been turned off in order to simplify the analysis of SPM. By increasing the power, SPM grows and depletes the signal, and the measured power (in a bandwidth equal to twice bit rate) actually decreases with the increasing of the transmitted power. Moreover, the channel has been demodulated. The eye diagram highlights the PM-AM conversion due to the SPM. Specifically the eye opening decreases with increasing transmitted power. Since there is no noise, estimation of the Q values is irrelevant.

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Chapter 1

INTRODUCTION

1.1 Introduction

In the information age, we are seeing a relentless demand for networks of higher capacities at lower costs. Optical communication technology has developed rapidly to achieve larger transmission capacity and longer transmission distance.

Focus on development of broadband optical communication systems is incredible since it offers combination of wide bandwidth and low losses unmatched by any other transmission medium but group velocity dispersion [1-3] and fiber nonlinearities due to Optical Kerr's effects [4-5] remain inherent limitations of such systems thereby degrading the performance. Therefore in order to realize broadband optical communication systems and networks, it is imperative to compensate the pulse spreading due to group velocity dispersion (GVD) and optical Kerr's effects.

With the advent of Erbium-doped fiber amplifiers (EDFAs), the attenuation limits on transmission distance have been overcome but since then nonlinearities have become critical issue in the advancement of optical communication systems. The nonlinear interactions of fiber material set an upper limit to the amount of information that can be transmitted. Optical Kerr's effects in optical fibers are due either to changes in the refractive index with optical power. Particularly for long haul transmission with number of WDM channels, the accumulated nonlinear effects lead to waveform distortion and cross talk between channels. Power dependence of refractive index is responsible to Kerr effects. Depending on the shape of the input signal, the Kerr nonlinearities manifest itself by different effects such as Self-Phase Modulation (SPM) [9,10], Cross-Phase Modulation (XPM) [11,12], and Four-Wave Mixing (FWM) [13].

These nonlinear effects are induced by high powers and long distances enabled by Erbium-doped fiber amplifiers (EDFA) at high bit rates [16]. These lead to attenuation, distortion and cross channel interference. These constrain the spacing between adjacent wavelength channels. These limit the maximum power on any channel and also limit the maximum bit rate.

In the recent past, various dispersion compensation methods have been studied, the impact of GVD on high bit-rate long-distance optical communications have been investigated and limitations of systems due to fiber dispersion and fiber nonlinearities due to optical Kerr's effect, have been discussed. However, such studies are very limited as far as the significance of higher order dispersion terms are concerned. In order to bridge the gap in available literature and to further analyze dispersion and higher order effects with optical Kerr's effects, it is important to analyze and investigate the performance of dispersive optical communication systems including higher-order dispersion terms. These dispersion and fiber nonlinear effects are further enhanced while realizing ultrahigh dense wavelength division multiplexed systems (DWDM) that are used to exploit optical bandwidth. Other important consideration includes propagation of modulation and noise characteristics of a laser diode with dispersion in the transmission medium. Also, optimization of high data rate long haul optical communication systems using practical methods of dispersion management is need of the hour. This synopsis focuses on investigating limitations on multi-wavelength optical fibers due to group velocity dispersion (GVD) and nonlinear effects due to optical Kerr's effects.

1.2 History

Optical communication got a kick in 1966 when Kao and Hockham [6] published a paper about the possibility to communicate optically. At that time it seemed impossible to cover up the attenuation of 1000dB/Km, but afterwards Kao found that all this attenuation was because of fiber impurities. In 1970, Kapron [7] et al. , practically showed that by using a pure silica fiber the losses could be reduced to 20 dB/Km. At this attenuation rate, the fiber optical communication has become an engineering reality. After that researcher have not looked back, so the optical communication is having exponential growth and it has played a key role in bringing the era of information technology. The explosive demand for bandwidth for data networking applications continues to drive optical technology toward ever increasing capacity in the backbone fiber network and toward flexible optical networking [1,2,3]. Already commercial Tb/s (per fiber) transmission systems have been announced and it can be expected that in the next several years we will begin to be limited by the 50 THz transmission bandwidth of silica optical fiber. Since the communication will be dominated by data, we can expect the network of the future (indeed the not-too-distant future) to consist of multi terabit packet switches to aggregate traffic at the edge of the network and cross connects with wavelength granularity and tens of terabits/s throughput in the core [1]. Efficient bandwidth utilization will be one of the challenges of optical communication research. Extensive research is underway on optical cross connects, optical packet switching, high port count mux-demux devices, reconfigurable add-drop multiplexers, wavelength agile lasers, broad band fiber amplifiers, high capacity fiber and elements for network management. All of these devices are aimed at increasing the flexibility of optical networking such as dynamic bandwidth allocation, optical restoration and wavelength routing in DWDM systems hence reducing system cost [2]. It is predicted that more than 30 million computers will be interconnected by the end of the year 2002, to meet this challenge plenty of work is done in India and abroad.

The phenomenon of intensity dependence of the refractive index in nonlinear media by which an intense and narrow optical pulse changes its phase is called Self phase modulation. This leads to spectral broadening of the optical pulse. When two or more optical waves co-propagate inside a fiber, they can interact with each other through fiber nonlinearity resulting in another nonlinearity called Cross Phase modulation (XPM). XPM is always accompanied by SPM and occurs because the effective refractive index of the wave depends not on the intensity of that wave but also on the intensity of copropagating waves. When three waves propagate in the same fiber, their fundamental frequencies are not only preserved but also along with it there is generation of new frequencies and various harmonics of the individual waves and their sums leading to mixing of waves called Four wave mixing.

The dispersion and nonlinearities both occur simultaneously in a system and play an important role in degrading the overall performance of optical communication system and networks. The interest in nonlinear fiber optics is expected to continue in view of the current emphasis on the development of the photonics based technologies for information management [4].The dispersion and nonlinear interactions of fiber material set an upper limit to the amount of information that can be transmitted [6-18].

The significance of impairments becomes more critical while realizing ultrahigh dense wavelength division multiplexed systems (DWDM) that are used to exploit optical bandwidth. Particularly for long haul transmission with number of WDM channels, the accumulated nonlinear effects lead to waveform distortion and crosstalk between channels [19-21].

Therefore, in order to realize broadband optical communication systems and networks, it is imperative to compensate the pulse spreading due to group velocity dispersion (GVD) and fiber nonlinearities due to optical kerr’s effects [6-21].

1.3 Literature survey

Different compensation methods like Optical Phase Conjugation method [18], Fiber chirped method [22], Bragg-Grating method [23], Filter method, Differential time delay method and dispersion equalizers [24] were studied in the last decade and based on these methods efforts were made to increase the transmission distances and bandwidth of optical communication systems. In the last few years, both dispersion Optical Kerr’s effects [25-30] have been studied together creating pathways to techniques called dispersion management techniques. The impact of higher order dispersion terms has also been studied these days by different authors.

Masaki [31] recently showed that there is a significant increase in the transmission speed of optical networks if the impact of higher order terms is clarified. The general expressions that describe pulse broadening due to even and odd higher order dispersion in a single mode fiber were discussed. The intrinsic impulsive response for even order dispersion (beyond the second order) were characterized by symmetrical waveforms with long trailing skirts, whereas the response for odd orders show asymmetrical strongly oscillating waveforms. The transmission limits were also analytically obtained for each higher n^{th} order that induces intersymbol interference.

Calvani *et al.* [32] demonstrated a simple technique of pulse compression based on linear chirp compensation of self phase modulation in dispersion-shifted fibers. Cartaxo *et al.* [33] derived expression for relative intensity noise due to dispersion and nonlinearity including fiber loss and showed its impact with first order dispersion term. The optimization procedure was carried out for short span of single mode fiber using parabolic law. Cartledge *et al.* [34] combined the use of SPM and joint optimization of the bias and modulation voltages to increase the dispersion limited transmission distance at 10 Gb/s. Tang *et al.* [35] presented a general treatment of multispan effects of Kerr nonlinearity on Shannon channel capacity for dispersion free nonlinear optical fiber transmission. Chiang *et al.* [36] reported that the phase modulation induced by cross phase modulation is inversely proportional to the signal base band modulation frequency. Yang *et al.* [37] derived expression for nonlinear crosstalk due to XPM effect. Sono *et al.* [38] described WDM transmission with SPM/XPM suppression through pre chirping and dispersion management. Yu et al. [39] demonstrated simultaneous demultiplexing and regeneration of 40 Gb/s optical time division multiplexed (OTDM) signal based on self phase and cross phase modulation in dispersion shifted fibers.

Numai and Kubota [40] again showed that by repeated unequally spaced channels, the FWM problem can be controlled to great extent. Recently, Radic *et al.* [41] investigated efficiency of FWM generation in quasi-distributed erobium doped fiber sections under general power evolution conditions using new theory. Measured FWM efficiency was found to be in good agreement with newly developed theory.

The dispersion management techniques are based on the solution to nonlinear shrodinger wave equation. Different methods are used to find solution to this equation. Variational method has been frequently used to find solution to this equation [2]. Solitons occur as a result of complex balance among the following factors: varying local and residual dispersion, nonlinearity, fiber loss and periodic amplification. The interplay among these factors lead to rich variety of possible transmission regimes. In soliton based WDM systems in which solitons [25] in different channels propagate at different speeds, collisions among them inevitable take place. The collisions induce nonlinear interaction between the solitons and produce frequency shifts. In the ideal collision process, the frequency shift returns to zero after the collision because of the underlying symmetric picture of whole collision process [27]. However when lumped amplifier exists in the middle of the collision process, the symmetric breaks down resulting in frequency shifts. This frequency shift may be completely cancelled out by some techniques called dispersion management techniques. It was found that collision also induces chirp degeneration. That the chirped solitons suffer less nonlinear interaction than regular solitons thus increasing the transmission capacity [25-30].

Tomohirio et al. [46] worked on 40Gb/s optical retiming, reshaping and retransmitting (3R). The regenerator was proposed and demonstrated using wavelength converters based on electroabsorption (EA) modulators for effectively implementing 40 Gb/s based or higher bit rate wavelength division multiplexing (WDM) optical networks. A Q-factor improvement of about 1.5 dB was obtained by them after transmission over 1000 Km, compared to evaluate without regenerator.

Ronald et al. [47] presented a novel linearization method to calculate accurate eye diagrams and bit error rates (BERs) for arbitrary optical transmission systems, apply it to a dispersion managed solition (DMS) system. Using Monte Carlo simulation techniques, the above said assumption the complete eye diagram, probability density function for marks and spaces can be evaluated. They presented a deterministic solution alternative to Monte Carlo.

Rongqing et al. [48] investigated the performance of high-speed digital fiber optics transmission using subcarrier multiplexing (SCM) both analytically and numerically. In order to reduce the impact of chromatic dispersion and increase the bandwidth, the optical single sideband (OSSB) modulation was used by them. After making a trade off between data rate per subcarrier, optical power and modulation indexes, a 10 Gb/s data streams were combined into one wavelength that occupied a 20-GHz optical bandwidth. The results got by them agree with the analytical results.

In India during the past few years’ fiber dispersion and nonlinearities have been studied and their impact on the system performance was investigated. In 1996, Rajappe et al. [55] reviewed the various fiber nonlinearities as well as the effects of these nonlinearities on the system performance. The techniques for minimizing the nonlinearities were also discussed. Sharma et al. [56-58] reviewed the various fiber dispersion compensation methods and investigated techniques for compensation of dispersion by differential delay method including the impact of higher order dispersion terms.

Kaler et al. [59] discussed the limitations due to GVD on transmission distance, bit rate and laser linewidth including the higher order dispersion effects. The power penalty analysis for different realistic weight functions for combating the pulse broadening effects of group-velocity dispersion in a fiber-optic communication link using differential time delay method with higher-order dispersion terms [60] was discussed. Further, the propagation of signal and noise in the transmission medium to observe the validity of higher order dispersion terms [61] was described. The comparison of pre-, post- and symmetrical-dispersion compensation schemes for 10 Gb/s NRZ links using standard and dispersion compensated fibers was also investigated [62]. It was also shown that the higher-order dispersion terms had significant role in controlling the FWM efficiency and hence cannot be ignored [63]. The simulation results for DWDM systems with an ultra-high capacity up to 1.28 Tbit/s and spectral efficiency approaching 0.4 bit/s/Hz were further analyzed [64-65] and explained on the basis of nonlinearities.

Therefore, in order to realize broadband optical communication systems and networks, it is imperative to compensate the pulse spreading due to group velocity dispersion (GVD) and fiber nonlinearities due to optical kerr's effects [6-21].

1.4 Objectives

In this thesis, the research is carried out keeping in view the following main objectives

1) To theoretical investigate and validate Bit Rate and Linewidth Analysis of FM-AM Conversion in Dispersive Optical Fibers for PCM systems including Higher Order Dispersion.
2) To investigate for optimum type of fiber by taking timing jitter performance at 10 Gb/s optical communication system
3) To investigate power effects on simulation of 10 Gb/s NRZ optical communication systems with self phase modulation (SPM)

1.5 Thesis outline

After studying the basic introduction, history and literature survey, we define the objectives in Chapter 1. In Chapter 2, we theoretical investigate and validate Bit Rate and Linewidth Analysis of FM-AM Conversion in Dispersive Optical Fibers for PCM systems including Higher Order Dispersion. In chapter 3, we investigate for optimum type of fiber by taking timing jitter performance at 10 Gb/s optical communication system. In Chapter 4, we investigate power effects on simulation of 10 Gb/s NRZ optical communication systems with self phase modulation (SPM). Finally we discuss conclusions in Chapter 5.

Chapter 2

BIT RATE AND LINEWIDTH ANALYSIS OF DISPERSIVE OPTICAL FIBERS FOR PCM SYSTEMS INCLUDING HIGHER ORDER DISPERSION

In this chapter, the FM-AM conversion with respect to binary intensity modulated PCM systems including higher order dispersion term are discussed using large signal analysis for dispersive optical fiber. The modified expression for power penalty has been derived and it's impact on laser linewidth and bit rate has been investigated. For power penalty less than 0.5 dB, the plots between bit rate and transmission distance are plotted. It is seen that the transmission distance increases with decrease in linewidth over significant bit rates. The transmission distance with first order dispersion term for 150 KHz linewidth is approximately 900 km for 40Gb/s bit rate and 10^{-12} bit error rate. With proper first order dispersion compensation i.e. with second order dispersion only, the transmission distance can be enhanced to 10^{6} km for this linewidth for the same bit rate. It is also seen that the linewidth requirement is narrow for larger bit rates and large transmission distances. For achieving transmission distance of 200 km, the linewidth requirement is 3 KHz, 60 KHz and 5 MHz for bit rates 100 Gb/s, 40 Gb/s and 10 Gb/s respectively with bit error rate of 10^{-9}. For WDM systems, with acceptable bit error rate of 10^{-12}, the linewidth requirement reduces to 2KHz, 40 KHz and 2 MHz for bit rates 100 Gb/s, 40 Gb/s and 10 Gb/s respectively.

2.1 Introduction

Recently, there has been great interest in using single mode fibers for high-bit-rate transmission in low loss transmission windows but dispersion is an important impairment that degrades overall system performance of an optical communication system. At high-bit-rate, the dispersion-induced broadening of short pulses propagating in the fiber causes crosstalk between the adjacent time slots, leading to errors when the communication distance increases beyond the dispersion length of the fiber. Higher order dispersion terms are the forces destructive of pulse propagation in ultra high-bit-rate optical transmission system and cause power penalty in the system. The invention of the erbium-doped fiber amplifier (EDFA) paved the way for the development of high bit rates all optical ultra long-distance communication systems. Specifically, periodic compensation of fiber loss by EDFAs eliminates the need for electronic repeaters along the transmission line and enables the construction of all-optical communication systems in which the transmission distance is limited by the fiber chromatic dispersion rather by the fiber loss because it introduces signal distortion and noise. However, if conventional 1.3 μm zero dispersion optical fiber systems and networks are used for the 1.55μm signal light, they exhibit a significant dispersion yielding, e.g. limitations with respect to transmission bandwidth.

To increase the transmission distance and the bandwidth, several techniques based on fiber nonlinearities have been introduced. Several authors have theoretically and experimentally shown the propagation of optical solitons through very long optical fiber links without distortion. But these investigations are very expensive and difficult to implement particularly in the optical systems that have been already installed. Also many authors have shown that it is very difficult to describe the propagation of optical signal near zero first order dispersion wavelength especially taking into account the effect of nonlinearities in the fiber. It is therefore very useful to investigate the performance of traditional optical systems in the linear regime owing to its simplicity and its application for realization of broadband optical communication systems. In the linear regime, the dispersion compensated fibers or Bragg's gratings can be solution to compensate for the dispersion effects (including higher order dispersion) but still the longer propagation length over single mode fiber is most desirable.

Different theories have been developed in the past to study the propagation of modulated signal produced by semiconductor lasers through dispersive medium. Wedding et al. [65] showed using small signal theory that frequency modulated optical transmitter at low loss wavelengths have high pass transfer characteristics. Equalizing this frequency response, the characteristics of the receiver low pass filter could be determined that were required for the method of dispersion supported transmission. Further using the same theory, Chraplyvy et al. [66] measured the induced amplitude modulation of sinusoidal phase modulated light signal in a single mode fiber. Amplitude modulation was observed for phase modulated wave at 4 GHz which produced poor penalty in the coherent transmission systems. Wang et al [67] developed a new approach to investigate the influence of the dispersion on optical fiber communication systems using small signal analysis. A conversion matrix describing the transfer function of intensity and frequency modulation at fiber input to the intensity and frequency modulation at fiber output was reported and the results were obtained to analyze the performance of optical communication systems. Claudio Crognale et al. [68] extended the analysis of Wang to include the second order dispersion term and results were compared with that of first order dispersion term .

Eva Pearl et al. [69] derived an expression for an exact large signal theory for propagation of an optical wave with sinusoidal amplitude and frequency modulation in a dispersive fiber. This was applied to direct modulation of semiconductor lasers. Petermann et al. [67] using large signal analysis discussed the FM-AM conversion for a dispersive optical fiber with respect to binary intensity modulated PCM systems. This was the same type of analysis [67] limited up to first order dispersion term only and the second order dispersion term was ignored. In this chapter, we extend the analysis for large signal theory [65] by including the second order dispersion term to study the FM-AM conversion for a dispersive optical fiber with respect to binary intensity modulated PCM systems as was done in [68] for small signal analysis.

2.2 Theory

We consider a single mode fiber transmission line; at the fiber input we have complex input field

$$E_a(t) = E_{in}(t)e^{j\omega_o t} \tag{1}$$

with the slowly varying complex amplitude $E_{in}(t)$ and the mean optical frequency ω_o. This input field will be transferred to the output field

$$E_b(t) = E_{out}(t)e^{j\omega_o t} \tag{2}$$

with the slowly varying complex field amplitude $E_{out}(t)$ at the fiber output. The propagation of a signal through an optical fiber can be described in terms of propagation constant β by the equation described in terms of Fourier transform as

$$E_{out}(\omega) = E_{in}(\omega)e^{-j\beta L} \tag{3}$$

where the propagation constant in terms of Taylor series can be expanded as

$$\beta = \beta_o + (\omega - \omega_o)\frac{d\beta}{d\omega} + \frac{1}{2}(\omega - \omega_o)^2\frac{d^2\beta}{d\omega^2} + \frac{1}{6}(\omega - \omega_o)^3\frac{d^3\beta}{d\omega^3}...... \quad (4)$$

where $\frac{d\beta}{d\omega} = \tau$ is the group delay for unit length

$$\beta = \beta_o + (\omega - \omega_o)\tau + \frac{1}{2}(\omega - \omega_o)^2\frac{d\tau}{d\omega} + \frac{1}{6}(\omega - \omega_o)^3\frac{d^2\tau}{d\omega^2}...... \quad (5)$$

$$\frac{d\tau}{d\omega} = -\frac{\lambda^2}{2\pi c}\frac{\partial\tau}{\partial\lambda} \quad (6)$$

is first order dispersion and

$$\frac{d^2\tau}{d\omega^2} = \frac{\lambda^2}{(2\pi c)^2}\left[\lambda^2\frac{\partial^2\tau}{\partial\lambda^2} + 2\lambda\frac{\partial\tau}{\partial\lambda}\right] \quad (7)$$

is second order dispersion.

Recalling Eqn. (3) the following expression is obtained for propagation constant term

$$e^{-j\beta L} = e^{-j\beta_o L - jL(\omega-\omega_o)\tau - jL\frac{1}{2}(\omega-\omega_o)^2\frac{\partial\tau}{\partial\omega} - jL\frac{1}{6}(\omega-\omega_o)^3\frac{\partial^2\tau}{\partial\omega^2} - ....} \quad (8)$$

where $\phi_o = \beta_o L$ at $\omega = \omega_o$. As reported in [65-68], we neglect the phase and group delay ($\phi_o = \beta_o L$ and $\frac{d\beta}{d\omega} = \tau$) because both terms produce only phase delay of the carrier signal and have no influence on the distortion of the signal. We define the following dispersion parameters

$$F_2 = -\frac{L}{2}\frac{d\tau}{d\omega} = \frac{L}{2}\frac{\lambda^2}{2\pi c}\frac{\partial\tau}{\partial\lambda} \quad (9)$$

$$F_3 = \frac{L}{6}\frac{d^2\tau}{d\omega^2} = \frac{L}{6}\frac{\lambda^2}{(2\pi c)^2}\left[\lambda^2\frac{\partial^2\tau}{\partial\lambda^2} + 2\lambda\frac{\partial\tau}{\partial\lambda}\right] \quad (10)$$

We rewrite the output equation in terms of Fourier domain as

$$E_{out}(\omega) = e^{(j(\omega-\omega_o)^2 F_2 - j(\omega-\omega_o)^3 F_3 ....)} E_{in}(\omega) \quad (11)$$

In time domain $\left(j\omega = \frac{\partial}{\partial t}\right)$, $\left((j\omega)^2 = -\omega^2 = \frac{\partial^2}{\partial t^2}\right)$ and $\left((j\omega)^3 = -j\omega^3 = \frac{\partial^3}{\partial t^3}\right)$

$$E_{out}(t) = e^{\left(-jF_2 \frac{\partial^2}{\partial t^2} + F_3 \frac{\partial^3}{\partial t^3} ....\right)} E_{in}(t) \tag{12}$$

The input field amplitude may be written as

$$E_{in}(t) = \sqrt{P(t)} e^{j\phi(t)} \tag{13}$$

with the phase $\phi(t)$ and optical power $P(t)$. Inserting eqn. (13) in eqn. (12)

$$E_{out}(t) = e^{\left(-jF_2 \frac{\partial^2}{\partial t^2} + F_3 \frac{\partial^3}{\partial t^3} ....\right)} \sqrt{P(t)} e^{j\phi(t)} \tag{14}$$

$$E_{out}(t) = E_{in}(t) + \Delta E(t) \tag{15}$$

where $|\Delta E(t)| \langle\langle |E_{in}(t)|$

From equation (14) and (15)

$$\Delta E(t) = \left(e^{\left(-jF_2 \frac{\partial^2}{\partial t^2} + F_3 \frac{\partial^3}{\partial t^3} ....\right)} - 1 \right) \sqrt{P(t)} e^{j\phi(t)} \tag{16}$$

$$P_{out}(t) = |E_{in}(t) + \Delta E(t)|^2 \approx |E_{in}(t)|^2 + 2\Re\left[E_{in}^*(t).\Delta E(t)\right] \tag{17}$$

Substituting eqn. (13) and eqn. (16) in eqn. (17)

$$P_{out}(t) = P + 2\Re\left[\sqrt{P(t)} e^{-j\phi(t)} \left(e^{\left(-jF_2 \frac{\partial^2}{\partial t^2} + F_3 \frac{\partial^3}{\partial t^3} ....\right)} - 1 \right) \sqrt{P(t)} e^{j\phi(t)} \right] \tag{18}$$

Expressing $e^x = 1 + x$, (the expansion has been carried out only up to first term because for pcm transmission, the spectrum due to noise is considered to be narrow), we get

$$P_{out}(t) = P + 2\Re\left[\sqrt{P(t)} e^{-j\phi(t)} \left(-jF_2 \frac{\partial^2}{\partial t^2} + F_3 \frac{\partial^3}{\partial t^3} .... \right) \sqrt{P(t)} e^{j\phi(t)} \right] \tag{19}$$

$$P_{out}(t) = P + 2\Re\left[\sqrt{P(t)}e^{-j\phi(t)}\left(-jF_2\frac{\partial^2}{\partial t^2}\sqrt{P(t)}e^{j\phi(t)}\right)\right]$$
$$+ 2\Re\left[\sqrt{P(t)}e^{-j\phi(t)}\left(jF_3\frac{\partial^3}{\partial t^3}\sqrt{P(t)}e^{j\phi(t)}\right)\right] \qquad (20)$$

$$P_{out}(t) = P + A + B \qquad (21)$$

where A and B correspond to first and second real parts in eqn. (20)

$$A = 2F_2\frac{d}{dt}\left(P\phi^{'}\right) = 2F_2P\phi^{''} + 2F_2\phi^{'}\frac{dP}{dt} \qquad (22)$$

$$B = 2F_3\left[-\frac{dP}{dt}\left(\phi^{'}\right)^2 - 3P\left(\phi^{'}\right)\left(\phi^{''}\right) - \frac{1}{2}\frac{dP}{dt}\left(\phi^{'}\right)^2 + \frac{1}{2}\frac{d^3P}{dt^3}\left(\phi^{'}\right)^2 - \frac{3}{4P}\left(\frac{dP}{dt}\right)\left(\frac{d^2P}{dt^2}\right) + \frac{3}{8P^2}\left(\frac{dP}{dt}\right)^3\right] \qquad (23)$$

where $\phi^{'} = \frac{d\phi}{dt}$ and $\phi^{''} = \frac{d^2\phi}{dt^2}$. For studying the transmission of PCM signals, we consider a sequence 101010….. sequence represented as

$$P = P_o\left[1 + \cos(\pi Bt)\right] \qquad (24)$$

where B is the bit rate. We assume chirp-free modulation is obtained by using external modulators. Thus for $\Delta P = A + B$, at the decision point, we have $\frac{dP}{dt} = 0$ for both ‘1’ and ‘ 0’. Because $P = 0$ for the space signal, there is noise ΔP only for the marl ‘1’ signal. ΔP is expressed as

$$\Delta P = 2P_o\left(2F_2\phi^{''} - 3F_3\phi^{''}\phi^{'}\right) \qquad (25)$$

$$\left\langle \Delta P^2 \right\rangle = 4P_o^2\left(2F_2\phi^{''} - 3F_3\phi^{''}\phi^{'}\right)^2 \qquad (26)$$

$$\frac{\left\langle \Delta P^2 \right\rangle}{P_o^2} = 16F_2^2\left\langle\left(\phi^{''}\right)^2\right\rangle + 36F_3^2\left\langle\left(\phi^{''}\right)^2\right\rangle\left\langle\left(\phi^{'}\right)^2\right\rangle - 48F_2F_3\left\langle\left(\phi^{''}\right)^2\right\rangle\left\langle\left(\phi^{'}\right)\right\rangle \qquad (27)$$

$\left\langle \Delta P^2 \right\rangle$ represents noise due to FM – AM conversion at the fiber output. The power penalty as expressed in [71, 72]

$$PP = -5\log_{10}\left(1 - Q^2\frac{\left\langle \Delta P^2 \right\rangle}{P_o^2}\right) \qquad (28)$$

The spectral power density is given by [73]

$$W_\phi = 2\pi\Delta\nu \qquad (29)$$

The frequency fluctuations are characterized by spectral power density.

$$\phi^{'} = W_{\phi} = 2\pi\Delta\nu \tag{30}$$

we obtain

$$\left\langle \left(\phi^{'}\right)^{2} \right\rangle = \int_{-B/2}^{B/2} W_{\phi}\, df \tag{31}$$

$$\left\langle \left(\phi^{'}\right)^{2} \right\rangle = 2\pi\Delta\nu B \tag{32}$$

Also the spectral power density for second derivative of frequency is given by

$$\phi^{''} = \frac{d\phi^{'}}{dt} = (2\pi f)^{2} W_{\phi} \tag{33}$$

we obtain

$$\left\langle \left(\phi^{''}\right)^{2} \right\rangle = \left\langle \left(\frac{d\phi^{'}}{dt}\right)^{2} \right\rangle = \int_{-B/2}^{B/2} (2\pi f)^{2} W_{\phi}\, df \tag{34}$$

$$\left\langle \left(\phi^{''}\right)^{2} \right\rangle = \frac{2}{3}\pi^{3}\Delta\nu B^{3} \tag{35}$$

Substituting eqn. (30), (32) and (35) in (27) and finally in (28), we get

$$PP = -5\log_{10}\left(1 - Q^{2}\left(\frac{32}{3}F_{2}^{2}\pi^{3}\Delta\nu B^{3} + \frac{144}{3}F_{3}^{2}\pi^{4}\Delta\nu^{2}B^{4} - \frac{192}{3}F_{2}F_{3}\pi^{4}\Delta\nu^{2}B^{3}\right)\right) \tag{36}$$

so that

$$\frac{\left\langle \Delta P^{2} \right\rangle}{P_{o}^{2}} = \frac{32}{3}F_{2}^{2}\pi^{3}\Delta\nu B^{3} + \frac{144}{3}F_{3}^{2}\pi^{4}\Delta\nu^{2}B^{4} - \frac{192}{3}F_{2}F_{3}\pi^{4}\Delta\nu^{2}B^{3} \tag{37}$$

2.3 Results and discussions

For system penalty to be less than 0.5dB and for $Q = 7$ (corresponding to 10^{-12} bit error rate)

$$\frac{\left\langle \Delta P^{2} \right\rangle}{P_{o}^{2}} \langle \frac{1}{X} = \frac{32}{3}F_{2}^{2}\pi^{3}\Delta\nu B^{3} + \frac{144}{3}F_{3}^{2}\pi^{4}\Delta\nu^{2}B^{4} - \frac{192}{3}F_{2}F_{3}\pi^{4}\Delta\nu^{2}B^{3} \tag{38}$$

The value of X as calculated from eqn. (28) is 239. Referring to ITU-T Rec.653 recommendation [74], we assume $\lambda_{o} = 1.55\mu m$, $\frac{\partial\tau}{\partial\lambda} = 20 ps/nm.km$ and

$\frac{\partial^2 \tau}{\partial \lambda^2} = 0.085 ps/nm^2 km$, we obtain following dispersion parameters using equations (9) and (10).

$F_2 = 12.75x10^{-24} L/km$

$F_3 = 2.955x10^{-38} L/km$

The $\Delta \nu$ maximum linewidth limit can be obtained from equation (38) where the ratio can be considered to be varying from zero to $5.3x10^{-3}$ or $6.2x10^{-3}$ for power penalty less than 0.5dB as shown in Figure 2.1.

In addition, there is usual modulation induced spectral broadening dispersion limit, which is given by [75].

$$B\sqrt{F_1} = 0.25 \text{ or } B\sqrt{L_1} = 70Gb/s\sqrt{km} \tag{39}$$

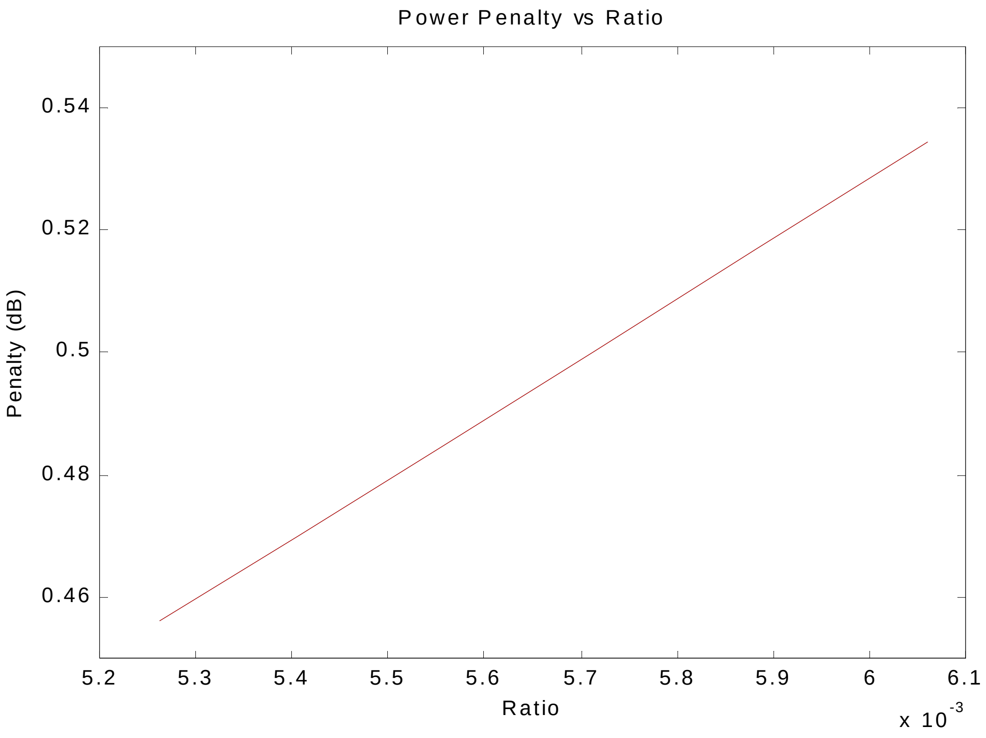

Figure 2.1: Power Penalty vs Ratio

The plot between bit rate and transmission distance for F_2 only is shown in Figure 2.2. It is clear that the bit rate decreases with total propagation distance. With decrease in linewidth of laser source, the curve shifts upward indicating the propagation distance enhancement for significant high bit rates. The modulation limit resulting in FM-AM conversion is function of linewidth and is achieved by reducing the linewidth. If the linewidth is further reduced, the plots greater than the modulation limit can be obtained. The modulation limit given by eqn. (39) is also plotted in the figure. The transmission distance with first order dispersion term for 150 KHz linewidth is approximately 900km for 40Gb/s bit rate and 10^{-12} bit error rate. The plot between bit rate and transmission distance for F_3 only is shown in Figure 2.3. There is tremendous in the transmission distance i.e. with proper first order dispersion compensation and second order dispersion only, the transmission distance can be enhanced to 10^6 km for 150 KHz linewidth and 40Gb/s bit rate. Also one more point to be noted here is that the plots for all linewidths are greater than the modulation limit. The graph for combined case is shown in Figure 2.4. It is clear that by including the second order dispersion term, the bit rate and transmission distance decreases. For higher linewidths, this decrease is very less and as the linewidth decreases, the decrease increases. For example, for 300 MHz linewidth, the decrease is transmission distance is just 30 km and for 30 MHz linewidth, the decrease is approximately 600 km over significant bit rates. From Figures 2.2, 2.3 and 2.4, it is also clear that the modulation limit given by eqn. (39), which signifies FM-AM noise conversion limit is well coincident with our plots.

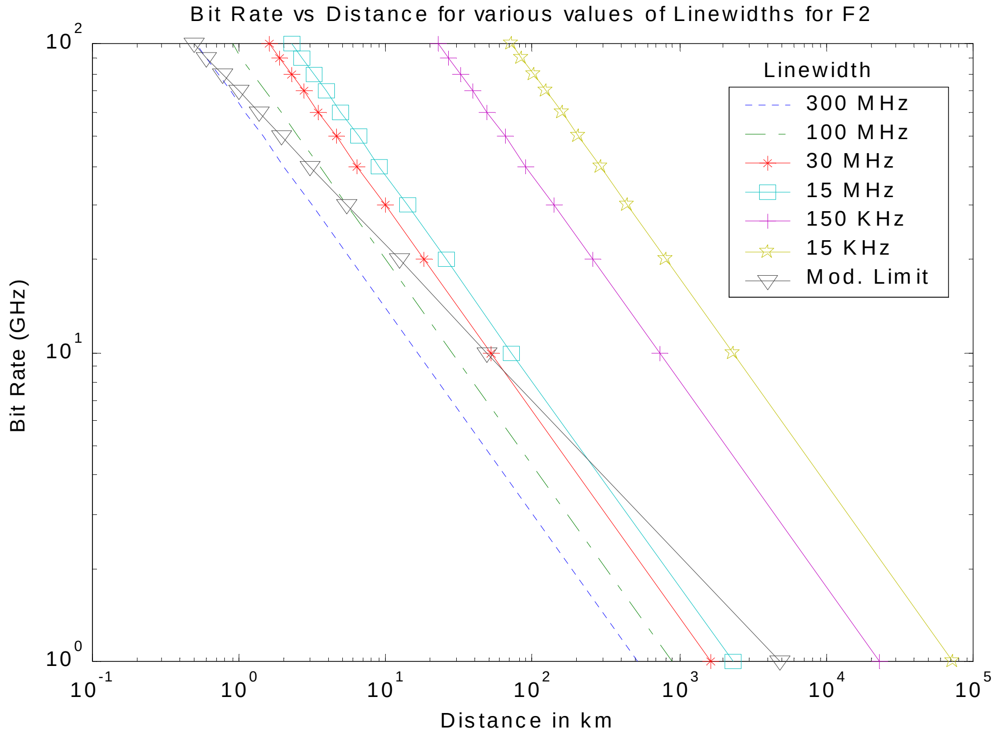

Figure 2.2 : Bit Rate vs Distance for various values for linewidth for F2

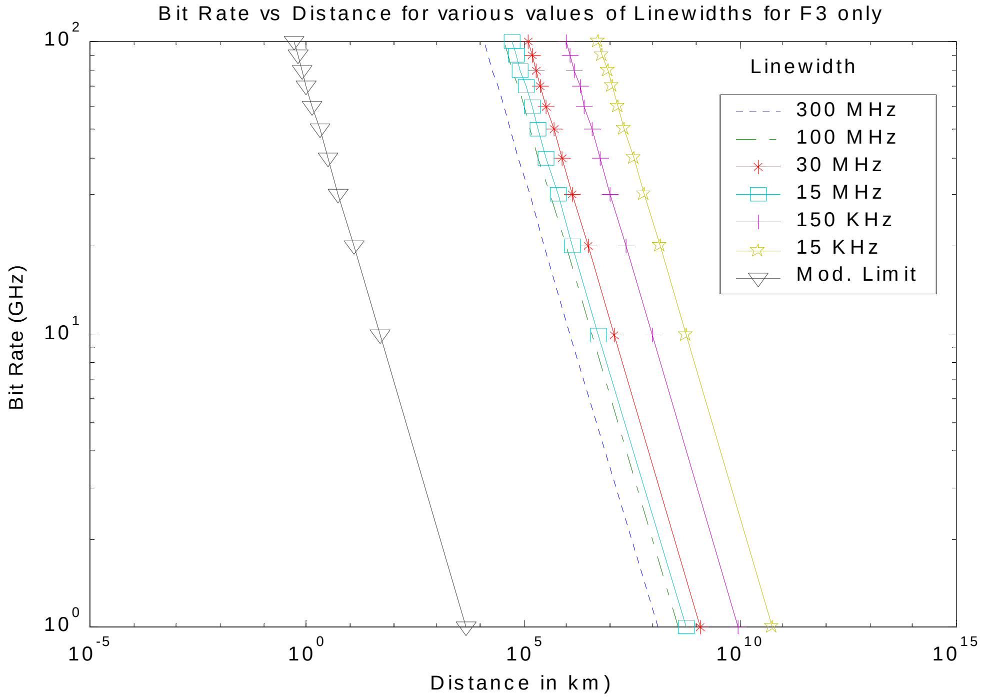

Figure 2.3 : Bit Rate vs Distance for various values for linewidth for F3

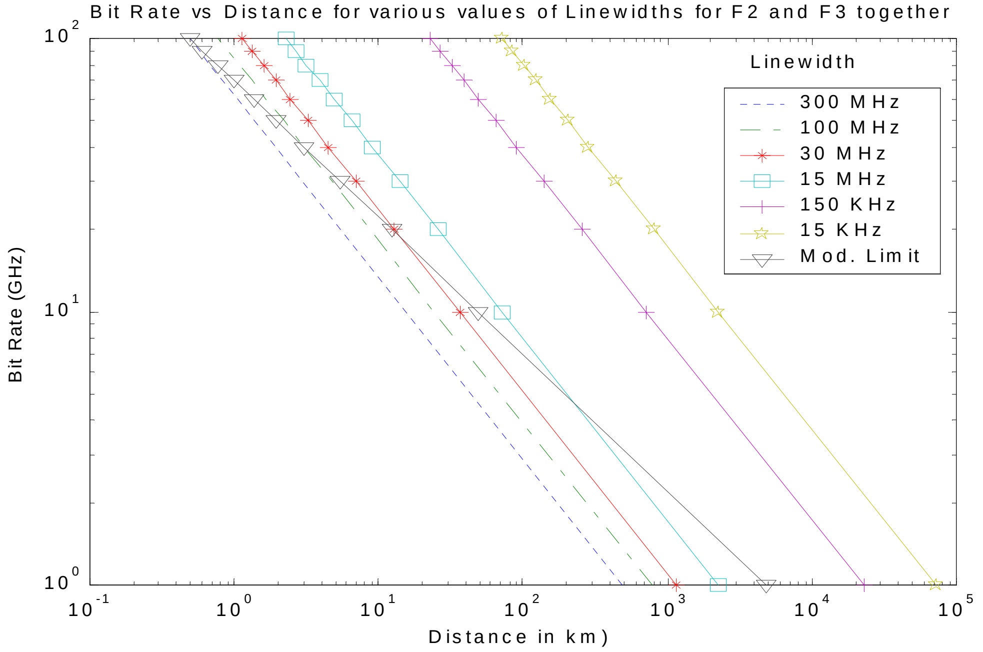

Figure 2.4 : Bit Rate vs Distance for various values for linewidth for F2 and F3

In order to further analyze the linewidth requirements, let us now consider other bit error rates also. Corresponding to equation (38), with Q=6, the bit rate is 10^{-9} and the value of X as calculated from eqn. (28) is 175 and corresponding to Q=8, the bit error rate is 10^{-15}

and the value of X is 311. The most acceptable bit error rate for optical communication systems for WDM systems is 10^{-12} although 10^{-9} is also acceptable for single channel systems. For futuristic DWDM systems, the bit error rate requirement will be 10^{-15}. The graph for first order dispersion between linewidth and propagation distance for different bit rates at 10^{-9} bit error is shown in Figure 2.5. It is clear from the figure that larger is the bit rate, lower is the requirement for laser linewidth. Also more is the transmission distance, the less is the linewidth required. For example, for achieving transmission distance of 200 km, for 100 Gb/s bit rate, the required linewidth is 3 KHz, for 40 Gb/s bit rate, the required linewidth is 60 KHz and for 10 Gb/s, the required linewidth is 5 MHz. Now if the requirement is of WDM systems, with acceptable bit error rate of 10^{-12}, the linewidth requirements are further decreased i.e. the curve has shifted downwards as shown in Figure 2.6. For 200 km transmission distance, the linewidth requirement is now 2KHz for 100Gb/s bit rate, 40 KHz for 40 Gb/s bit rate and 2 MHz for 10 Gb/s bit rate.

In order to see the dominance of first order dispersion term, let us say that the system is fully first order dispersion compensated i.e. $F_2=0$. It is observed that the transmission distance increases manifold as shown in Figure 2.7. For 5 MHz linewidth, it increases to 10^6 km for 100 Gb/s bit rate, 10^7 km for 40 Gb/s bit rate and 10^8 km for 10 Gb/s bit rate. Again on increasing the accuracy to 10^{-12} bit error rate, some changes although very small are visible from Figure 2.8.

The combined effects of first order dispersion and second order dispersion is studied by plotting Figure 2.9 and (10) for Q=6 and Q=7. It is seen that the effect is almost the same as for first order dispersion term as indicated in Figure 2.5 and 2.6. This shows the dominance of first order term and also that the second order dispersion has almost negligible effect while selecting the linewidth of the lasers.

The selection requirement of laser linewidths very much depends on the accuracy of the system i.e. bit error rate of the system. This is clear from Figures 2.11, 2.12 and 2.13 which illustrate the linewidth requirements versus transmission distance for different values of Q (bit error rate). For example, for 500 km transmission distance and 10 Gb/s bit rate, the required linewidth is 500 KHz, 300 KHz and 200 KHz for 10^{-9}, 10^{-12}, and 10^{-15} bit error rates respectively. For 100 Gb/s, it is clear from Figure 2.13 that for small transmission distances, the linewidth requirements for different accuracies are hardly the same but for larger distances, the linewidth requirements differ.

The exact linewidth requirement depends on the modulation format at the transmitter, the transmitted bit rate and demodulation technique at the receiver. For synchronous detection, the linewidth requirements are not so narrow and ordinary laser will be able to work. But for asynchronous detection, less linewidth requirement is placed on the systems at high bit rates and transmission distance. To achieve such narrow linewidth, one needs single longitudinal-mode devices such as quarter-wavelength shifted DFB laser, a distributed–Bragg-reflector laser or an external cavity laser.

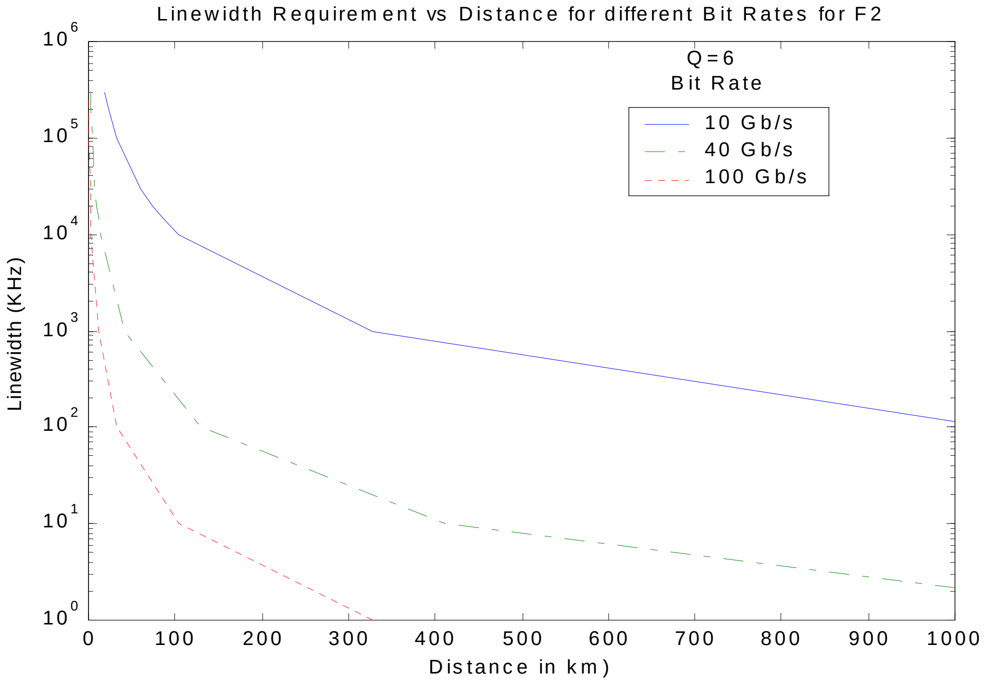

Figure 2.5 : Linewidth Requirements vs Distance for Diffrent bit rates for F2 (Q=6)

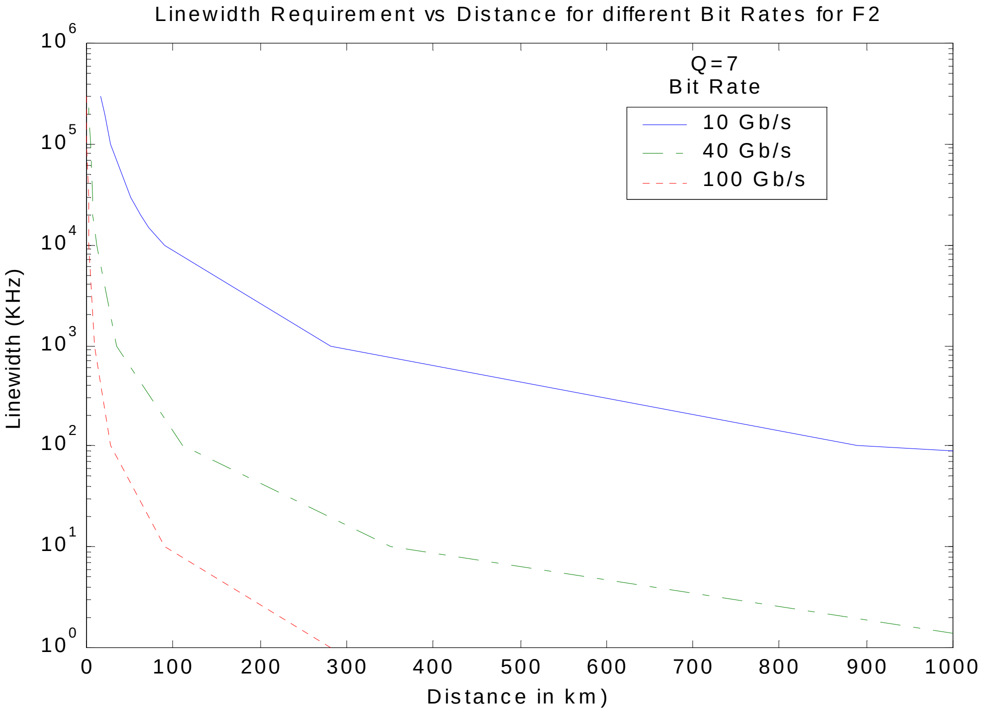

Figure 2.6 : Linewidth Requirements vs Distance for Diffrent bit rates for F2 (Q=7)

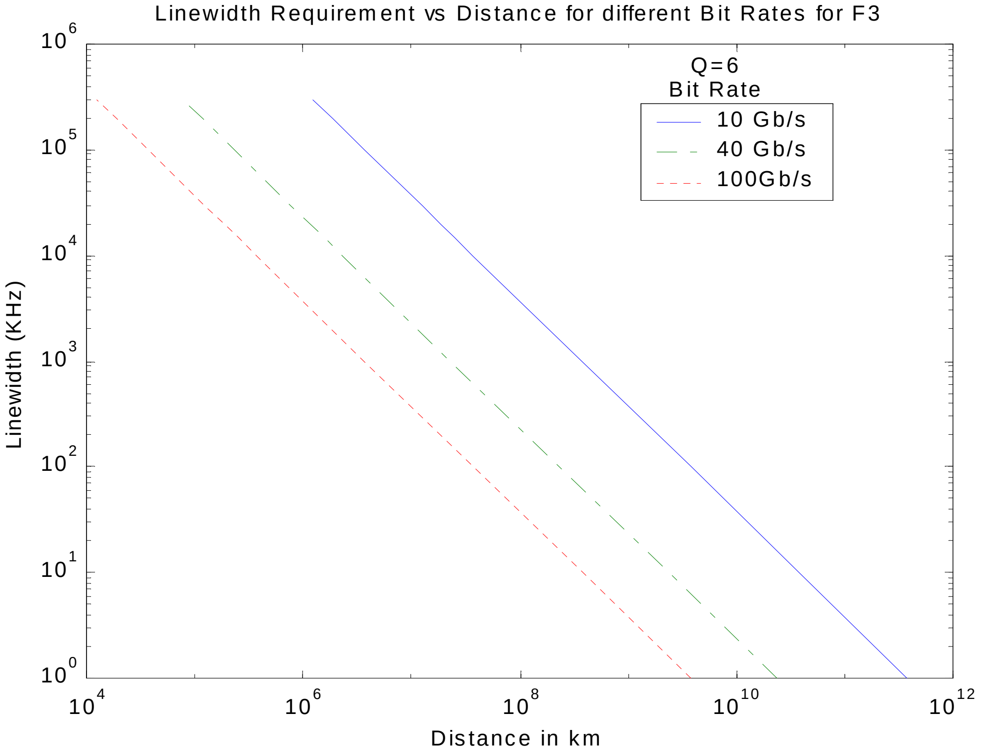

Figure 2.7 : Linewidth Requirements vs Distance for Diffrent bit rates for F3 (Q=6)

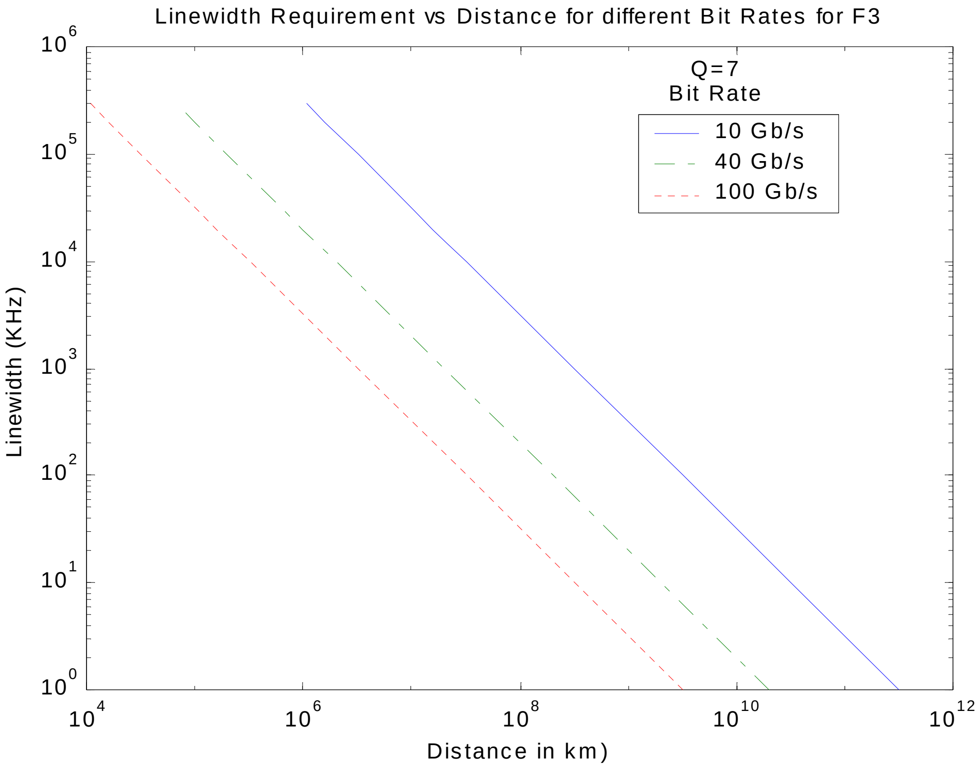

Figure 2.8 : Linewidth Requirements vs Distance for Diffrent bit rates for F3 (Q=7)

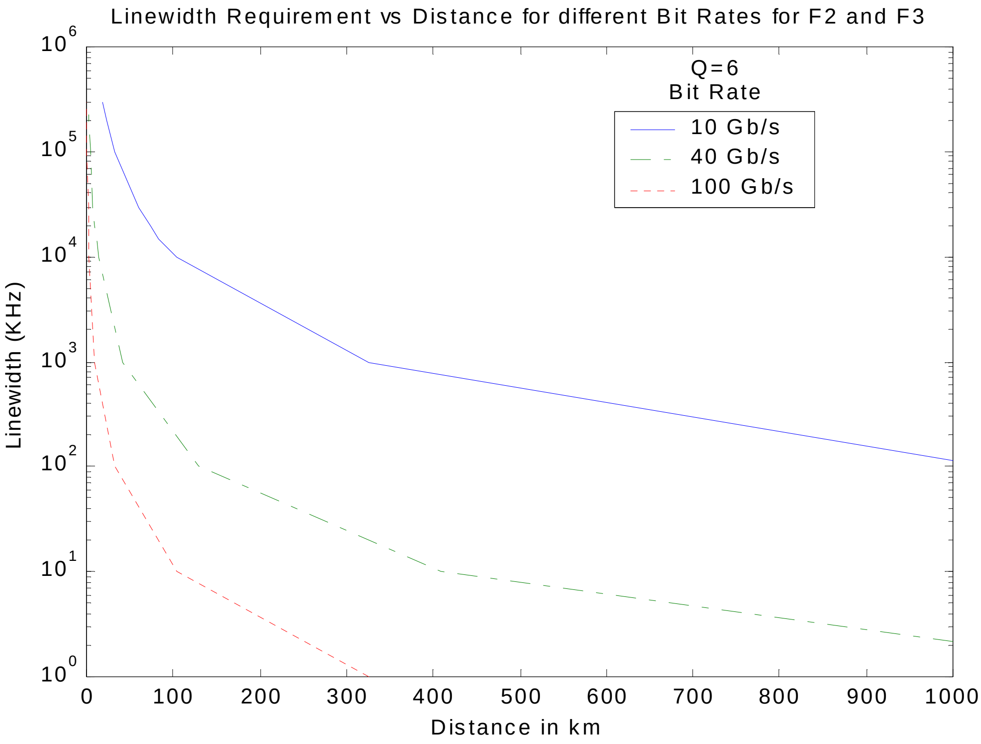

Figure 2.9 : Linewidth Requirements vs Distance for Diffrent bit rates for F2 and F3 (Q=6)

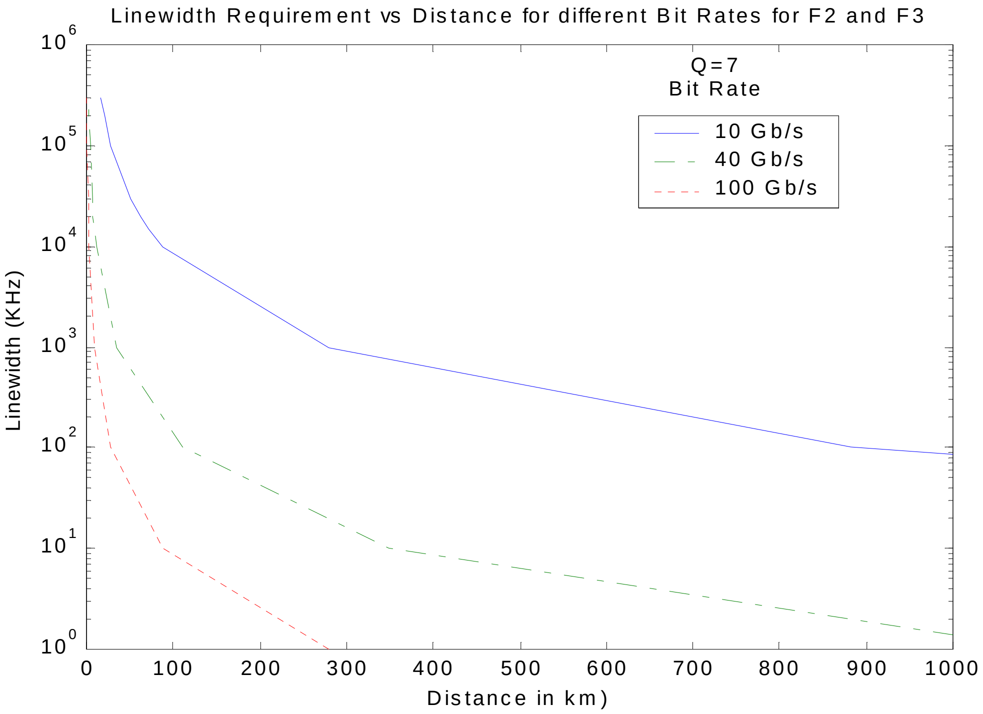

Figure 2.10 : Linewidth Requirements vs Distance for Diffrent bit rates for F2 and F3 (Q=7)

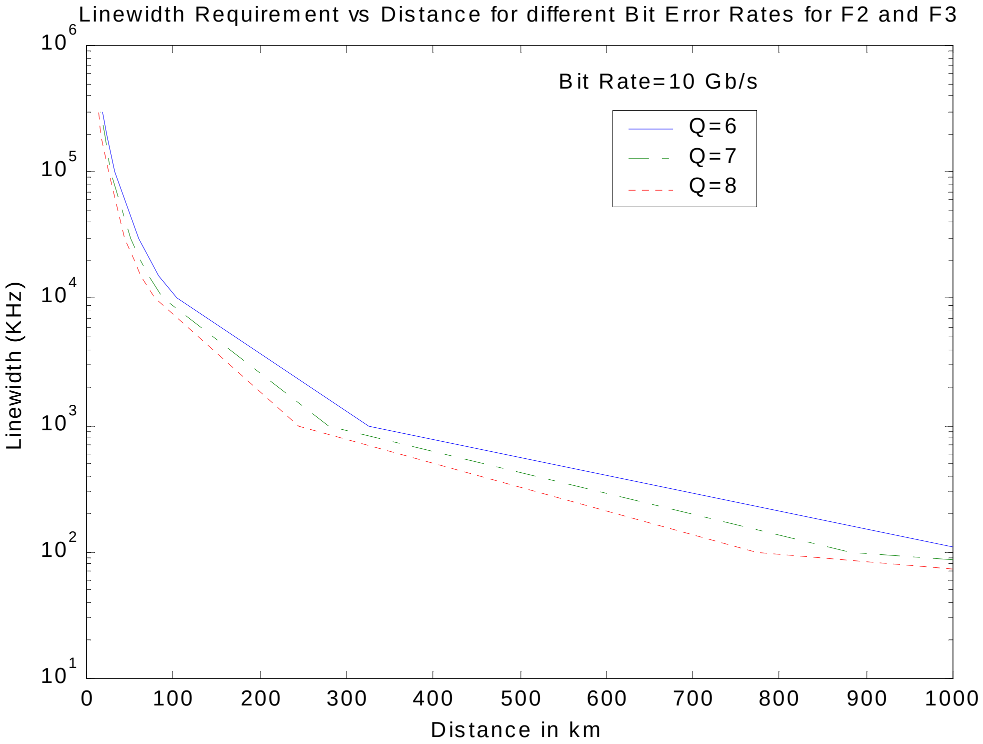

Figure 2.11 : Linewidth Requirements vs Distance for Diffrent bit rates for F2 and F3 (Bit Rate= 10 Gbps)

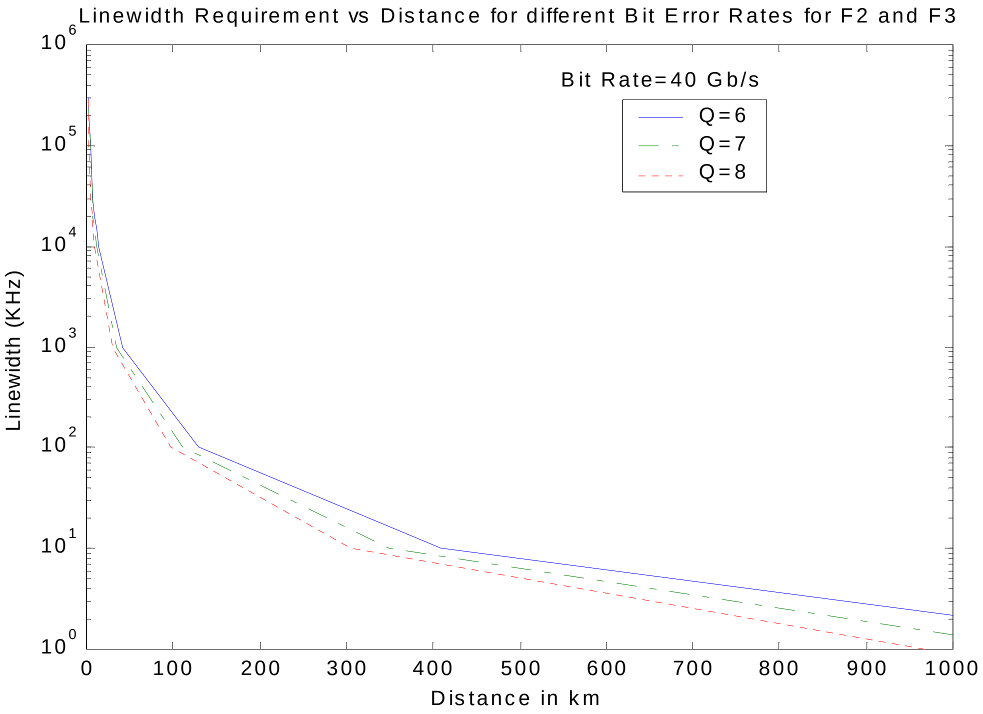

Figure 2.12 : Linewidth Requirements vs Distance for Diffrent bit rates for F2 and F3 (Bit Rate= 40 Gbps)

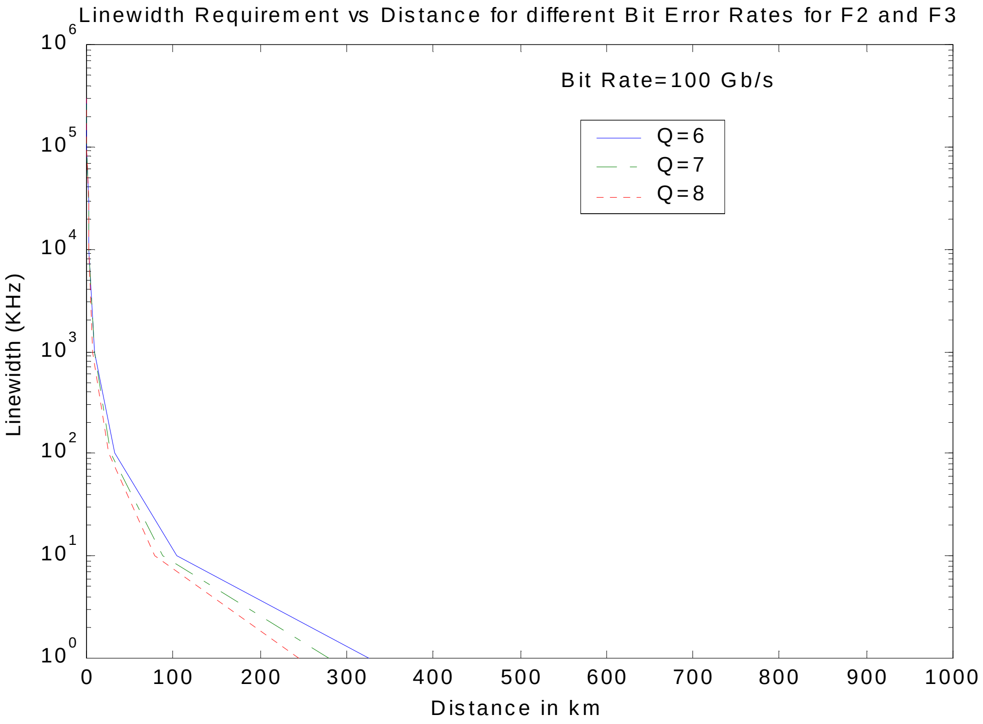

Figure 2.13 : Linewidth Requirements vs Distance for Diffrent bit rates for F2 and F3 (Bit Rate= 100 Gbps)

2.4 Conclusions

The modified expression for power penalty has been derived and it's impact on laser linewidth and bit rate has been investigated. For power penalty less than 0.5 dB, the plots between bit rate and transmission distance are plotted. . It is seen that the transmission distance increases with decrease in linewidth over significant bit rates. The transmission distance with first order dispersion term for 150 KHz linewidth is approximately 900 km for 40Gb/s bit rate and 10^{-12} bit error rate. With proper first order dispersion compensation i.e. with second order dispersion only, the transmission distance can be enhanced to 10^{6} km for this linewidth for the same bit rate. It is also seen that, there is significant change in the transmission distance and bit rate for combined case of first and second order dispersion terms together with that of first order dispersion term and this change increases with decrease in linewidth. For example, for 300 MHz linewidth, the decrease is transmission distance is just 30 km and for 30 MHz linewidth, the decrease is approximately 600 km over significant bit rates. The linewidth requirements for dispersive optical PCM systems are discussed for different bit rates and transmission distances including higher order dispersion terms. These requirements are further analyzed for different bit error rates under different bit rates. It is seen that the linewidth requirement is narrow for larger bit rates and large transmission distances. For achieving transmission distance of 200 km, the linewidth requirement is 3 KHz, 60 KHz and 5 MHz for bit rates of 100 Gb/s, 40 Gb/s and 10 Gb/s respectively with bit error rate of 10^{-9}. For WDM systems, with acceptable bit error rate of 10^{-12}, the linewidth requirement reduces to 2KHz, 40 KHz and 2 MHz for bit rates 100 Gb/s, 40 Gb/s and 10 Gb/s respectively. If the system is fully first order dispersion compensated, the transmission distance increases manifold. For 5 MHz linewidth, it increases to 10^{6} km for 100 Gb/s bit rate, 10^{7} km for 40 Gb/s bit rate and 10^{8} km for 10 Gb/s bit rate. Further it is seen that combined effect of first and second order dispersion is almost the same that of first order dispersion for the selection of laser linewidth. For higher bit rates, for small transmission distances, the linewidth requirements for different BER are hardly the same but for larger distances, the linewidth requirements differ.

Chapter 3

Investigations on fiber type at 10 Gb/s optical communication system with timing jitter

For long distance optical communication systems, the performance deciding parameter are bit error rate (BER), quality factor (Q value) and timing jitter (TJ). Many sources of degradation of these parameters in optical communication systems have been found and its remedial solutions have been proposed. Still there is lot to be done to find the proper solution of timing jitter and dispersion compensation. In this chapter, a simulation effort for 10 Gb/s optical communication system is done to select the fiber from the standard fibers available from some reputed fiber sources. The comparison on the basis of measures bit error rate (BER), Q-value, timing jitter and eye diagrams has been taken and presented. It was found that dispersion shifted normal & anomalous fibers give best performance among the fibers considered, second best performance is given by Corning LEAF fibers.

3.1 Introduction

It is widely known fact that communication channel plays a major deciding role in defining the performance of a communication system. Signal through the fiber as channel in the form of pulses, whatsoever shape may be, lose its identity at the farthest end over long distance of transmission. Periodically spaced amplifiers are added to the fiber line to boost the signal power and hence helping to preserve the information being carried. In the mid-eighties, it was discovered by Gordon and Haus that these amplifiers add noise to the pulses which caused a timing shift [76-78]. Essentially it means, the pulses are moved out of their allotted time slot and hence are misread at the receiver end of the channel. The problem of not maintaining the pulse position in such system due to spontaneous emission is known as Gordon-Haus timing jitter. Other factors that affect the optical system performance are Kerr effect, PMD, Raman crosstalk, fiber birefringence etc. With the addition of wavelength-division multiplexing, the role of pulse interactions in the system becomes important to watch. Sending multiple pulses along a fiber line requires that more than one pulse in the same channel and pair wise interactions will further degrade performance. The two main issues that arise when dealing with multiple pulse interactions are: collision-induced timing jitter, four-wave mixing products. Ultra-high performance optical fiber greatly reduces jitter and maintains optimum signal integrity.

To observe the effect of the fiber selection in optical communication system different type of fibers with typical values are taken & listed in the Table 3.1. System simulations are done under the objective to select a fiber of best performance is presented, onwards.

3.2 System description

The optical communication system model considered for simulation is shown in the following Figure 3.1. The model consists of components with their respective characteristics as per details given in the following lines, starting with data source. Data source block simulates a pseudo-random or a deterministic logical signal generator. Besides the logical signal, this component generates an electrical signal synchronized to the baud rate. The bit-time in simulation, i.e. the time-duration of the bit, must be an integer number of time-samples NS (Samples per bit value). Parameters of basic attribute section taken are 10 Gb/s bit rate, 10 Gb/s baud rate, 474 samples per bit, one bits/symbol and 7 degree pseudorandom sequence.

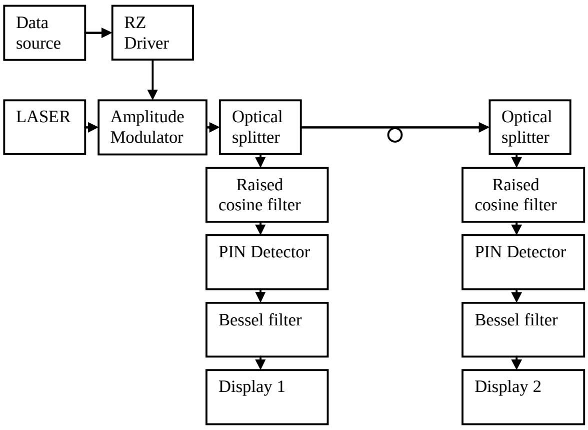

Figure 3.**1:** Simulation model under investigation to estimate timing jitter, Q value, BER of different optical fibers.

Driver block simulates an electrical driver which converts the logical input signal to a binary sequence of zeros and ones into an electrical signal. This component acts as RZ rectangular driver. It has an output signal that can assume two electrical levels. When a "1" is transmitted, the output signal is at the high level for a time equal to the product of the duty cycle by the bit time. Then it goes down to the low level for the remaining time.

When a "0" is transmitted, the output is constant at the low level for the entire bit time. Switching between the two levels is instantaneous with resulting square edges. It uses RZ rectangular shape as signal type, -2.5, 2.5 are low level and high level respectively with duty cycle 0.5.

Laser block shows simplified continuous wave (CW) laser. Its phase noise is taken into account by generating a Lorentzian emission line shape whose FWHM (Full Width Half Maximum) is specified by Laser parameters. In model considered has 193.42 THz center emission frequency, 1550 nm wavelength, 0 dBm CW Power, 1 mw CW power, ideal laser noise bandwidth, 10 FWHM line width and laser random phase.

The block Amplitude modulator simulates a single input modulator and implements a single arm Mach-zehnder amplitude modulator with $\sin^2$ electrical shaped input-output P-V characteristics. This transfer function is typical for a Mach-zehnder external modulator based on the electro-optic effects in the $LiNbO_3$ devices. It has 3db excess loss, 2.5 maximum transmissivity offset voltage, realistic extinction ratio, 30db extinction ratio and 0 chirp factor.

Optical splitter component simulates an "Ideal" optical splitter. It works as a balanced splitter with the same attenuation on each output. Attenuation is set to a default value of 0 dB, so this component implements an ideal splitter without any insertion loss, i.e. a component that perfectly splits the input signals.

Optical filter component implements a raised cosine transfer function filter having band pass filter synthesis, 1 as raised cosine exponent, 0.2 raised cosine roll off, 193.41 THz Center freq., 1550 nm center wavelength, 40 GHz B.W.

Photodiode considered as a PIN photodiode. The output current generated by the photo detection process depends on the input optical power and on the dark current. Its parameter are 193.42 THz/1550 nm reference freq./wavelength, 0.80 quantum efficiency, 0.99A/W responsively and zero dark current

Table 3.1: Typical values of parameter of optical fiber types considered in the optical communication system simulation. Where parameter units are D [ps/nm/km], D' slope [ps/nm^2/km], α_0 [dB/km], A_{eff} [µm^2] and PMD [ps/√km].

Sr. No.	**Fiber Type**	Attenuation α_0	**Chromatic Dispersion**		**MFD** A_{eff}	**Polarization** PMD
			D	D' slope		
1.	SMF@1550nm Alcatel	0.2	16	9.086	81.7	≤ 0.1
2.	SMF @ 1550nm ERALIGHT	0.21	8	0.06	65	≤ 0.1
3.	Corning LEAF	0.2	4	0.1	72	≤ 0.1
4.	Corning LEAF Submarine	0.2	4	0.1	71	≤ 0.1

The Bessel filter block is numerically implemented using an IIR (*Infinite Impulse Response*) algorithm together with the bilinear transformation method having 5 poles in number and as -3db B.W. 10 GHz. Electrical scope component simulates an oscilloscope for electrical signals. It collects data that will be available for the eye diagrams shown. Also may be used to obtain amplitude of the electrical signal, eye diagram, histogram at the optimum sampling instant, power spectrum of the electrical signal. Other parameters are 10 Gb/s bit rate and stimulated bit rate, 474 samples per bit over whole measured time span.

The fiber models the propagation of the optical signal along an optical fiber span. It is one of the fundamental and most complex components decide channel/medium performances. The non-linear Schrodinger equation governing the propagation of the optical field is integrated using Time Domain Split-Step (TDSS). Characteristics of fibers apart from type & length considered are the presence of fiber nonlinearity, fiber PMD, fiber birefringence but without Raman crosstalk and Raman amplifier. The typical fiber characteristics are shown in the Table 3.1 for the various fibers considered in table.

3.3 Results and Discussion

The optical communication model results are shown in tabular form in a Table 3.2, & in Figures 3.2 – 3.9.

Table 3.2: Table indicating maximum length to keep BER of the order 10^{-9}. Also Q (dB) values for various types of fibers

Sr. No.	**TYPES OF FIBER**	**MAX. LENGTH (Km)**	**BER (10^{-9})**	**Q (dB)**	**TIMING JITTER (ns)**
1.	Standard SM	51	7.128	15.17	0.028
2.	DS_Normal	396	3.28	15.68	0.029
3.	DS_Anomalous	406	2.91	15.64	0.028
4.	Alcatal_ SMF_1550	51	5.63	15.21	0.028
5.	Alcatel TERALIGHT	102	4.71	15.20	0.028
6.	CorningLEAF	205	5.61	15.14	0.029
7.	CorningLEAF_submarine	227	2.53	15.55	0.029

.

The Table 3.2 indicates simulation results of the model considered taking same 51 km fiber length for different types of fibers. It indicates that the least BER $1x10^{-40}$ & Timing jitter 0.000233 are noticed in DS anomalous fiber. Also standard single mode fiber and Alcatel SMF give maximum bit error rate $8x10^{-9}$ approximately. In reference to the Table 3.3 & evident from eye diagrams Figures 3.2 to 3.9, the simulation results show that dispersion shifted anomalous fiber gives best performance giving BER = $2.91x10^{-9}$ at a length up 406 km. Close performance is also observed in the case of dispersion shifted normal fibers giving usable length 396 Km. Worst performance is noticed in Standard Single mode fibers giving usable length 51 km. Corning LEAF fibers are giving performance up to the middle distances i.e. 200 km. Q value & timing jitter remains almost same. As indicated in Table 3.2 timing jitter is can not controlled by the selection fiber type. We need to apply other techniques like dispersion management, selection of data format type to control timing jitter & Q value.

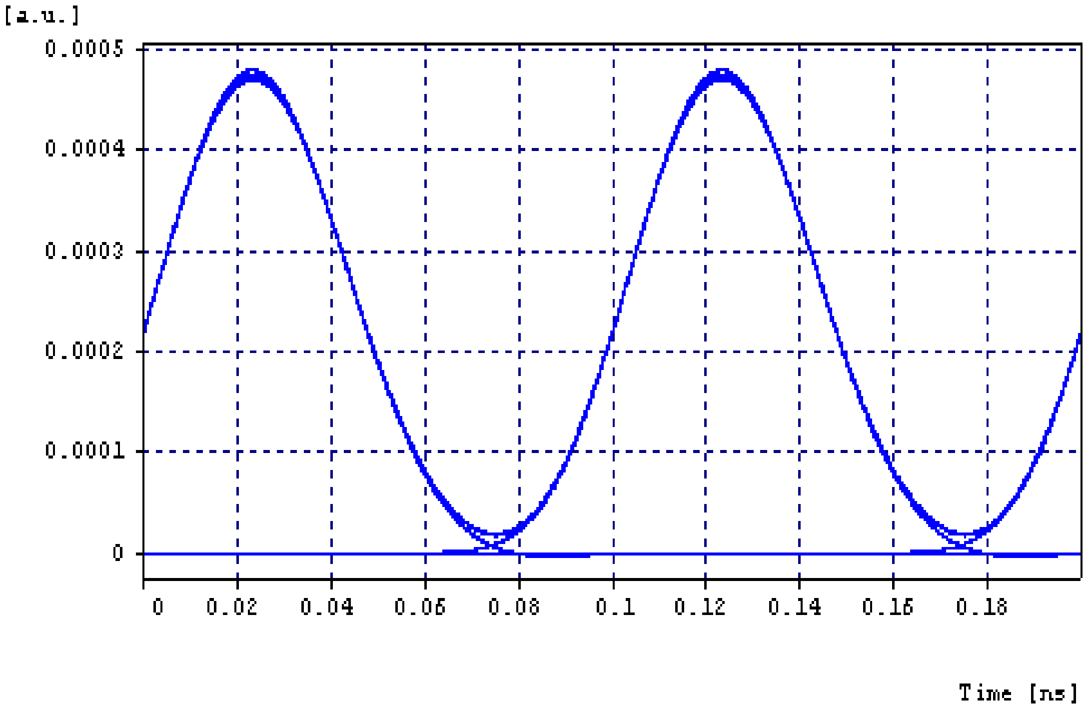

Figure 3.2: Eye diagram at display 1 to measure BER, Q and Timing Jitter at transmitter side.

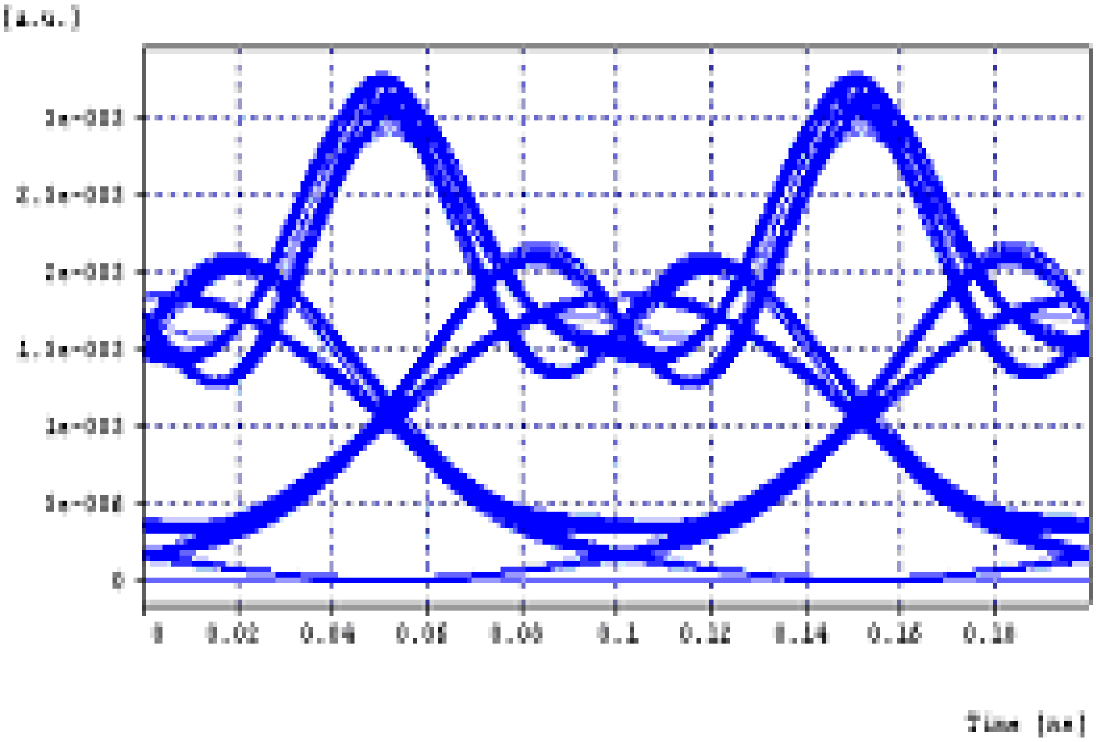

Figure 3.3: Eye diagram at receiver side of standard SM fiber.

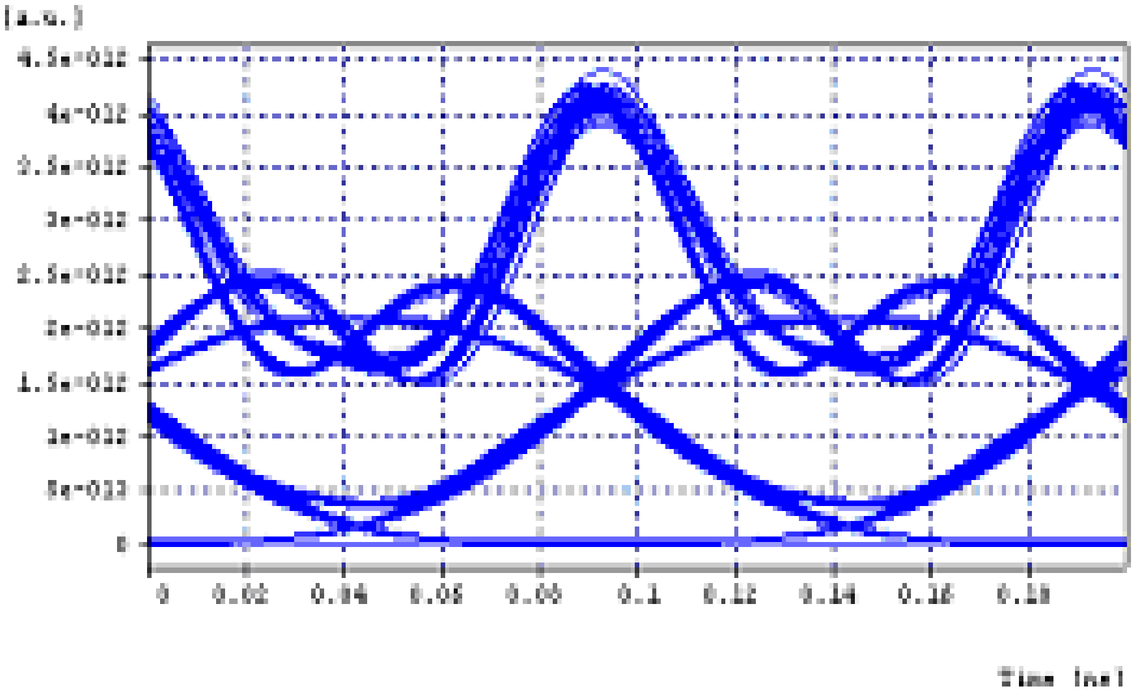

Figure 3.4: Eye diagram at receiver side of DS_Normal.

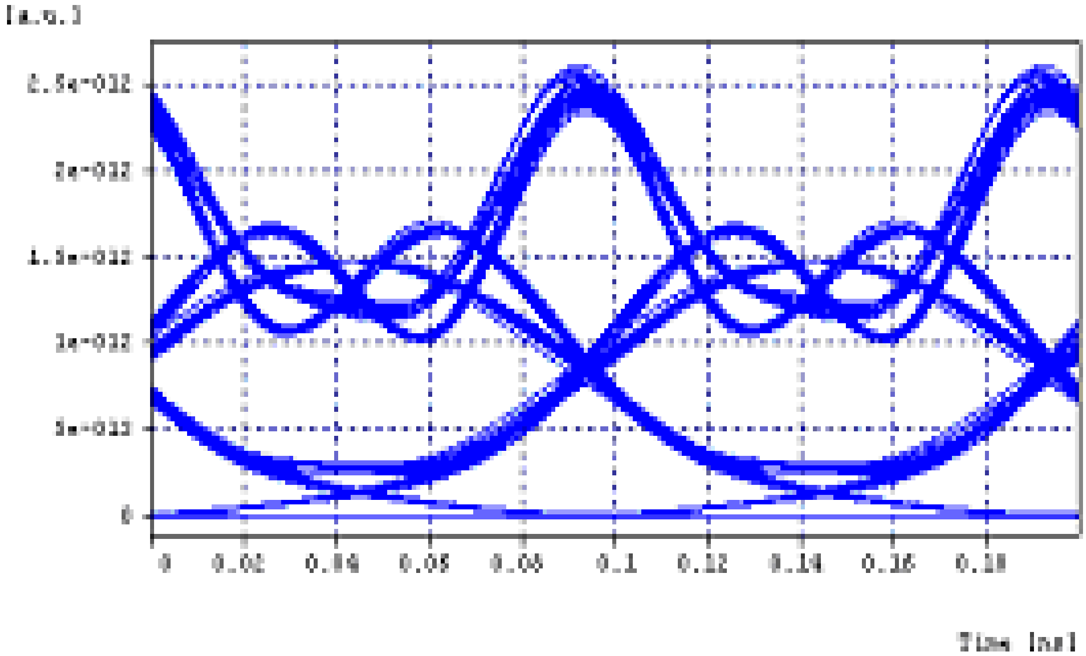

Figure 3.5: Eye diagram at receiver side of DS_Anomalous.

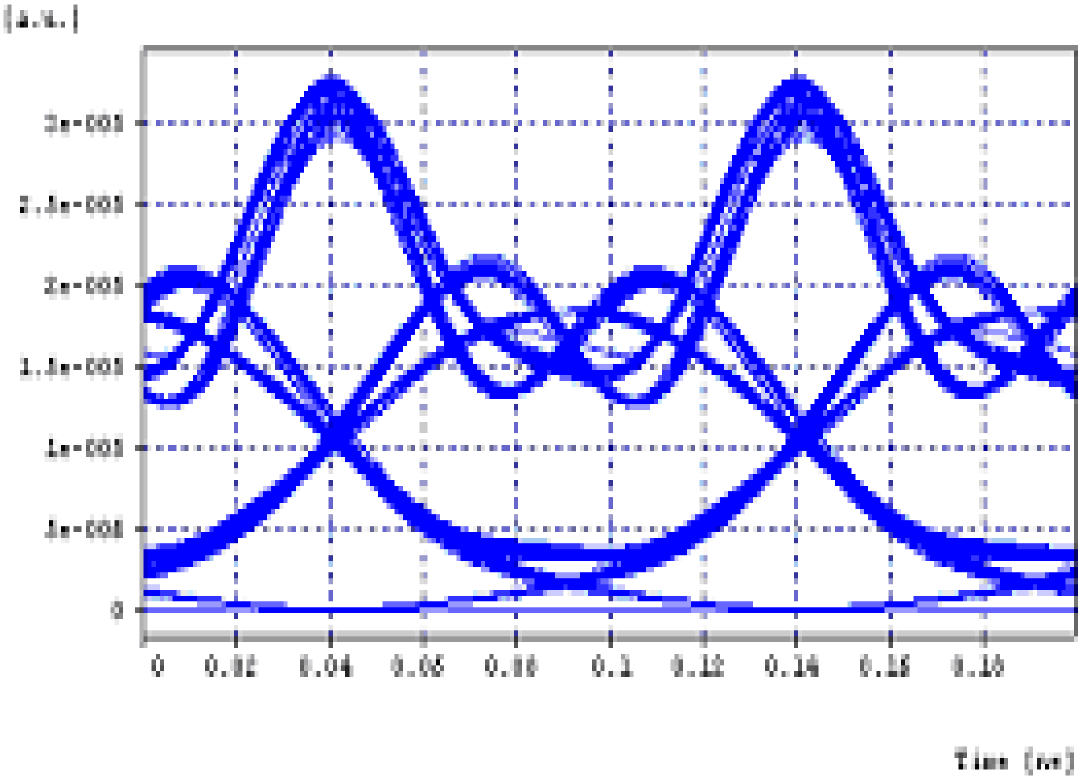

Figure 3.6: Eye diagram at receiver side of Alcatel SMF_1550

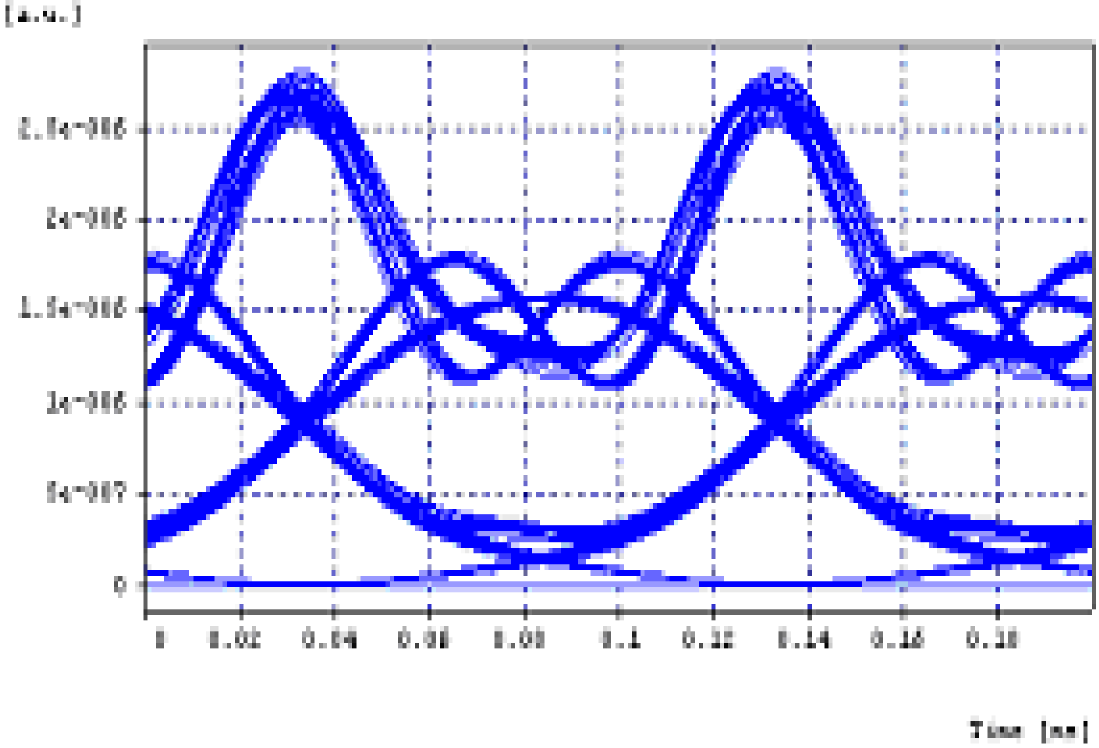

Figure 3.7: Eye diagram at receiver side of Alcatel ITERA LIGHT.

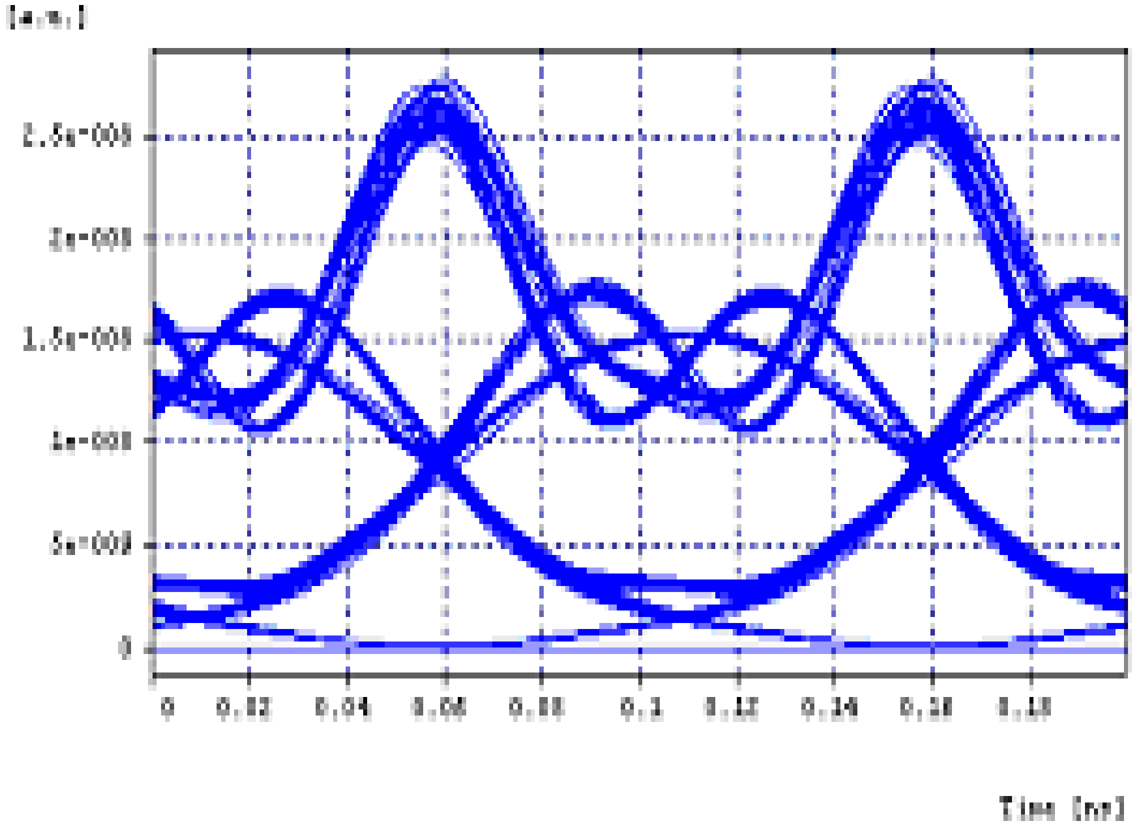

Figure 3.8**:** Eye diagram at receiver side of yy_corning LEAF.

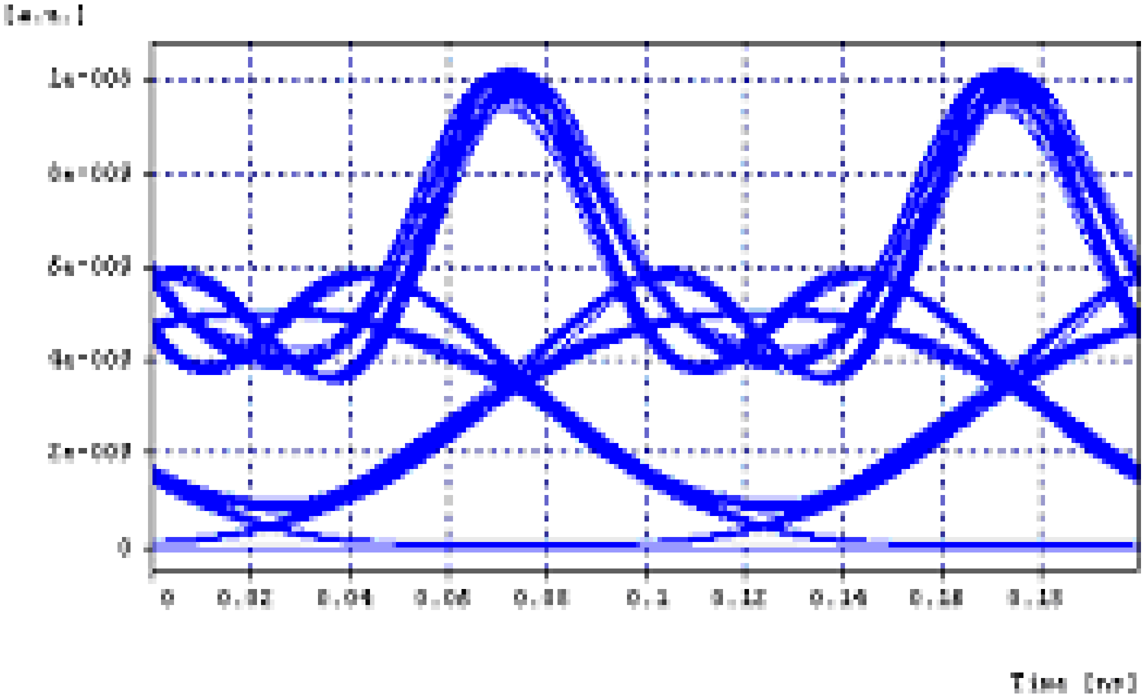

Figure 3.9**:** Eye diagram at receiver side of yy_corning LEAF submarine.

3.4 Conclusion

The bit error rate becomes deciding factor to select the fiber over long distance. From the results & discussion, it can be concluded that Dispersion shifted fibers anomalous & normal are performing better for long distances.

Chapter 4

POWER EFFECTS ON SIMULATION OF 10 GB/S NRZ OPTICAL COMMUNICATION SYSTEMS WITH SELF PHASE MODULATION (SPM)

In this chapter, the behavior of SPM versus the optical power for a two spans amplified system has been investigated. A 10 Gb/s NRZ signal is launched over two DS fiber spans (D=0.4 ps/nm/km) of 50 km, each. The power at the input to each span is varied from 10 to 17.5 dBm by using the parametric run feature in OptSim. EDFA noise has been turned off in order to simplify the analysis of SPM. By increasing the power, SPM grows and depletes the signal, and the measured power (in a bandwidth equal to twice bit rate) actually decreases with the increasing of the transmitted power. Moreover, the channel has been demodulated. The eye diagram highlights the PM-AM conversion due to the SPM. Specifically the eye opening decreases with increasing transmitted power. Since there is no noise, estimation of the Q values is irrelevant.

4.1 Introduction

An interesting manifestation of the intensity dependence of the refractive index in the nonlinear media occurs through self phase modulation (SPM) a phenomenon that leads to spectral broadening of the optical pulses[1]. SPM arises because the refractive index of the fiber has intensity dependent component. The nonlinear refractive index causes an induced phase shift that is proportional to the intensity of the pulse. Thus different parts of the pulse undergo different phase shifts, which gives rise to the chirping of the pulses. Pulse in turn enhances the pulse broadening effects of the dispersion. This chirping effect is proportional to the transmitted signal power so that SPM effects are more pronounced in system using high transmitted powers .The SPM induced chirping effects ,the pulse broadening effects of dispersion are thus important to consider for high Bit rate systems that always have dispersion limitations. For system operating at 10 G b/s or for lower bit rate systems that use higher transmitted powers, SPM can significantly increase the system penalty due to dispersion because of increased ISI.[9-12]

4.2 Simulation

A 10 Gb/s NRZ signal is sent over 2 fiber spans of 50 km each. Dispersion is completely compensated to isolate the SPM phenomenon. Input power values have been varied from 10 to 17 dBm through the parametric run feature. The Dispersion at the fiber input for each span has been set to 0.4ps/nm/km. EDFA noise has been turned off. By increasing the optical power, SPM grows and depletes the signal, therefore causing the measured power to decrease as the transmitted power increases. Note that in passing from the normal to the anomalous dispersion regime, the received optical spectrum at first widens and then narrows. The simulation setup is shown in block Figure 4.1. In the figure the transmitter section consists of data source, electrical driver, optical filter, laser source and amplitude modulator. The data source is non-return to Zero format at 10 G b/s bit rate and is indicated by b6. The electrical driver is important component that generates

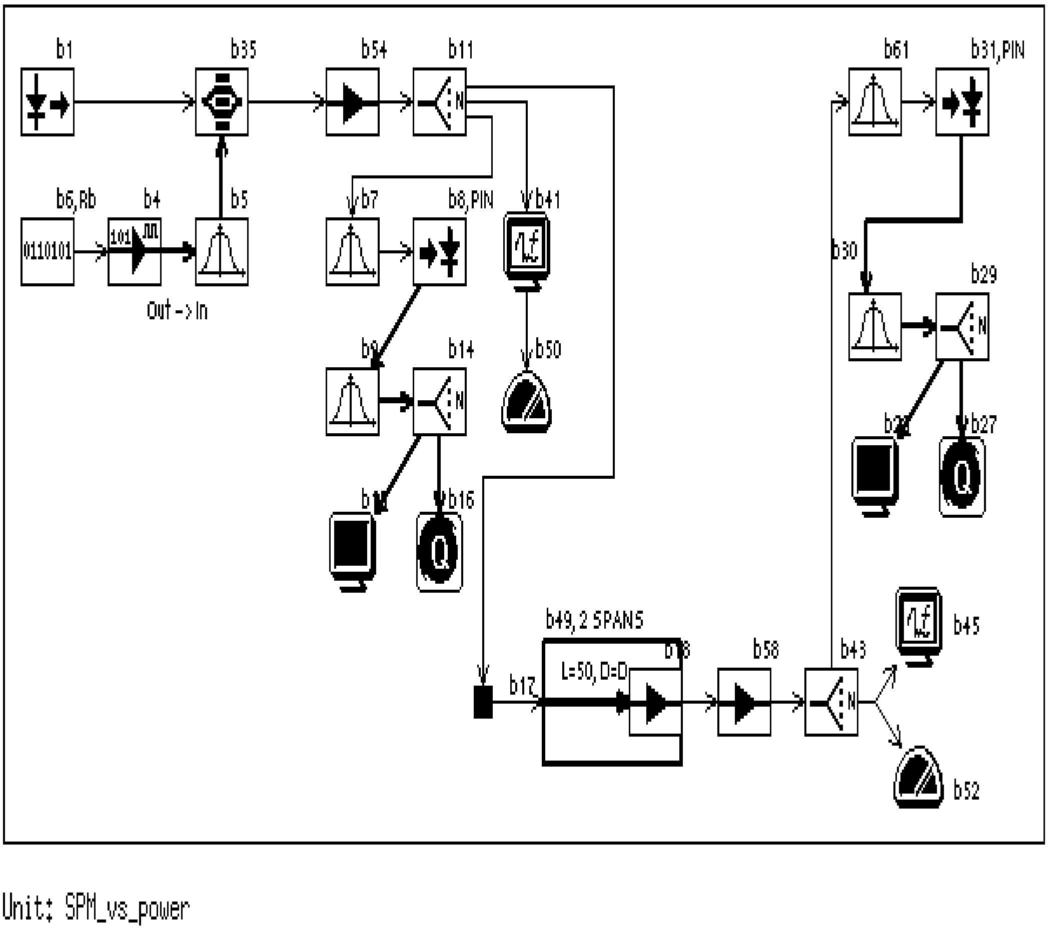

Figure 4.1: Simulation setup

the desired data transmission format. It converts the logical input, a binary sequence of zero and one into electrical signal. It is indicated by b4. The electrical filter is important component, which is a single pole low pass filter. The output of the modulator is fed to EDFA amplifier, which is indicated by b54. The output of the EDFA amplifier is given to optical splitter. The optical splitter is indicated by b11. One output of the optical splitter through splice is given to optical fiber link. The second output of the optical splitter is fed to optical spectrum analyzer, which is indicated by b41. The output of the spectrum analyzer is given to the optical power meter, which is indicated by b50. Optical power meter evaluates the power, defined as the mean square value of an optical signal. The evaluation can be performed over the whole time domain simulation bandwidth or in a selected sub range of frequencies. The third output of the optical splitter is fed to an optical filter. The optical filter is indicated by b7.

Output of the filter is fed to photo detector. It is a PIN type photo diode. It converts the optical signal into electrical signal. It is indicated by b8. Output of the photo detector is given to electrical filter of butterworth type. It is indicated by b9. Its output is given to the electrical splitter. It splits the input electrical signal into two parts .It is indicated by b14. At the output of the electrical splitter is connected oscilloscope for electrical signal. It collects data for diagram such as amplitude. Eye diagram .It is indicated by b18. At the second output of the optical splitter is connected Q estimator. It measures the Q value a pattern length for system affected by ISI can be specified. Besides the Q value, the following can be provided; optical threshold, eye closure, average eye opening, eye opening, tolerance to sampling instant variation, diagram of Q value versus sampling instant. The one output optical splitter is fed to optical fiber grating and EDFA amplifier consists of optical link. Optical fiber grating is indicated b64 and EDFA amplifier is indicated by b18. An ideal fiber grating introduces a certain amount of dispersion, without influencing the optical power spectrum if the bandwidth of the channel is neglected. Two spans (D=0.4ps/nm/km) of optical fiber link of each 50 km are considered. The optical power at input to each span is varied from 10 to 17.5 dBm. At the output of optical link, spectrum analyzer and optical power meter are connected at one output of optical splitter and electrical scope and Q estimator are connected at the other output. Optical splitter is indicated by b43. PIN type photo detector is used to convert optical signal into electrical signal .It is indicated by b31. Optical filter at the input of the photodiode and electrical filter at output is used is this diagram. They are indicated by b61 and b30 respectively. One electrical splitter is used split the electrical signal between electrical oscilloscope and Q estimator at its output. It is indicated by b29. Optical splice is also used to connect optical fiber link at its input to the fiber. It is indicated by b17..Optical fiber link is indicated by b68 in the diagram. The laser is of type CW lorentzian with laser center frequency 1550 nm (193.4145 THz). The amplitude modulator is of type sine square with excess loss of 3 db. The simulated bit rate is 10 GHz. The electrical filter is of the type Bessel. The detector is PIN diode with responsibity 0.875.

4.3 Results and Discussions

The optical power at b50 for various runs are shown in Figure 4.1(a) . It has been shown that as the optical power is increased, the received optical power increases. The constant values of Q , eye closure penalty and eye opening at b16 indicates the signal before it is transmitted at input as shown in Figure 4.1(b), (c) and (d). The eye diagrams for different runs under consideration are shown in Figure 4.2. The optical spectrum at b45 and b41 for different runs is shown in Figure 4.3 and Figure 4.4. Figure 4.5 shows the impact of power at the fiber output through eye diagrams. Figure 4.6(a-d) shows the eye opening, average eye opening, eye closure penalty and Q value at b27.

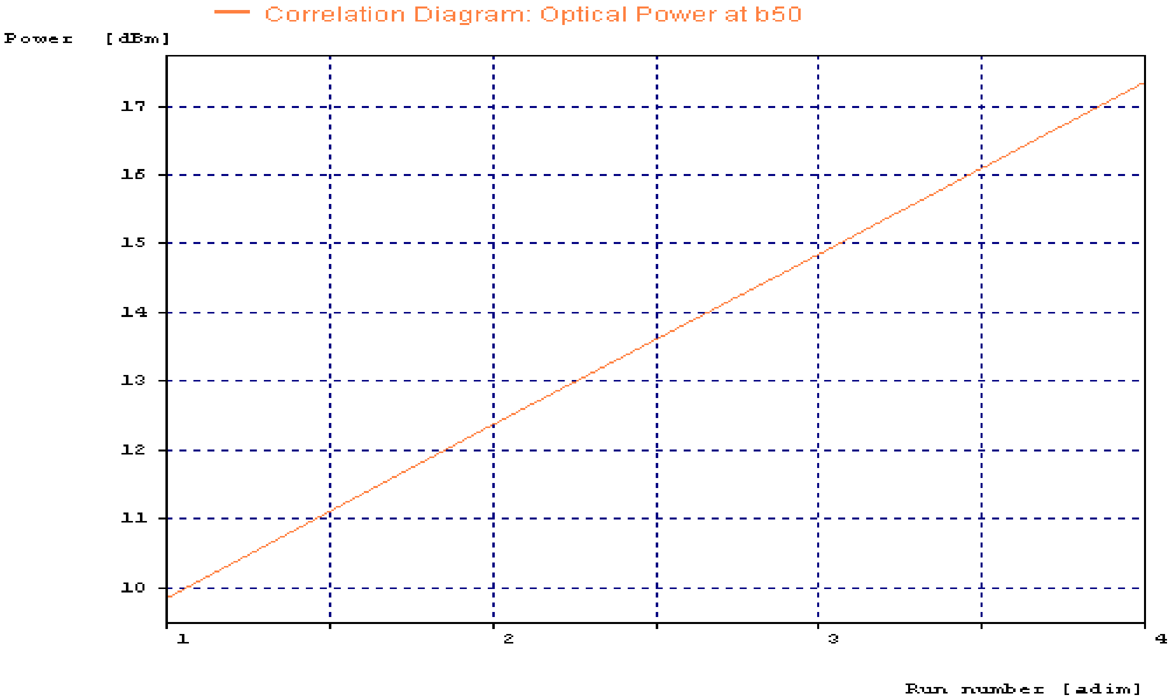

Figure 4.1 (a) Optical power at b50

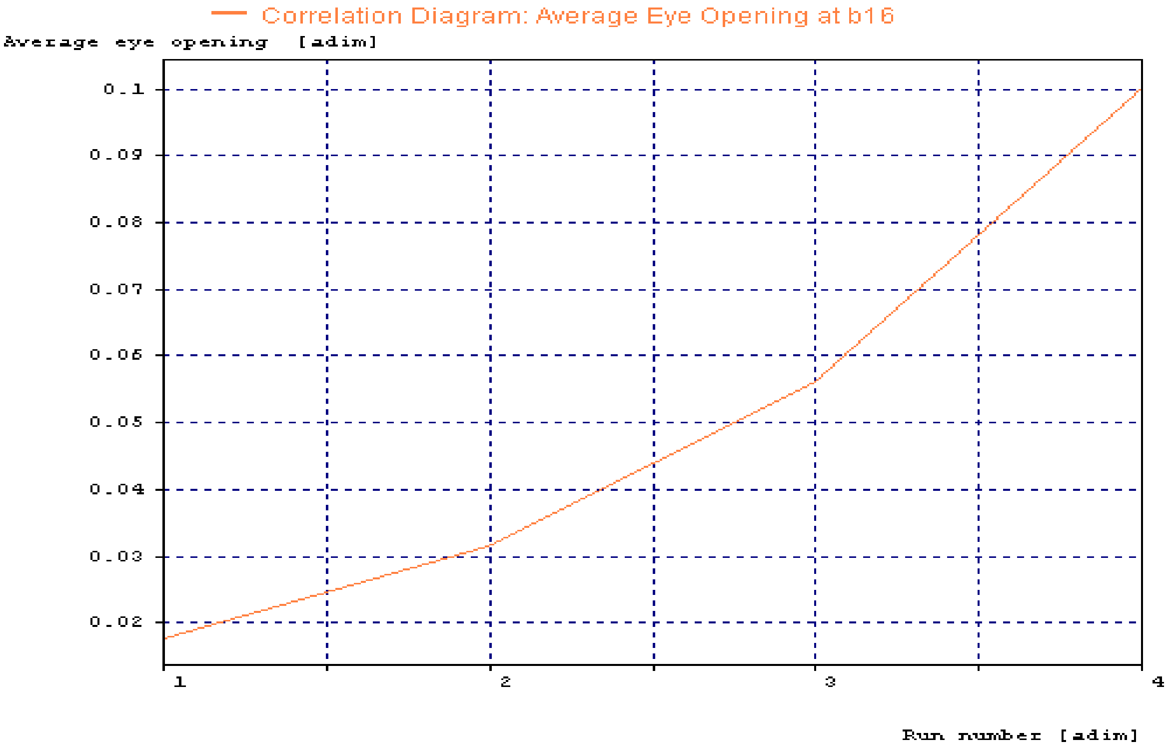

Figure 4.1(b): Average Eye opening at b16

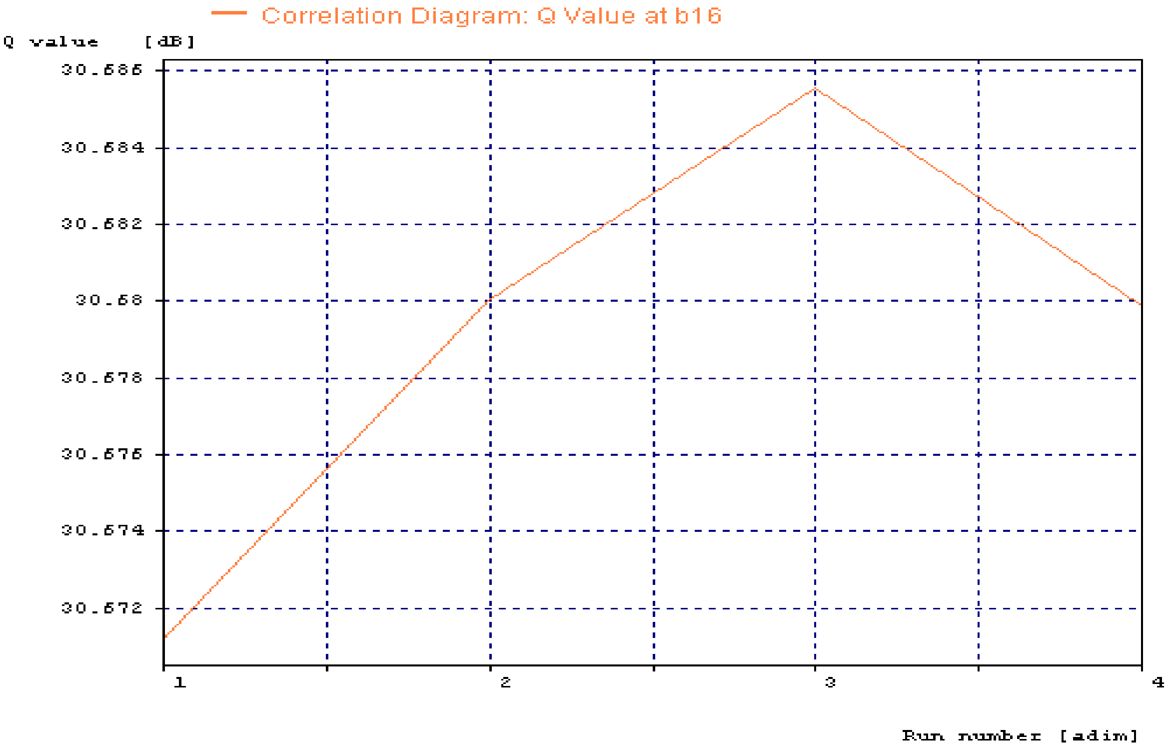

Figure 4.1(c): Q value at b16

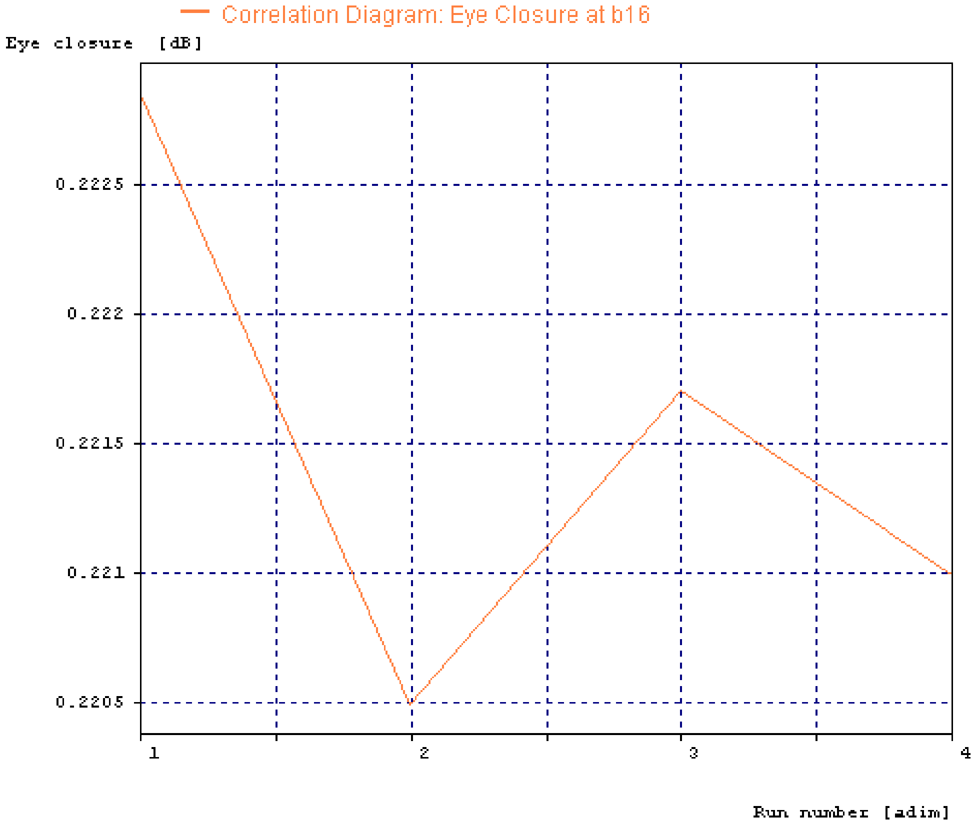

Figure 4.1(d): Eye closure at b16

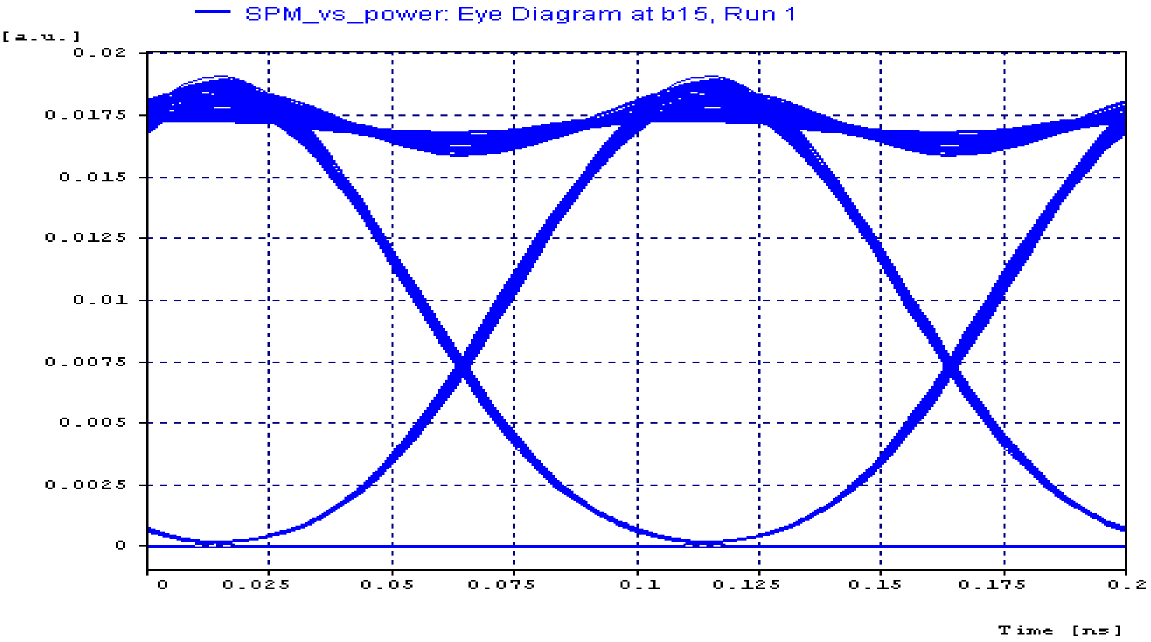

Figure 4.2(a): Eye diagram at b15, Run 1

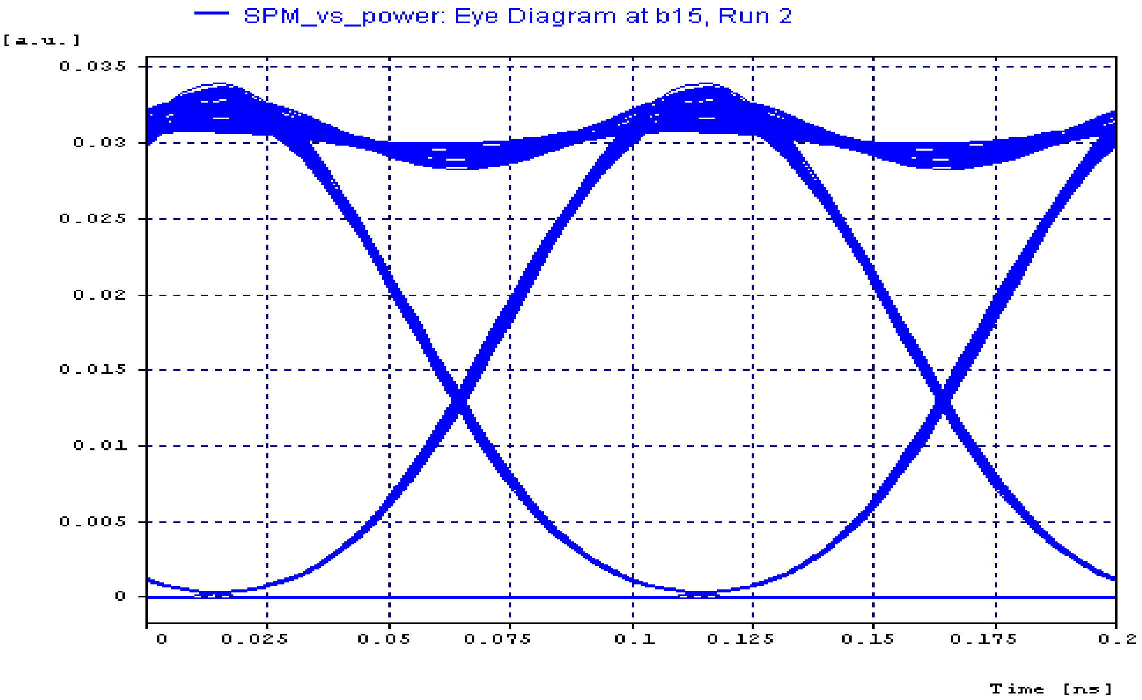

Figure 4.2(b): Eye diagram at b15, Run 2

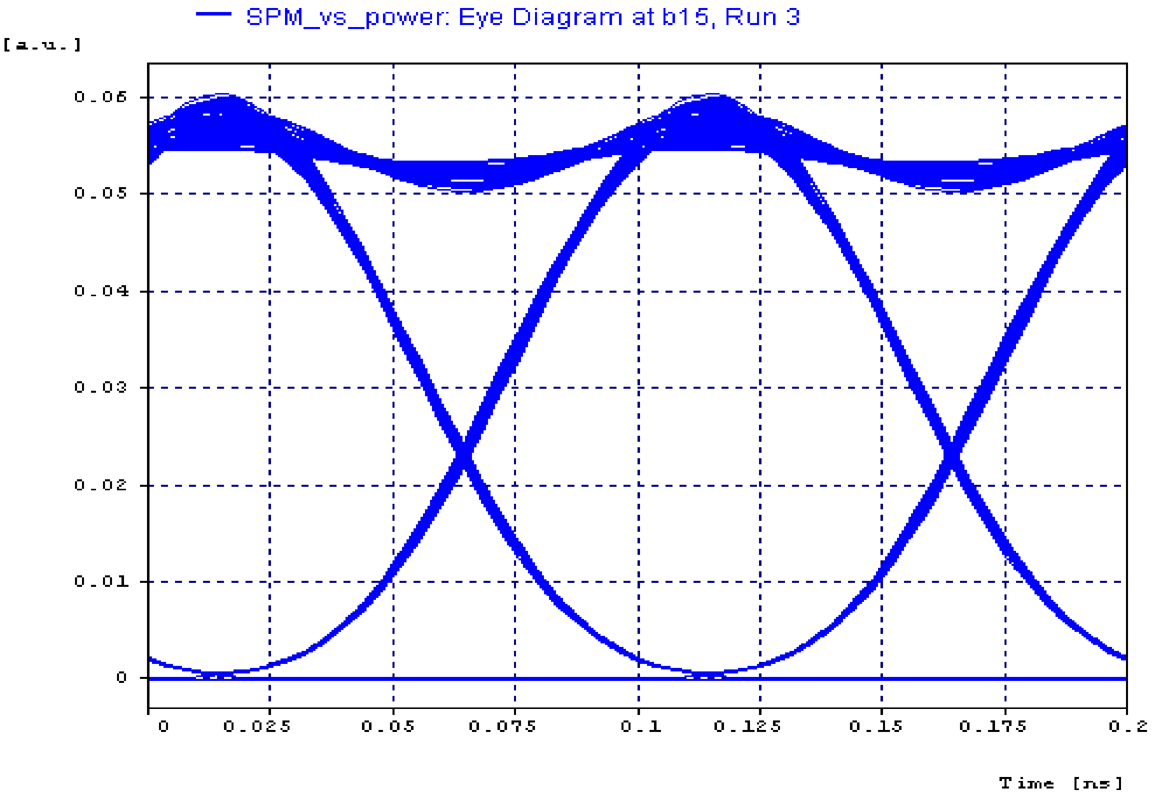

Figure 4.2(c): Eye diagram at b15, Run 3

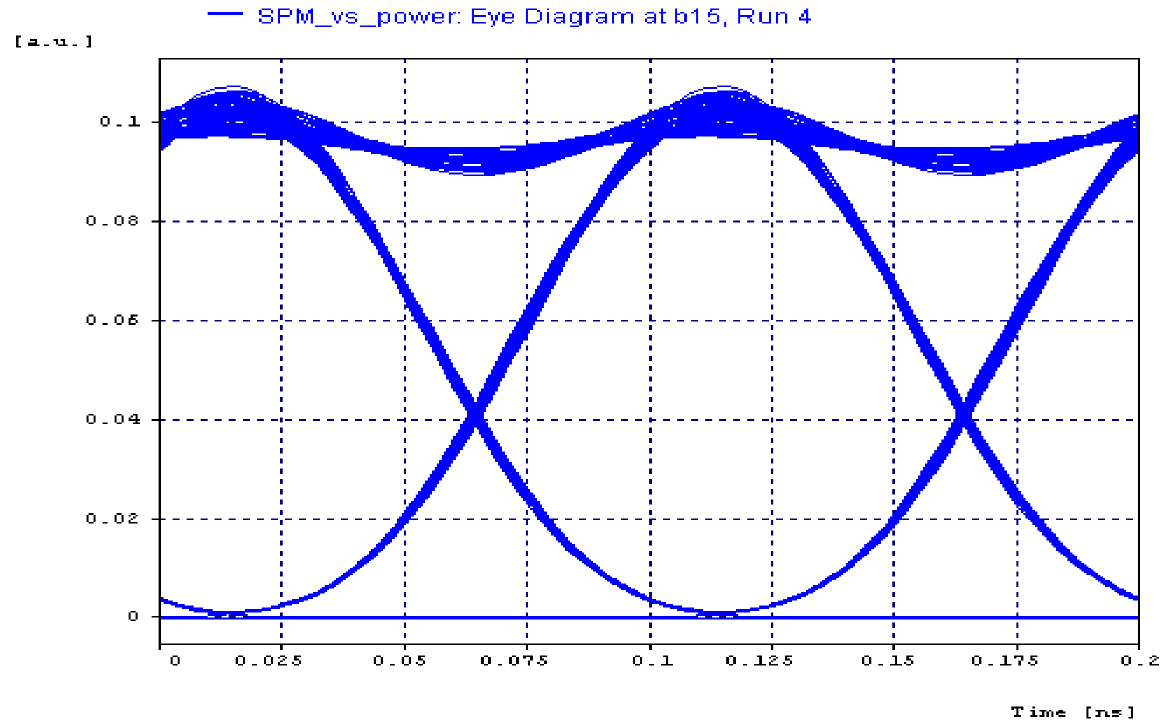

Figure 4.2(d): Eye diagram at b15, Run 4

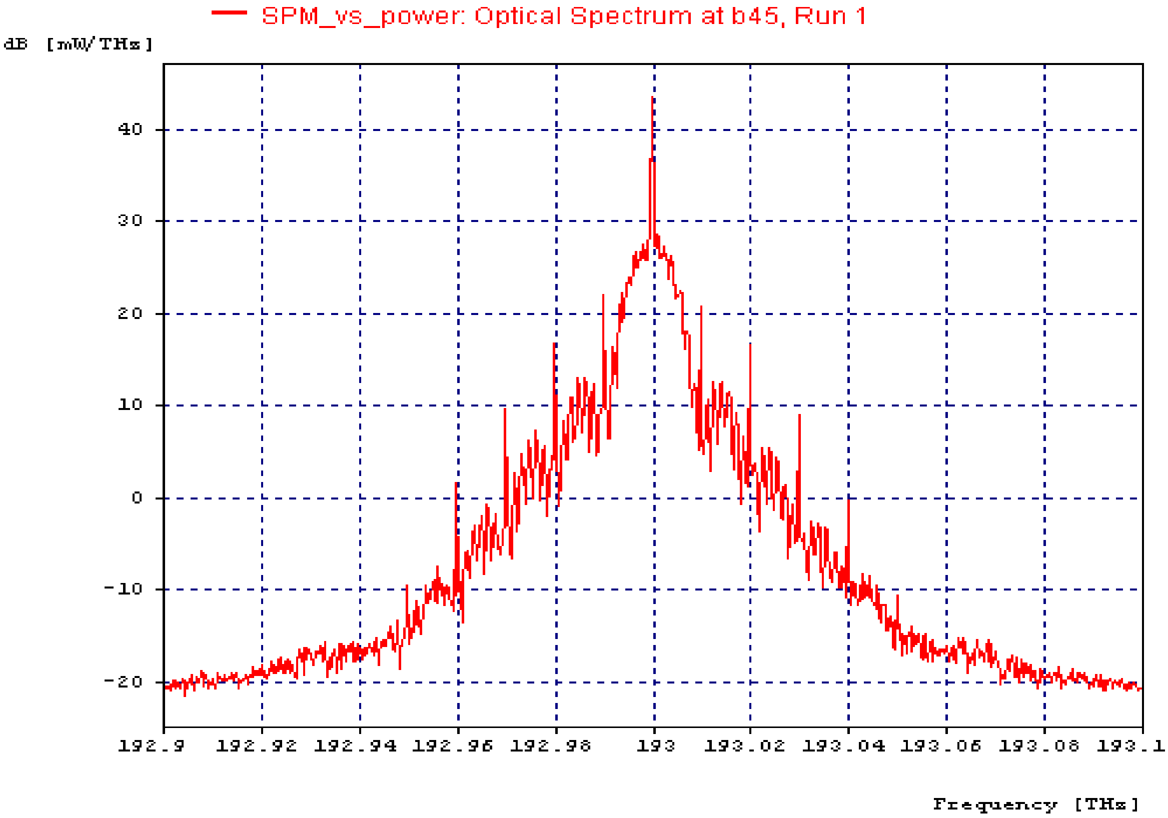

Figure 4.3(a): Optical spectrum at b15, Run 1

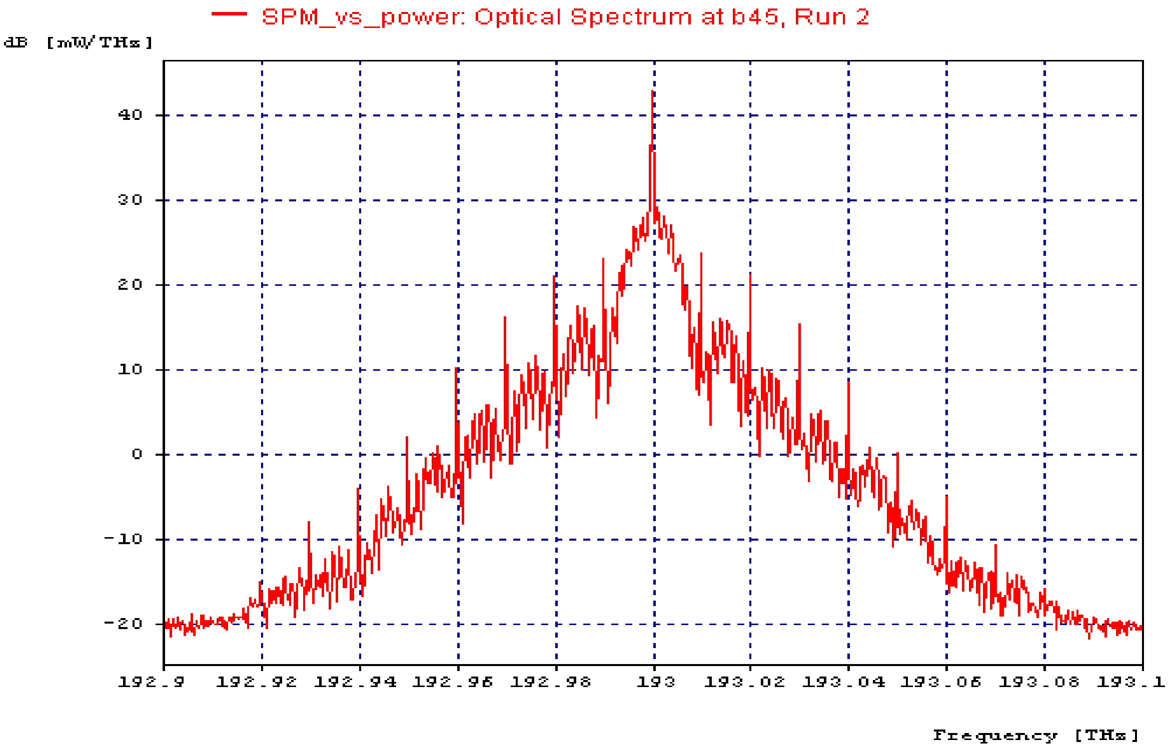

Figure 4.3(b): Optical spectrum at b15, Run 2

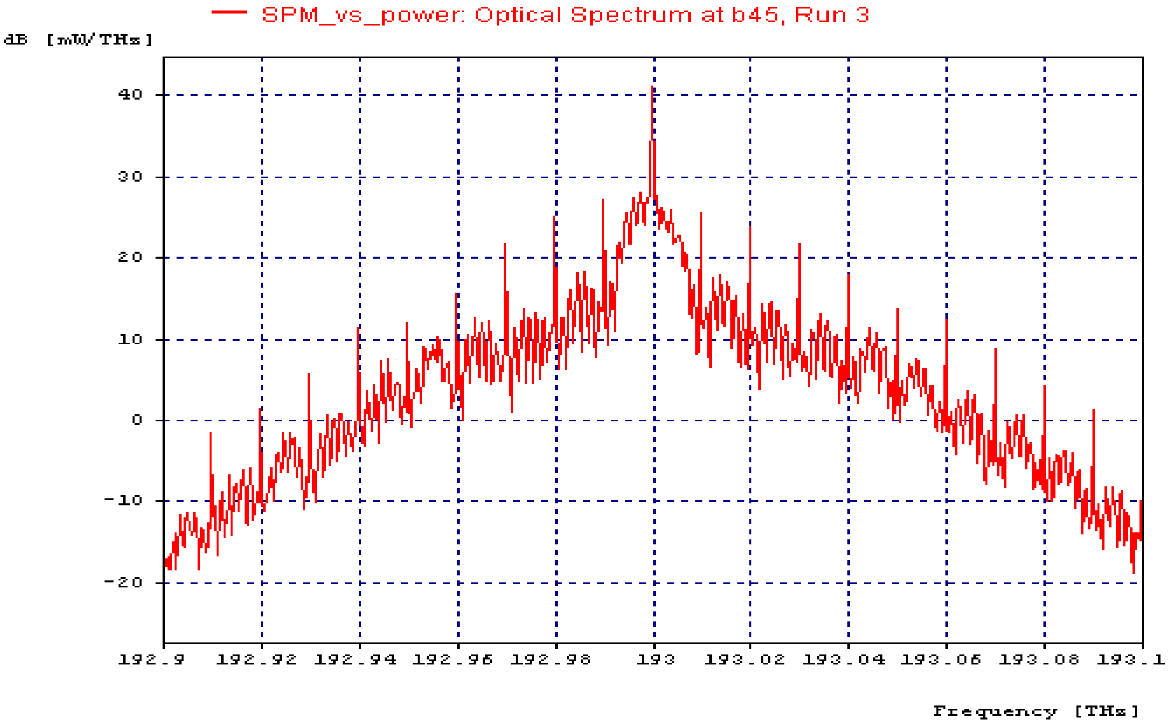

Figure 4.3(c): Optical spectrum at b15, Run 3

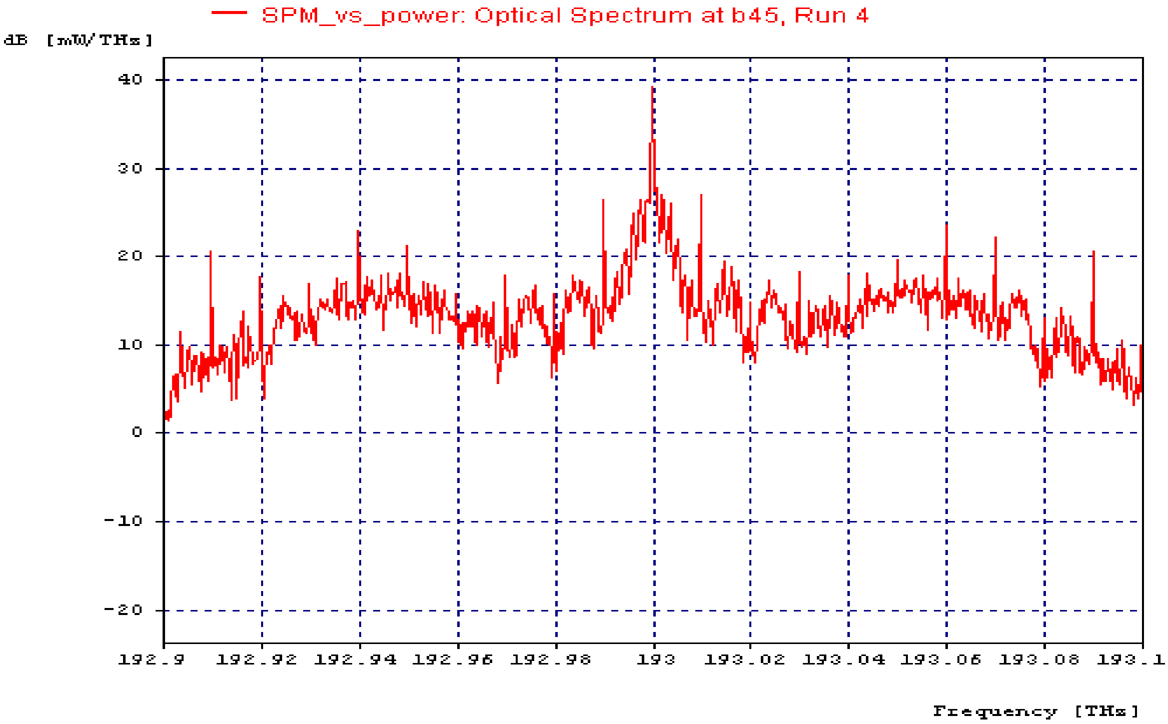

Figure 4.3(d): Optical spectrum at b15, Run 4

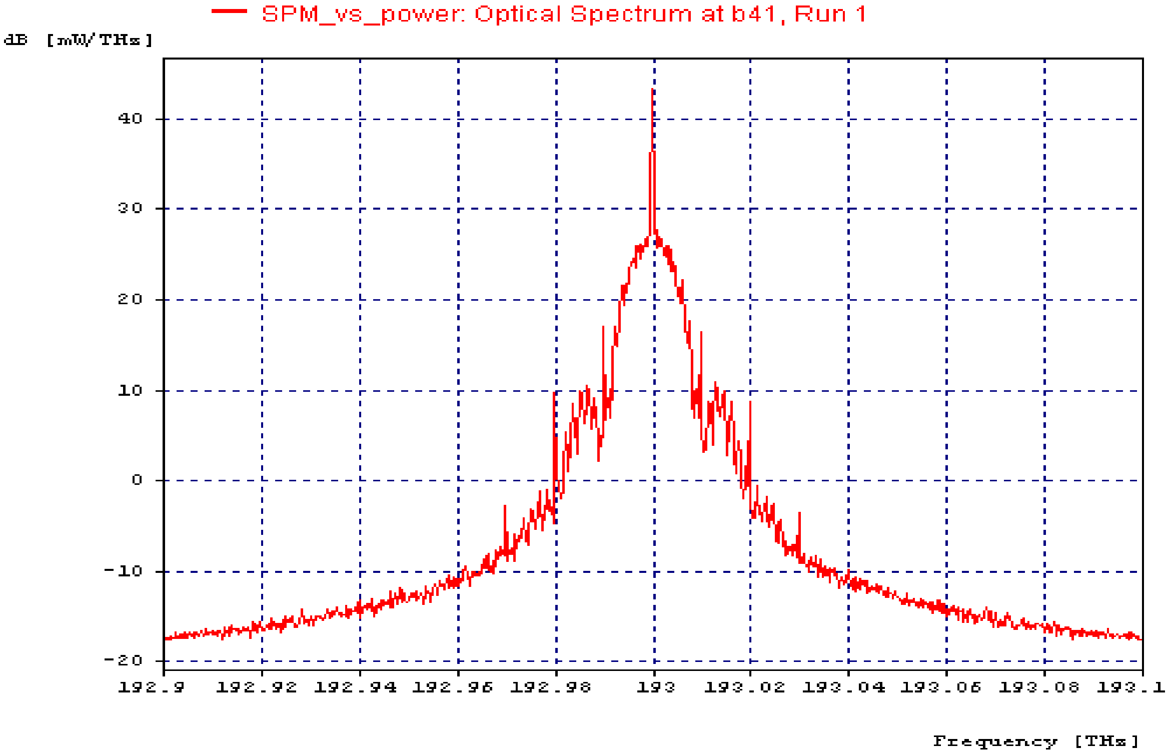

Figure 4.4(a): Optical spectrum at b41, Run 1

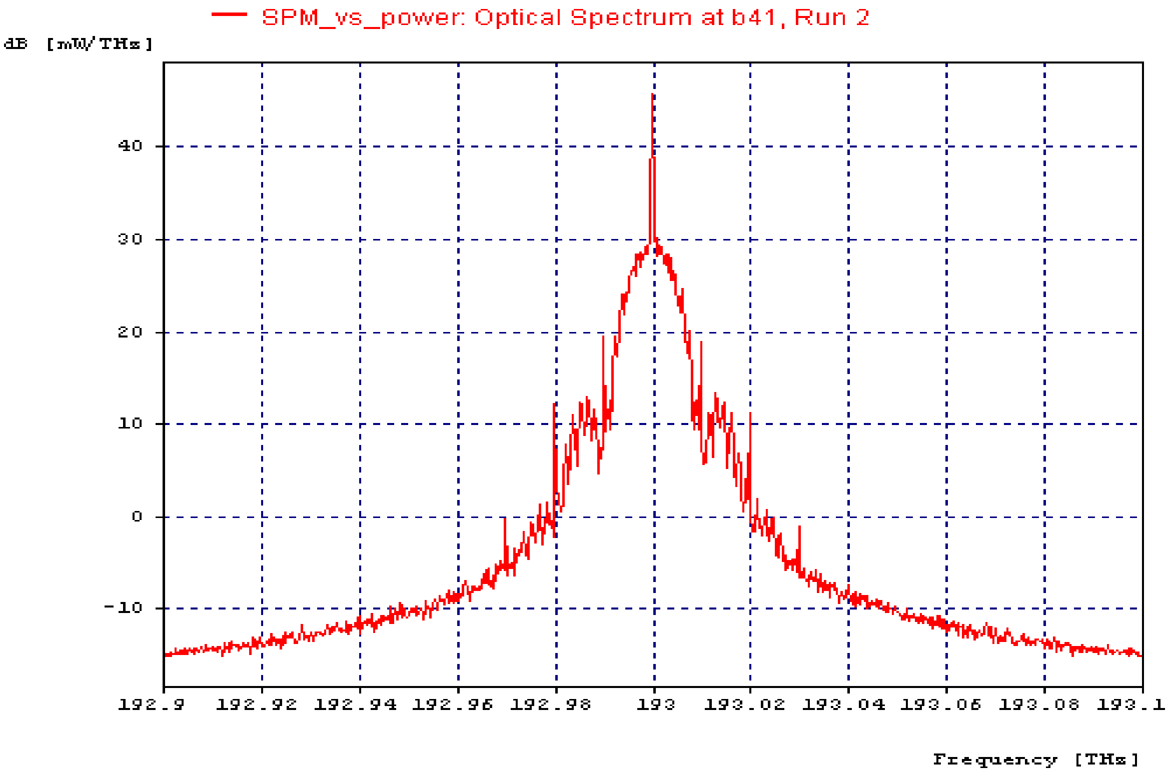

Figure 4.4(b): Optical spectrum at b41, Run 2

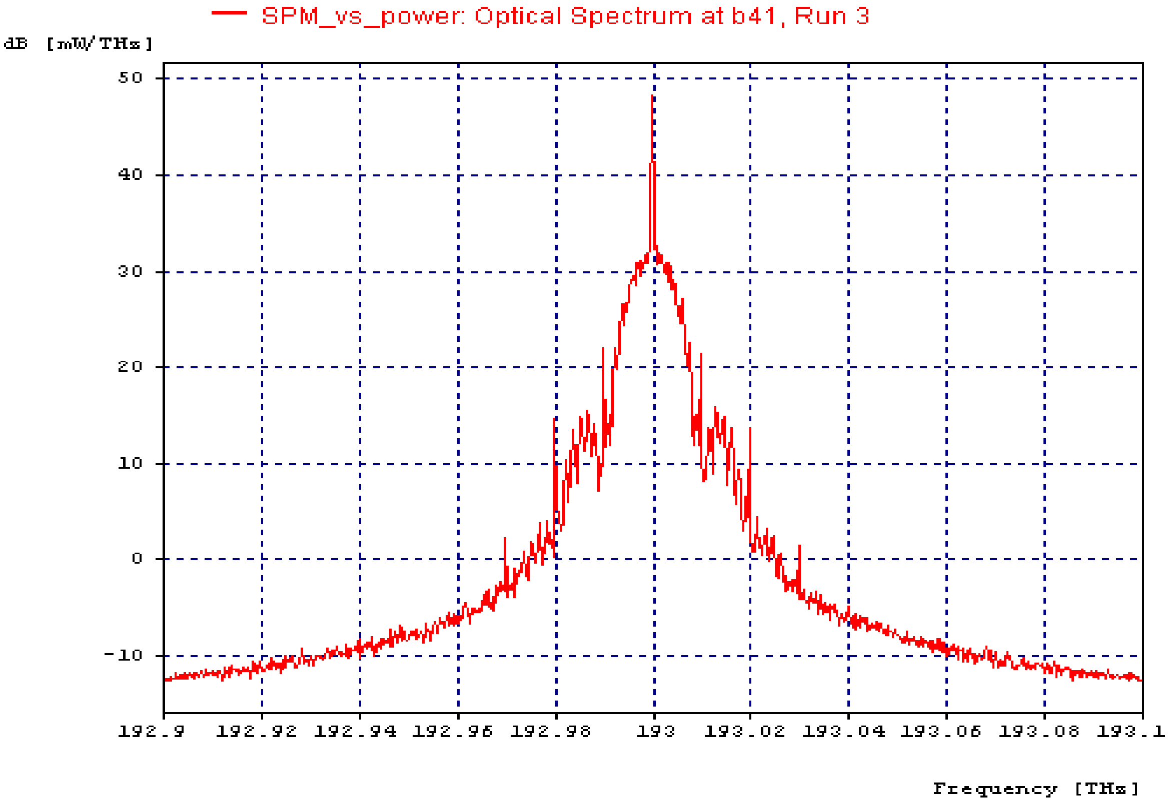

Figure 4.4(c): Optical spectrum at b41, Run 3

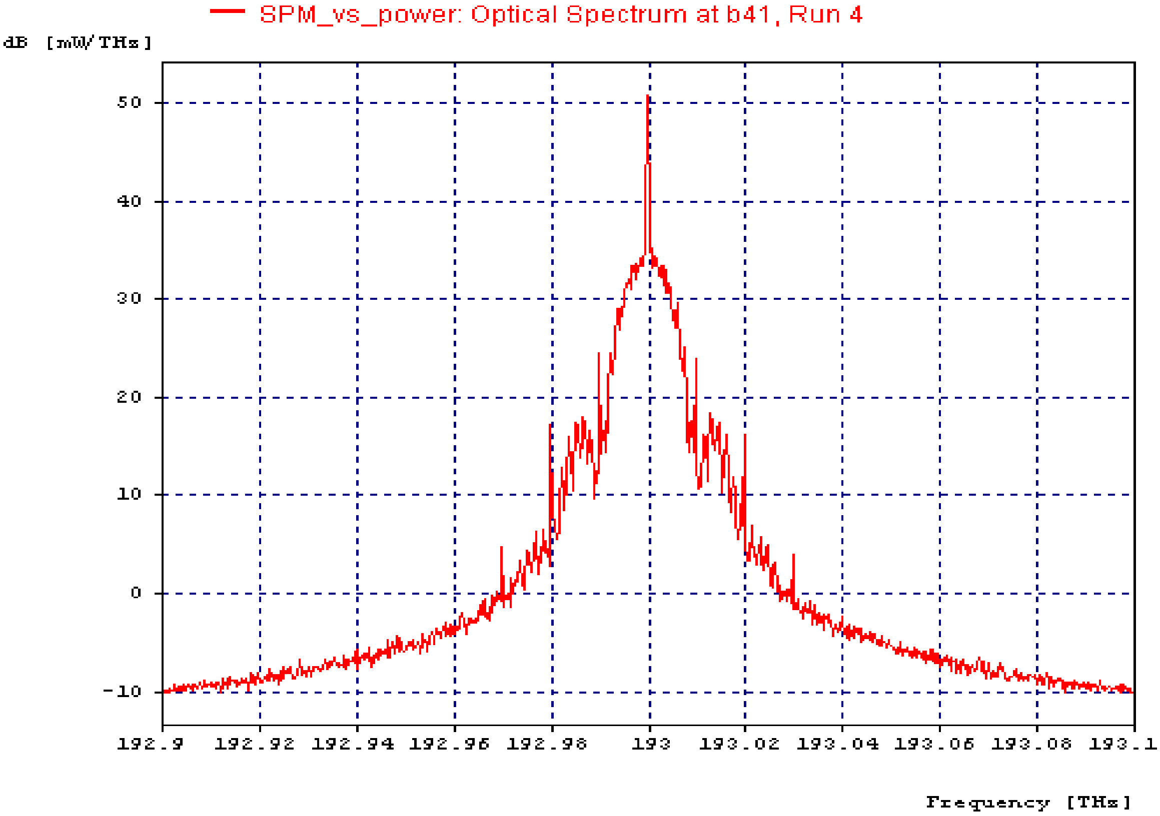

Figure 4.4(d): Optical spectrum at b41, Run 4

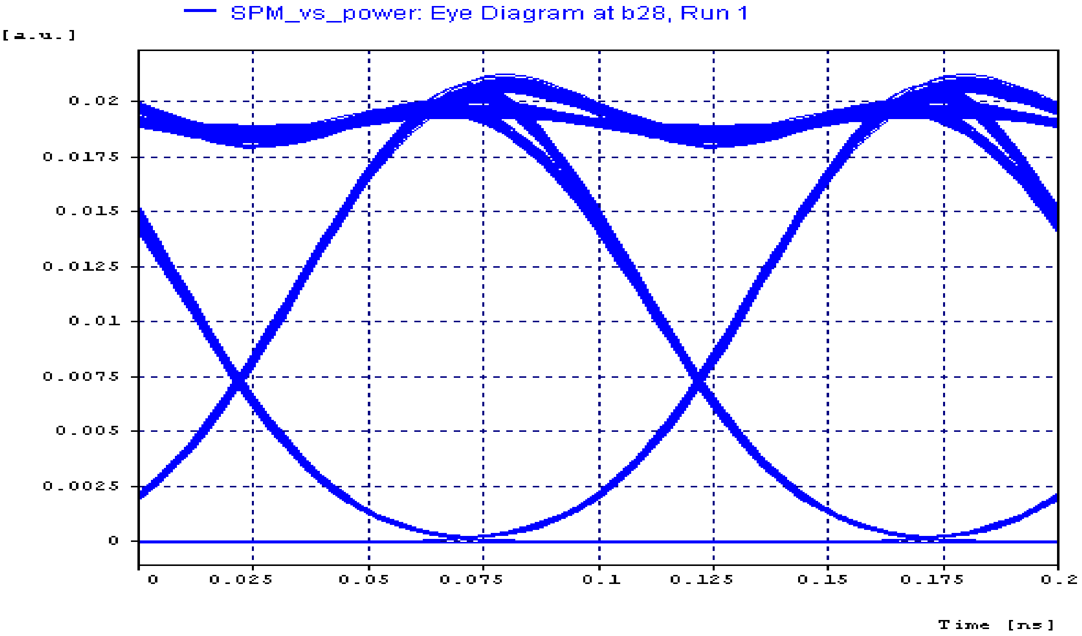

Figure 4.5 (a): Eye diagram at b28, Run 1

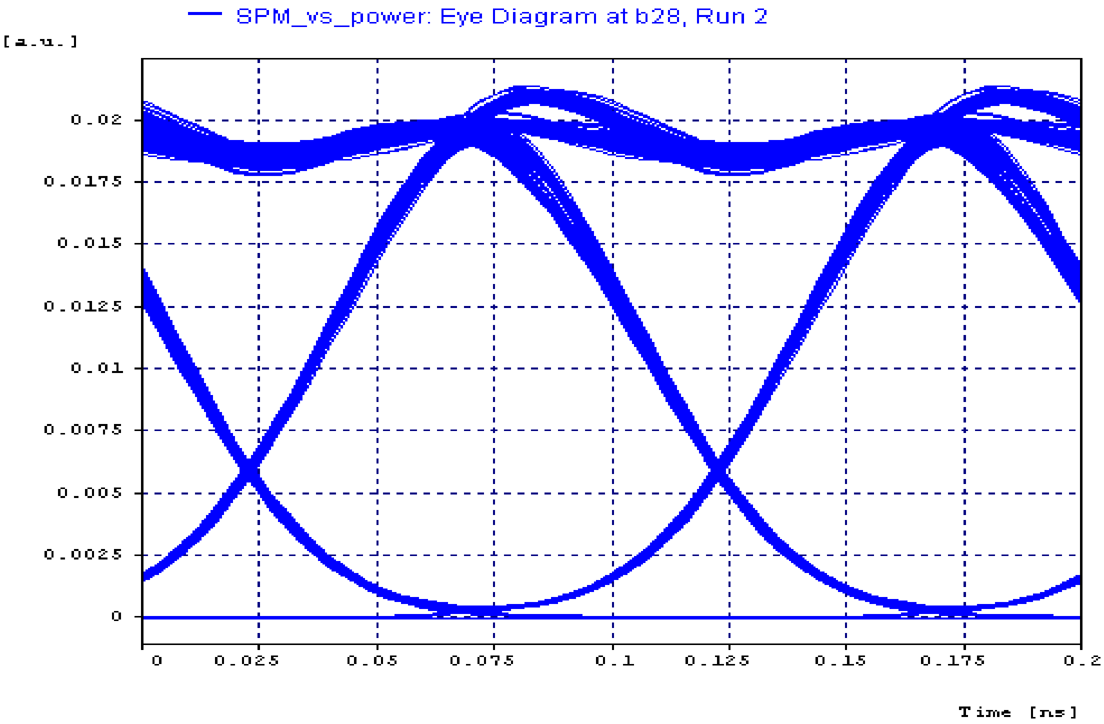

Figure 4.5 (b): Eye diagram at b28, Run 2

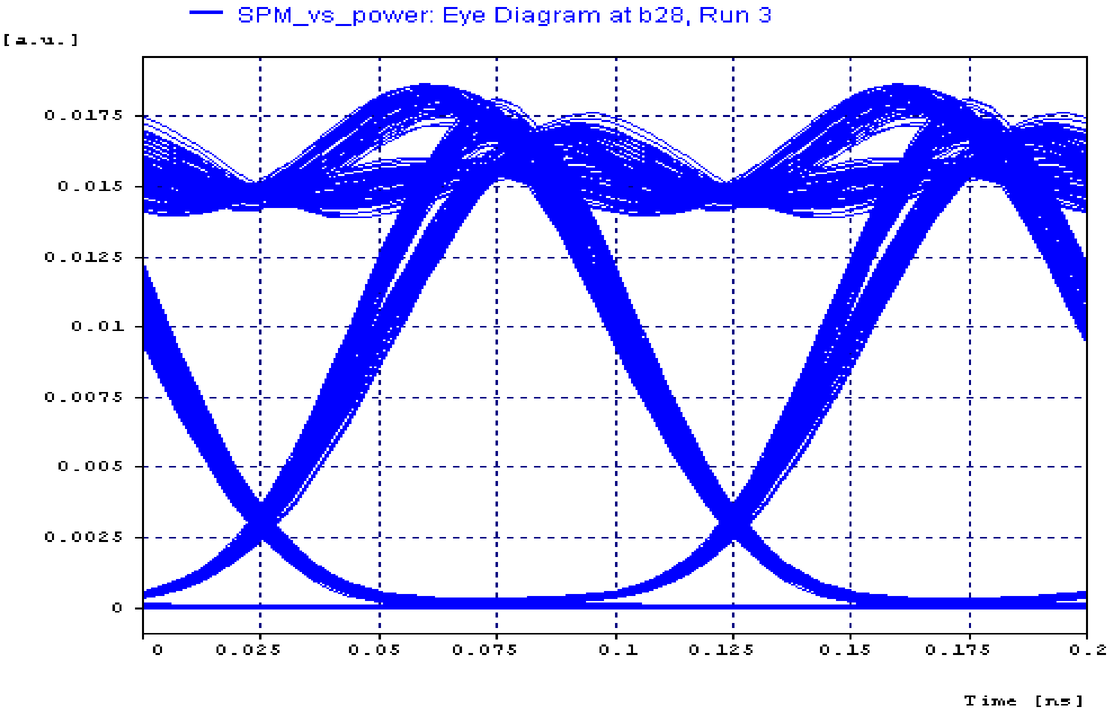

Figure .45 (c): Eye diagram at b28, Run 3

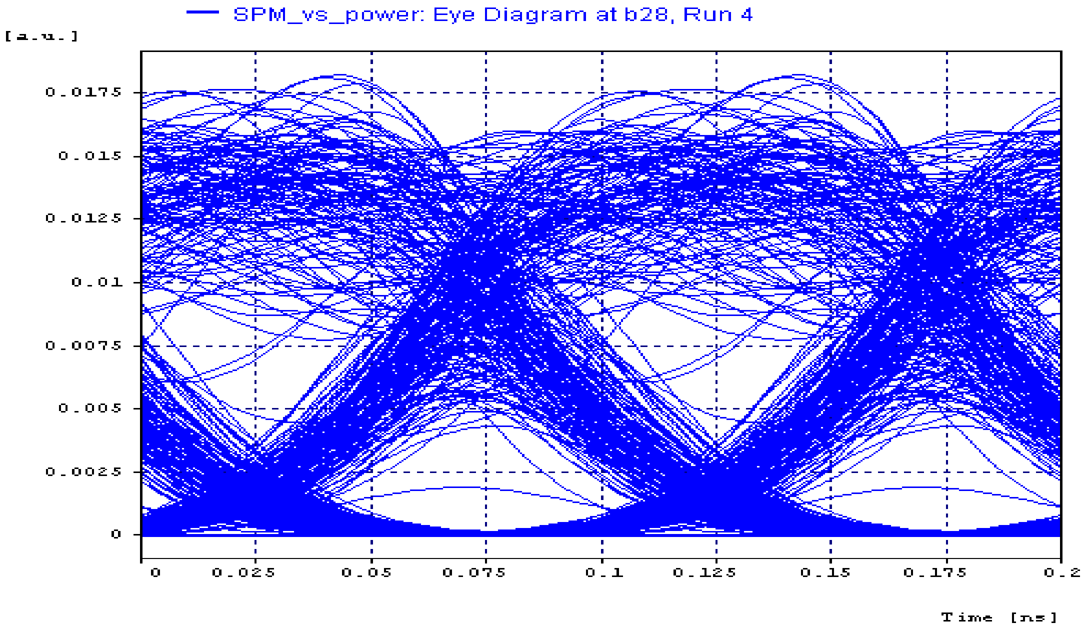

Figure 4.5 (d): Eye diagram at b28, Run 4

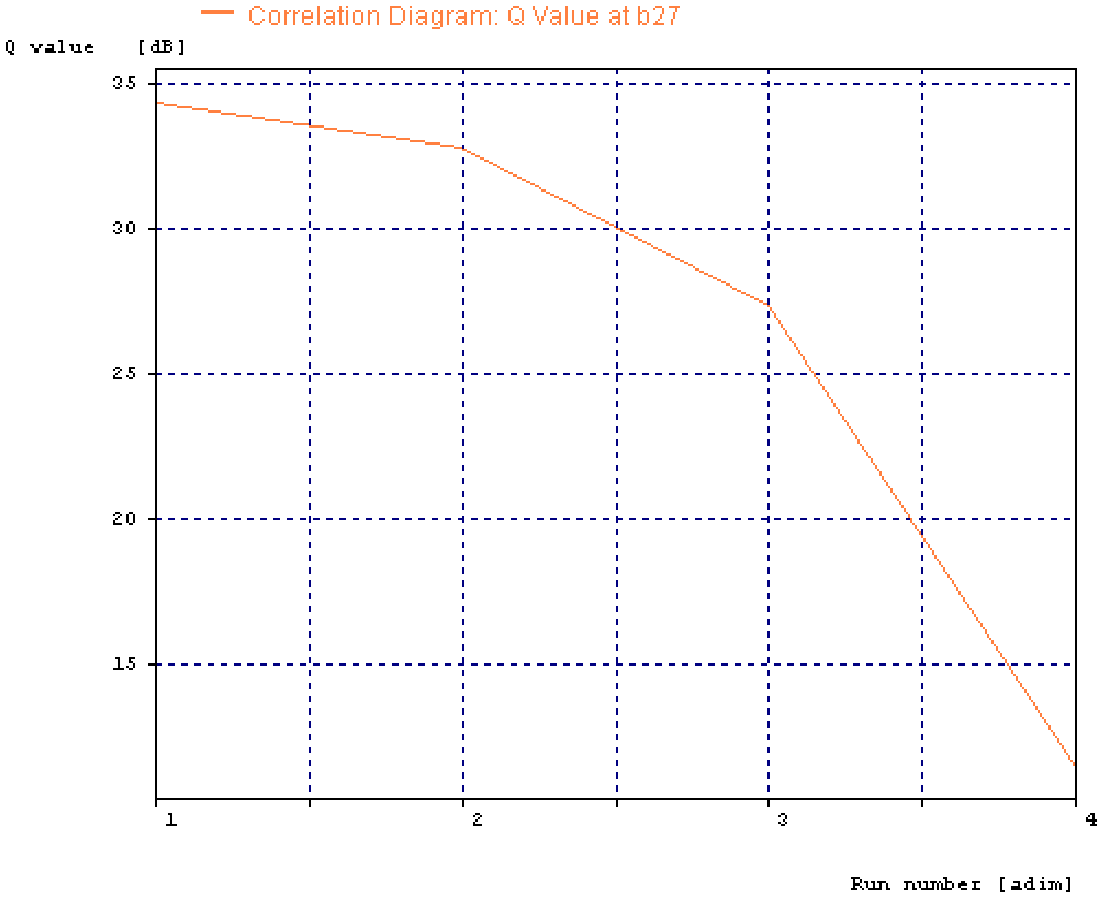

Figure 4.6 (a): Q value at b27

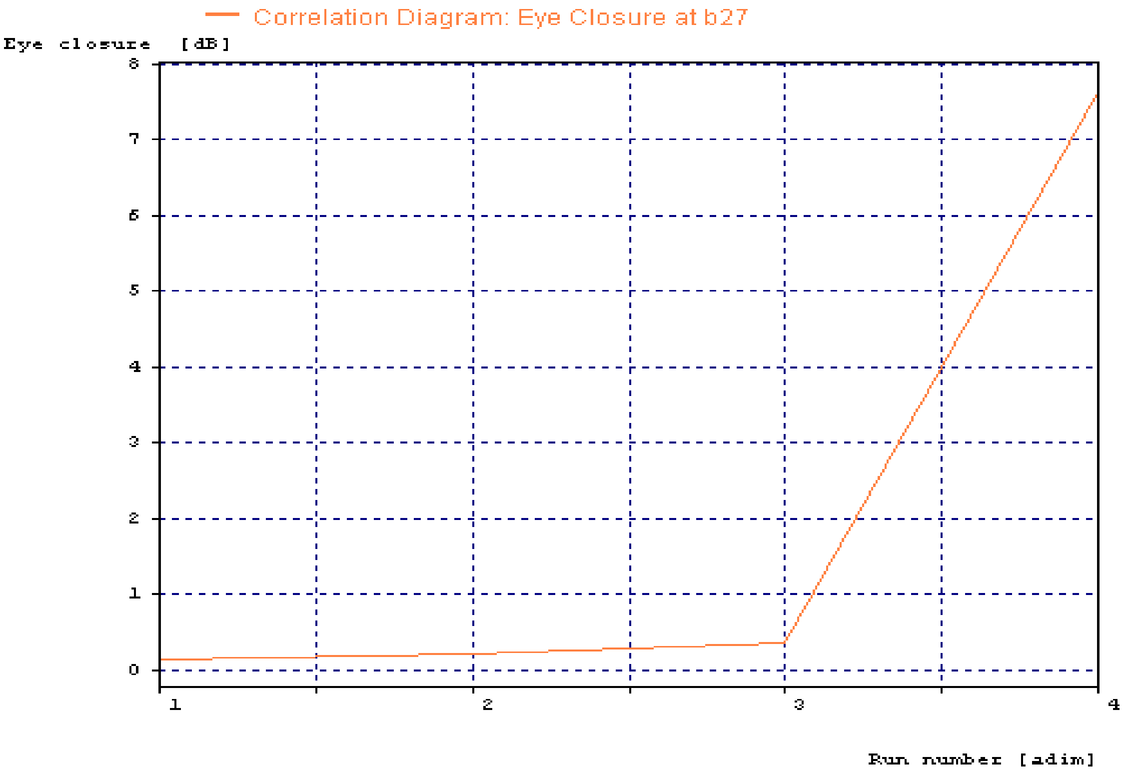

Figure 4.6 (b): Eye closure at b27

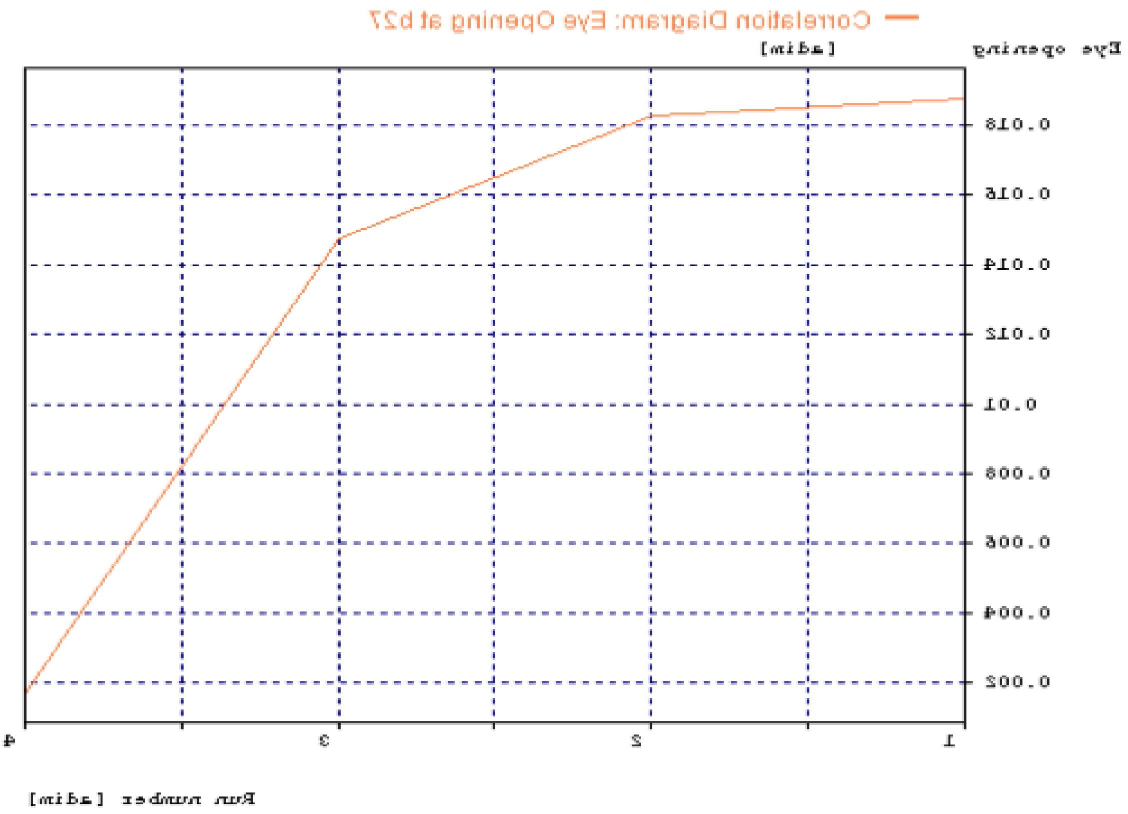

Figure 4.6 (c): Eye opening at b27

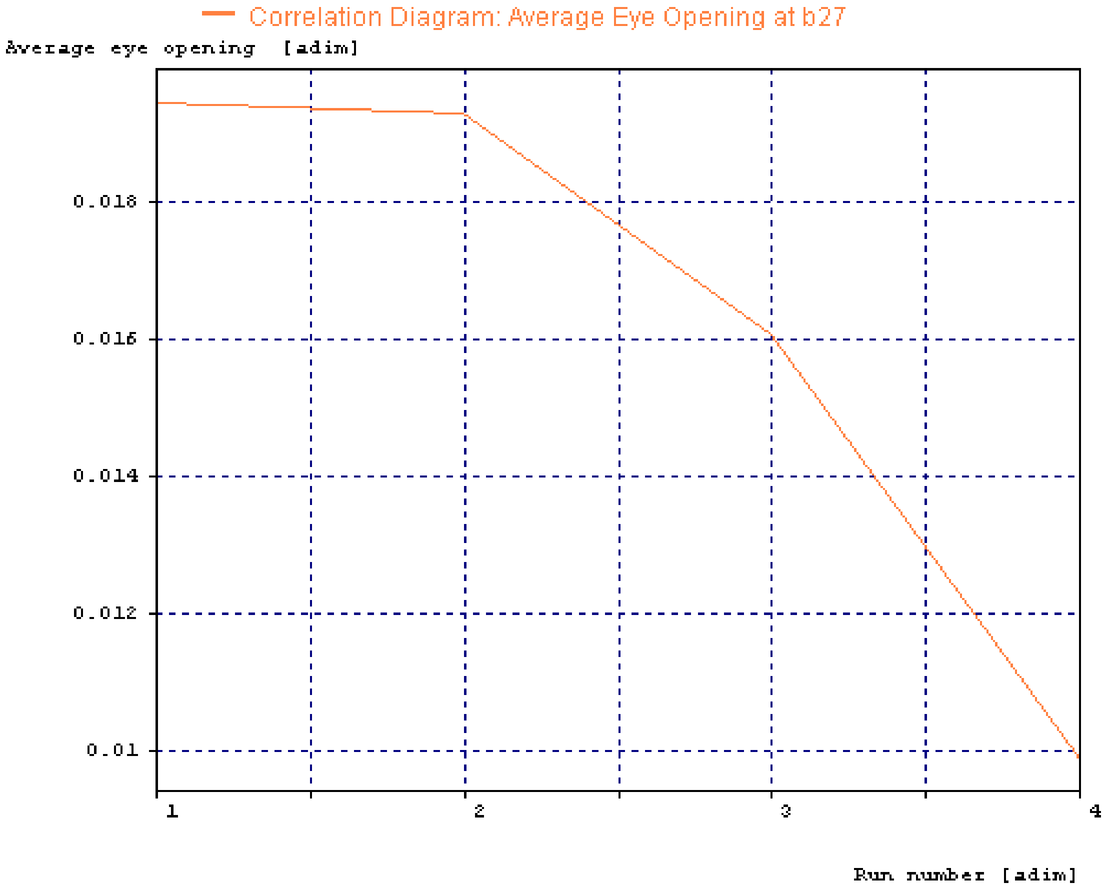

Figure 4.6 (d): Average Eye opening at b27

4.4 Conclusions

The behavior of SPM versus the optical power for two spans amplified system has been investigated. A 10 Gb/s NRZ signal is launched over two DS fiber spans (D=0.4 ps/nm/km) of 50 km, each. The power at the input to each span is varied from 10 to 17.5 dBm by using the parametric run feature in OptSim. EDFA noise has been turned off in order to simplify the analysis of SPM. By increasing the power, SPM grows and depletes the signal, and the measured power (in a bandwidth equal to twice bit rate) actually decreases with the increasing of the transmitted power. Moreover, the channel has been demodulated. The eye diagram highlights the PM-AM conversion due to the SPM. Specifically the eye opening decreases with increasing transmitted power. Since there is no noise, estimation of the Q values is irrelevant.

Chapter 5

CONCLUSIONS AND FUTURE WORK

In this final chapter, we summarize the conclusions that can be drawn from the research performed for this thesis, and then provide suggestions for future research.

5.1 Summary

The main motivation of this work was to study simulation studies of broadband optical communication systems due to dispersion and fiber nonlinearities. The GVD effect is the major factor that degrades the performance of high bit-rate long-distance optical communications systems. The studies on dispersion are very limited as far as the significance of higher order dispersion terms are concerned. The RIN originates from a fluctuation induced by the spontaneous emission in semiconductor lasers and is enhanced by a process called phase-to-intensity noise conversion due to dispersion in transmission medium. Fiber nonlinearities have become one of most significant limiting factors of system performance since the advent of erbium-doped fiber amplifiers (EDFAs) because input power is increasing and the effects of fiber nonlinearities are accumulating with the use of EDFAs. In wavelength-division-multiplexing (WDM) systems, inter-channel interference due to fiber nonlinearities may limit the system performance significantly.

In this thesis, an attempt has been made to realize broadband optical communication systems and networks by studying electrical drivers and self phase modulation (fiber nonlinearities).

The major results obtained this study are summarized as follows:

1. The FM-AM conversion with respect to binary intensity modulated PCM systems including higher order dispersion term is discussed using large signal analysis for dispersive optical fiber. The modified expression for power penalty has been derived and it's impact on laser linewidth and bit rate has been investigated. For power penalty less than 0.5 dB, the plots between bit rate and transmission distance are plotted. It is seen that the transmission distance increases with decrease in linewidth over significant bit rates. The transmission distance with first order dispersion term for 150 KHz linewidth is approximately 900 km for 40Gb/s bit rate and 10^{-12} bit error rate. With proper first order

dispersion compensation i.e. with second order dispersion only, the transmission distance can be enhanced to 10^6 km for this linewidth for the same bit rate. It is also seen that the linewidth requirement is narrow for larger bit rates and large transmission distances. For achieving transmission distance of 200 km, the linewidth requirement is 3 KHz, 60 KHz and 5 MHz for bit rates 100 Gb/s, 40 Gb/s and 10 Gb/s respectively with bit error rate of 10^{-9}. For WDM systems, with acceptable bit error rate of 10^{-12}, the linewidth requirement reduces to 2KHz, 40 KHz and 2 MHz for bit rates 100 Gb/s, 40 Gb/s and 10 Gb/s respectively.

2. The bit error rate becomes deciding factor to select the fiber over long distance. From the results & discussion, it can be concluded that Dispersion shifted fibers anomalous & normal are performing better for long distances. Also observed, Q value & Timing jitter are not affected much by the selection of fiber type.

3. We further investigate power effects on simulation of 10 gb/s nrz optical communication systems with self phase modulation (SPM). In this, the behavior of SPM versus the optical power for a two spans amplified system has been investigated. A 10 Gb/s NRZ signal is launched over two DS fiber spans (D=0.4 ps/nm/km) of 50 km, each. The power at the input to each span is varied from 10 to 17.5 dBm by using the parametric run feature in OptSim. EDFA noise has been turned off in order to simplify the analysis of SPM. By increasing the power, SPM grows and depletes the signal, and the measured power (in a bandwidth equal to twice bit rate) actually decreases with the increasing of the transmitted power. Moreover, the channel has been demodulated. The eye diagram highlights the PM-AM conversion due to the SPM. Specifically the eye opening decreases with increasing transmitted power. Since there is no noise, estimation of the Q values is irrelevant.

Therefore, this study establishes simulation of broadband optical communication systems and networks with dispersion and fiber nonlinearities.

5.2 Suggestions for Future Research

During the course of this thesis, several avenues for the continuation of this study became evident. The topics that were considered worthwhile are summarized as under:

We have neglected the all other fiber nonlinearities Cross Phase Modulation, Four Wave Mixing, Stimulated Raman Scattering and Stimulated Brillouin Scattering. All these nonlinearities can be simulated for different aspects. Another assumption made in these chapters are that the chirp in light sources is negligible. In the linear regime, it is well known that that the chirp may broaden or compress the output pulse width depending on the dispersion region. Therefore, in the presence of the fiber nonlinearities, it is of interest to see how these results change with the chirp parameter.

In this thesis, the polarization effects have been ignored. These effects along with dispersion and the fiber nonlinearities may be treated in simulation studies and results can be compared with present analytical methods.

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