MODULATION FORMATS FOR WAVELENGTH DIVISION MULTIPLEXING (WDM) SYSTEMS

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ABSTRACT

MODULATION FORMATS FOR WAVELENGTH DIVISION MULTIPLEXING (WDM) SYSTEMS

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Optical communication networks are becoming the backbone of both national and international telecommunication networks. With the progress of optical communication systems, and the constraints brought by WDM transmissions and increased bit rates, new ways to convert the binary data signal on the optical carrier have been proposed.

There are different factors that should be considered for the right choice of modulation format, such as information spectral density (ISD), power margin, and tolerance against group-velocity dispersion (GVD) and against fiber nonlinear effects like self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), and stimulated Raman scattering (SRS).

In this dissertation, the several very important modulation formats such as Non Return to Zero (NRZ), Return to Zero (RZ), Chirped Return to Zero (CRZ), Carrier Suppressed Return to Zero (CSRZ), Differential Phase Shift Keying (PSK) and Carrier Suppressed Return to Zero- Differential Phase Shift Keying (CSRZ-DPSK) will be detailed and compared.

In order to make performance analysis of such modulation formats, the simulation will be done by using VPItransmissionMaker™ WDM software.

Keywords: Optical fiber communication, optical modulation, Wavelength Division Multiplexing (WDM).

ÖZ

DALGA BOYU BÖLMELİ ÇOĞULLAMA (WDM) SİSTEMLERİ İÇİN MODÜLASYON FORMATLARI

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Optik iletişim ağları hem ulusal hem de uluslararası iletişim ağlarının bel kemiğini oluşturmaktadır. Optik iletişim sistemlerdeki gelişme, WDM iletimindeki sınırlamalar ve artan bit oranları, optik taşıyıcı üzerindeki ikili veriyi çevirmede yeni yollara gereksinim getirmektedir.

Modülasyon formatının seçiminde dikkat edilmesi gereken faktörler vardır. Bilgi spektrumu yoğunluğu (ISD), güç payı, grup hız dağınımı (GVD) ve kendinden kaymalı faz modülasyonu (SPM), karşı faz modülasyonu (XPM), dört-dalga karışımı (FWM) ve uyarılmış Raman saçılımı (SRS), gibi lineer olmayan etkilere karşı direnç dikkate alınmalıdır.

Bu tezde, önemli modülasyon formatlarından Non Return to Zero (NRZ), Return to Zero (RZ), Chirped Return to Zero (CRZ), Carrier Suppressed Return to Zero (CSRZ), Differential Phase Shift Keying (PSK) and Carrier Suppressed Return to Zero- Differential Phase Shift Keying (CSRZ-DPSK) incelenerek, karşılaştırma yapılacaktır.

WDM sistemlerinde, belirtilen modülasyon formatlarında performans analizi yapmak için VPItransmissionMaker^{TM} WDM yazılımı kullanılarak simülasyon yapılacaktır.

Anahtar Kelimeler: Fiber optik iletişim, optik modülasyon, Dalgaboyu Bölmeli Çoğullama iletim sistemleri (WDM).

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LIST OF ABBREVIATIONS

ASE	Amplified Spontaneous Emission Noise.
ASK	Amplitude Shift Keying.
BER	Bit Error Rate.
CD	Chromatic Dispersion.
CPFSK	Continuous Phase Frequency Shift Keying.
CRZ	Chirped Return to Zero.
CSRZ DPSK	Carrier Suppressed Return to Zero Differential Phase Shift Key.
CSRZ	Carrier Suppressed Return to Zero.
CWDM	Coarse wavelength division multiplexing.
DCF	Dispersion Compensating Fiber.
DMS-RZ	Dispersion-Managed Soliton-Based Return to Zero.
DPSK	Differential Phase Shift Key.
DQPSK	Quaternary Phase Shift Keying.
DWDM	Dense Wavelength Division Multiplexing.
EAM	Electro-Absorption Modulator.
EDFA	Erbium-Doped Fiber Amplifiers.
EOM	Electro-Optic Modulators.
FEC	Forward Error Correction.
FSK	Frequency Shift Keying.
FWM	Four Wave Mixing.
GVD	Group-Velocity Dispersion.
IM/DD	Intensity Modulated-Direct Detection.
ISD	Information Spectral Density.
ISI	Intersymbol Interference
ITU	International Telecommunication Union.
MSK	Minimum Shift Keying.
MZIM	Mach-Zehnder Interferometer.
NF	Noise Figure.

NRZ DPSK	Non Return to Zero Differential Phase Shift Key.
NRZ	Non Return to Zero.
OOK	On-Off Keying.
PMD	Polarization Mode Dispersion.
PolSK	Polarization Shift Keying.
PSK	Phase Shift Keying.
RZ DPSK	Return to Zero Differential Phase Shift Key.
RZ	Return to Zero.
SBS	Stimulated Brillouin Scattering.
SMF	Single Mode Fiber.
SOP	State of Polarization.
SPM	Self-Phase Modulation.
SRS	Stimulated Raman Scattering.
SSMF	Standard Single Mode Fiber.
VSB-RZ	Vestigial sideband Return to Zero.
WDM	Wavelength Division Multiplexing.
XPM	Cross Phase Modulation.

CHAPTER 1

WDM SYSTEMS

1.1 INTRODUCTION

Communication systems can be defined as the transfer of information from one point to another. The information transfer is frequently achieved by superimposing or modulating the information on to an electromagnetic wave acting as a carrier for the information signal. This modulated carrier is then transmitted to the required destination where it is received and the original information signal is obtained by demodulation. Electromagnetic carrier wave can operate at radio frequencies, microwave frequencies, millimeter wave frequencies and optical range of frequencies [1]. Optical communication systems also called lightwave systems use carrier frequencies in the visible or near infrared region of the electromagnetic spectrum. Fiber optic communication systems are lightwave systems where the information is transmitted through the optical fiber [2]. In recent years, fiber optic communication systems become a most desirable communication system because of the present and the future demand for combined voice, video and data transmission, high-speed Internet access, multimedia broadcast systems, high-capacity data networking for grid computing and remote storage.

The tremendous growth in demand for bandwidth has led to various technologies to increase the capacity. The use of wavelength-division multiplexing (WDM) technology, which supports multiple simultaneous channels on a single fiber, offers a further boost in fiber transmission capacity. WDM transmission systems with transmission capacity exceeding a Tera-bit per second are becoming commercially available. Two different versions of WDM, defined by standards of the International Telecommunication Union (ITU), are distinguished: Coarse wavelength division multiplexing (CWDM) uses a relatively small number of channels (four or eight), and a large channel spacing of 20 nm. The nominal wavelengths range from 1310 nm to 1610 nm. The single channel bit rate is usually between 1 and 3.125 Gb/s. Dense wavelength division multiplexing (DWDM) enhance the total transmission capacity by increasing the number of multiplexed channels. It uses large number of channels (40, 80, or 160), and a correspondingly small channel spacing of 12.5GHz (0.1nm), 25 GHz (0.2nm), 50 GHz (0.4nm) or 100 GHz (0.8nm). All optical channel frequencies refer to a reference frequency of 193.10 THz (1552.5 nm). The single-channel bit rate can be 10 Gb/s, 20Gb/s, 40Gb/s and also 100 Gb/s [3].

Figure 1.1 shows the implementation of typical WDM link. At the transmitting end there are several independently modulated light sources, each emitting signals at a unique wavelength. To combine these optical outputs into a continuous spectrum of signals and couple them onto a single fiber, a multiplexer is needed. To separate the optical signals into appropriate detection channels for signal processing a demultiplexer is required at the receiving end. The fiber losses are compensated for using the amplifier. Optical amplifiers are divided into three categories in terms of the function they perform such as boosters or a post-amplifier, in-line amplifiers, and preamplifiers. A post-amplifier is placed immediately after a transmitter. A post-amplifier magnifies a signal before sending it down a fiber. Its main function is to produce maximum optical power. An in-line amplifier is placed in the middle of a fiber optic link to compensate for power losses caused by fiber attenuation, connections, and signal distribution in networks. The number of in-line amplifiers needed depends on the length of the fiber-optic link and the network's configuration. For long-haul links, in-line amplifiers are usually installed every 80 to 100 km. These amplifiers compensate for losses caused by fiber attenuation and splices. They are also needed for short-distance networks to compensate for losses caused by signal distribution in a local area network. A preamplifier magnifies a signal immediately before it reaches the receiver [4].

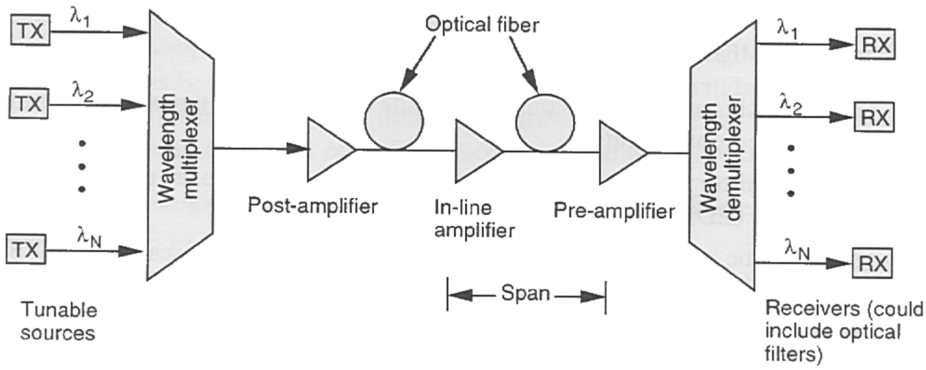


Figure 1.1 Implementation of typical WDM link [4].

1.2 TRANSMISSION IMPAIRMENTS

There are several factors that seriously degrade the WDM system performance. When an optical signal transmits over a fiber, it suffers from linear and nonlinear degrading effects in the fiber. Optical loss or attenuation, amplified spontaneous emission noise (ASE), polarization mode dispersion (PMD), and chromatic dispersion (CD) are linear degrading effects; Stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS) and Kerr effect are nonlinear degrading effects. The effects of self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM), due to Kerr effect, and stimulated Raman scattering (SRS) effects arise from the interaction two or more channels, so these effects are particular concern in WDM systems [5]. In order to understand the requirements on the modulation formats, it is important to know the limitations of optical communication systems. Therefore, in this dissertation the various phenomena that limit the transmission reach will be described.

1.2.1 Linear Effects

1.2.1.1 Fiber Attenuation

Attenuation is the most fundamental impairments that affect signal propagation and limit transmission distance in fiber. It is given as a specification for a particular fiber type. Attenuation is a property of the fiber, and it is result of the various material, structural, and modular impairments in a fiber [6].

When optical signal is transmitted over fiber, its power is lost and its amplitude is reduced. This amplitude reduction or attenuation coefficient α is expressed in dB/km.

Power attenuation inside an optical fiber is governed by Beer's Law.

$$\frac{dP}{dz} = -\alpha P \tag{1.1}$$

In Eq. (1.1) $\frac{dP}{dz}$ is the change in power with respect to length and α is the attenuation coefficient. If P_{in} is the input optical power (W), P_{out} is the output optical power (W) and L (km) is the total length of the fiber, we can express the output power P_{out} as the following equation.

$$P_{out} = P_{in} exp(-\alpha L) \tag{1.2}$$

The attenuation constant α can be written in common units of dB/km. Decibel is defined in terms of the logarithm of a power or intensity ratio. by using following relation

$$\alpha(dB/km) = -\frac{10}{L} log_{10} \frac{P_{out}}{P_{in}} \tag{1.3}$$

and it is referred as fiber loss.

Thanks to the progress of fiber manufacturing, the attenuation of fibers has gone down to slightly below 0.2 dB/km at 1.55 μm where the attenuation is nearly minimum [2][6].

Material absorption and Rayleigh scattering are most important factors that cause a fiber loss. Optical fiber absorption is material specific and can be divided into two categories: intrinsic absorption and extrinsic absorption. Intrinsic absorption results from the interaction of free electrons and the operating wavelength within the fiber material. Extrinsic absorption results from the presence of the impurities. The metal ions are most undesirable impurities in an optical fiber. Rayleigh scattering arises from microscopic variations in the material density, from compositional fluctuations and from structural inhomogenities. Rayleigh scattering causes a small part of the optical ray to escape from its path thus, causing small attenuation [7].

Attenuation depends on the wavelength of transmitted light. Figure 1.2 shows the loss spectrum of a single mode fiber. Attenuation at 1.55μm is only 0.2 dB/km, the lowest value first realized in 1979. This value is close to the limit of the silica fibers about 0.16dB/km. Attenuation has strong peak near 1.39μm and minimum peak near 1.3μm where the attenuation is below 0.5dB/km. this low-loss window was used for second-generation lightwave systems. For shorter wavelengths attenuation is higher exceed 5dB/km in the visible region and this wavelengths are not suitable for long-haul transmission. The material absorption and Rayleigh scattering are also shown in this figure. The intrinsic material absorption for silica in the wavelength range 0.8-1.6μm is below 0.1dB/km as shown in this figure. In fact, it is less than 0.03dB/km in the 1.3μm to 1.6μm wavelength range which are commonly used for lightwave systems. The main source of extrinsic absorption in silica fiber is the presence of water vapors. Its harmonic and combination tones with silica produce absorption at the 1.39μm, 1.24μm and 0.95μm wavelengths. In dry fiber, the OH ion concentration is reduced to low levels that the 1.39μm peak almost disappears as shown in Figure 1.3. Any wavelength below 0.8μm is unusable for optical communication because Rayleigh scattering is high. In addition propagation above the 1.7μm is not possible because of high losses from infrared absorption [2].

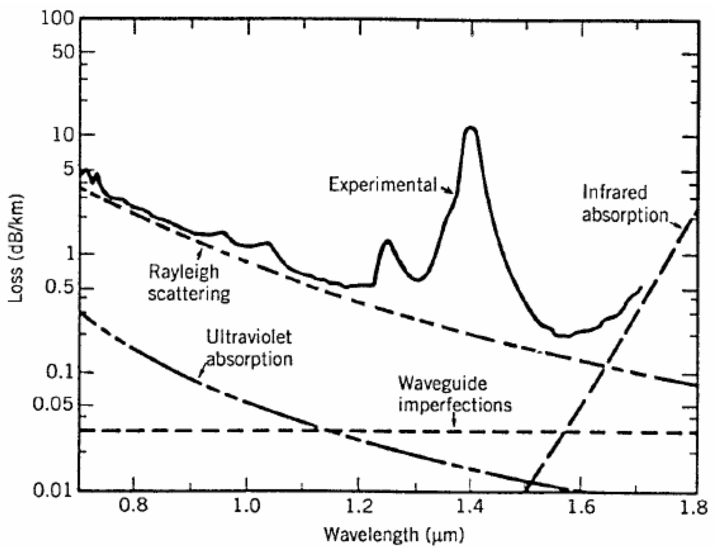


Figure 1.2 Loss Spectrum of single mode fiber [2].

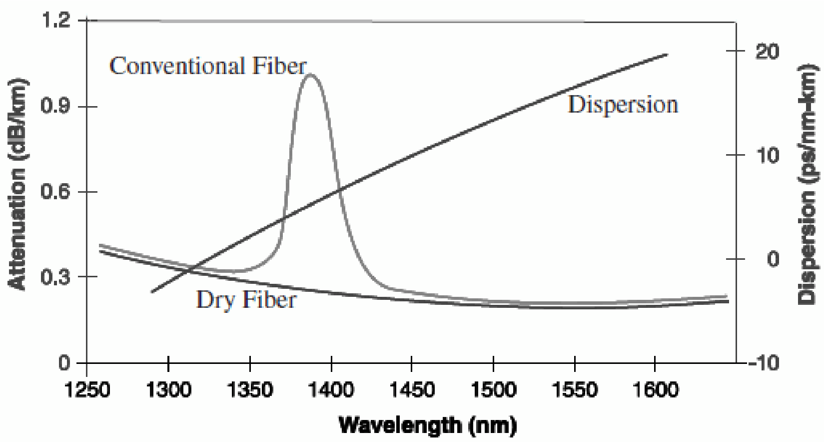


Figure 1.3 Loss and dispersion of dry fiber [2].

1.2.1.2 Amplified Spontaneous Emission Noise (ASE)

Amplified spontaneous emission (ASE) is the dominant noise generated in an optical amplifier. The spontaneous recombination of electrons and holes in the amplifier medium cause an ASE. Due to nonlinear interaction between the amplified spontaneous emission (ASE) noise from optical amplifiers and the signal, the ASE noise is being amplified by the signal during propagation.

The amount of noise generated by the amplifier depends on factors such as the amplifier gain spectrum, the noise bandwidth, and the population inversion parameter, which specifies the degree of population inversion that has been achieved between two energy levels. If multiple optical amplifiers are cascaded to periodically compensate for fiber loss, ASE builds up in the system. Each subsequent amplifier in the cascade amplifies the noise generated by previous amplifiers.

Optical amplifiers based on erbium-doped fibers are now widely deployed within terrestrial and submarine systems. They provide high gain, large optical bandwidth, and low-noise figure (NF), and several tens of erbium-doped fiber amplifiers (EDFA) can be cascaded [3][8].

1.2.1.3 Dispersion

Dispersion is the broadening of the signal pulse while through the fiber. Figure 1.4 shows how dispersion limits the information capacity. Dispersion cause pulses to spread in time. When pulses arrive at the output, they have broadened.

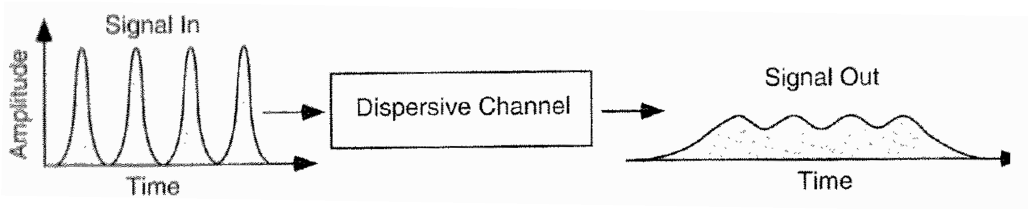


Figure 1.4 Limitation of dispersion on information capacity [9].

There are three types of dispersion in waveguides: material dispersion, waveguide dispersion and modal dispersion.

1.2.1.3.1 Material Dispersion

In material dispersion, different wavelengths of light travel at different velocities within a medium. In a dispersive medium pulse spread out in time and space .

The index of refraction is the most widely used parameter for waveguide design. Material dispersion occurs because of the variation of index of refraction as a function of the optical wavelength [4][9]. The refractive index, *n (w)*, is estimated by the Sellmeier equation (Eq.(1.4)). Material dispersion is proportional to the differential of the group index.

$$n^2(w) = 1 + \sum_{J=1}^{m} \frac{B_j w_j^2}{w_j^2 - w^2} \tag{1.4}$$

where w_j is the resonance frequency and B_j is the oscillator strength [6].

1.2.1.3.2 Waveguide Dispersion

Waveguide dispersion is similar to material dispersion, in that different wavelengths propagate at slightly different speeds. It is usually the smallest magnitude compared to material and modal dispersion [9]. Waveguide dispersion can be ignored in multimode fibers, but it is significant in single mode fibers. The amount of waveguide dispersion depends on the fiber design and varies with wavelength [4]. It is possible to design the fiber with low dispersion wavelength in 1.55µm, such fibers are called dispersion shifted fibers. It is also possible to design a fiber with relatively small dispersion in the range of 1.3µm to 1.6µm. Such fibers are called dispersion flattened fibers. Figure 1.5 shows the dispersion wavelength dependence of dispersion for standard, dispersion shifted and dispersion flattened fibers [2].

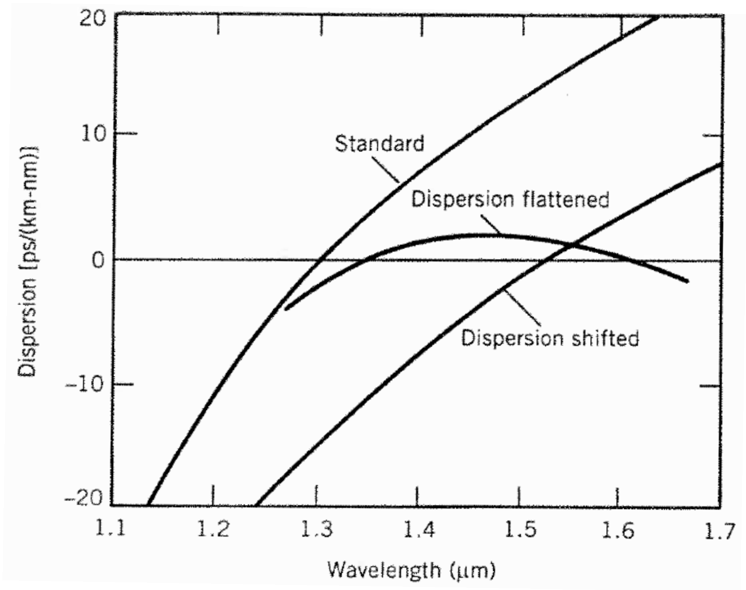


Figure 1.5 Dispersion wavelength dependence of dispersion for standard, dispersion shifted and dispersion flattened fibers [2].

Figure 1.6 shows the magnitudes of material and waveguide dispersion for silica core standard single mode fiber. Waveguide dispersion is important around 1320nm. At this point the two dispersion factors cancel to give zero total dispersion. On the other hand material dispersion dominates at 900nm and 1550nm [4].

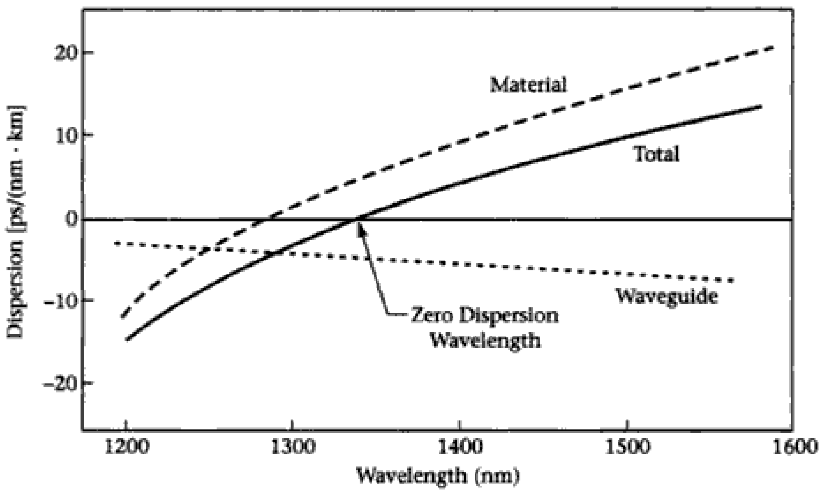


Figure 1.6 Magnitudes of material and waveguide dispersion as a function of wavelength for silica core standard single mode fiber [4].

Chromatic dispersion includes both material and waveguide effects. Chromatic dispersion is a pulse spreading that occurs within a single mode. This pulse broadens lead to bit-to-bit overlaps and the information after detection may be corrupted because of the intersymbol interference. Dispersion resulting from group velocity is termed chromatic dispersion due to the wavelength dependence. Chromatic dispersion depends on the wavelength, its effect on signal distortion increases with the spectral width of the optical signal [4].

Chromatic dispersion is also effect the transmission length of an optical system. Dispersion length L_D (km) is a parameter that governs this effect. Dispersion limit can be estimated by the following equation.

$$L_D = \frac{10^5}{DB^2} \tag{1.5}$$

where B (Gb/s) is the bit rate and D (ps/nm/km) is the dispersion factor. It can be seen from this equation that the effect of chromatic dispersion is increased with the bit rate [3].

1.2.1.3.3 Modal Dispersion

Modal dispersion occurs when more than one propagation mode in a waveguide with each travel with a different speeds [9].

A special case of modal dispersion Polarization mode dispersion (PMD). It is a result of each mode having a different value of group velocity at a single frequency. The asymmetry of the fiber core, the imperfections of fiber manufacturing, fiber deformation also cause a PMD. Contrary to chromatic dispersion, the PMD changes quickly with time [4].

Some techniques have been proposed to mitigate impairment of PMD. The optical methods, which use one or several sections of birefringent elements which have to be dynamically adjusted per channel to mitigate the impact of the PMD. However, the cost associated with such optical PMD compensators appears too large and they have not been used yet. The other method is using dispersion-maintaining fiber commercially available. Another method is choosing a modulation format that is more tolerant to PMD impairments [10].

1.2.2 Nonlinear Effects

The nonlinear effects can be divided into two categories as scattering effects and optical Kerr effects. The latter is the result of intensity dependence of the refractive index of an optical fiber leading to a phase constant, whereas the former is a result of scattering leading to an intensity dependent attenuation constant. Stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) are scattering related nonlinearities. Self-phase modulation (SPM), cross phase modulation (XPM) and four wave mixing (FWM) are refractive index-related nonlinear effects. The greatest influences on efficiency of WDM transmission systems are XPM and FWM phenomena. These effects grow with increasing number of channels.

1.2.2.1 Stimulated Brillouin Scattering (SBS)

The stimulated Brillouin scattering is a single-channel effect caused by the interaction between the optical signal and sound waves in the fiber. The result is that power from the optical signal can be scattered back towards the transmitter. The SBS effect has a high threshold, which also increases with the signal bandwidth. Therefore, as long as the signal power in the WDM channels does not exceed the threshold, the SBS does not cause significant impact on the system [11].

1.2.2.2 Stimulated Raman Scattering (SRS)

Stimulated Raman Scattering (SRS) is the nonlinear parametric interaction between the light and vibrations of silica molecules. This interaction can lead to the transfer of power from shorter wavelength, higher photon energy channels, to longer wavelength, lower photon energy channels. The spectrum of equal amplitude channels tilt as it moves through the fiber because of the SRS effect. It effect becomes more significant when the WDM signal bandwidth is broad and the power is increased [12].

1.2.2.3 Self-Phase Modulation (SPM)

The self phase modulation (SPM) is a single channel effect. It originates from the intensity dependence of the refractive index in nonlinear fiber. The main effect of SPM is to broaden the spectrum of optical pulses propagating through the fiber. SPM leads to change in the optical frequency.

The refractive index, n, is dependent on the signal power, P. It increases with the optical power:

$$n = n_0 + n_2 \frac{P}{A_{eff}} \tag{1.5}$$

where n_2 is the nonlinear refractive index, n_0 is the linear refractive index, A_{eff} is the effective area of the optical mode in the fiber. The nonlinear refractive index causes a phase change of the transmitted optical field over distance L.

$$\emptyset_{SPM} = \gamma P L_{eff} = \gamma P_{av} L \tag{1.6}$$

where

$$\gamma = \frac{2\pi n_2}{\lambda}, \quad P_{av} = \frac{P}{L}\frac{\left(1-e^{-\alpha L}\right)}{\alpha}, \quad L_{eff} = \frac{\left(1-e^{-\alpha L}\right)}{\alpha}$$

and γ is the nonlinear coefficient, λ is the signal wavelength, P_{av} is the average signal power, α is the fiber loss (attenuation), L is the fiber length, and L_{eff} is the fiber effective length [11].

1.2.2.4 Cross Phase Modulation (XPM)

As SPM, Cross-phase modulation (XPM) also originates from the intensity dependence of the refractive index. Unlike SPM, XPM is caused by the signals in other wavelengths. XPM is an interaction, via the nonlinear refractive index, between the intensity of one lightwave and the optical phase of other lightwaves. It gradually broadens the signal spectrum and cause crosstalk. XPM can be controlled by increasing the channel spacing [11].

1.2.2.5 Four Wave Mixing (FWM)

Four-Wave Mixing (FWM) is due to multiple signals causing variations in refractive index at their difference frequencies. The refractive index then modulates the original carriers to produce sidebands at new frequencies. A number of new frequencies are generated due to interaction of two or more frequencies in FWM. Three frequencies (f_i, f_j, f_k) co-propagate in the fiber, generate new frequencies (f_{ijk}) given by:

$$f_{ijk} = f_i + f_j - f_k \tag{1.7}$$

When the WDM channels are equally spaced, FWM cause nonlinear crosstalk. One way to manage with FWM is to use unequal channel spacing so that the mixing products do not coincide with signal frequencies. Another, and very effective, way is fiber dispersion management method. This method is also effective for SPM and XPM [13].

CHAPTER 2

MODULATION FORMATS IN WDM SYSTEMS

2.1 INTRODUCTION

High capacity WDM systems suffer from impairments arising from fiber nonlinear effects, chromatic dispersion, polarization mode dispersion (PMD), and amplified spontaneous emission noise. These factors limit the transmission capacity and distance in WDM systems. To improve the transmission performance of WDM systems, a wide variety of techniques have been proposed:

- advanced modulation formats are used to trade off noise resilience, fiber propagating characteristics,
- fiber types reducing nonlinear signal distortions and enabling higher signal launch power,
- techniques for dispersion, dispersion slope, and PMD compensation;
- management of nonlinear impairments,
- distributed amplification scheme lower the noise accumulated along transmission lines,
- signal equalization,
- forward error correction (FEC).

The use of advanced modulation formats is the most effective solution in managing transmission impairments. In general, different data formats lead to different signal quality at the receiver end for a given transmission link, because they exhibit different waveforms and spectra. At the same time, links with different system parameters (reach, channel spacing, fiber type, amplification schemes, etc.) may also require different optimal data formats. The ideal modulation format for long-haul, high-speed WDM transmission links is one that has a compact spectrum, low susceptibility to fiber nonlinear effects, large dispersion tolerance, and simple and cost-effective configurations for generation and detection [14].

In this dissertation, the important and most used modulation formats such as NRZ, RZ, CRZ, CSRZ, DPSK and CSRZ-DPSK will be explained, and compared. We will firstly focus on propagating single channel with known different modulation techniques. And we gradually increase the number of channels, bitrates and system complexity using different type of optical fibers, components and amplifiers. Different fiber type and different modulation format could affect the system performance. Therefore, there is a need to compare various modulation formats. And we will make a detailed analysis required the investigation of optical linear and nonlinear effects for optimal system performance, i.e., minimal bit error ratio (BER). The system performance will be monitored by means of eye-diagram. Throughout the research, VPItransmissionMaker^{TM} WDM software will be used for performance analysis.

2.2 OPTICAL MODULATOR

There are two basic modulator technologies widely used: direct modulation and external modulation.

2.2.1 Direct Modulation

In 1980s and 1990s, direct modulation of semiconductor lasers was the choice for low capacity coherent optical systems over short transmission distance. For short ranges, they are cost effective and useful. However, direct modulation induces chirping that causes a signal carrier frequency to vary with time, thus causing pulse broadening or dispersion of the signal. In addition, laser phase noise and induced also limit the advance of direct modulation to higher capacity and higher bit rate transmission. It cannot be used at bit rates that are greater than 2.5Gb/s. Moreover, direct modulation creates nonlinearity especially SPM [15].

2.2.2 External Modulation

The limitations of direct modulation can be overcome by using the external modulation technique. External Modulation avoids nonlinearities and excessive chirp. External modulation can be implemented using either electro-optic modulators (EOM) or electro-absorption (EA) modulator.

The EOM operate according to principles of electro optic effect. The change of refractive index in solid state or polymeric or semiconductor material is proportional to the applied electric field. Their performance in terms of chirp, extinction ratio and modulation speed are better. Over the years, the waveguides of the electro optic modulators are mainly integrated on the material platform of lithium niobate ($LiNbO_3$) which is high efficient, low loss, easy to fabricate. After the advent of the Erbium-doped optical fiber amplifier (EDFA) in the late 1980s, it becomes more popular. EOMs are utilized for modulation of either the phase or the intensity of the lightwave carrier.

Electro optic phase modulator manipulates the phase of optical carrier signals under the influence of an electric field created by the applied voltage. The refractive index changes accordingly inducing variation amount of delays of the propagating lightwave, when a RF driving voltage is applied onto the electrode. Electro optic phase modulator is used to carry out the phase modulation of the optical carrier because the delays correspond to the phase changes.

Optical intensity modulation is operating based on the principle of interference of the optical field of the two lightwave components. Mach-Zehnder interferometer (MZIM) based on $LiNbO_3$ is most popular modulator. It is widely used in 2.5, 10, and 40GB/s communication systems.

Figure 2.1 shows the structure of the Mach-Zehnder interferometer (MZIM) based on $LiNbO_3$. The incoming light is split into two arms when entering the modulator. The power splitter splits the power of the optical signals. Each arm of the $LiNbO_3$ modulator employs an electro optic phase modulator in order to manipulate the phase of the optical carrier if required. At the output of the MZIM, the lightwaves of the two arm phase modulators are coupled and interfered with each other. $V_1(t)$ and $V_2(t)$ are the input voltages launched into the arms of the modulator.

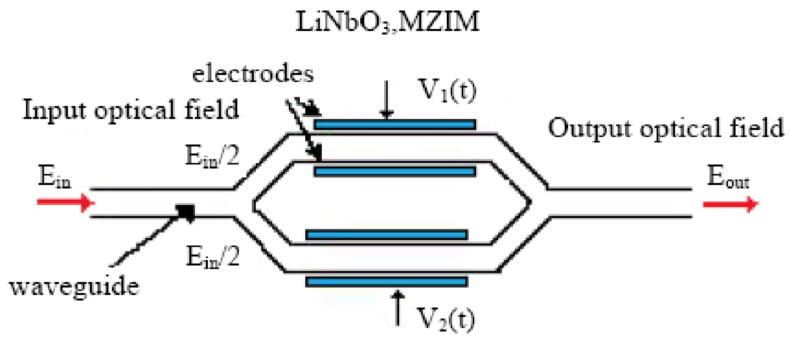


Figure 2.1 Optical intensity modulator based on Mach- Zehnder interferometric structure [15].

The EA modulator is another external modulator that can be fabricated using semiconductor laser technology. EA Modulators feature relatively low drive voltages about 2-3V as compared to $LiNbO_3$ type having 5-7V drive voltages. Also they are cost-effective in volume production. However, similar to direct modulation techniques, they produce some residual chirp. In addition the total insertion loss of modulator is rather high. However, this loss can be compensated by the integration with semiconductor optical amplifiers (SOAs). Moreover extension ratio is typically not exceeding 10 dB, and limited optical power handling capabilities. The $LiNbO_3$ type has 25 dB extension ratios [16][3].

2.3 MODULATION FORMATS

The modulation format describes how the data is coded onto the optical signal. The amplitude, phase, frequency and state of polarization (SOP) of optical signal can be modulated. The variety of modulation formats can be classified into the following four categories, depending on which of the four optical properties of the electric field of carrier belongs:

$$E(t) = \hat{e}Ae^{j(wt+\phi)} \tag{2-1}$$

A: Amplitude Shift Keying (ASK) or on-off keying (OOK)

Φ: Phase Shift Keying (PSK)

ω: Frequency Shift Keying (FSK)

$\hat{e}$: Polarization Shift Keying (PolSK) [17].

ASK encodes data by turning on or off the amplitude of light, depending on whether the symbol to be transmitted is a mark ("1") or a space ("0"), at a rate equal to the information frequency. In this modulation format, each binary symbol ("1" or "0") is represented by the presence or the absence of light. It includes non return to zero (NRZ), return to zero (RZ), and duobinary formats. There are also a number of variations of the RZ format. It includes simple RZ, carrier suppressed RZ (CSRZ), chirped RZ (CRZ), vestigial sideband RZ (VSB-RZ), and dispersion-managed soliton-based RZ (DMS-RZ).

PSK encodes data by modulating the phase of light. In this modulation format, each binary symbol ("1" or "0") is represented by light phase of "0" or "π". It includes differential PSK (DPSK), RZ-DPSK, CSRZ-DPSK, and differential quaternary PSK (DQPSK) and its pulse-carved forms.

FSK encodes data via the modulation of the frequency of light, and includes FSK, continuous phase FSK (CPFSK), and minimum shift keying (MSK) [14][17].

PolSK encodes data by the modulating the polarization of light. In polarization shift keying, the modulator generates two orthogonal polarization states, which correspond to "1" and "0" bits.

There is variety of factors that should be considered for the right choice of modulation format: spectral efficiency, power margin, and tolerance against group-velocity dispersion (GVD) and against fiber nonlinear effects like self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), and stimulated Raman scattering (SRS) [18].

2.3.1 Non Return To Zero (NRZ)

The non return to zero (NRZ) has been the dominant modulation format in intensity modulated-direct detection (IM/DD) fiber-optical communication systems for the last years because it is easy to generate, detect and process.

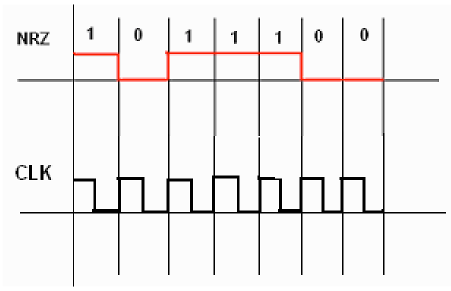


Figure 2.2 Representation of the NRZ code [19].

Figure 2.3 shows the diagram of the NRZ transmitter. The intensity of the carrier light wave is modulated by the applied electric field which voltage varies with a determined function. The Mach- Zehnder modulator (MZM) is driven at the quadrature point of the modulator power transfer function with an electrical NRZ signal.

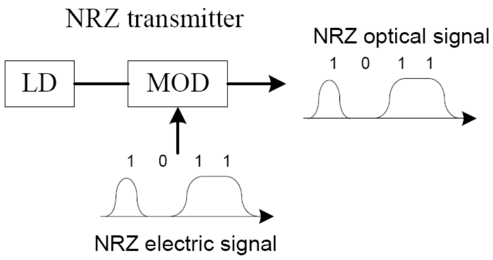


Figure 2.3 NRZ transmitter diagram [13].

Figure 2.4 shows the optical spectrum and waveform of NRZ. The NRZ pulses possess a narrow optical spectrum due to the lower on-off transitions. The reduced spectral width improves the dispersion tolerance and enables higher spectral efficiency, but on the other hand it affects the inter-symbol interference (ISI) between the pulses. NRZ modulated optical signal is less resistive to fiber nonlinear effect compared to its NR counterpart. On the other hand, NRZ has the simplest configuration of transmitter and receiver. It requires a relatively law electrical bandwidth for transmitters and receivers compared with RZ. NRZ requires roughly half the bandwidth of RZ, and is thus easier to implement, and is less costly [17].

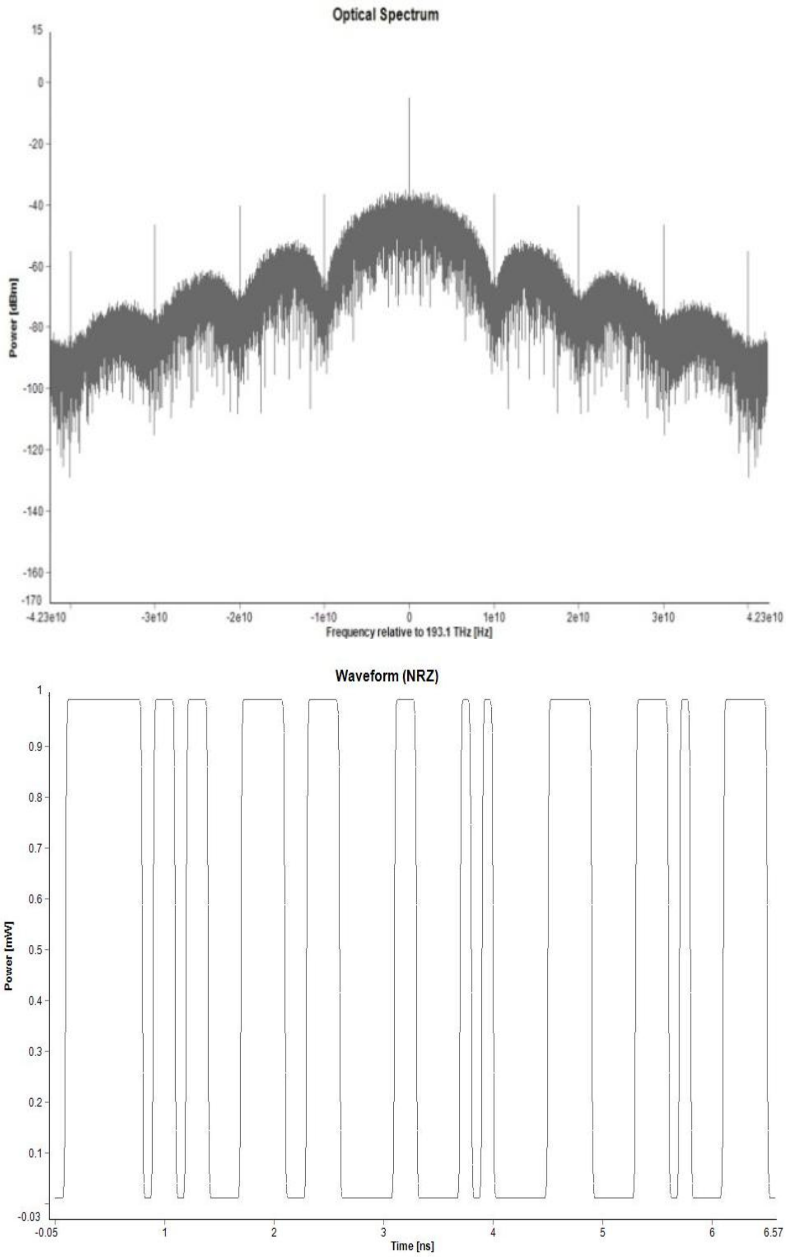


Figure 2.4 The optical spectrum and waveform of 10Gb/s NRZ modulation (simulated by VPItransmissionMaker^{TM}WDM and its simulation setup is shown in Figure A.1 at Appendix A).

2.3.2 Return To Zero (RZ)

Recent analysis and investigations have shown that RZ turned out to be superior compared to conventional NRZ systems. In RZ format for the logical 1 bit, the power level returns to 0 after half of the period, whereas for the 0 bit, the power level is 0 continuously. Binary 0 is represented by the absence of an optical pulse during the entire bit duration.

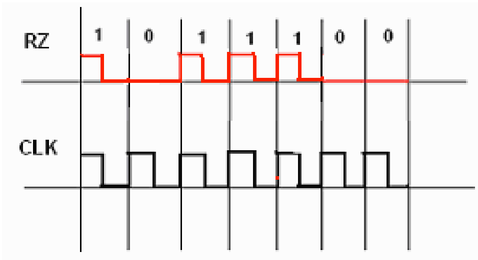


Figure 2.5 Representation of the RZ code [19].

Figure 2.6 shows the RZ transmitter. First, NRZ optical signal is generated by an external intensity modulator. Then, it is modulated by a synchronized pulse train with the same data rate as the electrical signal using another intensity modulator. The optical spectrum and waveform of RZ is shown in Figure 2.7.

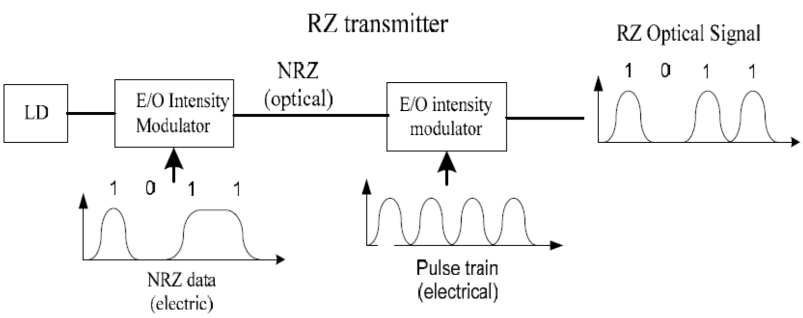


Figure 2.6 RZ transmitter [13].

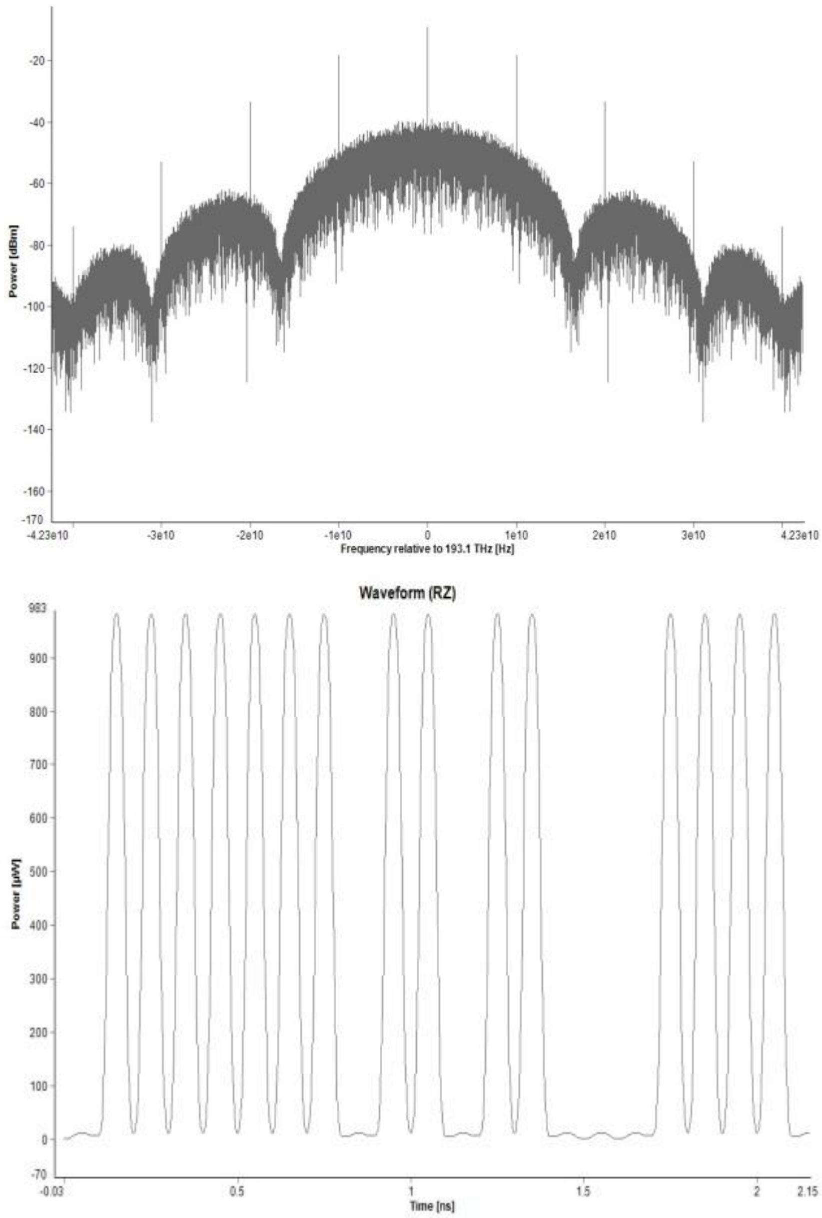


Figure 2.7 The optical spectrum and waveform of 10Gb/s RZ (simulated by VPItransmissionMaker^{TM}WDM and its simulation setup is shown in Figure A.2 at Appendix A).

RZ optical signal has been found to be more tolerant to nonlinearity than NRZ optical signal. It is reported that RZ format is effective against self phase modulation (SPM) in standard single mode fiber links. The reason for its superior resistance to nonlinearity than NRZ is probably due to its regular data pattern of optical signal. Because of characteristic of ‘return-to-zero’ of RZ optical signals, an isolated digital bit '1' and continuous digital "1"s would require the same amount of optimal dispersion compensation for the best eye opening. So with the optimal dispersion compensation in the system, RZ format shows better tolerance to nonlinearity than NRZ [13].

The bandwidth required by RZ is twice larger than that of NRZ as shown in Figure 2.8. Therefore it only requires half of NRZ power in transmission and twice the switching time that required for NRZ. In addition RZ modulated signals is a relatively broad optical spectrum, resulting in a reduced dispersion tolerance and a reduced spectral efficiency.

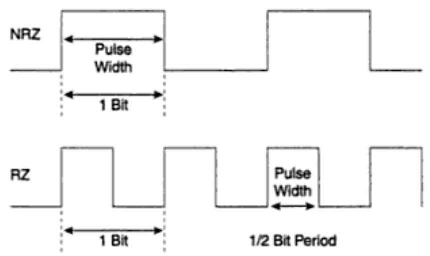


Figure 2.8 Bandwidth of NRZ and RZ [6].

Figure 2.9 shows the optical spectrums and waveforms of a 10Gb/s RZ and NRZ.

RZ modulation format is mostly preferred in submarine systems where more costly transmitters and receivers are used. Terrestrial WDM transmission systems, where cost is a primary driving factor, typically NRZ modulation format is employed [18]. Chirped RZ (CRZ), Carrier Suppressed RZ (CSRZ) are some important varieties of RZ format.

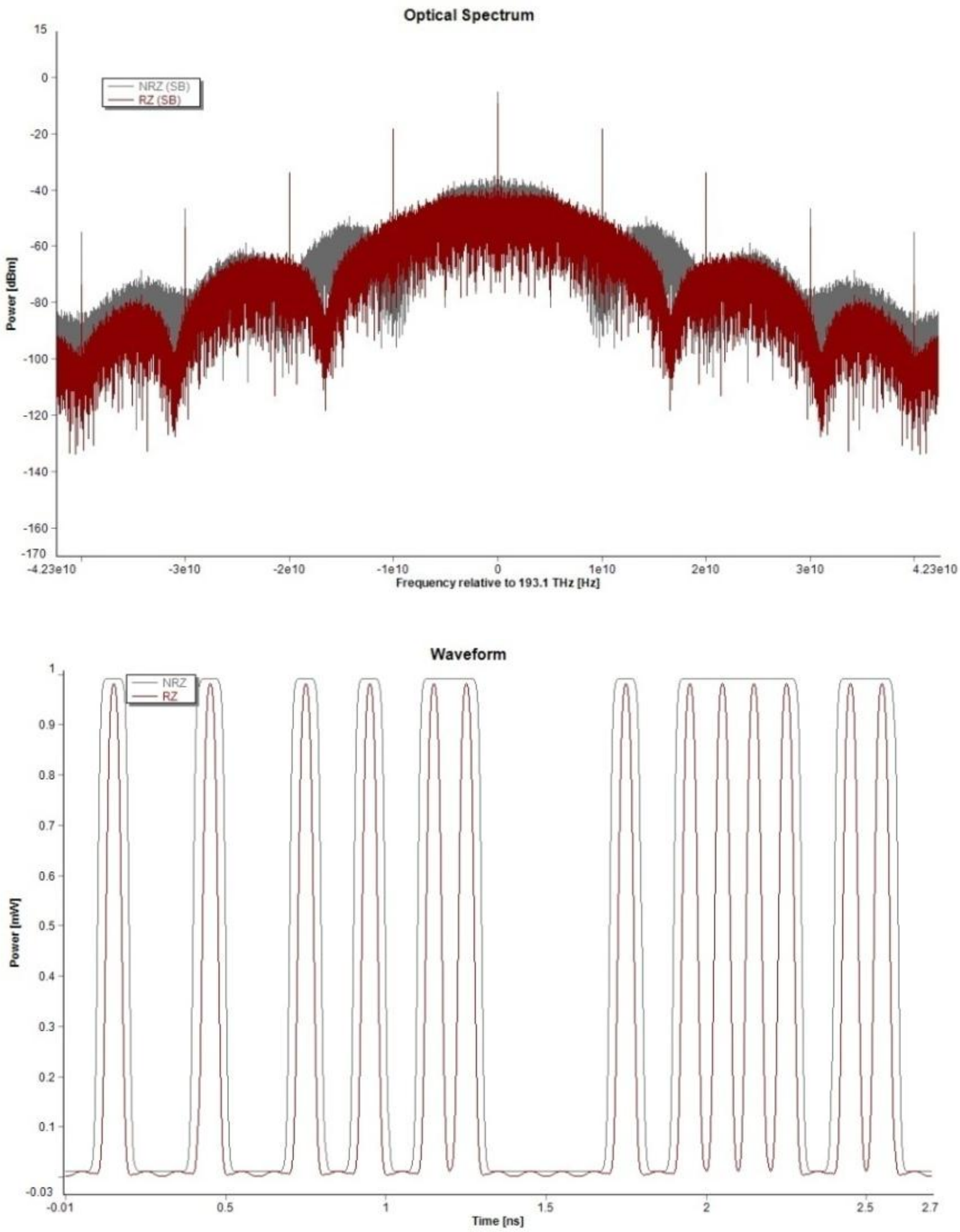


Figure 2.9 Optical Spectrum and waveform of 10Gb/s RZ and NRZ (simulated by VPItransmissionMaker^{TM} WDM).

2.3.2.1 Chirped RZ (CRZ)

Chirped RZ (CRZ) is one of the variations of the RZ format. Figure 2.10 shows the diagram of the CRZ transmitter. The laser source is modulated with data to create an NRZ signal, and then it enters to RZ modulator to create RZ pulses. Finally a phase modulator is used to synchronously modulate the RZ pulse to chirp the output with the center of the pulse having maximum chirp. The optimum phase modulation is about 1.5 radians.

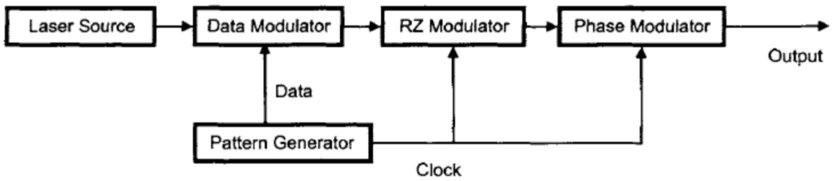


Figure 2.10 Chirped RZ transmitter [20].

In CRZ, bit-synchronous periodic chirp spectrally broadens the signal bandwidth. Although this reduces the format's suitability for high spectral efficiency WDM systems, it generally increases its robustness to fiber nonlinearity [16].

The optical spectrum and waveform of CRZ is shown in Figure 2.11.

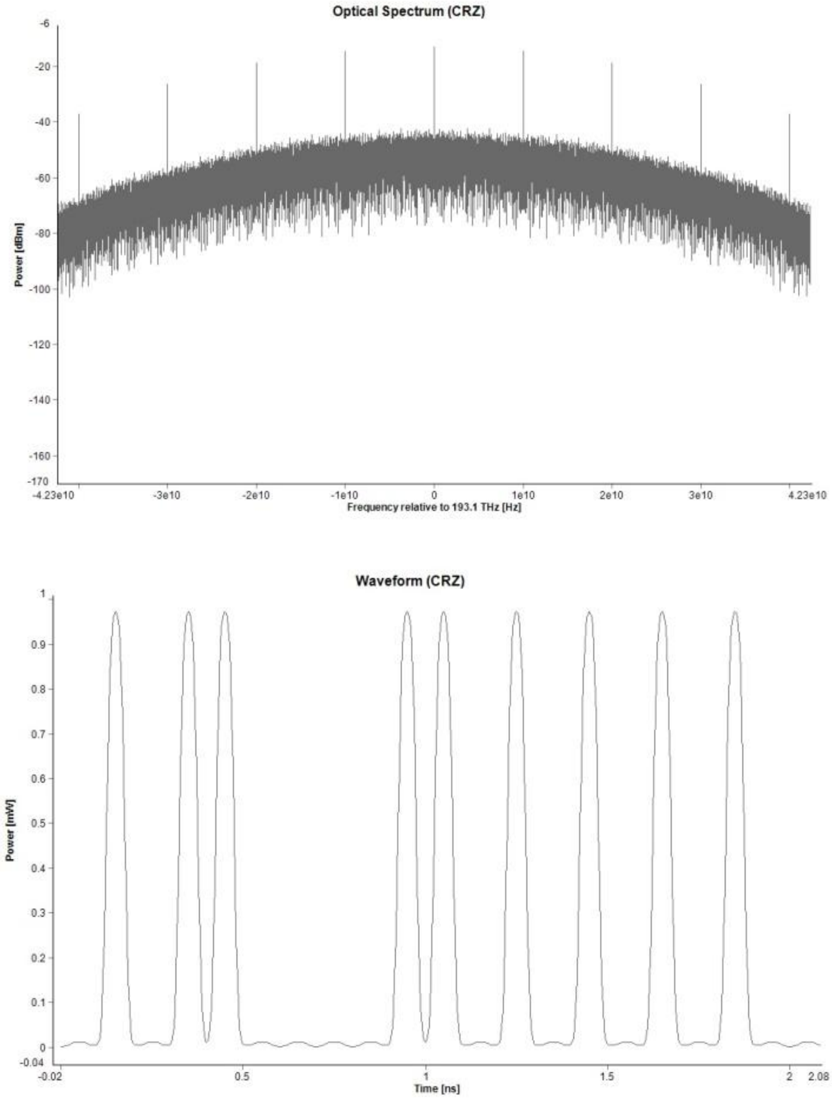


Figure 2.11 The optical spectrum and waveform of 10Gb/s CRZ (simulated by VPItransmissionMaker^{TM}WDM and its simulation setup is shown in Figure A.3 at Appendix A).

2.3.2.2 Carrier Suppressed RZ (CSRZ)

CSRZ is a special form of RZ where the carrier is suppressed. CSRZ format reduces the nonlinear impairments in a channel and improves the spectral efficiency in high bit rate systems. The difference between CSRZ and conventional RZ is that the CSRZ signal has π phase shift between adjacent bits. This phase alternation, in the optical domain, produces no DC component; thus, there is no carrier component for CSRZ [17]. Phase alternating between adjacent bit slots reduces the fundamental frequency components to half of the data rate. CSRZ has better tolerance to chromatic dispersion due to its lower optical power, allowing for more channels multiplexed in transmission. In addition, carrier suppression reduces the efficiency of FWM in WDM systems [21].

Figure 2. 12 shows the block diagram of the CSRZ transmitter. The generation of a CSRZ optical signal requires two electro-optic modulators as shown in this figure. The first MZ modulator encodes the NRZ data. Then the generated NRZ optical signal is modulated by the second MZ modulator to generate a CSRZ optical signal [17].

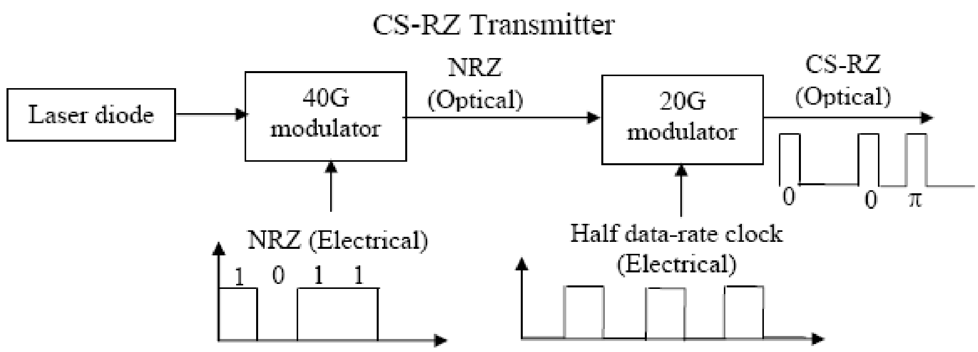
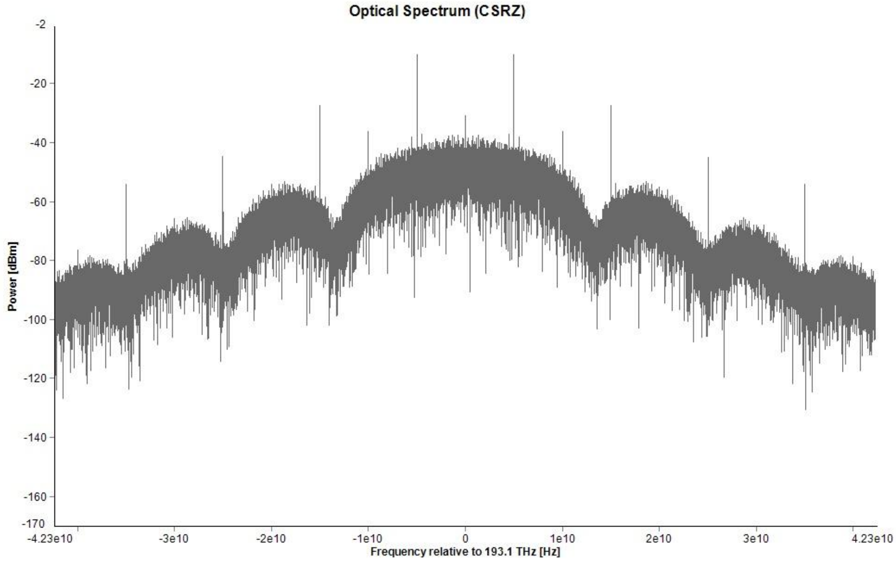


Figure 2. 12 Block diagram of CSRZ transmitter [17].

The optical spectrum and waveform of CSRZ is shown in Figure 2.13.



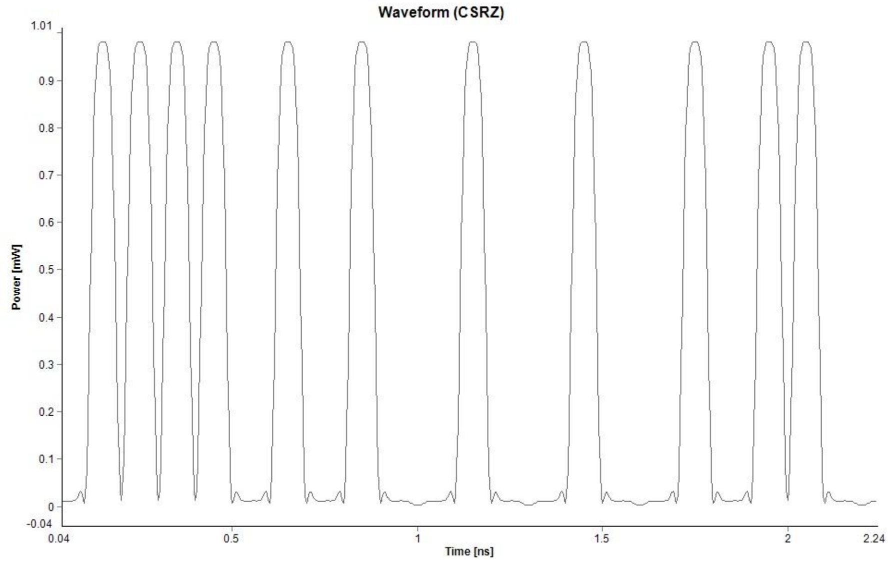


Figure 2.13 The optical spectrum and waveform of 10Gb/s CSRZ (simulated by VPItransmissionMaker^{TM}WDM and its simulation setup is shown in Figure A.4 at Appendix A).

2.3.3 Differential Phase Shift Key (DPSK)

Digital signal can be represented by instantaneous optical power levels with optical intensity modulation. Similarly, digital signal can also be represented by the phase of an optical carrier and this is commonly referred to as optical phase shift key (PSK). In the early days of optical communications, the optical phase was not stable enough for phase based modulation schemes, because of the immaturity of semiconductor laser sources. In recent years, with the rapid improvement of single frequency laser sources and the application of active optical phase locking, PSK becomes feasible in practical optical systems. More specifically, differential phase shift key (DPSK) is the most often used format [17].

DPSK modulation is an encoding format which records changes in the binary stream. DPSK encodes information on the binary phase change between adjacent bits: a 1-bit is encoded onto a π phase change, whereas a 0-bit is represented by the absence of a phase change. Like intensity modulation, DPSK can be implemented in RZ and NRZ format. The main advantage of using DPSK with compared to intensity modulation is a 3-dB receiver sensitivity improvement [16]. DPSK is also more tolerant to nonlinear effects. It has better resilience to XPM and FWM, as compared with intensity modulation formats. It has also been demonstrated that RZ-DPSK and CSRZ-DPSK exhibit superior transmission performance than simple DPSK [14].

The optical spectrum and waveform of CSRZ is shown in Figure 2.14.

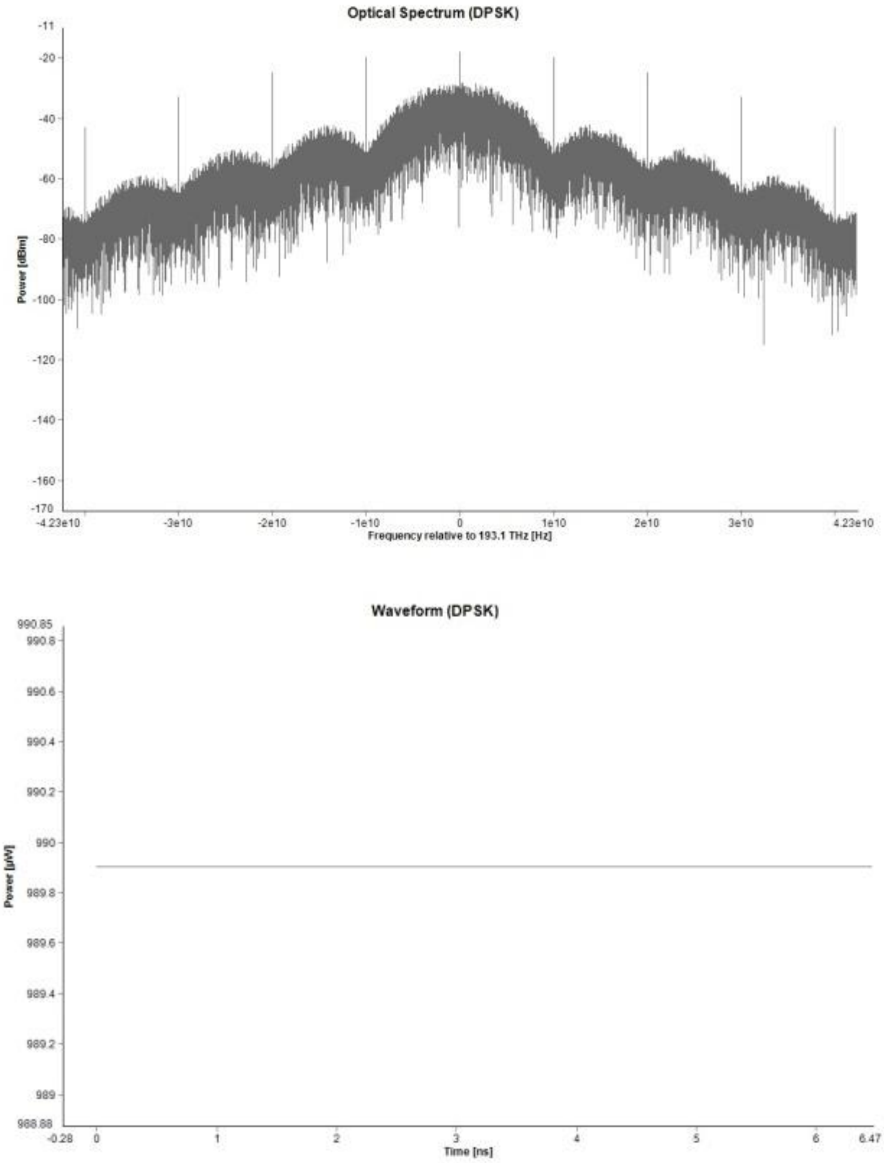


Figure 2.14 The optical spectrum and waveform of 10Gb/s DPSK (simulated by VPItransmissionMaker^{TM}WDM and its simulation setup is shown in Figure A.5 at Appendix A)

2.3.3.1 Non Return To Zero DPSK (NRZ-DPSK)

Figure 2.15 shows the block diagrams of a typical NRZ-DSPK transmitter and receiver. As shown in this transmitter block diagram, firstly, NRZ electrical signal is encoded by a DPSK encoder. This DPSK encoded electrical signal is then used to drive an electro optic phase modulator to generate a DPSK optical signal. A digital “1” is represented by a π phase change between the consecutive data bits in the optical carrier, while there is no phase change between the consecutive data bits in the optical carrier for a digital “0”. The important characteristic of NRZ-DPSK is that its signal optical power is always constant [17].

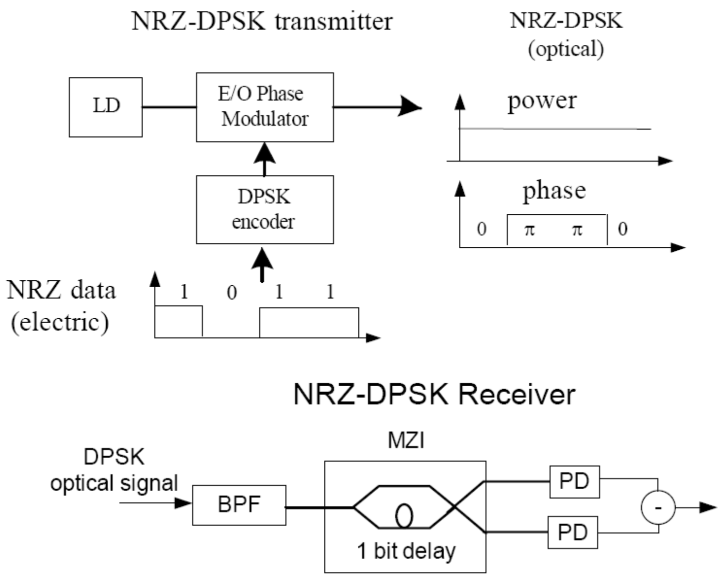


Figure 2.15 Block diagrams of NRZ-DPSK transceiver and receiver [21].

As Shown in Figure 2.15, at a DPSK optical receiver, a one-bit-delay Mach-Zehnder Interferometer (MZI) is usually used which correlates each bit with its neighbor and makes the phase-to-intensity conversion. When the two consecutive bits are in-phase, they are added constructively in the MZI and results in a high signal level. Otherwise, if the there is a π phase difference between the two bits, they cancel each other in the MZI and results in a low signal level. MZI has two balanced output ports consist of constructive port and destructive port. A photodiode can be used at each MZI output and then the two photocurrents are combined to double the signal level. In this configuration, the receiver sensitivity is improved by 3dB compared to using only a single photodiode. In a DPSK system, since signal amplitude swings from “1” to “-1”, in the ideal case, when a balanced photodetection and matched optical filter is used, its receiver sensitivity is 3dB better than a conventional NRZ system, where the signal swings only from "1" to "1".

For NRZ-DPSK, the optical power is constant, however, the optical field shifts between "1" and "-1" (or the phase shifts between "0" and "π") and the average optical field is zero. As a consequence, there is no carrier component in the optical field spectrum. This differs from the spectrum of NRZ, where the carrier component is strong [13].

The performance of NRZ-DPSK is not affected by optical power modulation related nonlinear effect such as SPM and XPM, because of its constant optical power. However, it is affected from chromatic dispersion. Phase modulations can be converted into intensity modulation through group velocity dispersion (GVD), and then SPM and XPM may contribute to waveform distortion to some extent. In a long distance DPSK system with optical amplifiers, nonlinear phase noise is usually the limiting factor for phase shift keying optical signals [22]. Amplified spontaneous emission (ASE) noise generated by optical amplifiers are converted into phase noise through the Kerr effect nonlinearity in the transmission fiber, this disturbs the signal optical phase and causes waveform distortions [21].

2.3.3.2 Return To Zero DPSK (RZ-DPSK)

In order to improve system tolerance to nonlinear distortion and to achieve a longer transmission distance, return-to-zero DPSK (RZ-DPSK) has been proposed. Similar to NRZ-DPSK modulation format, the binary data is encoded as either a "0" or a "π" phase shift between adjacent bits. In general, the width of the optical pulses is narrower than the bit slot and therefore, the signal optical power returns to zero at the edge of each bit slot.

Figure 2.16 shows the block diagram of a RZ-DPSK transmitter. In order to generate the RZ-DPSK optical signal, one more intensity modulator has to be used compare to the generation of NRZ-DPSK. First, a conventional NRZ-DPSK optical signal is generated by an electro optic phase modulator, and then, this NRZ-DPSK optical signal is sampled by a periodic pulse train at the clock rate through an electro optic intensity modulator. In RZ-DPSK modulation format, the signal optical intensity is no longer constant this will introduce the sensitivity to SPM. In addition, due to the narrow pulse intensity sampling, the optical spectrum of RZ-DPSK is wider than a conventional NRZ-DPSK. This cause more susceptibility to chromatic dispersion. However, in long distance optical systems, periodic dispersion compensation is often used and RZ modulation format makes it easy to find the optimum dispersion compensation because of its regular bit patterns [21].

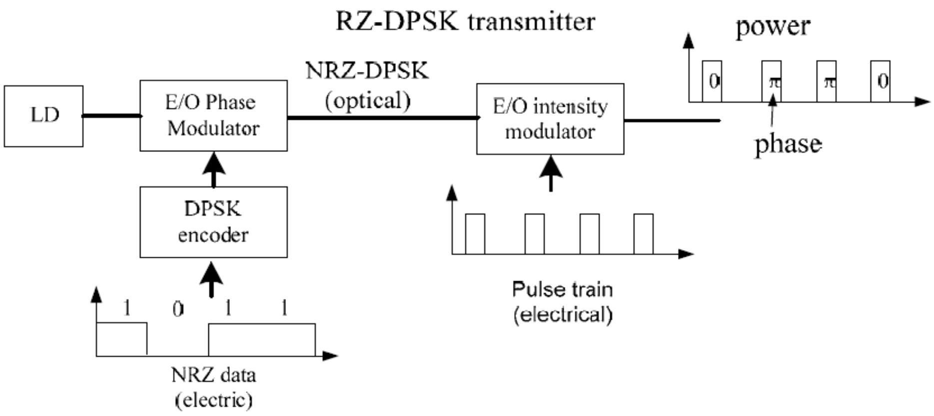


Figure 2.16 Block diagram of RZ-DPSK transmitter [21]**.**

2.3.3.3 Carrier Suppressed RZ-DPSK (CSRZ-DPSK)

The significant progress made on DPSK modulation, where all formats of ASK were tried onto the phase of the optical carrier. The transmitter consists of a laser, followed by two dual-drive intensity modulators. This method produced phase modulation with a near-perfect 180° phase shift. The CSRZ-DPSK pulses posses a RZ signal shape and due to the reduced spectral width, CSRZ-DPSK modulation shows an increased dispersion tolerance and it is more robust to nonlinear impairments than conventional RZ format [17].

The optical spectrum and waveform of CSRZ DPSK is shown in Figure 2.17.

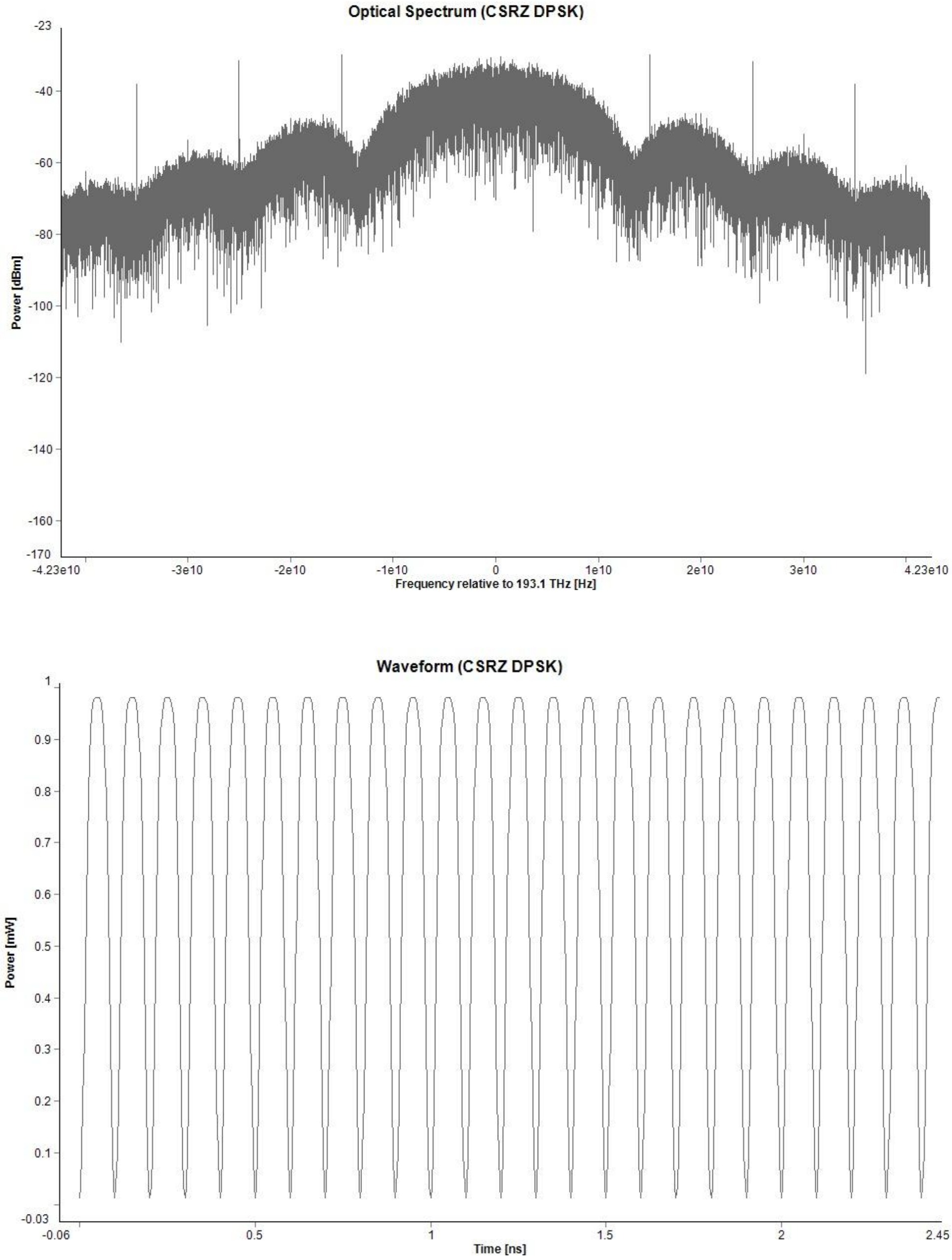


Figure 2.17 The optical spectrum and waveform of 10Gb/s CSRZ DPSK (simulated by VPItransmissionMaker^{TM}WDM and its simulation setup is shown in Figure A. **6** at Appendix A)

CHAPTER 3

SIMULATIONS FOR MODULATION FORMATS

3.1 SIMULATION MODEL

In order to compare the transmission performances of modulation formats we have performed a computer simulation. Firstly single channel for different modulation formats were focused on. 40Gb/s, 100Gb/s data rate were considered. Then, channel numbers were increased. For 40Gb/s data-rate, 25 channels were used with the channel spacing of 160GHz (1.28nm) and total capacity was 1Tb/s. For 100Gb/s data-rate, 11 channels were used with the channel spacing of 400GHz (3.2nm) and total capacity was 1.1Tb/s. In all cases, simulations were performed in the C-band (1530nm – 1565nm).

Different fiber types and different modulation formats could affect the system performance. In this simulations, Standard Single mode fiber (SSMF) was used.

In order to compensate the accumulated dispersion in the fiber, there are several techniques, including Dispersion Compensating Fiber (DCF) or Fiber Bragg Grating. In this dissertation three different schemes of dispersion compensating fiber are used, pre-, post-, and symmetrical compensation, to compensate the fiber dispersion. Table 3.1 lists the major physical parameters of transmission and dispersion compensating fibers used simulations.

Table 3.1 Parameters of transmission fiber and dispersion compensating fiber at 1550nm.

Fiber Type	**Dispersion (D) [ps/nm/km]**	**Dispersion slope (S) [ps/nm^2/km]**	**Nonlinear refractive index (n_2) [10^{-20} m^2/W]**	**Effective core area (A_{eff}) [µm^2]**	**Fiber attenuation (α) [dB/km]**
SSMF	$16\text{x}10^{-6}$	$0.08\text{x}10^{3}$	$2.6\text{x}10^{-20}$	$80\text{x}10^{-12}$	$0.2\text{x}10^{-3}$
DCF	$-90\text{x}10^{-6}$	$0.21\text{x}10^{3}$	$2.6\text{x}10^{-20}$	$80\text{x}10^{-12}$	$0.5\text{x}10^{-3}$

Pre-, post-, and symmetrical compensation configurations are shown in Figure 3. 1 In our simulations we have used EDFA amplifiers after each fiber to compensate for the span loss. It is the widely used amplifier type in optical transmission systems because it provides an efficient optical amplification in the 1.55µm region.

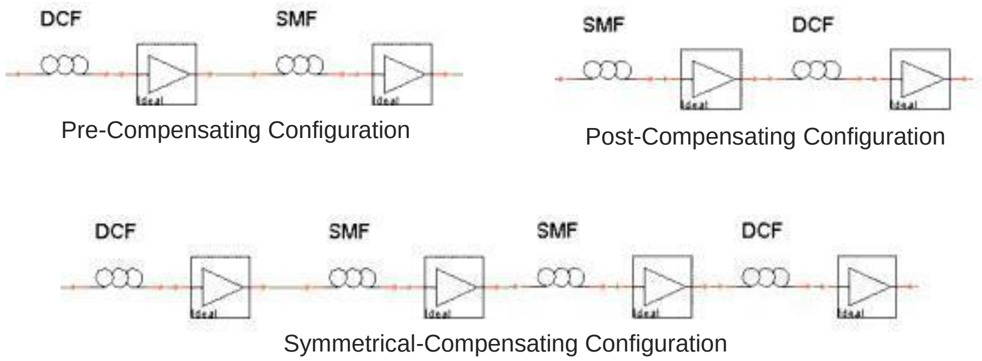


Figure 3. 1 Configurations of the pre-, post-, and symmetrical compensation.

In pre-compensating case, DCF is precompensating the accumulated dispersion of the transmission fiber. The gain G of the amplifier following the DCF is balancing the fiber loss of the DCF and can be determined by:

$$G = \alpha_{DCF} L_{DCF} \tag{3.1}$$

where α_{DCF} is the attenuation of the dispersion fiber, L_{DCF} is the length of the transmission fiber. For the gain of the amplifier succeeding the transmission fiber is a similar equation holds. The linear dispersive compensation length of the DCF, L_{DCF}, should be chosen to compensate the dispersion of the transmission fiber:

$$L_{DCF} = \frac{L_{TF} D_{TF}}{-D_{DCF}} \tag{3.2}$$

where L_{TF} is the length of the transmission fiber, D_{TF} is the dispersion of the transmission fiber, D_{DCF} is the dispersion of the DCF.

In post-compensating case, the dispersion compensating fiber (DCF) is postcompensating the dispersion of the transmission fiber. The gain of the amplifier, G, following the SMF compensates the fiber loss of the SMF and can be determined by:

$$G = \alpha_{TF} L_{TF} \tag{3.3}$$

where α_{TF} is the attenuation of the transmission fiber, L_{TF} is the length of the transmission fiber. For the gain of the amplifier succeeding the DCF a similar equation holds on. The linear dispersive compensation length of the DCF should be chosen to compensate completely the dispersion of the transmission fiber:

$$L_{DCF} = \frac{L_{TF} D_{TF}}{-D_{DCF}} \tag{3.4}$$

where L_{TF} is the length of the transmission fiber, D_{TF} is the dispersion of the transmission fiber, D_{DCF} is the dispersion of the DCF.

In the symmetrical compensation case, fiber placement follows the sequence of, DCF, transmission fiber, transmission fiber, DCF [24].

3.2 PERFORMANCE ANALYSIS

The system performance was monitored by means of eye-diagram. The eye diagram is a useful tool for the analysis of signal used in digital transmission. It provides visual information that can be useful in the performance of transmission systems. Many characteristics can be calculated from the eye diagram: eye width, eye height, extinction ratio, jitter, crossing position, Q factor and bit error rate (BER).

Figure 3.2 shows general configuration of the eye diagram and the simplified drawing shown in Figure 3.3 [4].

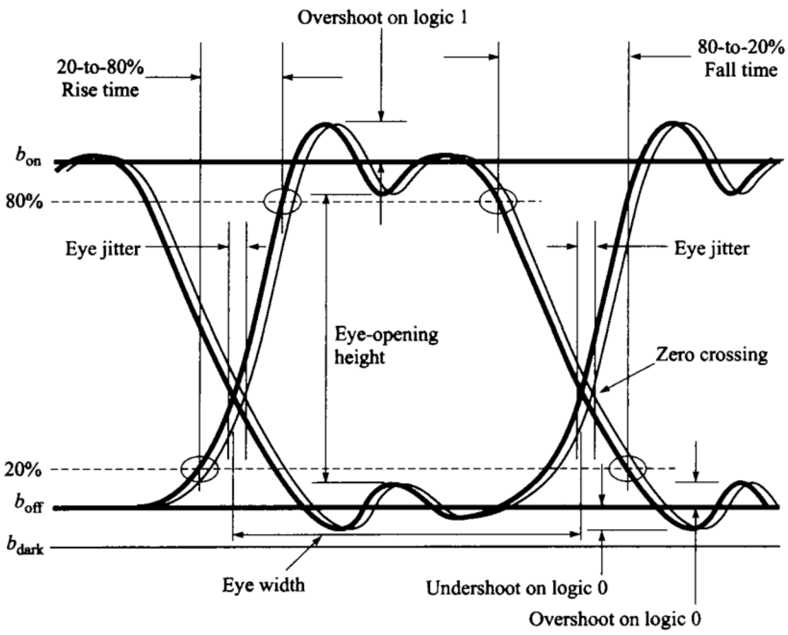


Figure 3.2 General configuration of eye diagram.

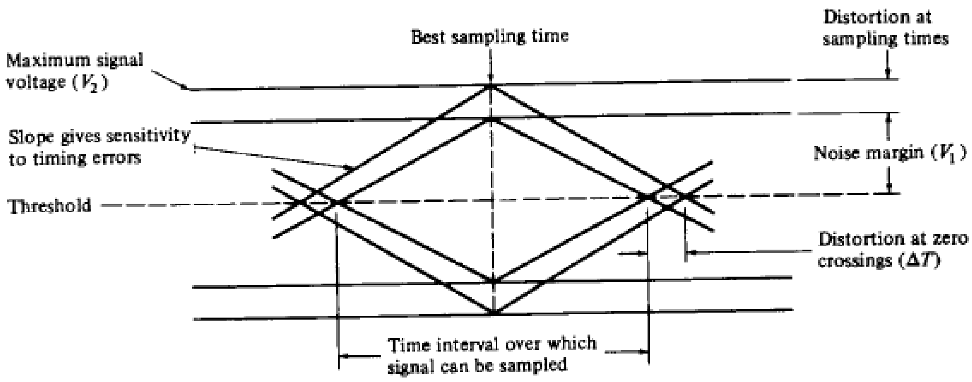


Figure 3.3 Simplified eye diagram.

The following information can be determined from the eye diagram:

- Time interval over which the received signal can be sampled without error from intersymbol interference is defined with the width of the eye opening.

- The best time to sample the received waveform is when the height of the eye opening is largest. Amplitude distortion in the data signal causes a reduction in the height. The maximum distortion is determined from the vertical distance between the top of the eye opening and the maximum signal level.

- The height of the eye opening at the specified sampling time shows the noise margin or immunity to noise.

- The rate at which the eye closes as the sampling time is varied determines the sensitivity of the system to timing errors. The possibility of timing errors increases as the slope becomes more horizontal.

- Timing jitter is a phase distortion in an optical fiber system. Noise in the receiver and pulse distortion in the optical fiber cause a jitter. Timing jitter is thus given by

$$\text{Timing jitter (percent)} = \frac{\Delta T}{T_b} \times 100 \text{ percent} \tag{2-3}$$

where ΔT is the amount of distortion at the threshold level, T_b is a bit interval [4]. As shown in Figure 3.4, Jitter can cause a receiver to misinterpret transmitted digital data [25].

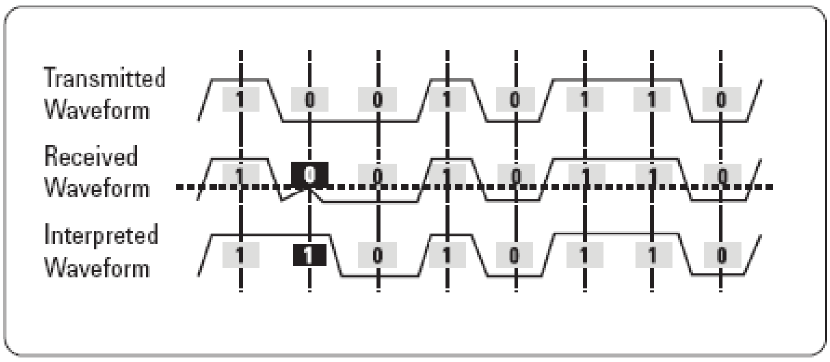


Figure 3.4 Misinterpret transmitted digital data caused by jitter [25].

- The rise time is defined as the time interval between the point where the rising edge of the signal reaches 10 percent of its final amplitude and the time it reaches 90 percent of its final amplitude. However, these points are often obscured by noise and jitter effects so the more distinct values at the 20-percent and 80-percent threshold points are normally measured [4].

To analyze system performance BER is another method. BER is the ratio of number of erroneous bits to the total number of bits transmitted. This error rate depends on the signal-to-noise ratio at the receiver which is the ratio of signal power to noise power. Q is the ratio of signal current to noise current, which is another way to represent the signal-to-noise relationship. The larger Q is the less BER will be [4]. BER also can be evaluated by using the following formula [26].

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{3-5}$$

where erfc(x) denotes the complementary error function given by

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_0^{\infty} e^{-y^2} dy$$

For telecommunications links BER of 10^{-9} acceptable. Typical error rates ranges from 10^{-9} to 10^{-12}. For computer data communication links, a BER of a 10^{-15} is specified. To achieve BER > 10^{-12}, we need to obtain Q > 7. BER of 10^{-9} requires Q=6, BER of 10^{-15} requires Q=8 [27].

In WDM optical systems, because of the nonlinear crosstalk, the middle channel generally has the worst performance. Channels that are far away do not affect each other much because they pass through each other quickly due to the dispersion. Therefore, in our simulations, we considered the middle channel of the system.

In all simulations, VPItransmissionMaker™ WDM software was used. The basic mechanism behind the simulator is to solve the nonlinear Schrödinger equation using the split-step Fourier Transformation.

3.3 40Gb/s WDM SYSTEM

For 40Gb/s data-rate, firstly single channel were analyzed for different modulation formats with different compensation configuration. Then 25 channels were used with the channel spacing of 160GHz (1.28nm) around the 193.100 THz center frequency and total capacity was 1Tb/s.

3.3.1 Single Channel 40Gb/s WDM System

For single 40Gb/s WDM system, modulation formats of NRZ, RZ, CRZ, CSRZ, DPSK and CSRZ-DPSK were analyzed with pre-, post- and symmetrical compensation configurations. Total transmission distance is 12x80km=960km. for each configuration.

3.3.1.1 NRZ Format

The simulation layouts for single channel 40Gb/s NRZ format with pre-, post and symmetrical compensating configurations are shown in Figure A.7 at Appendix A.

For pre- and post- compensating configurations transmission fiber length is 80km. and compensating fiber length is 14.2km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers length of 40km and two DCFs length of 7.1km were used. In all configurations, BER and eye diagram analysis were done for 960km. fiber length.

For pre- compensating configuration, the gain of the EDFA's are 7.1dB and 16dB, for post- compensating configuration the gain of the EDFA's are 16dB and 7.1dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 40Gb/s single channel NRZ format with all compensating configurations are shown in Figure 3.5. For all compensating case BER is less than equal 10^{-9} up to 960km. As shown in this figure, BER values of pre- and post- compensating configuration are nearly the same, post- compensating configuration enables better performance compared to pre- compensating configuration. Symmetrical compensating configuration represents the best case among all considered configurations.

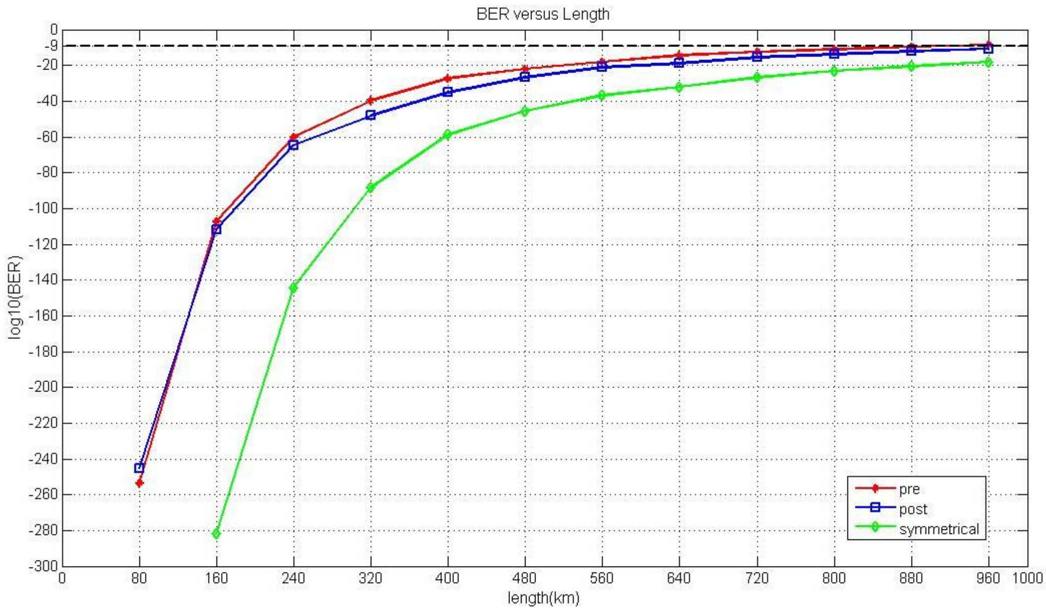
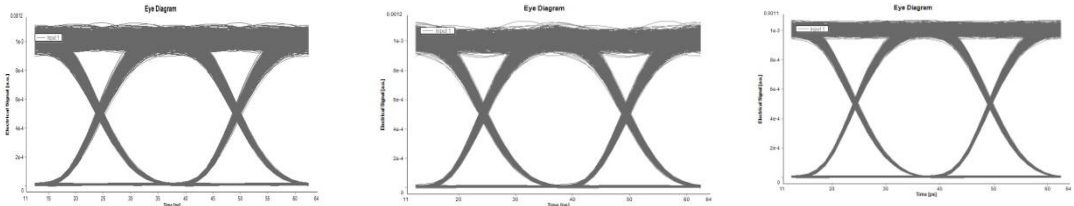


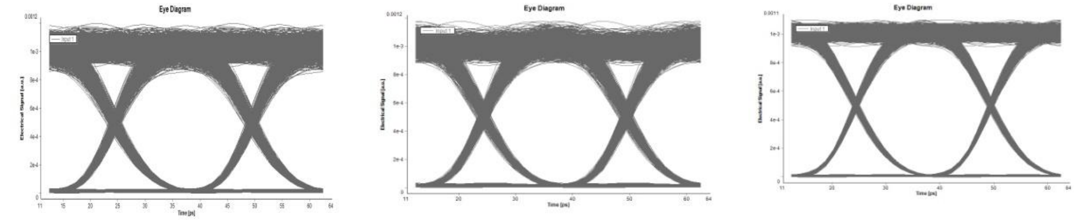
Figure 3.5 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system according to dispersion compensating configurations are shown in Figure 3.6. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 80km. As seen from this figure eye opening is good up to 960km.

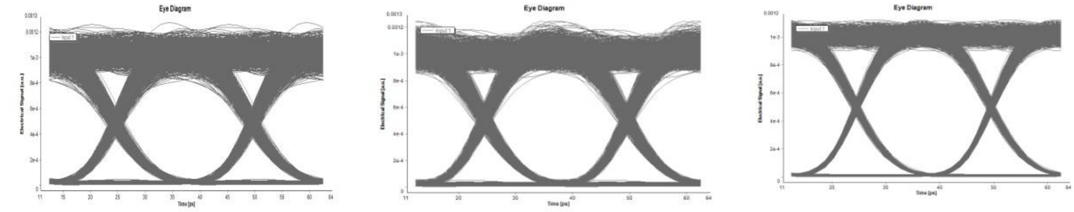
Pre-compensating configuration | Post- compensating configuration | Symmetrical- compensating configuration



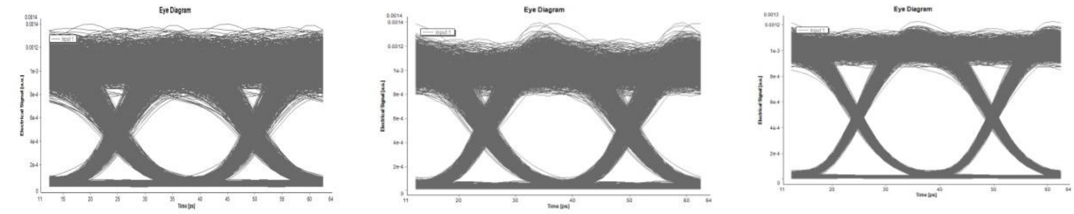
Fiber Length=80km. Fiber Length=80km. Fiber Length=80km.



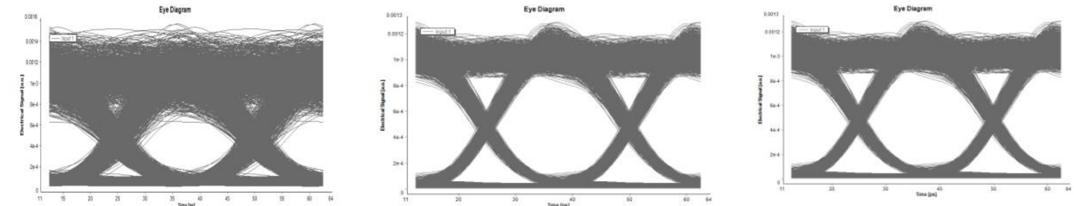
Fiber Length=160km. Fiber Length=160km. Fiber Length=160km.



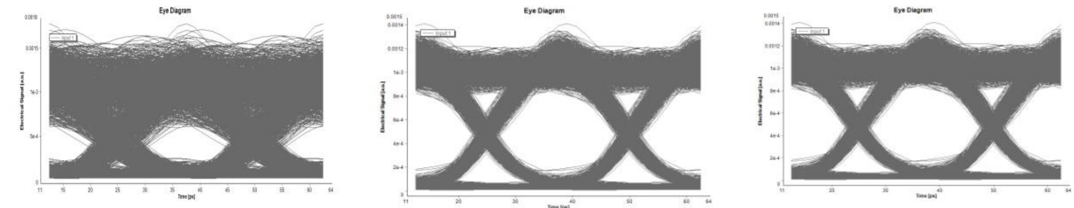
Fiber Length=320km. Fiber Length=320km. Fiber Length=320km.



Fiber Length=480km. Fiber Length=480km. Fiber Length=480km.



Fiber Length=720km. Fiber Length=720km Fiber Length=720km



Fiber Length=960km. Fiber Length=960km. Fiber Length=960km.

Figure 3.6 Eye diagrams of system for different fiber lengths.

3.3.1.2 RZ Format

The simulation layouts for single channel 40Gb/s RZ format with pre-, post and symmetrical compensating configurations are shown in Figure A.8 at Appendix A.

For pre- and post- compensating configurations transmission fiber length is 80km. and compensating fiber length is 14.2km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers length of 40km and two DCFs length of 7.1km were used. In all configurations, BER and eye diagram analysis were done for 960km. fiber length.

For pre- compensating configuration, the gain of the EDFA's are 7.1dB and 16dB, for post- compensating configuration the gain of the EDFA's are 16dB and 7.1dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 40Gb/s single channel RZ format with all compensating configurations are shown in Figure 3.7. For all compensating case BER is less than equal 10^{-9} up to 960km. As shown in this figure, BER values of pre- and post- compensating configuration are mostly the same. Symmetrical compensating configuration represents the best case among all considered configurations.

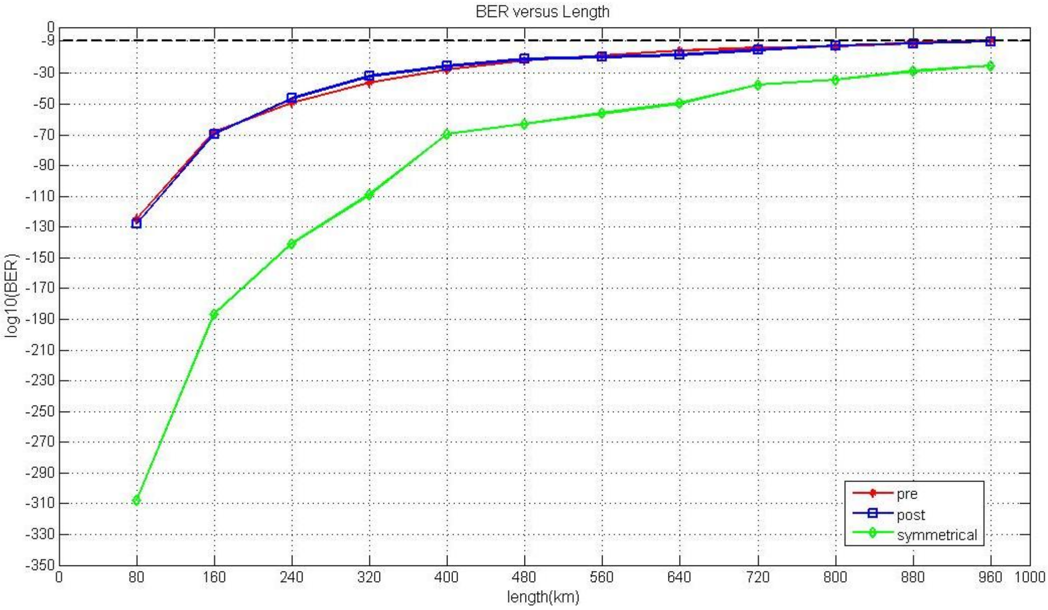


Figure 3.7 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.8. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 80km. As seen from this figure eye opening is good up to 960km.

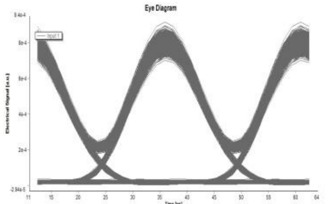
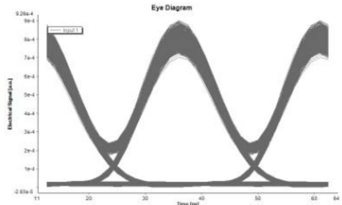
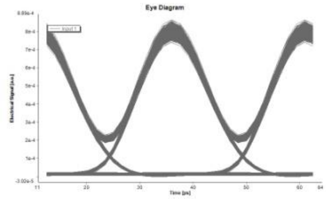
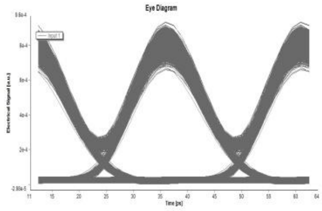
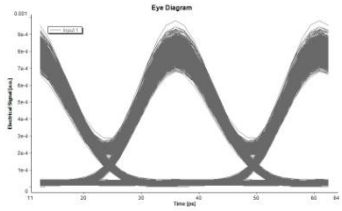
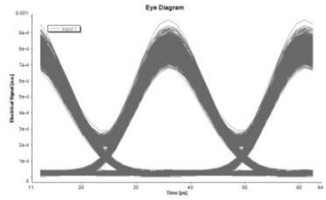
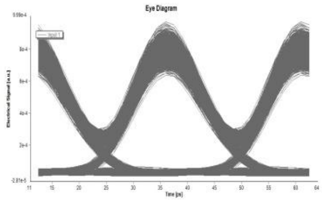
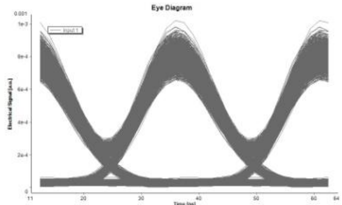
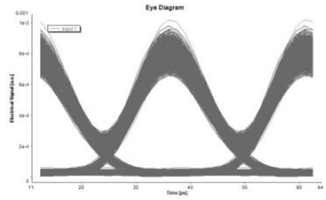
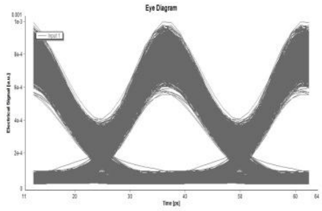
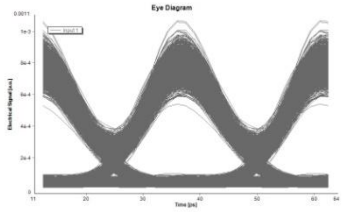
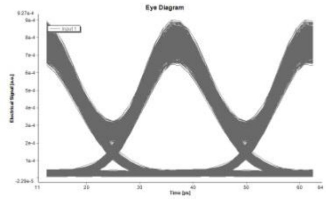
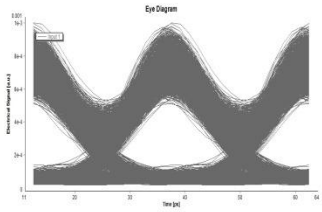
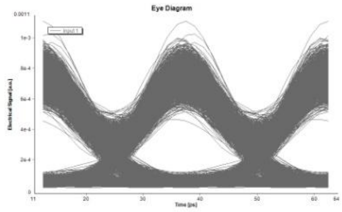
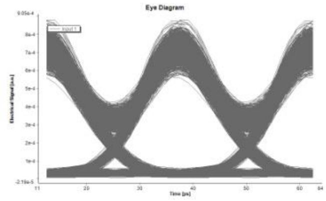
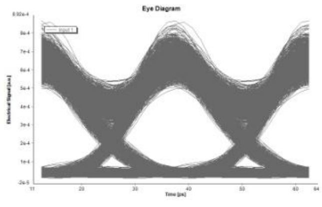
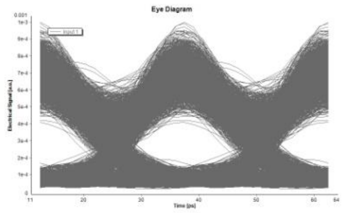
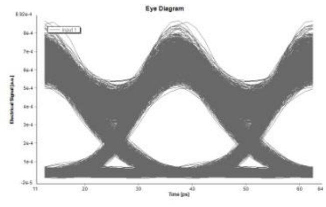
Pre-compensating configuration	Post- compensating configuration	Symmetrical- compensating configuration
		
Fiber Length=80km.	Fiber Length=80km.	Fiber Length=80km.
		
Fiber Length=160km.	Fiber Length=160km.	Fiber Length=160km.
		
Fiber Length=320km.	Fiber Length=320km.	Fiber Length=320km.
		
Fiber Length=480km.	Fiber Length=480km.	Fiber Length=480km.
		
Fiber Length=720km.	Fiber Length=720km	Fiber Length=720km
		
Fiber Length=960km.	Fiber Length=960km.	Fiber Length=960km.

Figure 3.8 Eye diagrams of system for different fiber lengths.

3.3.1.3 CRZ Format

The simulation layouts for single channel 40Gb/s CRZ format with pre-, post and symmetrical compensating configurations are shown in Figure A.9 at Appendix A.

For pre- and post- compensating configurations transmission fiber length is 80km. and compensating fiber length is 14.2km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers length of 40km and two DCFs length of 7.1km were used. In all configurations, BER and eye diagram analysis were done for 960km. fiber length.

For pre- compensating configuration, the gain of the EDFA's are 7.1dB and 16dB, for post- compensating configuration the gain of the EDFA's are 16dB and 7.1dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 40Gb/s single channel CRZ format with all compensating configurations are shown in Figure 3. 9. For all compensating case BER is less than equal 10^{-9} up to 960km. As shown in this figure, BER values of pre- and post- compensating configuration are mostly the same. Symmetrical compensating configuration represents the best case among all considered configurations.

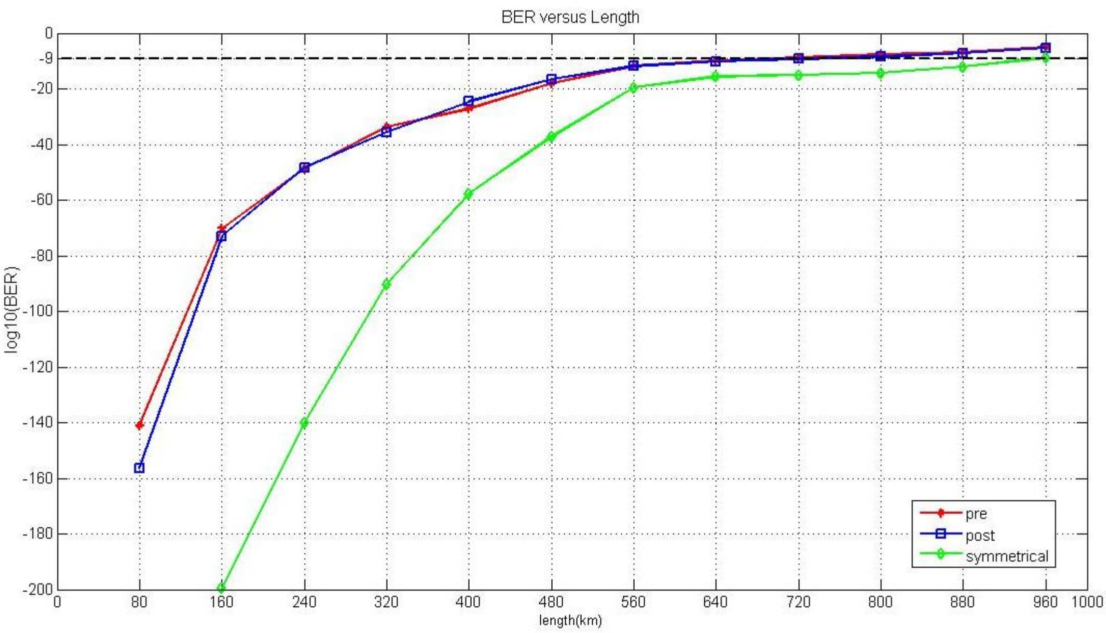


Figure 3. 9 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.10. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 80km. As seen from this figure eye opening is good up to 960km.

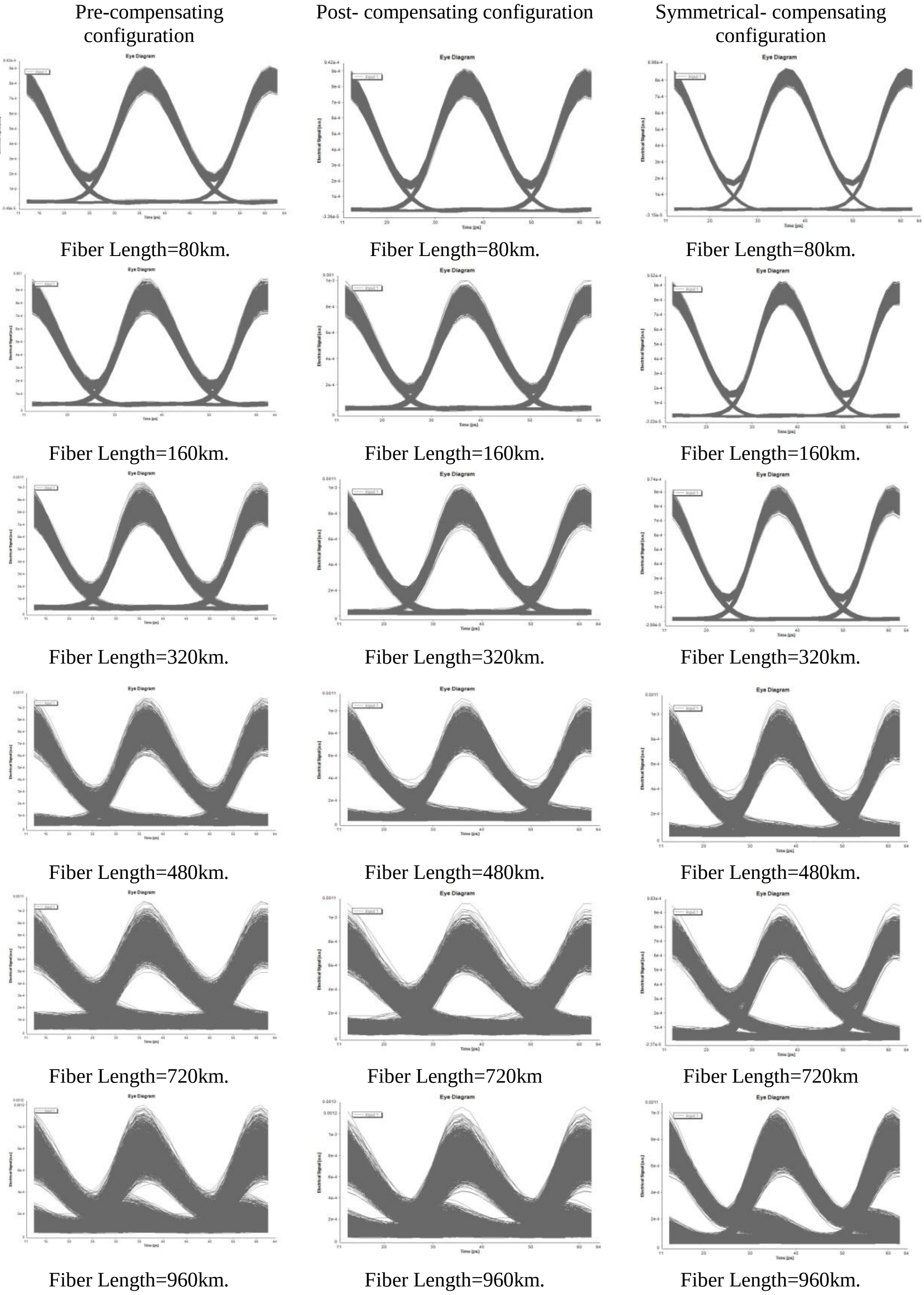


Figure 3.10 Eye diagrams of system for different fiber lengths.

3.3.1.4 CSRZ Format

The simulation layouts for single channel 40Gb/s CSRZ format with pre-, post and symmetrical compensating configurations are shown in Figure A.10 at Appendix A.

For pre- and post- compensating configurations transmission fiber length is 80km. and compensating fiber length is 14.2km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers length of 40km and two DCFs length of 7.1km were used. In all configurations, BER and eye diagram analysis were done for 960km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 7.1dB and 16dB, for post-compensating configuration the gain of the EDFA's are 16dB and 7.1dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 40Gb/s single channel CSRZ format with all compensating configurations are shown in Figure 3. 11. For all compensating case BER is less than equal 10^{-9} up to 960km. As shown in this figure, BER values of pre-, and post- compensating configuration are mostly the same. Symmetrical compensating configuration represents the best case among all considered configurations.

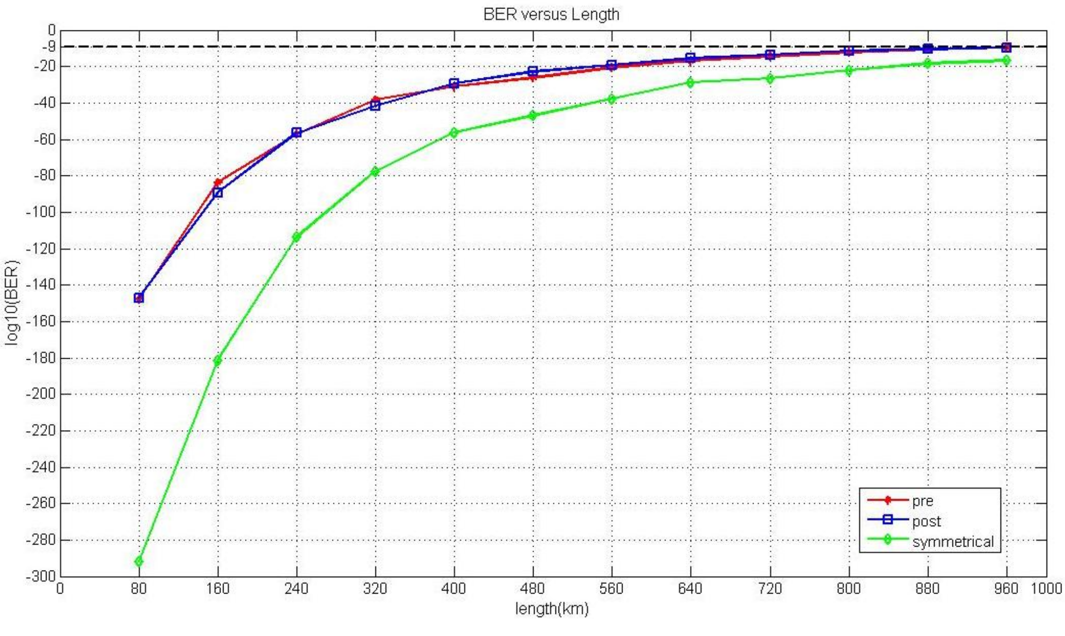
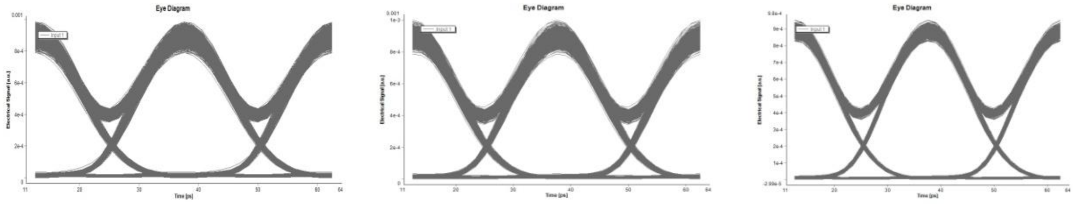


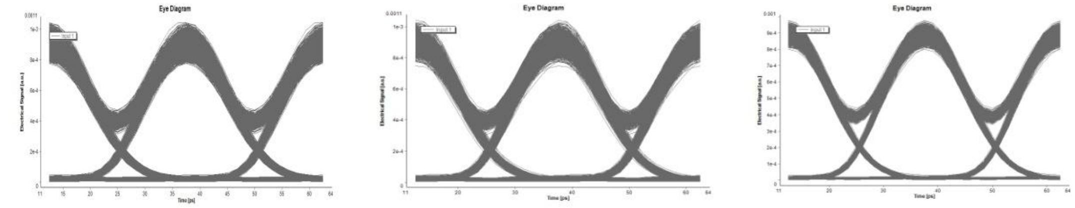
Figure 3. 11 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.12. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 80km. As seen from this figure eye opening is good up to 960km.

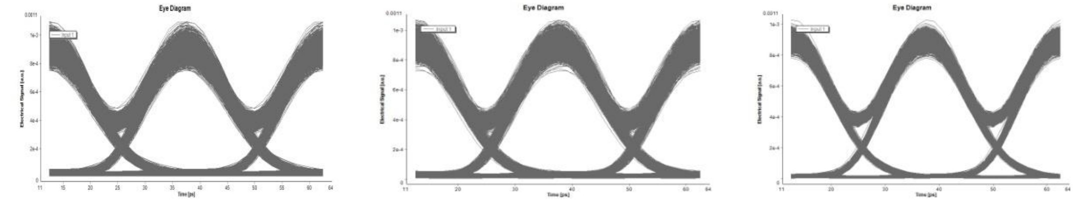
Pre-compensating configuration	Post- compensating configuration	Symmetrical- compensating configuration



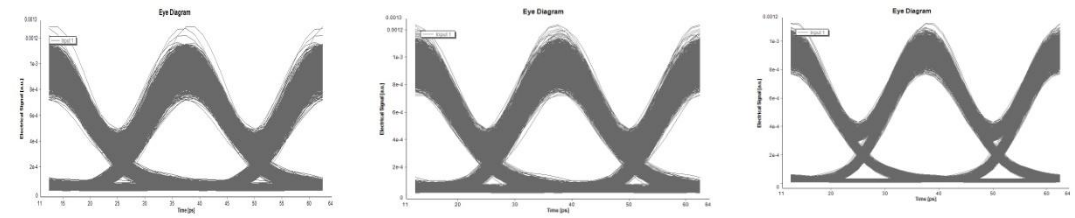
Fiber Length=80km. Fiber Length=80km. Fiber Length=80km.



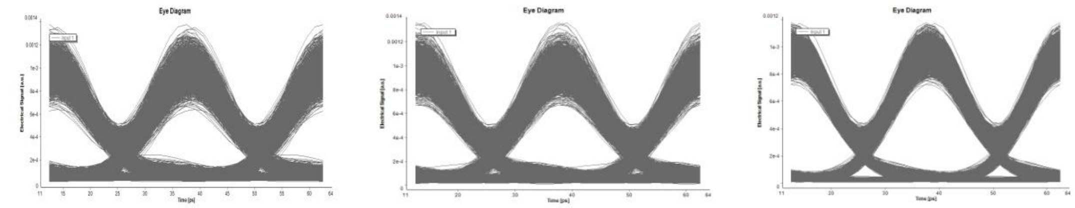
Fiber Length=160km. Fiber Length=160km. Fiber Length=160km.



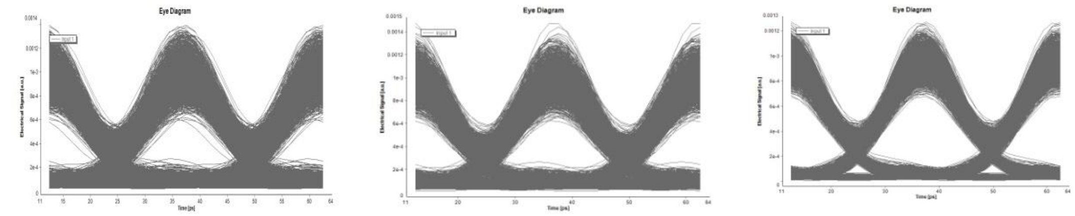
Fiber Length=320km. Fiber Length=320km. Fiber Length=320km.



Fiber Length=480km. Fiber Length=480km. Fiber Length=480km.



Fiber Length=720km. Fiber Length=720km Fiber Length=720km



Fiber Length=960km. Fiber Length=960km. Fiber Length=960km.

Figure 3.12 Eye diagrams of system for different fiber lengths.

3.3.1.5 DPSK Format

The simulation layouts for single channel 40Gb/s DPSK format with pre-, post and symmetrical compensating configurations are shown in Figure A.11 at Appendix A.

For pre- and post- compensating configurations transmission fiber length is 80km. and compensating fiber length is 14.2km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers length of 40km and two DCFs length of 7.1km were used. In all configurations, BER and eye diagram analysis were done for 960km. fiber length.

For pre-compensating configuration, the gain of the EDFA’s are 7.1dB and 16dB, for post-compensating configuration the gain of the EDFA’s are 16dB and 7.1dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 40Gb/s single channel DPSK format with all compensating configurations are shown in Figure 3.13. For all compensating case BER is less than equal 10^{-9} up to 960km. As shown in this figure, BER values of pre-, and post- compensating configuration are mostly the same. Symmetrical compensating configuration represents the best case among all considered configurations.

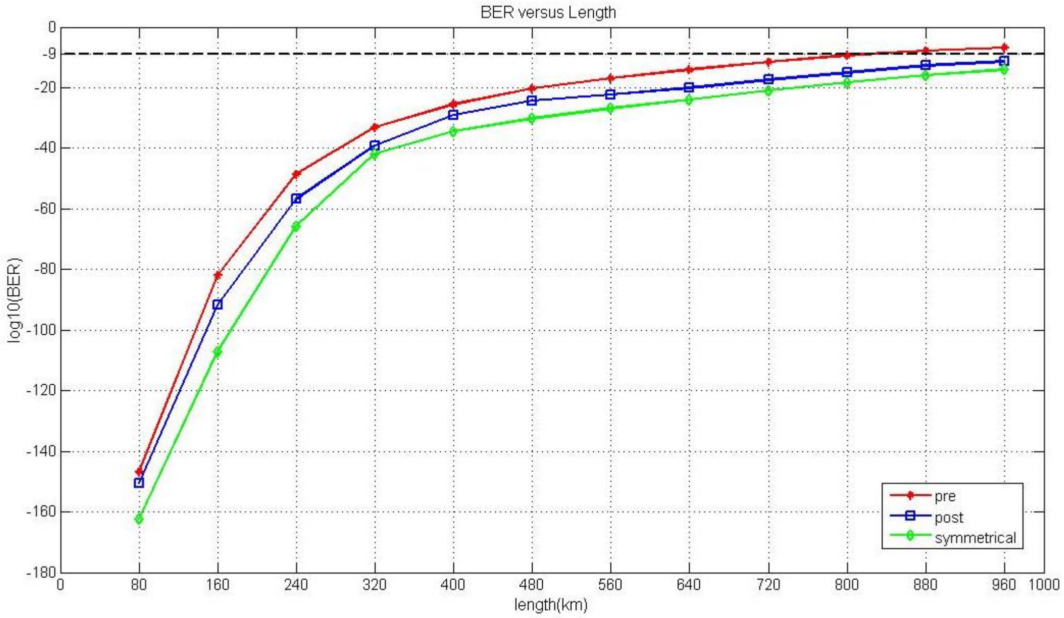


Figure 3.13 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.14. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 80km. As seen from this figure eye opening is good up to 960km.

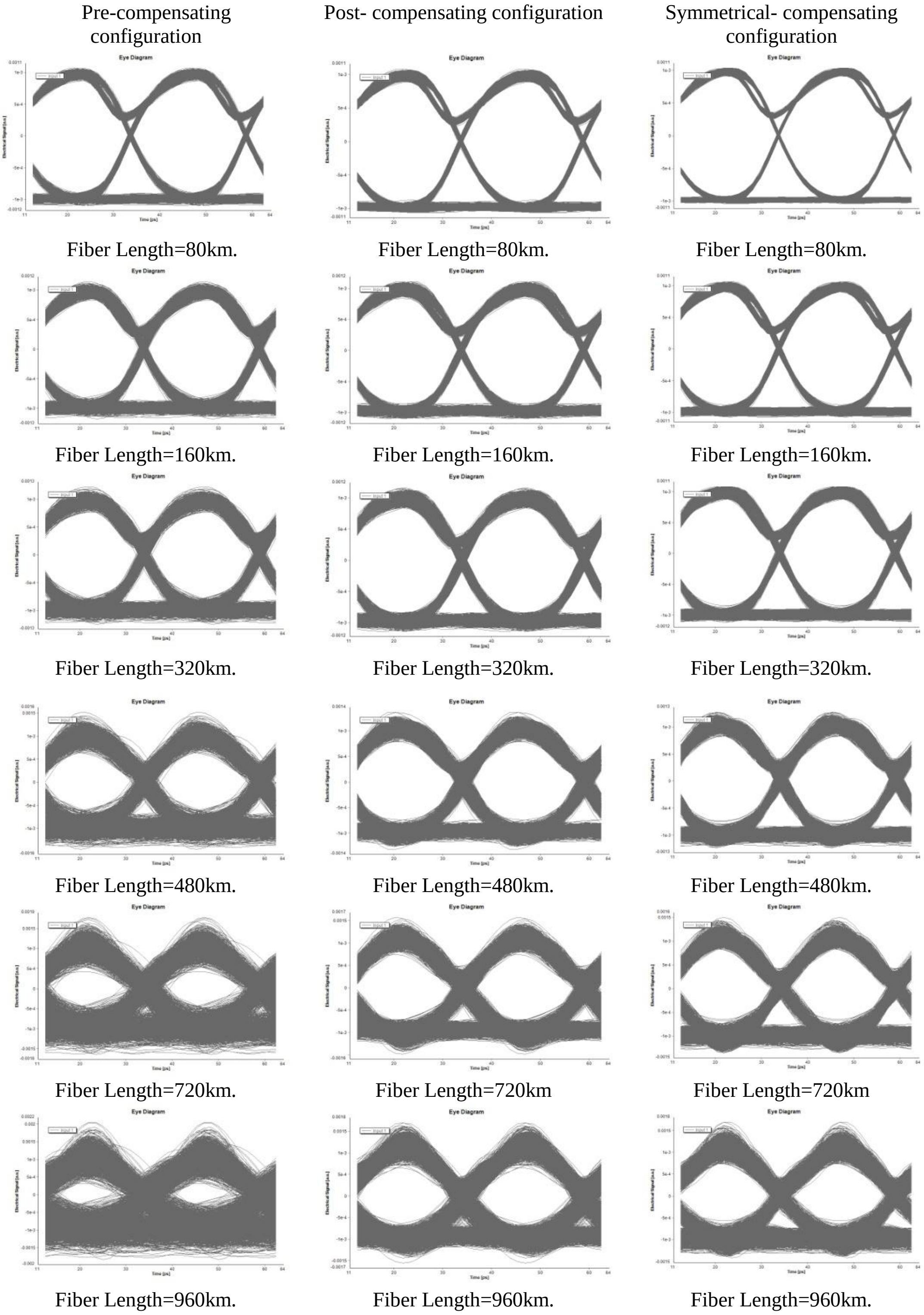


Figure 3.14 Eye diagrams of system for different fiber lengths.

3.3.1.6 CSRZ-DPSK Format

The simulation layouts for single channel 40Gb/s CSRZ-DPSK format with pre-, post and symmetrical compensating configurations are shown in Figure A. 12 at Appendix A.

For pre- and post- compensating configurations transmission fiber length is 80km. and compensating fiber length is 14.2km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers length of 40km and two DCFs length of 7.1km were used. In all configurations, BER and eye diagram analysis were done for 960km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 7.1dB and 16dB, for post-compensating configuration the gain of the EDFA's are 16dB and 7.1dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 40Gb/s single channel CSRZ DPSK format with all compensating configurations are shown in Figure 3.15. For all compensating case BER is less than equal 10^{-9} up to 960km. As shown in this figure, BER values of post-compensating configuration is better compared to pre-compensating configuration. Symmetrical compensating configuration represents the best case among all considered configurations.

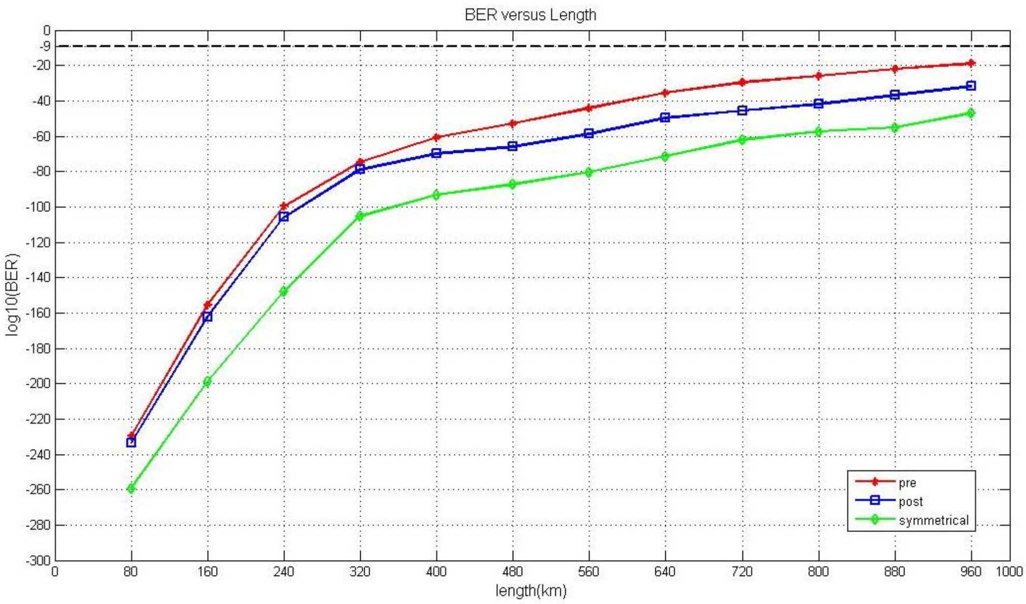


Figure 3.15 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.16. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 80km. As seen from this figure eye opening is good up to 960km.

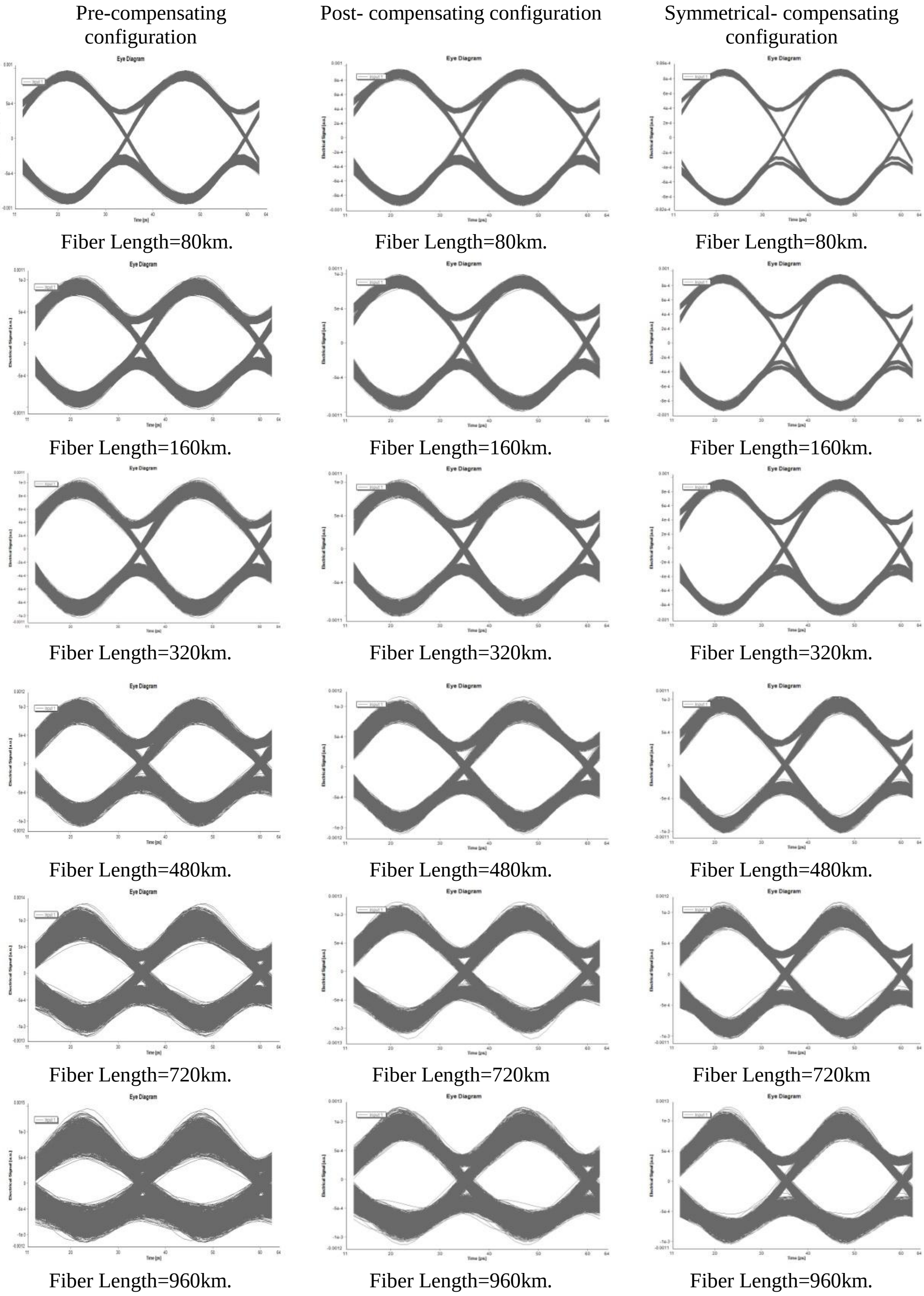


Figure 3.16 Eye diagrams of system for different fiber lengths.

Single channel 40Gb/s for all modulation formats with pre- compensating configuration is shown in Figure 3.17. As shown in this figure the performance of CSRZ-DPSK modulation format represents the best case among all considered formats.

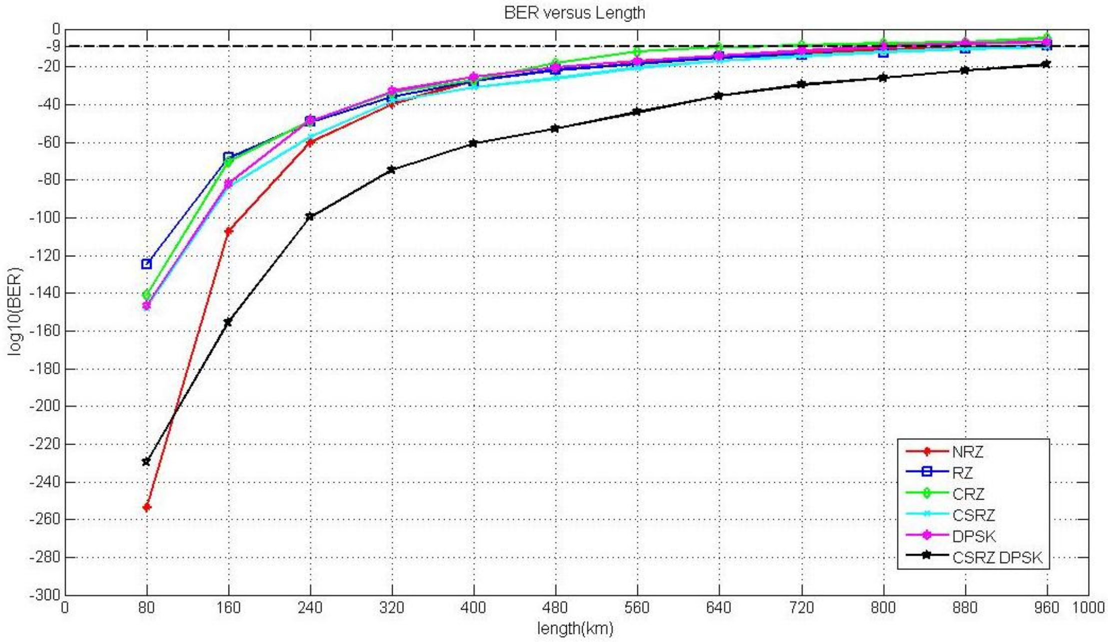


Figure 3.17 BER versus Length for single channel 40Gb/s system for all modulation formats with pre-compensating configuration.

Figure 3.18 shows the single channel 40Gb/s for all modulation formats with post-compensating configuration. As shown in this figure the performance of CSRZ-DPSK modulation format represents the best case among all considered formats.

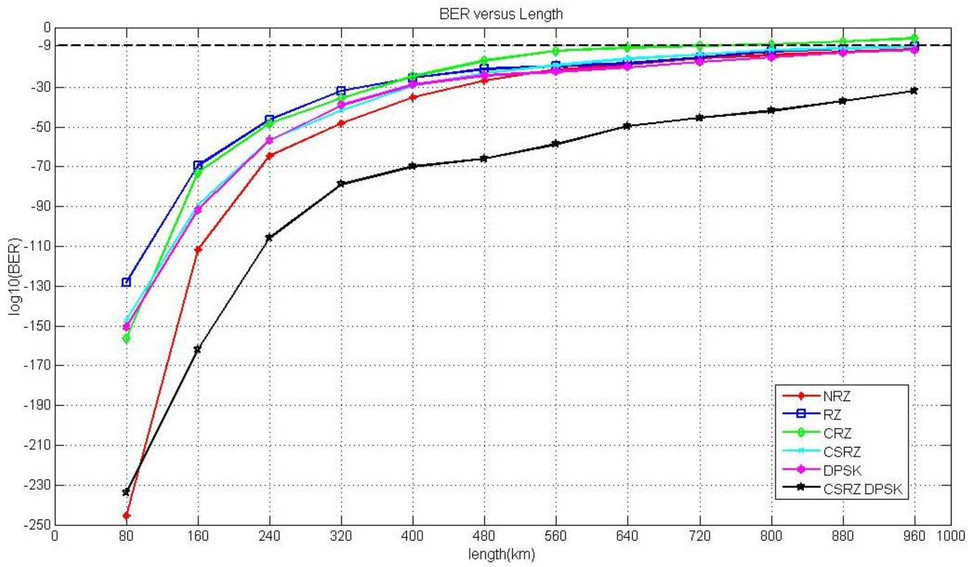


Figure 3.18 BER versus Length for single channel 40Gb/s system for all modulation formats with post-compensating configuration.

Single channel 40Gb/s for all modulation formats with symmetrical compensating configuration is shown in Figure 3.19. As shown in this figure up to 240 km. the performance of NRZ modulation format is better compared the others. After that length CSRZ-DPSK modulation format represents the best case among all considered formats.

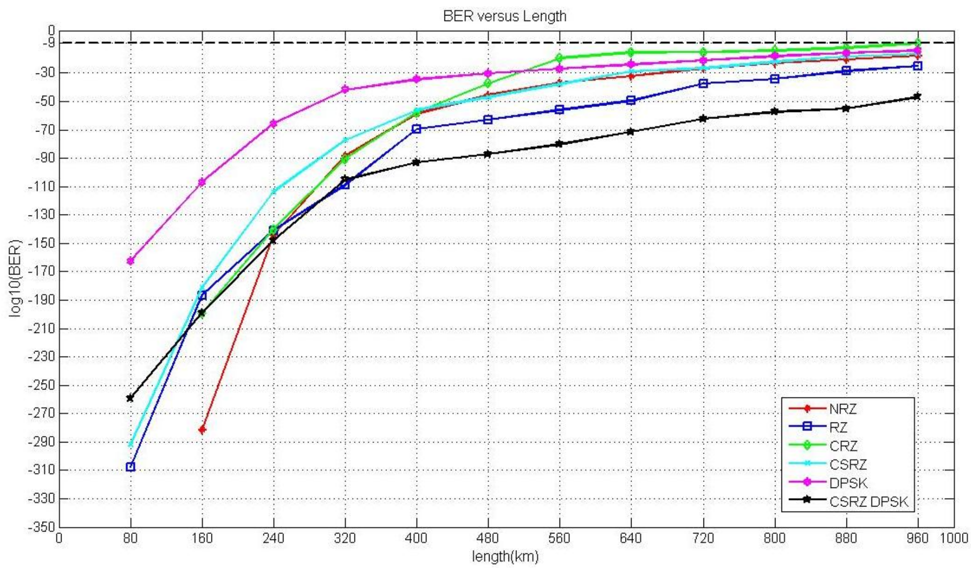


Figure 3.19 BER versus Length for single channel 40Gb/s system for all modulation formats with symmetrical compensating configuration.

3.3.2 25 Channels 40Gb/s WDM System

For 40Gb/s data-rate, 25 channels were used with the channel spacing of 160Ghz (1.28nm) and total capacity was 1Tb/s. For this system, modulation formats of NRZ, RZ, CRZ, CSRZ, DPSK and CSRZ-DPSK were analyzed with pre-, post- and symmetrical compensation configurations. Total transmission distance is 12x80km=960km. for each configuration.

In WDM optical systems, because of the nonlinear crosstalk, the middle channel generally has the worst performance. Channels that are far away do not affect each other much because they pass through each other quickly due to the dispersion. Therefore, in our simulations, we considered the middle channel 13 of the system.

3.3.2.1 25 Channels NRZ Format

The simulation layouts for 25 Channels 40Gb/s NRZ format with pre-, post and symmetrical compensating configurations are shown in Figure A.13 at Appendix A.

For pre- and post- compensating configurations transmission fiber length is 80km. and compensating fiber length is 14.2km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers length of 40km and two DCFs length of 7.1km were used. In all configurations, BER and eye diagram analysis were done for 960km. fiber length.

For pre-compensating configuration, the gain of the EDFA’s are 7.1dB and 16dB, for post-compensating configuration the gain of the EDFA’s are 16dB and 7.1dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for channel 13 based on NRZ format with all compensating configurations are shown in Figure 3.20. For post- and pre-compensating configurations BER is less than equal 10^{-9} up to 400km., for symmetrical case it is up to 240km. As shown in this figure, BER values of post-compensating configuration is better compared to symmetrical compensating configuration. Pre- compensating configuration represents the best case among all considered configurations.

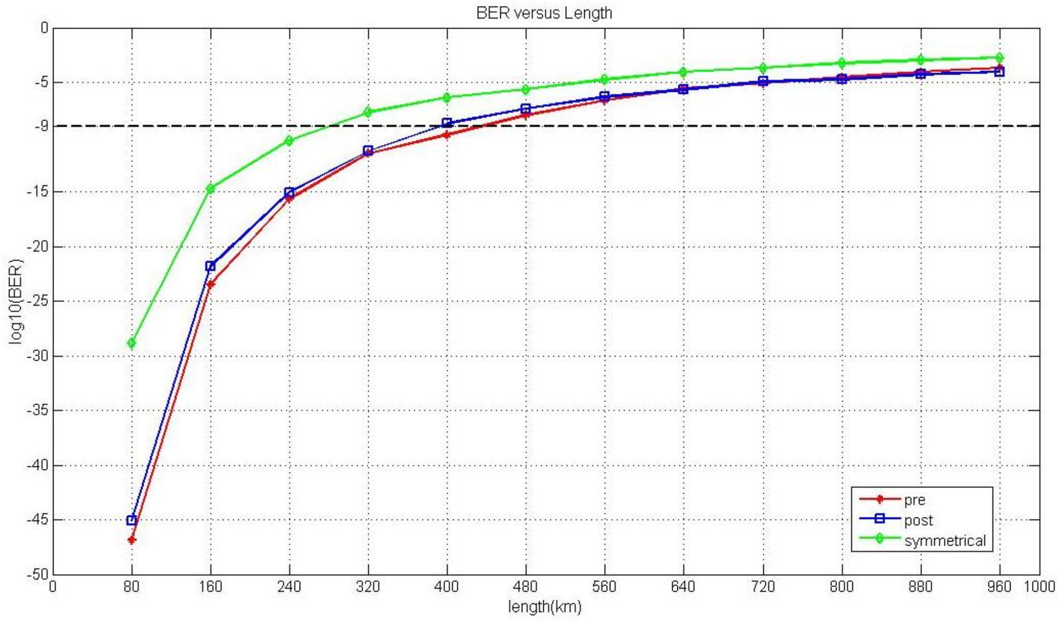
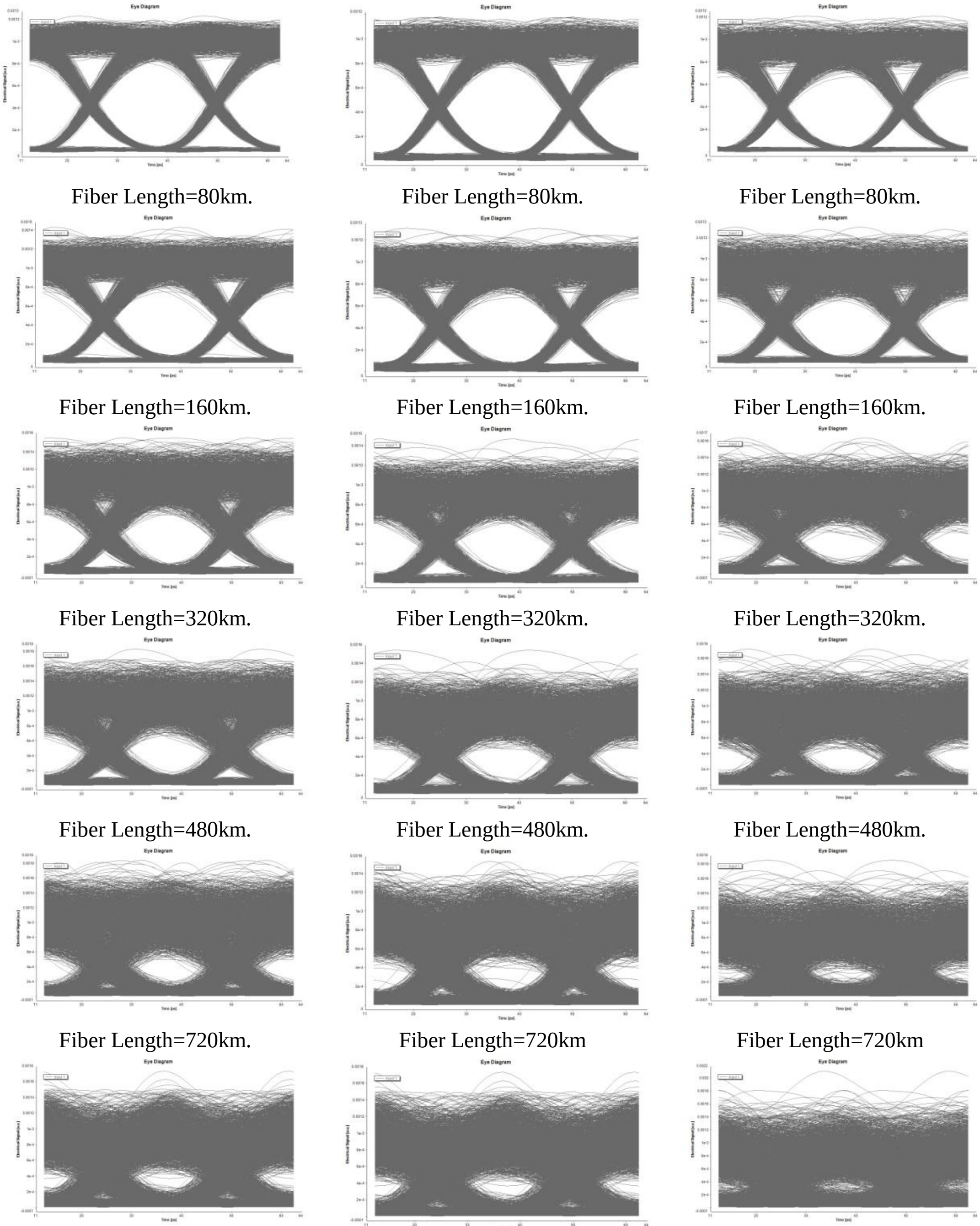


Figure 3.20 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.21. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 80km. As seen from this figure eye opening is good up to 400km.

Pre-compensating configuration | Post- compensating configuration | Symmetrical- compensating configuration



Fiber Length=80km. | Fiber Length=80km. | Fiber Length=80km.

Fiber Length=160km. | Fiber Length=160km. | Fiber Length=160km.

Fiber Length=320km. | Fiber Length=320km. | Fiber Length=320km.

Fiber Length=480km. | Fiber Length=480km. | Fiber Length=480km.

Fiber Length=720km. | Fiber Length=720km | Fiber Length=720km

Fiber Length=960km. | Fiber Length=960km. | Fiber Length=960km.

Figure 3.21 Eye diagrams of system for different fiber lengths.

3.3.2.2 25 Channels RZ Format

The simulation layouts for 25 Channels 40Gb/s RZ format with pre-, post and symmetrical compensating configurations are shown in Figure A.14 at Appendix A.

For pre- and post- compensating configurations transmission fiber length is 80km. and compensating fiber length is 14.2km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers length of 40km and two DCFs length of 7.1km were used. In all configurations, BER and eye diagram analysis were done for 960km. fiber length.

For pre-compensating configuration, the gain of the EDFA’s are 7.1dB and 16dB, for post-compensating configuration the gain of the EDFA’s are 16dB and 7.1dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for channel 13 based on RZ format with all compensating configurations are shown in Figure 3.22. For symmetrical and pre-compensating configuration BER is less than equal 10^{-9} up to 960km., and for post case it is up to 800km. As shown in this figure, BER values of pre- compensating configuration is better compared to post- compensating configuration. Symmetrical compensating configuration represents the best case among all considered configurations.

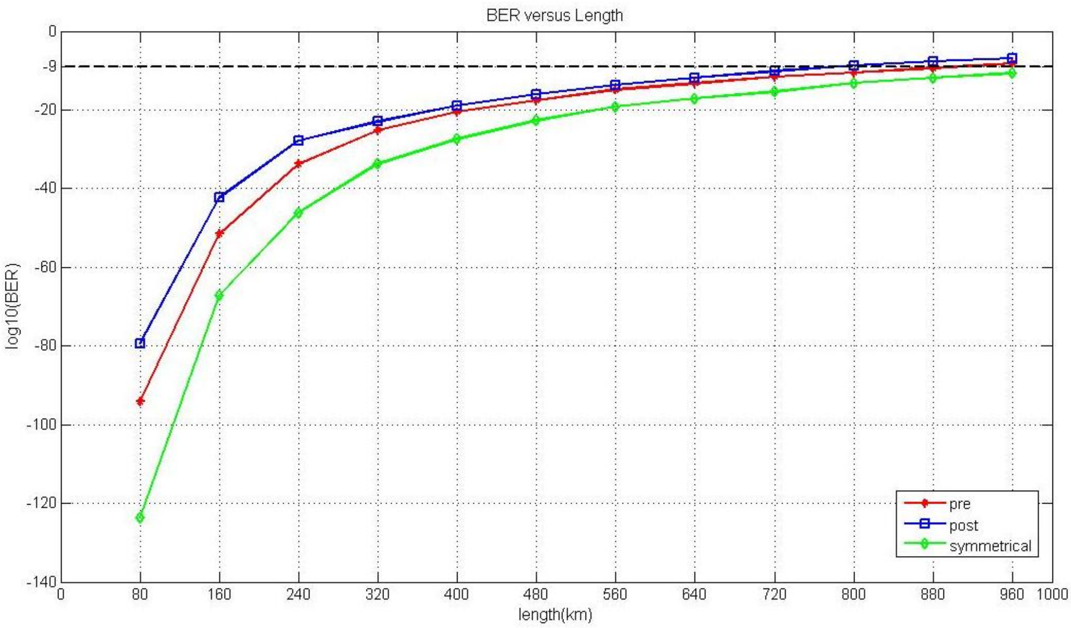


Figure 3.22 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.23. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 80km.

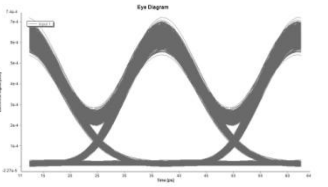
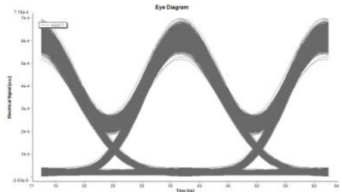
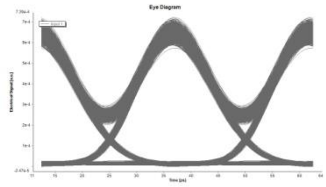
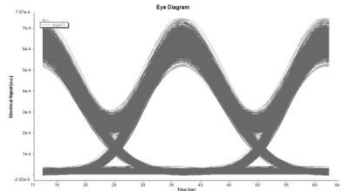
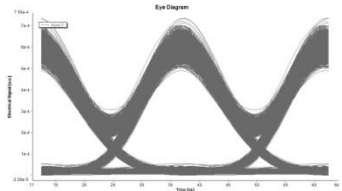
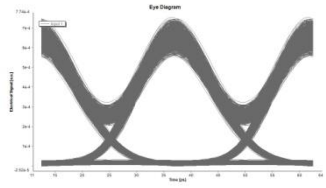
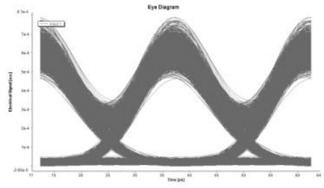
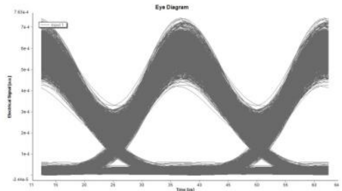
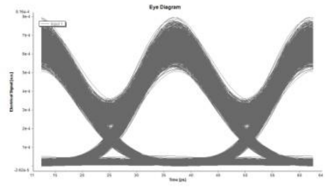
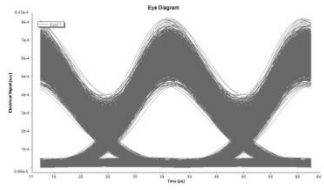
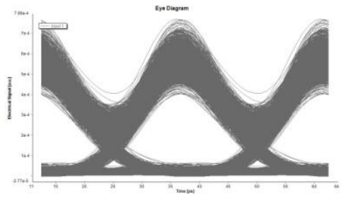
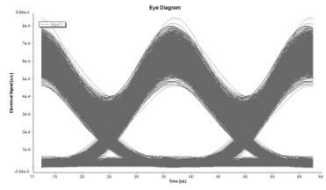
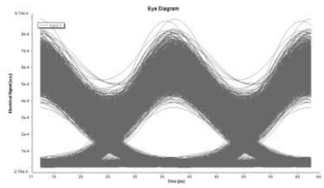
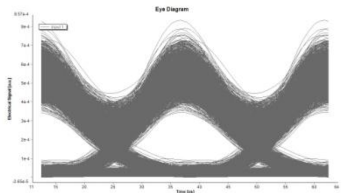
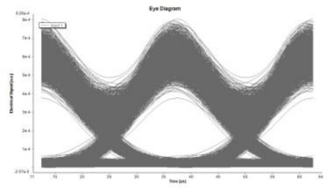
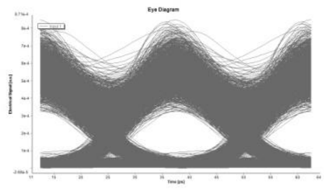
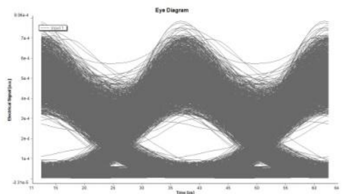
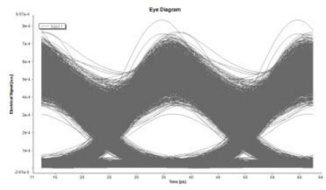
Pre-compensating configuration	Post- compensating configuration	Symmetrical- compensating configuration
		
Fiber Length=80km.	Fiber Length=80km.	Fiber Length=80km.
		
Fiber Length=160km.	Fiber Length=160km.	Fiber Length=160km.
		
Fiber Length=320km.	Fiber Length=320km.	Fiber Length=320km.
		
Fiber Length=480km.	Fiber Length=480km.	Fiber Length=480km.
		
Fiber Length=720km.	Fiber Length=720km	Fiber Length=720km
		
Fiber Length=960km.	Fiber Length=960km.	Fiber Length=960km.

Figure 3.23 Eye diagrams of system for different fiber lengths.

As seen from this figure eye opening is good up to 960km for symmetrical and pre- compensating cases, for post- case is good up to 800km.

3.3.2.3 25 Channels CRZ Format

The simulation layouts for 25 Channels 40Gb/s CRZ format with pre-, post and symmetrical compensating configurations are shown in Figure A.15 at Appendix A.

For pre- and post- compensating configurations transmission fiber length is 80km. and compensating fiber length is 14.2km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers length of 40km and two DCFs length of 7.1km were used. In all configurations, BER and eye diagram analysis were done for 960km. fiber length.

For pre-compensating configuration, the gain of the EDFA’s are 7.1dB and 16dB, for post-compensating configuration the gain of the EDFA’s are 16dB and 7.1dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for channel 13 based on CRZ format with all compensating configurations are shown in Figure 3.24. For symmetrical compensating configuration BER is less than equal 10^{-9} up to 640km., for pre- and post- cases it is up to 240km. As shown in this figure, BER values of pre- and post- compensating configurations are mostly the same. Symmetrical compensating configuration represents the best case among all considered configurations.

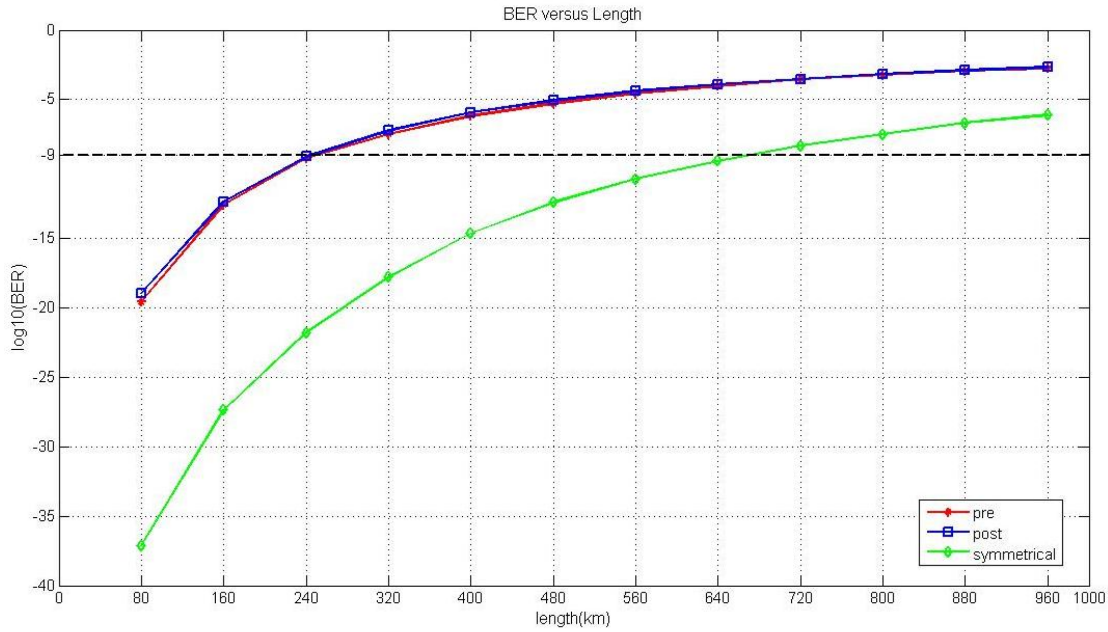


Figure 3.24 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.25. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 80km. Eye opening is good up to 640km for symmetrical compensating case, for pre- and post-cases are good up to 240km.

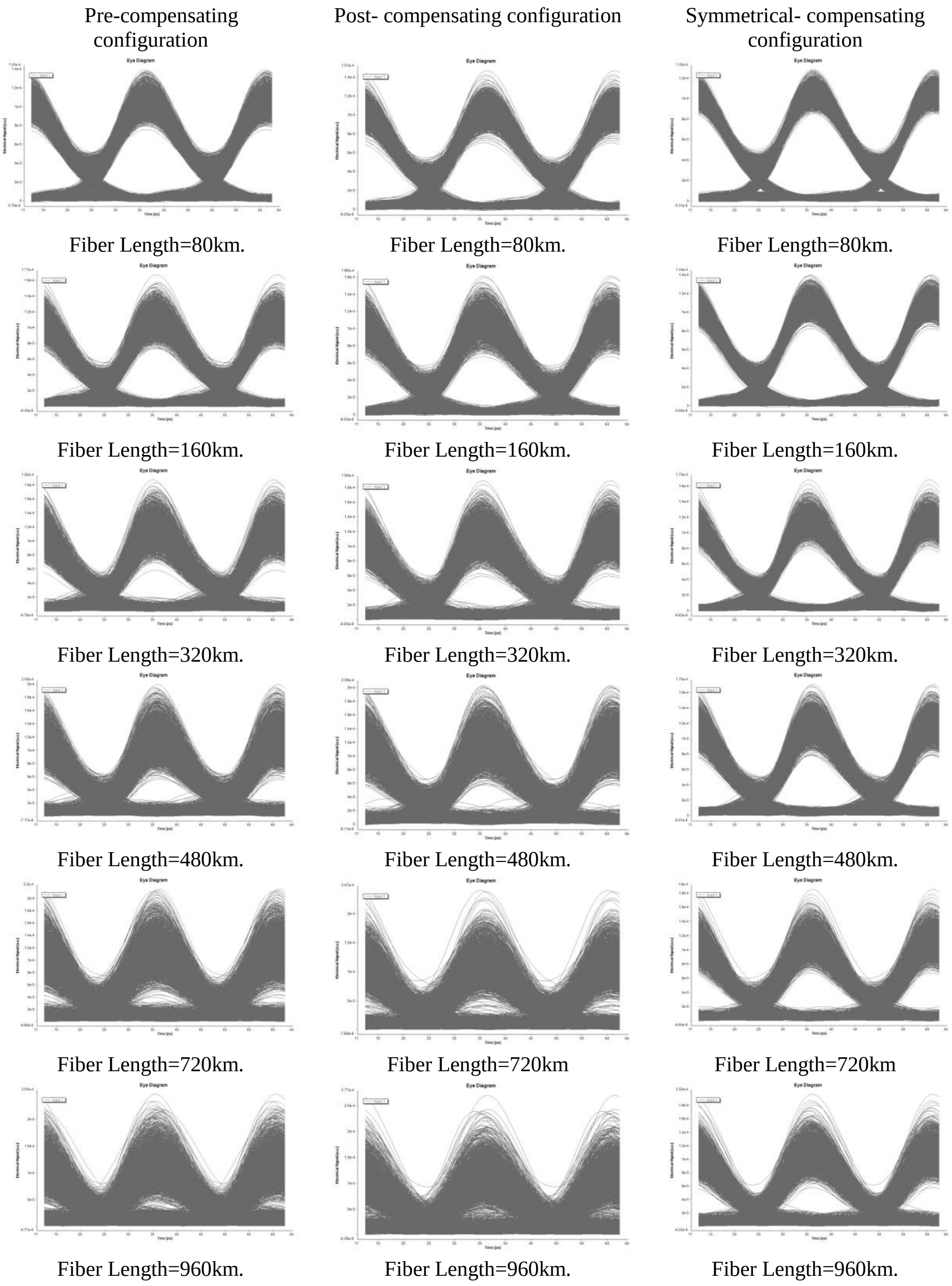


Figure 3.25 Eye diagrams of system for different fiber lengths.

3.3.2.4 25 Channels CSRZ Format

The simulation layouts for 25 Channels 40Gb/s CSRZ format with pre-, post and symmetrical compensating configurations are shown in Figure A.16 at Appendix A.

For pre- and post- compensating configurations transmission fiber length is 80km. and compensating fiber length is 14.2km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers length of 40km and two DCFs length of 7.1km were used. In all configurations, BER and eye diagram analysis were done for 960km. fiber length.

For pre-compensating configuration, the gain of the EDFA’s are 7.1dB and 16dB, for post-compensating configuration the gain of the EDFA’s are 16dB and 7.1dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for channel 13 based on CSRZ format with all compensating configurations are shown in Figure 3.26. For symmetrical compensating configuration BER is less than equal 10^{-9} up to 960km., for post- and pre- cases it is up to 640km. As shown in this figure, BER values of pre- and post-compensating configurations are nearly the same. Symmetrical compensating configuration represents the best case among all considered configurations.

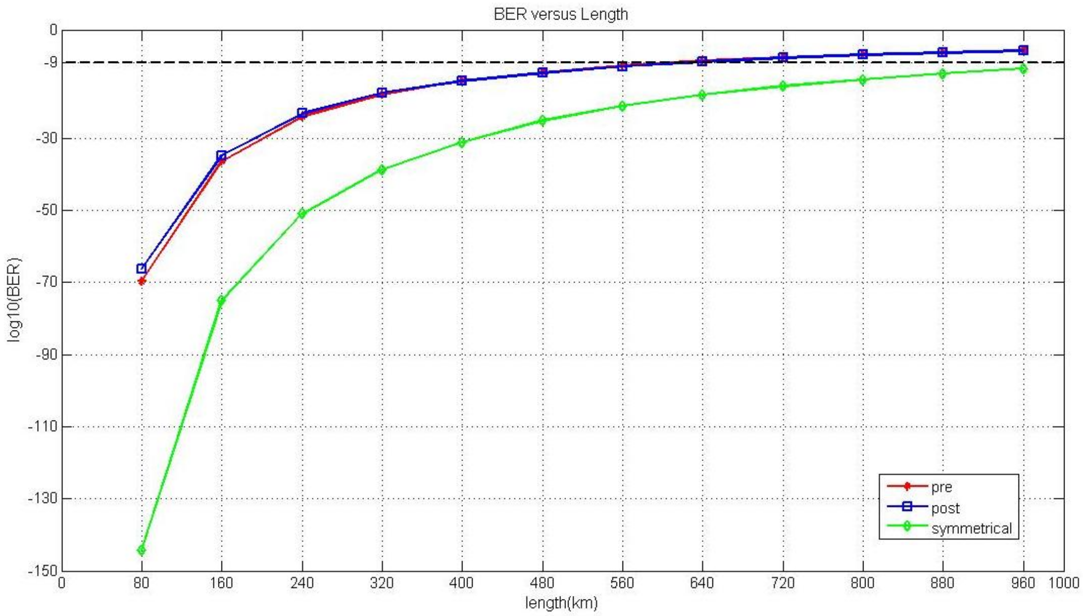
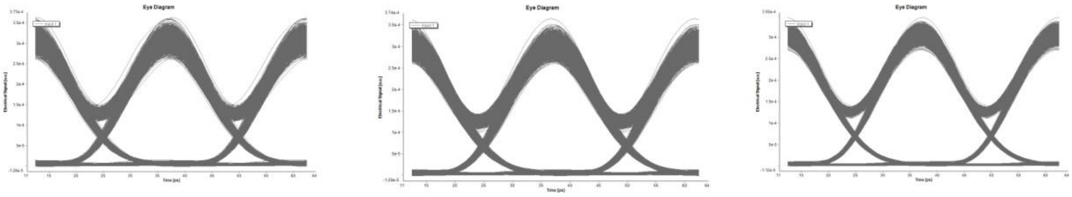
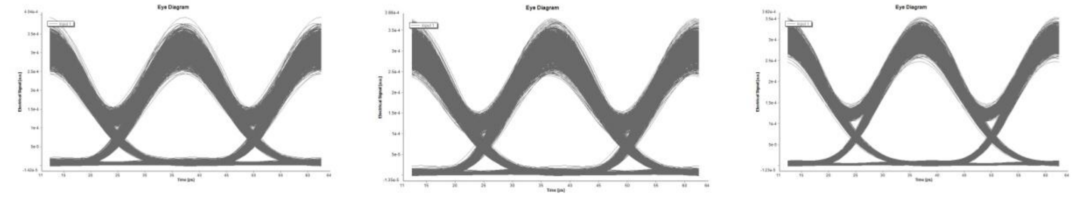


Figure 3.26 BER versus Length with all dispersion compensating configuration.

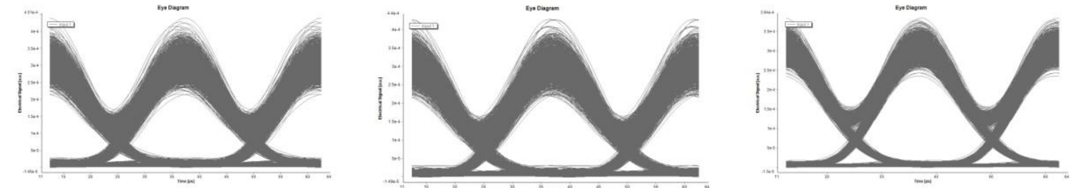
Pre-compensating configuration | Post- compensating configuration | Symmetrical- compensating configuration



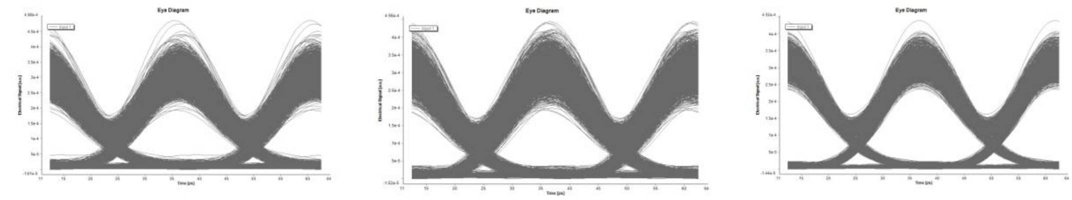
Fiber Length=80km. | Fiber Length=80km. | Fiber Length=80km.



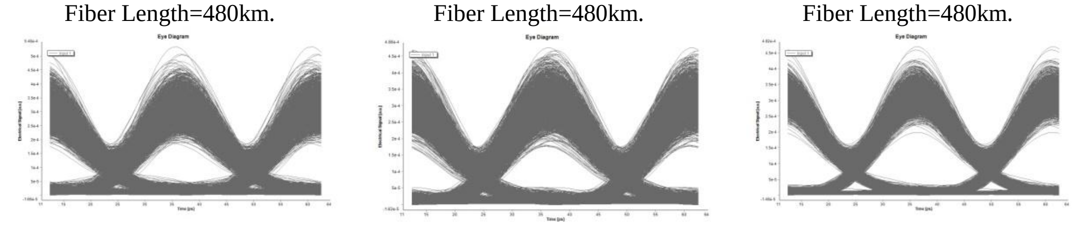
Fiber Length=160km. | Fiber Length=160km. | Fiber Length=160km.



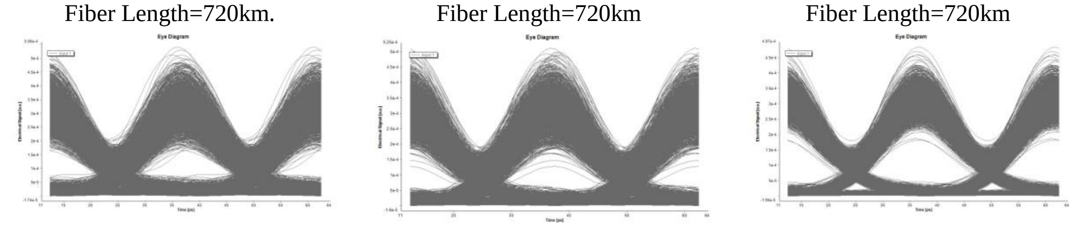
Fiber Length=320km. | Fiber Length=320km. | Fiber Length=320km.



Fiber Length=480km. | Fiber Length=480km. | Fiber Length=480km.



Fiber Length=720km. | Fiber Length=720km | Fiber Length=720km



Fiber Length=960km. | Fiber Length=960km. | Fiber Length=960km.

Figure 3. 27 Eye diagrams of system for different fiber lengths.

The eye diagrams of this system are shown in Figure 3. 27. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 80km. Eye opening is good up to 960km for symmetrical compensating case, for pre- and post- cases are good up to 640km.

3.3.2.5 25 Channels DPSK Format

The simulation layouts for 25 Channels 40Gb/s DPSK format with pre-, post and symmetrical compensating configurations are shown in Figure A. 17 at Appendix A.

For pre- and post- compensating configurations transmission fiber length is 80km. and compensating fiber length is 14.2km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers length of 40km and two DCFs length of 7.1km were used. In all configurations, BER and eye diagram analysis were done for 960km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 7.1dB and 16dB, for post-compensating configuration the gain of the EDFA's are 16dB and 7.1dB evaluated from Eq. (3.1)and Eq. (3.3).

The graph of BER versus Length for channel 13 based on DPSK format with all compensating configurations are shown in Figure 3.28. For post- and pre-compensating configurations BER is less than equal 10^{-9} up to 720km., for symmetrical- case it is up to 480km. As shown in this figure, BER values of pre-compensating configuration is better compared to symmetrical compensating configuration. Post- compensating configuration represents the best case among all considered configurations.

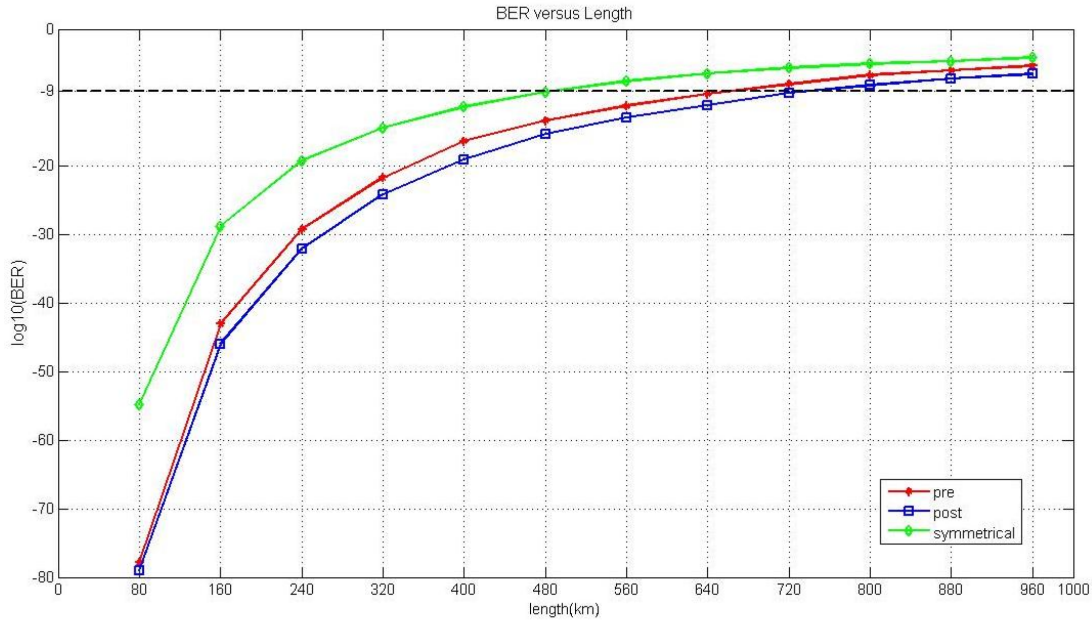


Figure 3.28 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.29. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 80km. Eye opening is good up to 720km for pre- and post- compensating cases, 480km. for symmetrical case.

Pre-compensating configuration	Post- compensating configuration	Symmetrical- compensating configuration

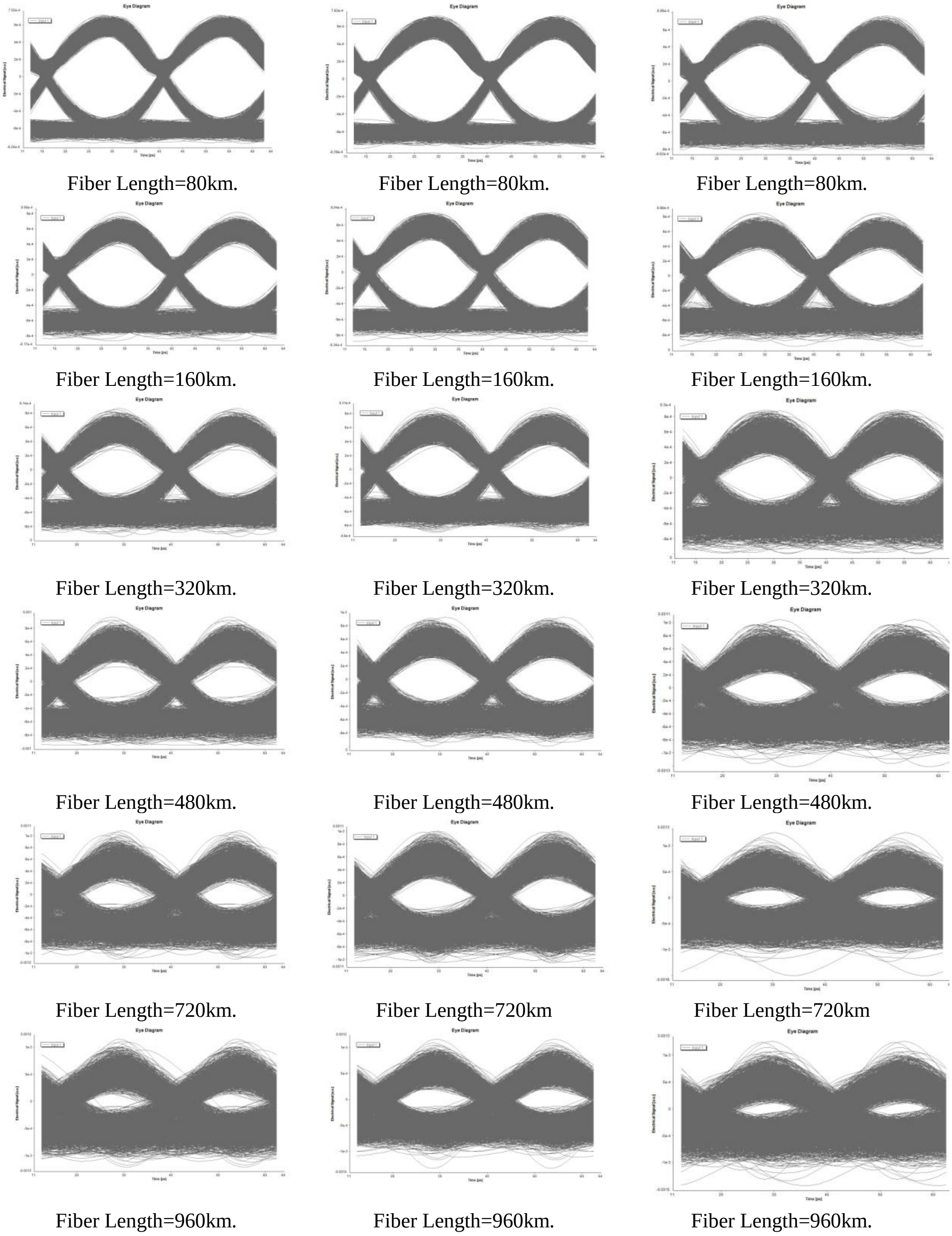


Figure 3.29 Eye diagrams of system for different fiber lengths.

3.3.2.6 25 Channels CSRZ DPSK Format

The simulation layouts for 25 Channels 40Gb/s CSRZ DPSK format with pre-, post and symmetrical compensating configurations are shown in Figure A.16 at Appendix A.

For pre- and post- compensating configurations transmission fiber length is 80km. and compensating fiber length is 14.2km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers length of 40km and two DCFs length of 7.1km were used. In all configurations, BER and eye diagram analysis were done for 960km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 7.1dB and 16dB, for post-compensating configuration the gain of the EDFA's are 16dB and 7.1dB evaluated from Eq. (3.1)and Eq. (3.3).

The graph of BER versus Length for channel 13 based on CSRZ DPSKformat with all compensating configurations are shown in Figure 3.30. For all compensating configurations BER is less than equal 10^{-9} up to 960km. As shown in this figure, BER values of post- compensating configuration is better compared to pre-compensating configuration. Symmetrical compensating configuration represents the best case among all considered configurations.

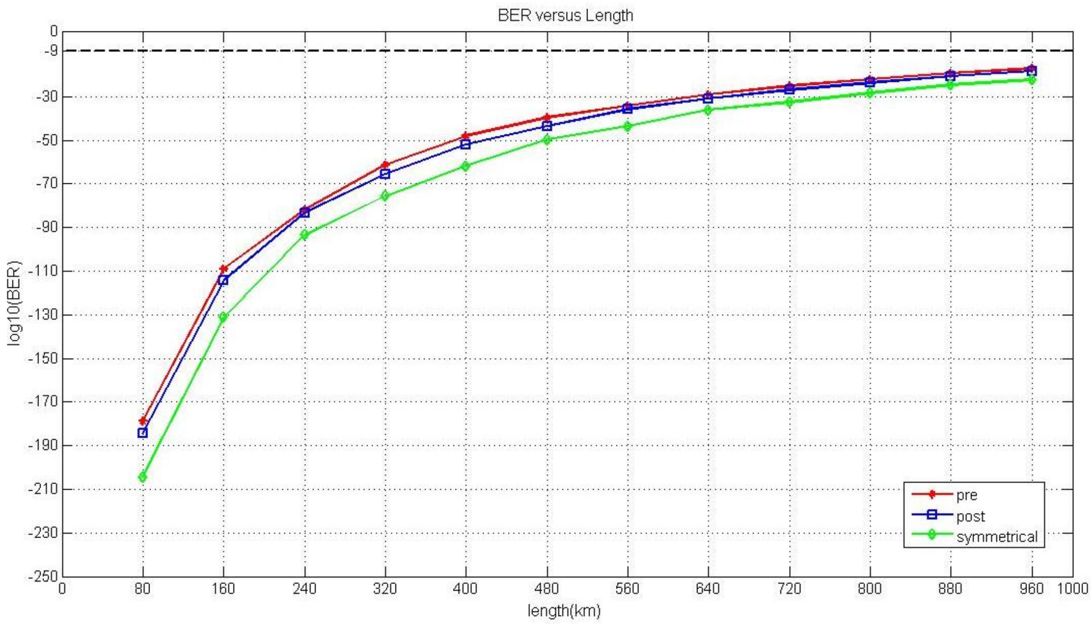
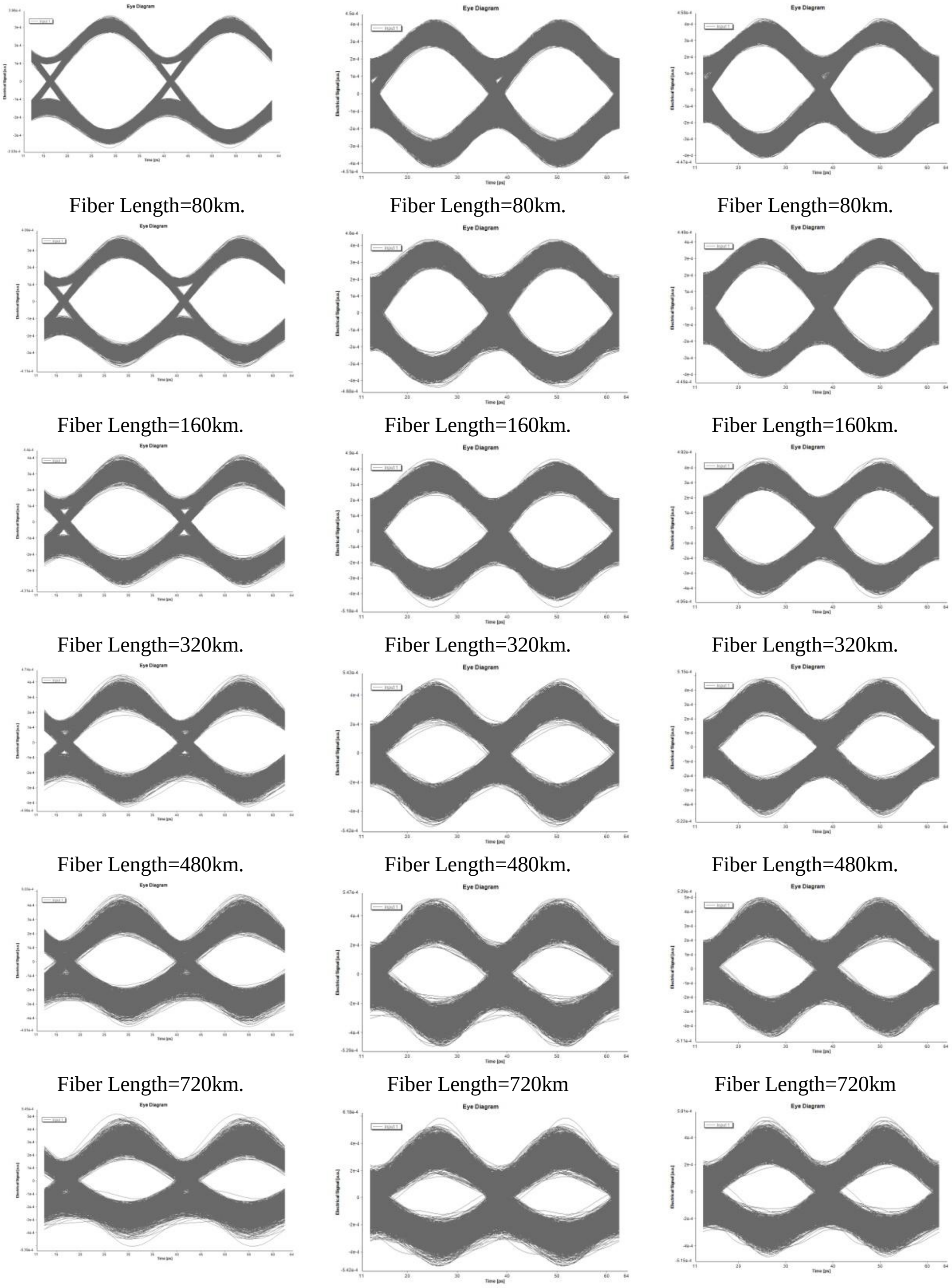


Figure 3.30 BER versus Length with all dispersion compensating configuration.

Pre-compensating configuration | Post- compensating configuration | Symmetrical- compensating configuration



Fiber Length=80km. Fiber Length=80km. Fiber Length=80km.

Fiber Length=160km. Fiber Length=160km. Fiber Length=160km.

Fiber Length=320km. Fiber Length=320km. Fiber Length=320km.

Fiber Length=480km. Fiber Length=480km. Fiber Length=480km.

Fiber Length=720km. Fiber Length=720km Fiber Length=720km

Fiber Length=960km. Fiber Length=960km. Fiber Length=960km.

Figure 3.31 Eye diagrams of system for different fiber lengths.

The eye diagrams of this system are shown in Figure 3.31. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 80km. Eye opening is good up to 240km for symmetrical compensating case, for pre- and post-cases are good up to 160km.

25 channels 40Gb/s for all modulation formats with pre- compensating configuration is shown in Figure 3.32. As shown in this figure the performance of CSRZ-DPSK modulation format represents the best case among all considered formats. RZ is also good. CRZ is the worst case.

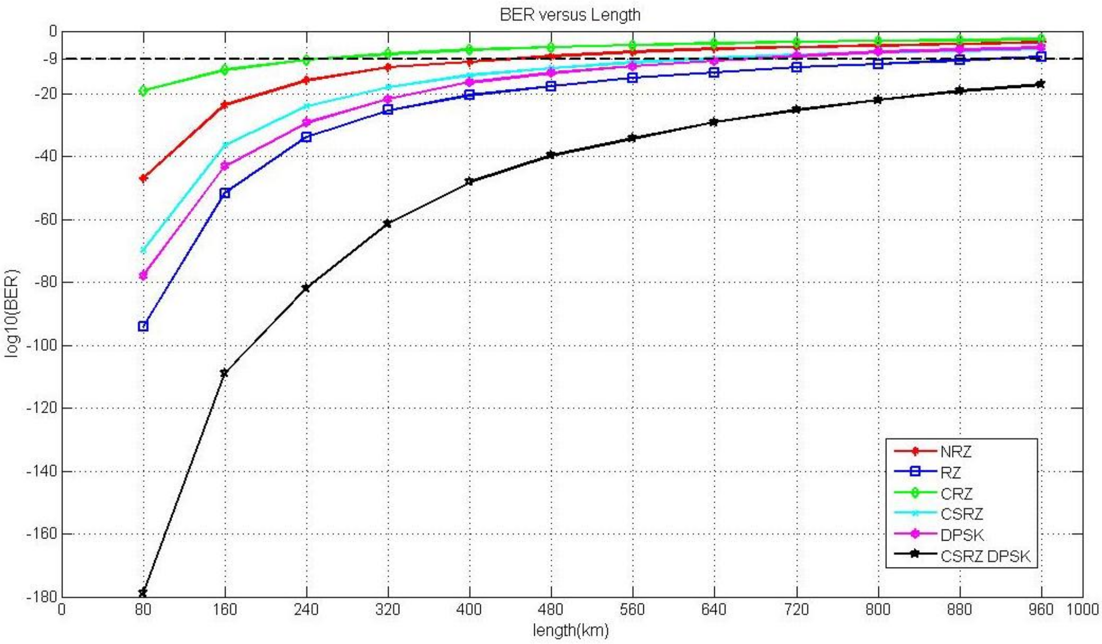


Figure 3.32 BER versus Length for 25 channels 40Gb/s system for all modulation formats with pre-compensating configuration.

Figure 3.33 shows the 25 channels 40Gb/s for all modulation formats with post-compensating configuration. As shown in this figure the performance of CSRZ-DPSK modulation format represents the best case among all considered formats. RZ and DPSK are good up to 800km. CRZ is the worst case.

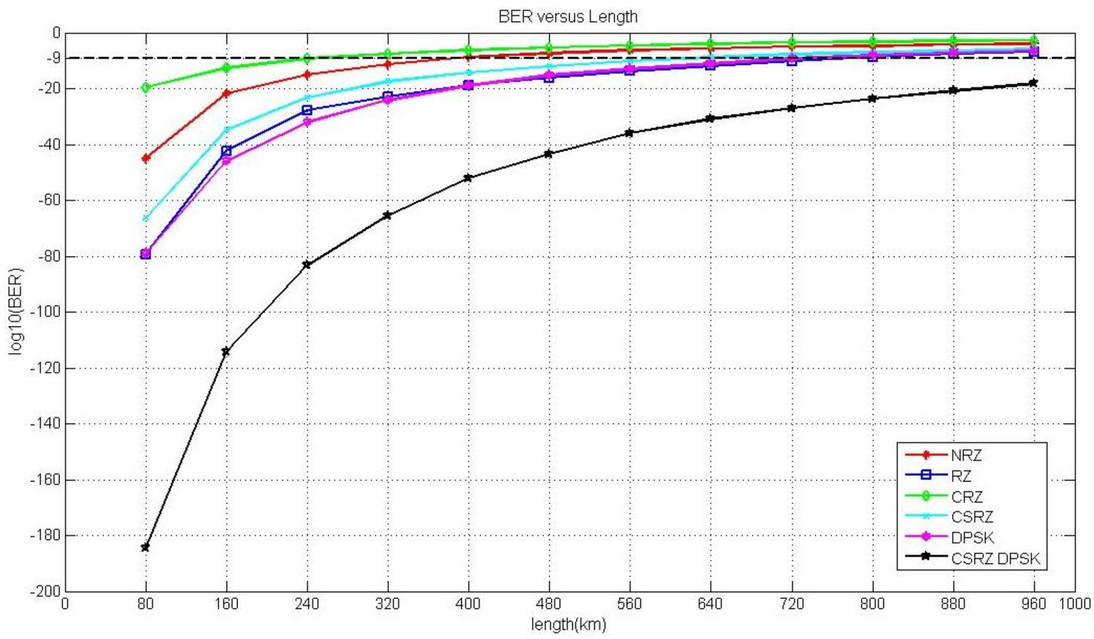


Figure 3.33 BER versus Length for 25 channels 40Gb/s system for all modulation formats with post-compensating configuration.

25 channels 40Gb/s for all modulation formats with symmetrical compensating configuration is shown in Figure 3.34. As shown in this figure CSRZ-DPSK modulation format represents the best case among all considered formats. RZ and CSRZ are good up to 960km. CRZ is the worst case.

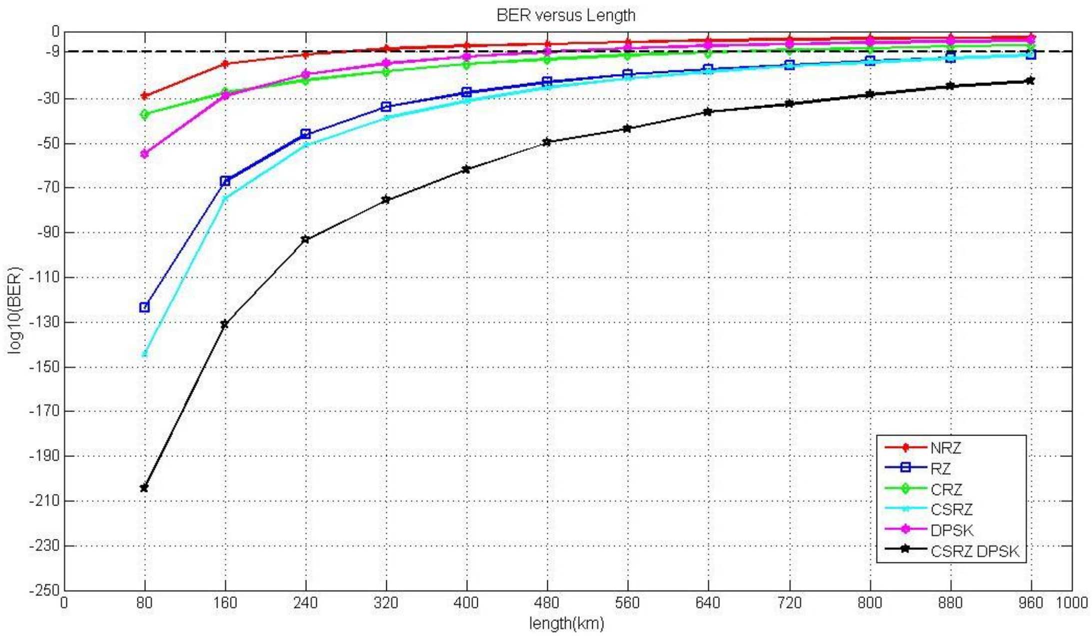


Figure 3.34 BER versus Length for 25 channels 40Gb/s system for all modulation formats with symmetrical compensating configuration.

3.4 100 Gb/s WDM SYSTEM

For 100Gb/s data-rate, firstly single channel were analyzed for different modulation formats with different compensation configuration. Then 11 channels were used with the channel spacing of 400GHz (3.2nm) around the 193.100 THz center frequency and total capacity was 1.1Tb/s.

3.3.1 Single Channel 100Gb/s WDM System

For single 100Gb/s WDM system, modulation formats of NRZ, RZ, CRZ, CSRZ, DPSK and CSRZ-DPSK were analyzed with pre-, post- and symmetrical compensation configurations.

The effect of nonlinearities and dispersion in fiber is increased when the data rate is increased. Therefore, in 100Gb/s data rate 40km fiber length span was used and total transmission distance is 6x40km=240km.

3.3.1.1 NRZ Format

The simulation layouts for single channel 100Gb/s NRZ format with pre-, post and symmetrical compensating configurations are same as 40Gb/s NRZ format except the data rate, transmission fiber length, dispersion compensating fiber length and EDFA gain.

For pre- and post- compensating configurations transmission fiber length is 40km. and compensating fiber length is 7.1 km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers each length of 20km and two DCFs each length of 3.55km were used. In all configurations, BER and eye diagram analysis were done for 240km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 3.55dB and 8dB, for post-compensating configuration the gain of the EDFA's are 8dB and 3.55dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 100Gb/s single channel NRZ format with all compensating configurations are shown in Figure 3.35. For pre- and post-compensating configurations BER is less than equal 10^{-9} up to 240km. for all compensating configurations. As shown in this figure, BER values of post-compensating configuration are better than pre- compensating configuration. Symmetrical compensating configuration represents the best case among all considered configurations.

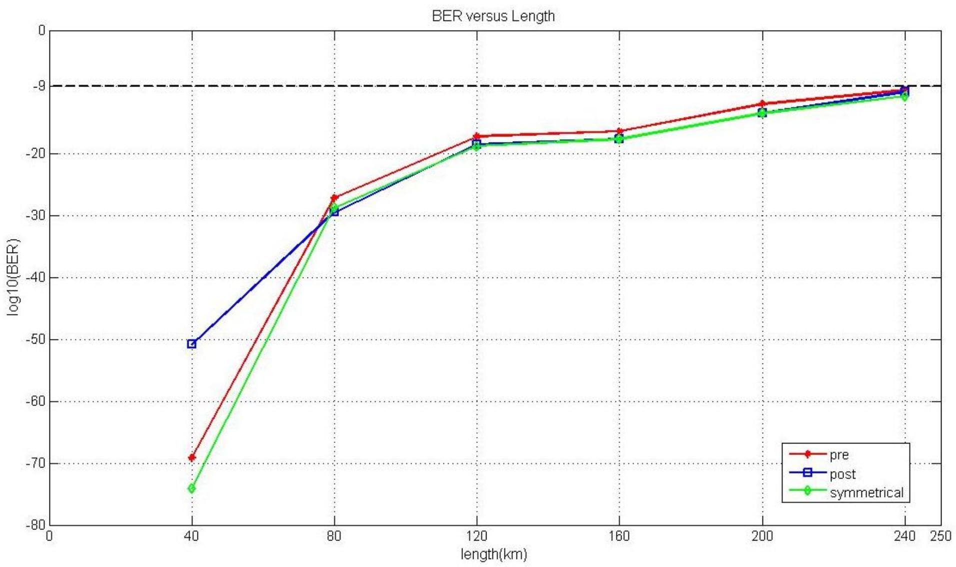


Figure 3.35 BER versus Length with all dispersion compensating configuration.

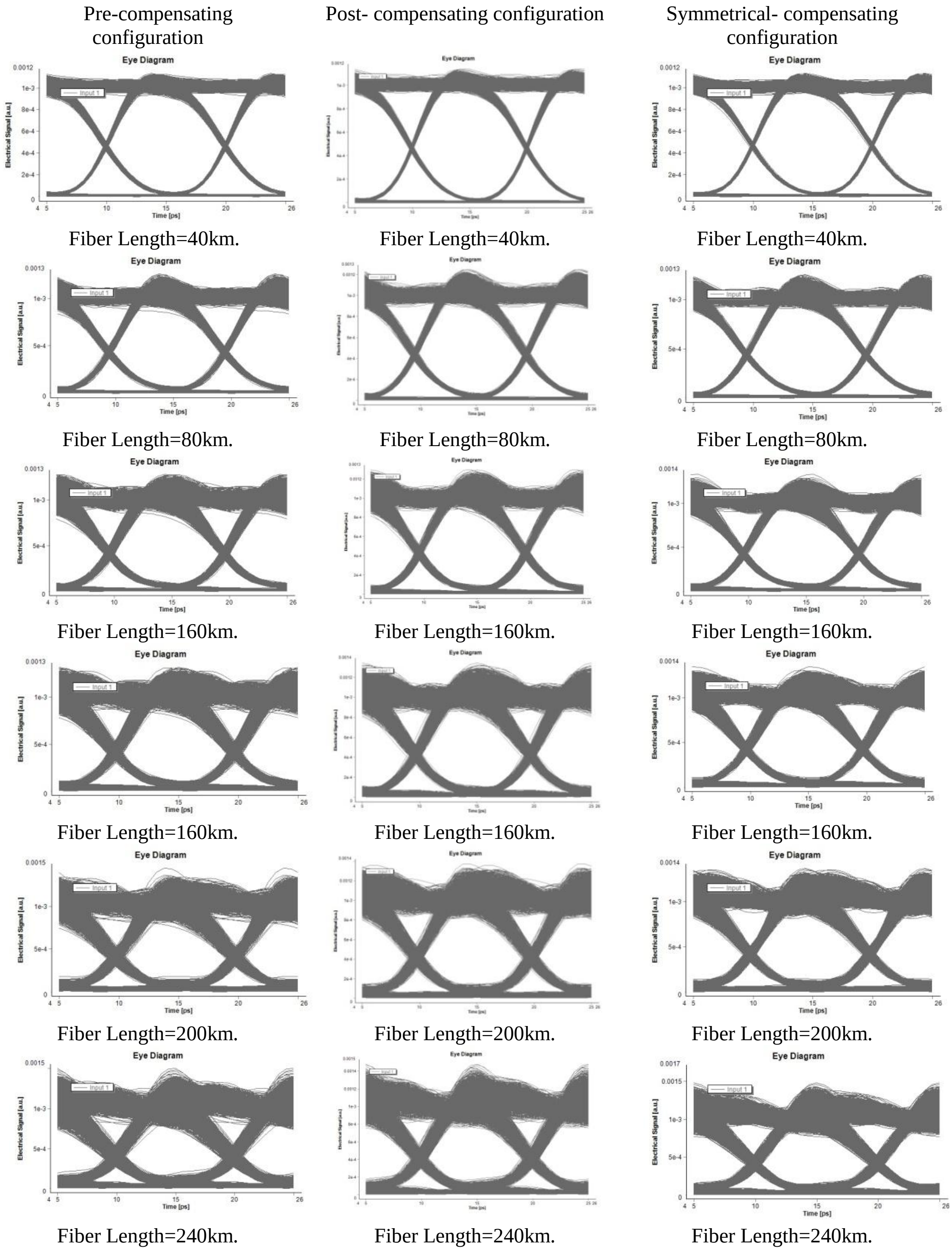


Figure 3.36 Eye diagrams of system for different fiber lengths; (a) Pre-compensating configuration, (b) Post-compensating configuration, (c) Symmetrical compensating configuration.

The eye diagrams of this system are shown in Figure 3.36. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 40km. As seen from this figure eye opening is good up to 240km. for all compensating configuration.

3.3.1.2 RZ Format

The simulation layouts for single channel 100Gb/s RZ format with pre-, post and symmetrical compensating configurations are same as 40Gb/s RZ format except the data rate, transmission fiber length, dispersion compensating fiber length and EDFA gain.

For pre- and post- compensating configurations transmission fiber length is 40km. and compensating fiber length is 7.1 km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers each length of 20km and two DCFs each length of 3.55km were used. In all configurations, BER and eye diagram analysis were done for 240km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 3.55dB and 8dB, for post-compensating configuration the gain of the EDFA's are 8dB and 3.55dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 100Gb/s single channel RZ format with all compensating configurations are shown in Figure 3.37. For all compensating configurations BER is less than equal 10^{-9} up to 200km. As shown in this figure, BER values of post- and pre- compensating configurations are mostly the same. Symmetrical compensating configuration represents the best case among all considered configurations.

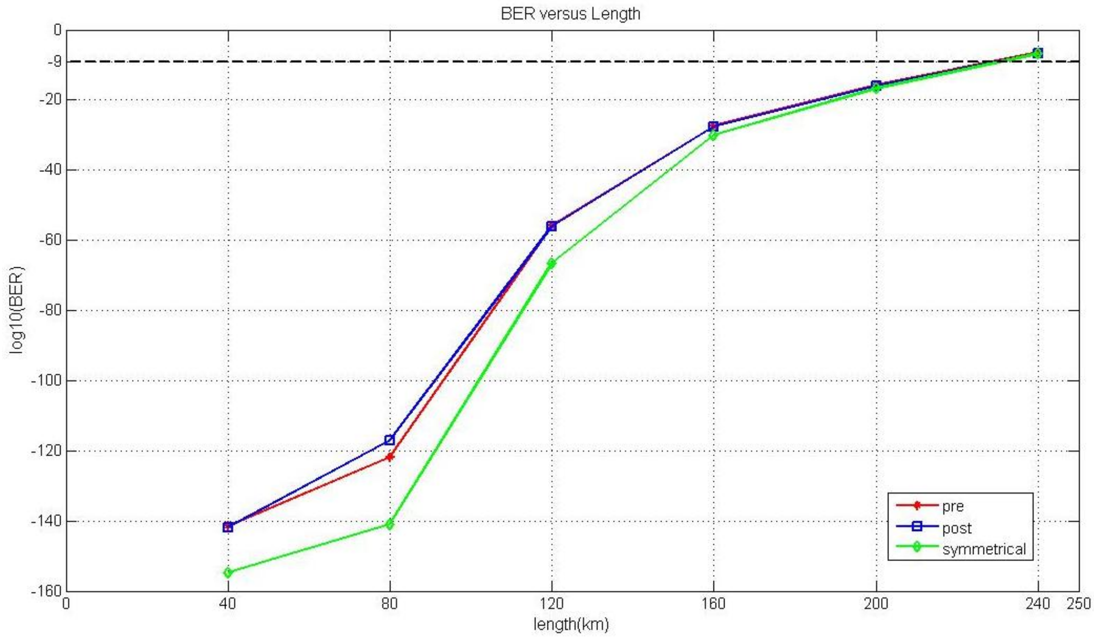


Figure 3.37 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.38. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 40km. As seen from this figure eye opening is good up to 200km. for all compensating cases.

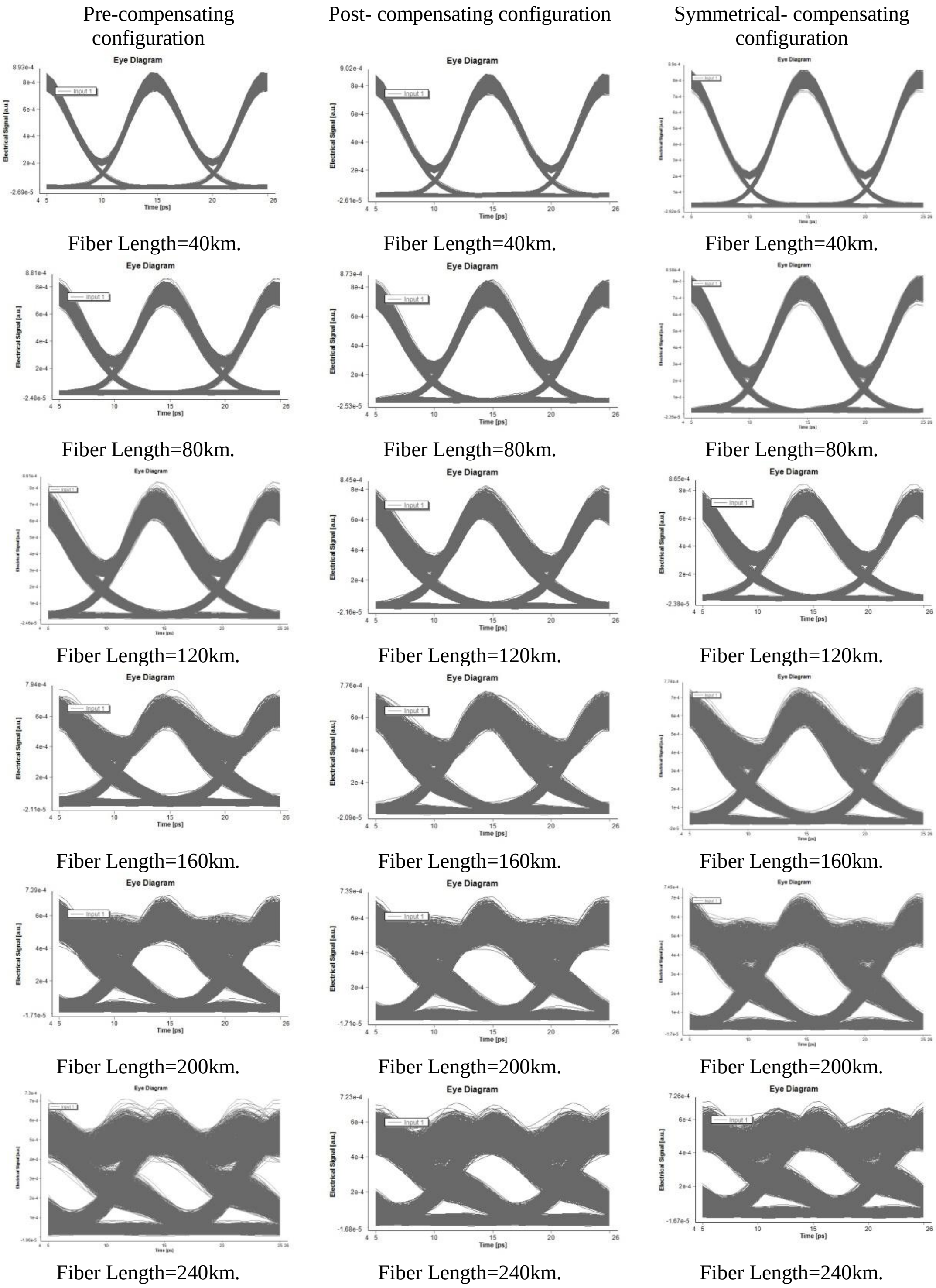


Figure 3.38 Eye diagrams of system for different fiber lengths; (a) Pre-compensating configuration, (b) Post-compensating configuration, (c) Symmetrical compensating configuration.

3.3.1.3 CRZ Format

The simulation layouts for single channel 100Gb/s CRZ format with pre-, post and symmetrical compensating configurations are same as 40Gb/s CRZ format except the data rate, transmission fiber length, dispersion compensating fiber length and EDFA gain.

For pre- and post- compensating configurations transmission fiber length is 40km. and compensating fiber length is 7.1 km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers each length of 20km and two DCFs each length of 3.55km were used. In all configurations, BER and eye diagram analysis were done for 240km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 3.55dB and 8dB, for post-compensating configuration the gain of the EDFA's are 8dB and 3.55dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 100Gb/s single channel CRZ format with all compensating configurations are shown in Figure 3.39. For all compensating configurations BER is less than equal 10^{-9} up to 80km. As shown in this figure, BER values of all compensating configurations are mostly the same. Symmetrical compensating configuration represents the best case among all considered configurations.

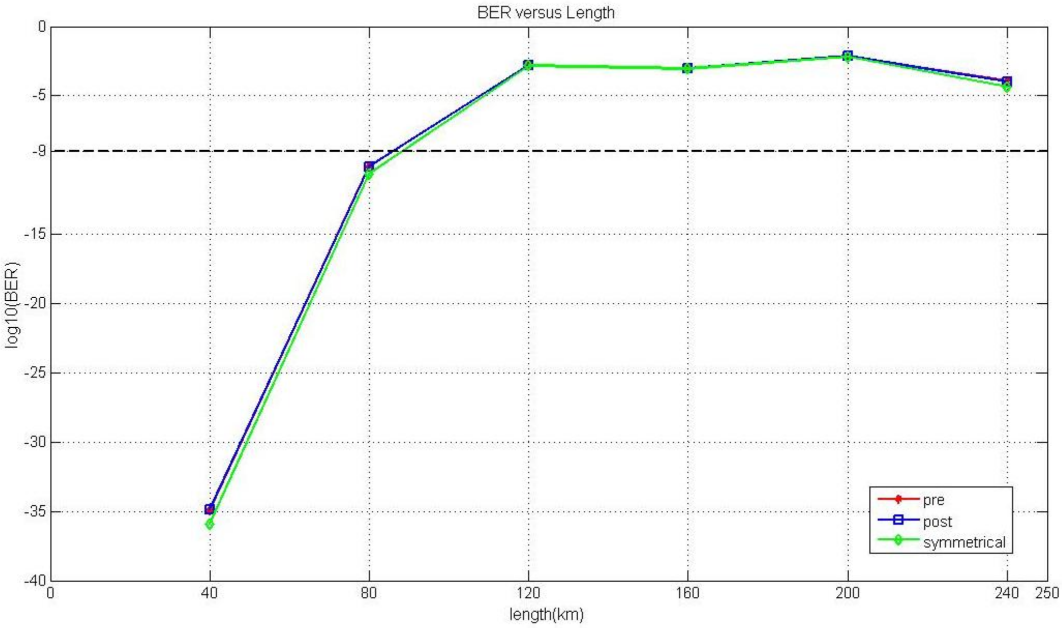


Figure 3.39 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.40. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 40km. As seen from this figure eye opening is good up to 80km.

Pre-compensating configuration | Post- compensating configuration | Symmetrical- compensating configuration

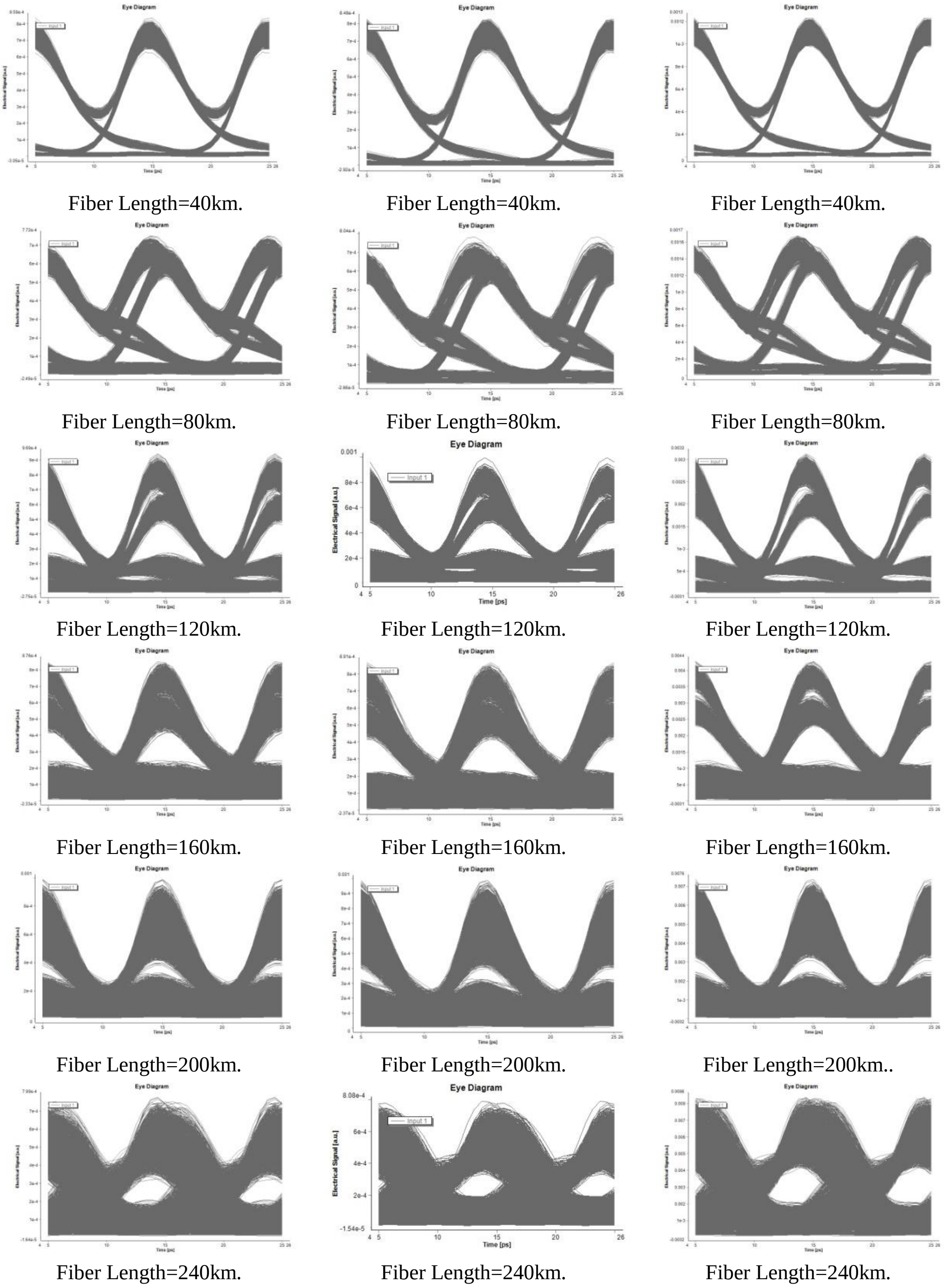


Figure 3.40 Eye diagrams of system for different fiber lengths; (a) Pre-compensating configuration, (b) Post-compensating configuration, (c) Symmetrical compensating configuration.

3.3.1.4 CSRZ Format

The simulation layouts for single channel 100Gb/s CSRZ format with pre-, post and symmetrical compensating configurations are same as 40Gb/s CSRZ format except the data rate, transmission fiber length, dispersion compensating fiber length and EDFA gain.

For pre- and post- compensating configurations transmission fiber length is 40km. and compensating fiber length is 7.1 km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers each length of 20km and two DCFs each length of 3.55km were used. In all configurations, BER and eye diagram analysis were done for 240km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 3.55dB and 8dB, for post-compensating configuration the gain of the EDFA's are 8dB and 3.55dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 100Gb/s single channel CSRZ format with all compensating configurations are shown in Figure 3.41. For all compensating configurations BER is less than equal 10^{-9} up to 240km. As shown in this figure, BER values of pre-and post- compensating configurations are nearly the same. Symmetrical compensating configuration represents the best case among all considered configurations.

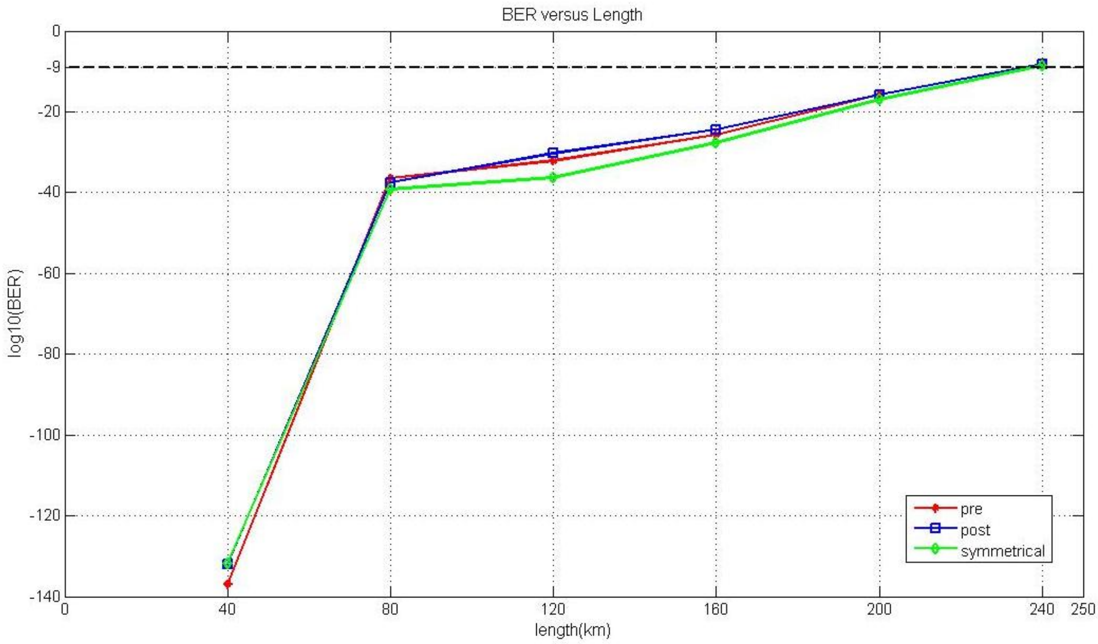


Figure 3.41 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.42. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 40km. As seen from this figure eye opening is good up to 240km.

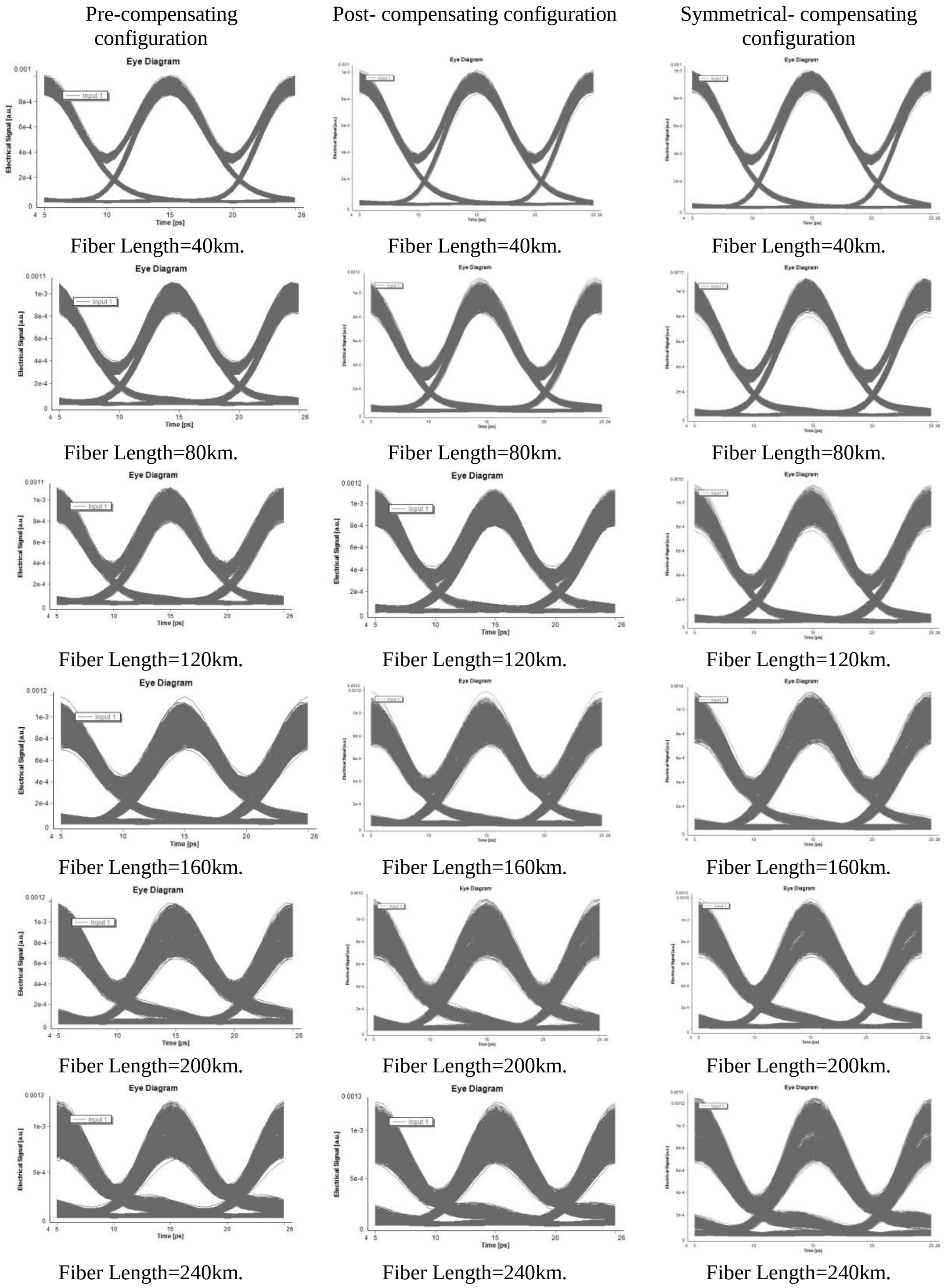


Figure 3.42 Eye diagrams of system for different fiber lengths; (a) Pre-compensating configuration, (b) Post-compensating configuration, (c) Symmetrical compensating configuration.

3.3.1.5 DPSK Format

The simulation layouts for single channel 100Gb/s DPSK format with pre-, post and symmetrical compensating configurations are same as 40Gb/s DPSK format except the data rate, transmission fiber length, dispersion compensating fiber length and EDFA gain.

For pre- and post- compensating configurations transmission fiber length is 40km. and compensating fiber length is 7.1 km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers each length of 20km and two DCFs each length of 3.55km were used. In all configurations, BER and eye diagram analysis were done for 240km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 3.55dB and 8dB, for post-compensating configuration the gain of the EDFA's are 8dB and 3.55dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 100Gb/s single channel DPSK format with all compensating configurations are shown in Figure 3.43. For all compensating configurations BER is less than equal 10^{-9} up to 240km. As shown in this figure, BER values of all compensating configurations are mostly the same. Symmetrical compensating configuration represents the best case among all considered configurations.

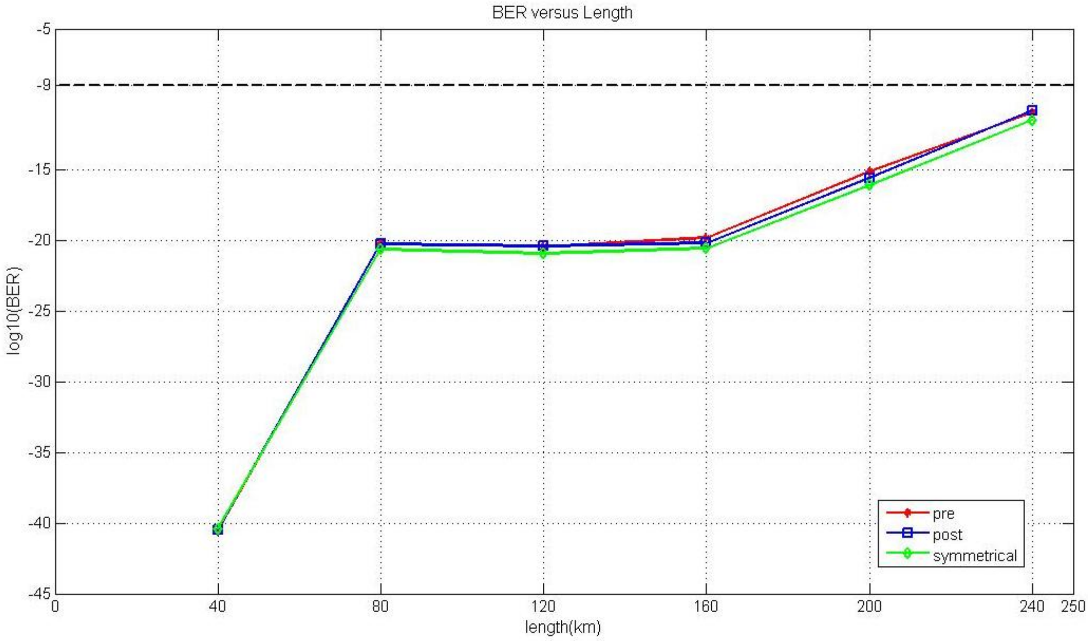
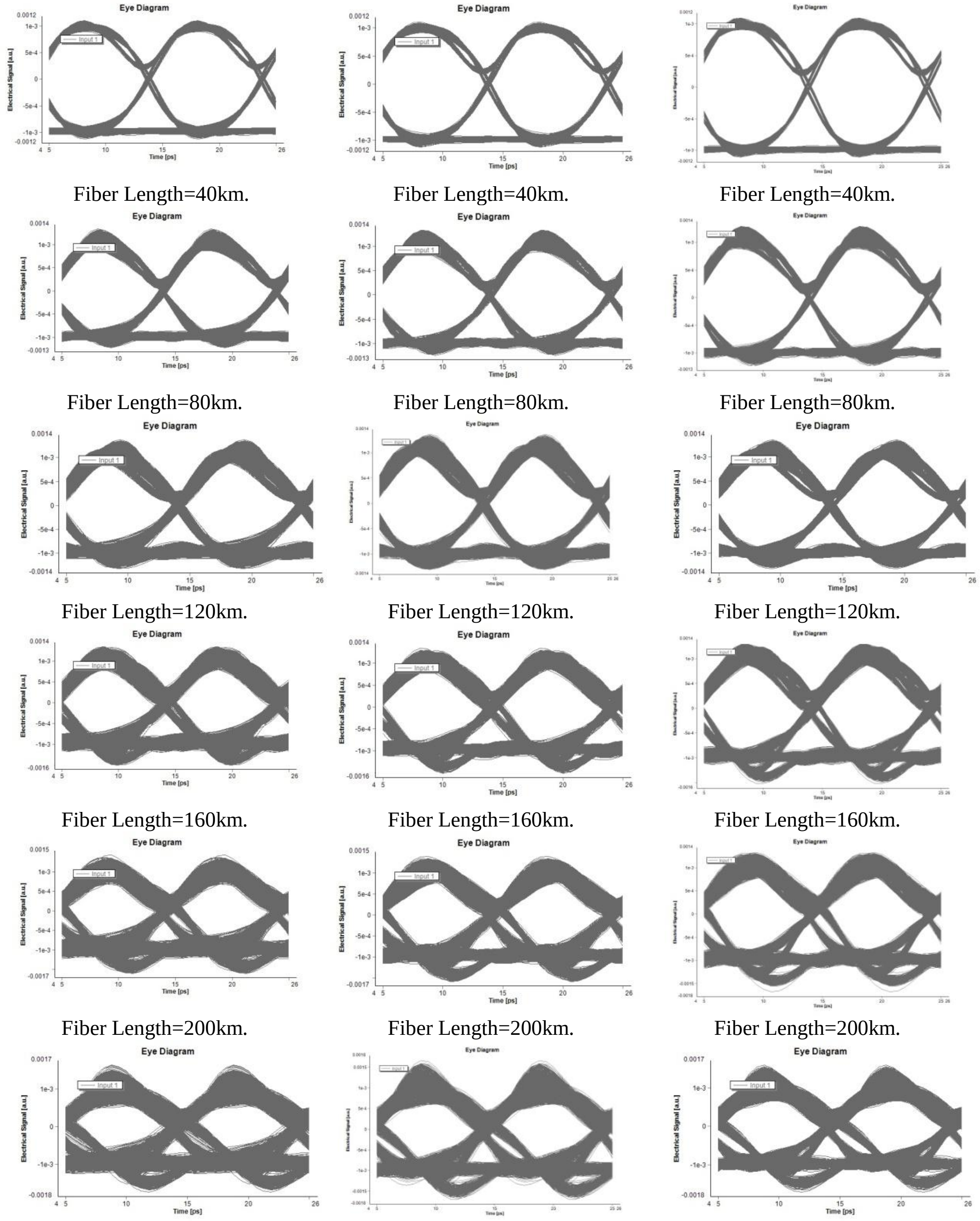


Figure 3.43 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.44. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 40km. As seen from this figure eye opening is good up to 240km.

Pre-compensating configuration | Post- compensating configuration | Symmetrical- compensating configuration



Fiber Length=240km. Fiber Length=240km. Fiber Length=240km.

Figure 3.44 Eye diagrams of system for different fiber lengths; (a) Pre-compensating configuration, (b) Post-compensating configuration, (c) Symmetrical compensating configuration.

3.3.1.6 CSRZ DPSK Format

The simulation layouts for single channel 100Gb/s CSRZ DPSK format with pre-, post and symmetrical compensating configurations are same as 40Gb/s CSRZ DPSK format except the data rate, transmission fiber length, dispersion compensating fiber length and EDFA gain.

For pre- and post- compensating configurations transmission fiber length is 40km. and compensating fiber length is 7.1 km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers each length of 20km and two DCFs each length of 3.55km were used. In all configurations, BER and eye diagram analysis were done for 240km. fiber length.

For pre-compensating configuration, the gain of the EDFA’s are 3.55dB and 8dB, for post-compensating configuration the gain of the EDFA’s are 8dB and 3.55dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 100Gb/s single channel CSRZ DPSK format with all compensating configurations are shown in Figure 3.45. For all compensating configurations BER is less than equal 10^{-9} up to 240km. As shown in this figure, BER values of post- and symmetrical compensating configurations are nearly the same and are better compared to pre- compensating configuration. Symmetrical compensating configuration represents the best case among all considered configurations.

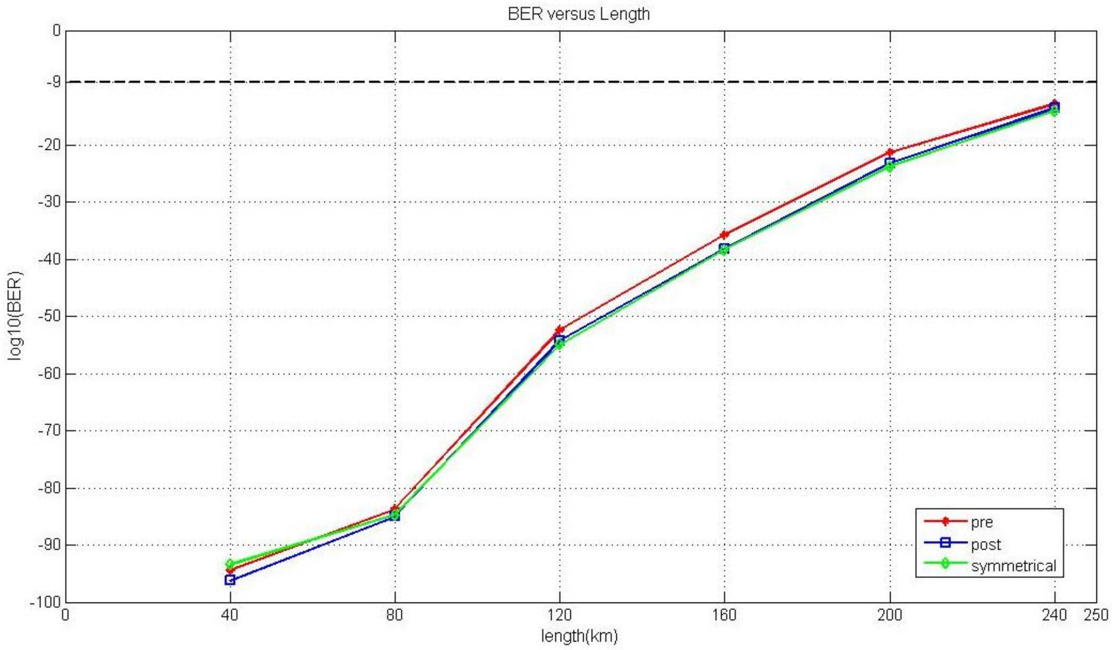


Figure 3.45 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.46. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 40km. As seen from this figure eye opening is good up to 240km.

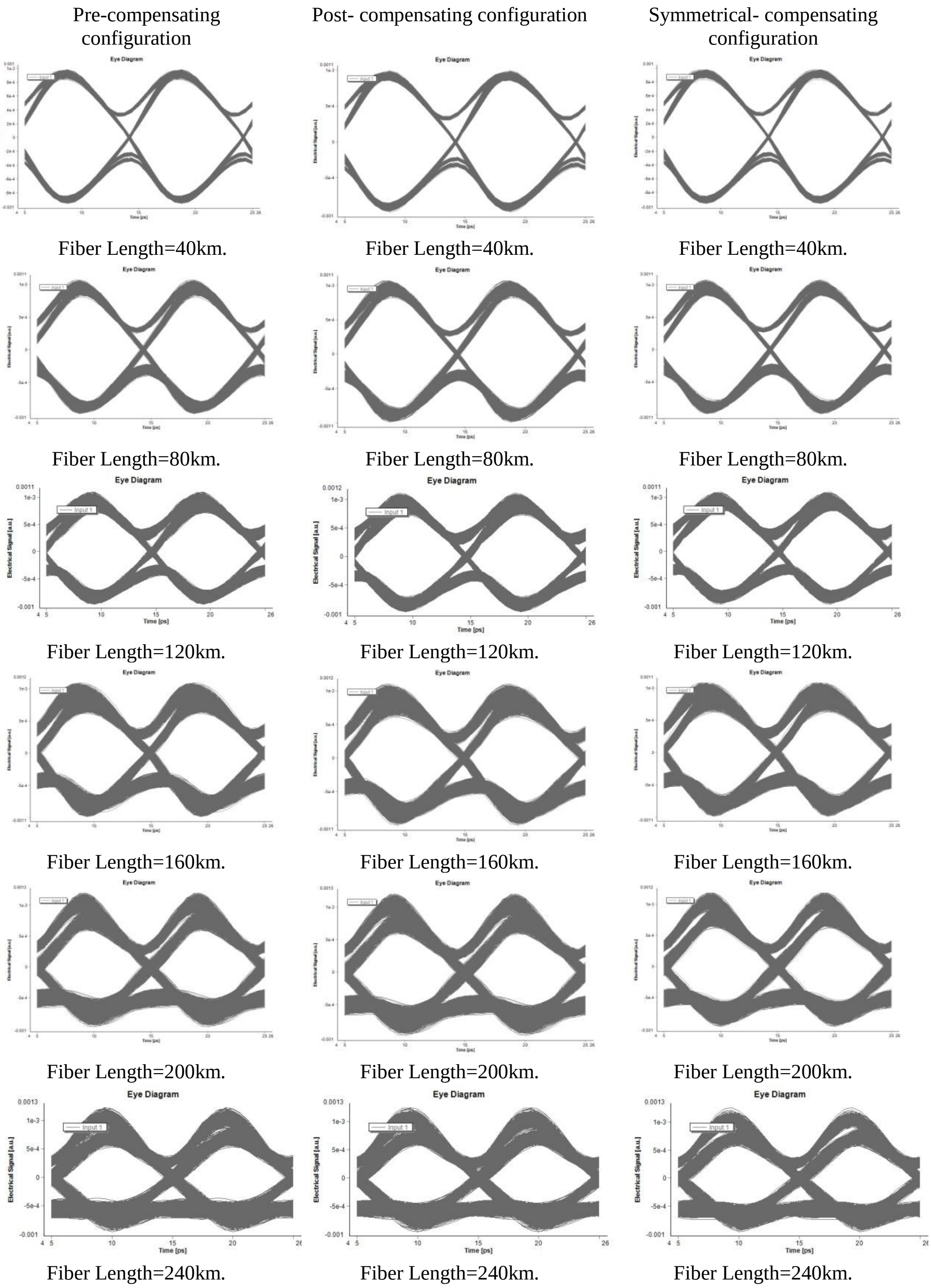


Figure 3.46 Eye diagrams of system for different fiber lengths; (a) Pre-compensating configuration, (b) Post-compensating configuration, (c) Symmetrical compensating configuration.

Single channel 100Gb/s for all modulation formats with pre- compensating configuration is shown in Figure 3.47. As shown in this figure the performance of RZ is better compared to others up to 120km. CSRZ-DPSK modulation format represents the best case among all considered formats up to 240km.

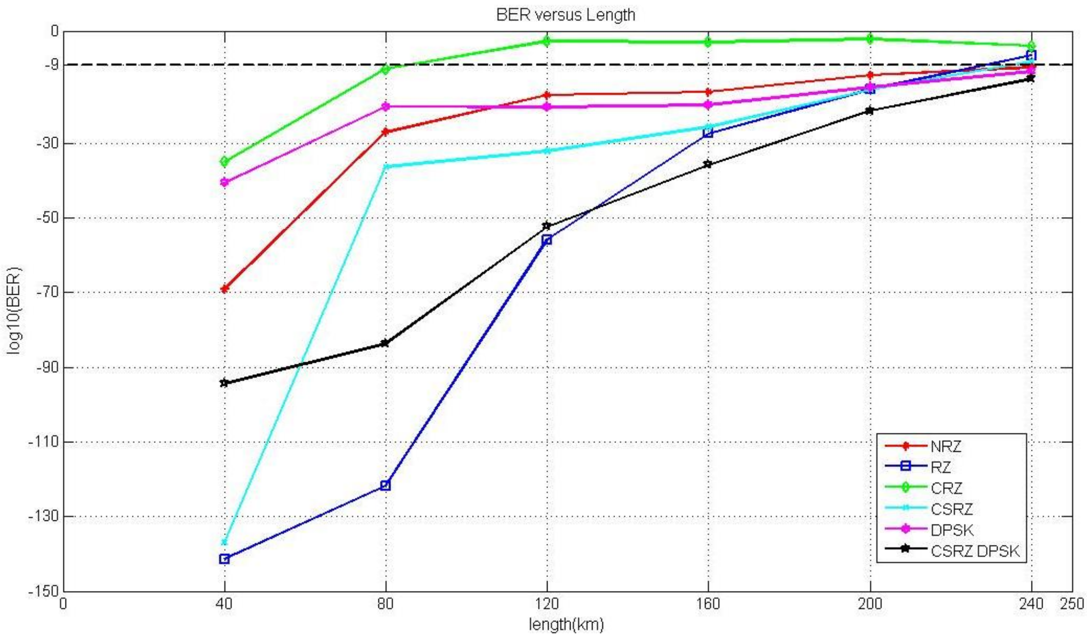


Figure 3.47 BER versus Length for single channel 100Gb/s system for all modulation formats with pre-compensating configuration.

Figure 3.48 shows the single channel 100Gb/s for all modulation formats with post-compensating configuration. As shown in this figure the performance of RZ is better compared to others up to 120km. CSRZ-DPSK modulation format represents the best case among all considered formats up to 240km.

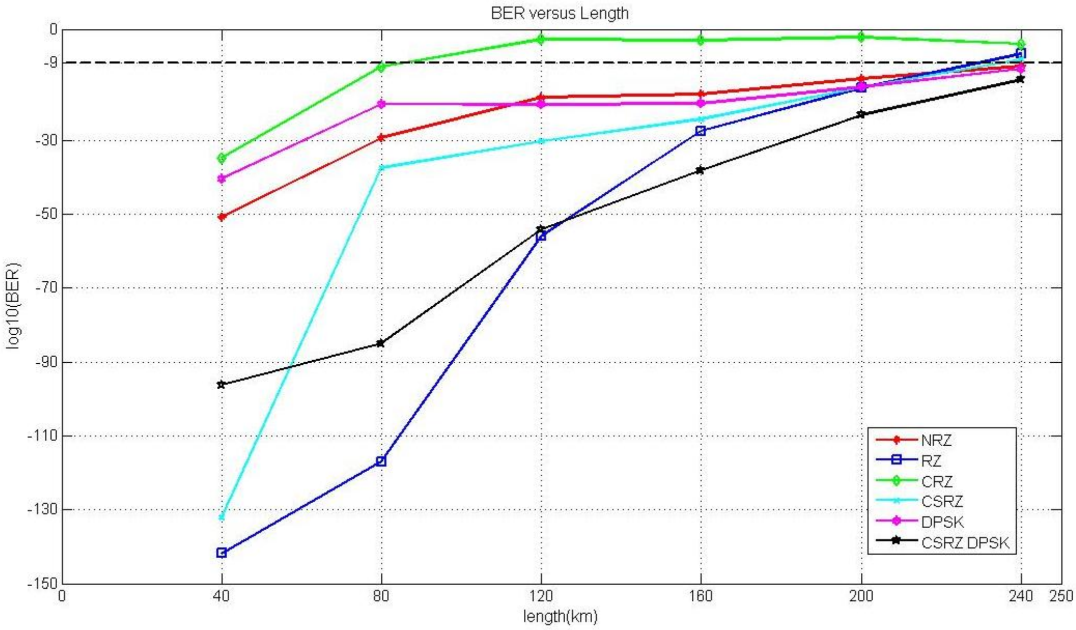


Figure 3.48 BER versus Length for single channel 100Gb/s system for all modulation formats with post-compensating configuration.

Single channel 100Gb/s for all modulation formats with symmetrical compensating configuration is shown in Figure 3.49. As shown in this figure the performance of RZ is better compared to others up to 120km. CSRZ-DPSK modulation format represents the best case among all considered formats up to 240km.

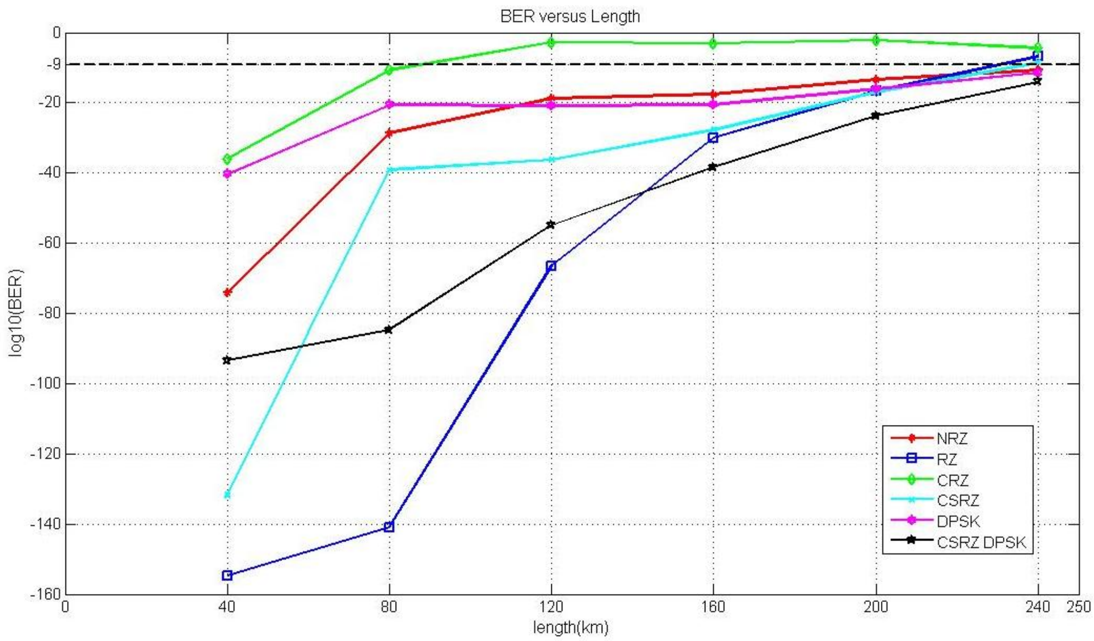


Figure 3.49 BER versus Length for single channel 100Gb/s system for all modulation formats with symmetrical compensating configuration.

3.3.2 11 Channels 100Gb/s WDM System

For 100Gb/s data-rate, 11 channels were used with the channel spacing of 400Ghz (3.2nm) and total capacity was 1.1Tb/s. For this system, modulation formats of NRZ, RZ, CRZ, CSRZ, DPSK and CSRZ-DPSK were analyzed with pre-, post- and symmetrical compensation configurations. Total transmission distance is 6x40km=240km. for each configuration.

In WDM optical systems, because of the nonlinear crosstalk, the middle channel generally has the worst performance. Channels that are far away do not affect each other much because they pass through each other quickly due to the dispersion. Therefore, in our simulations, we considered the middle channel 6 of the system.

3.3.2.1 NRZ Format

The simulation layouts for 11 channel 100Gb/s NRZ format with pre-, post and symmetrical compensating configurations are same as 40Gb/s NRZ format except the data rate, transmission fiber length, dispersion compensating fiber length and EDFA gain.

For pre- and post- compensating configurations transmission fiber length is 40km. and compensating fiber length is 7.1 km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers each length of 20km and two DCFs each length of 3.55km were used. In all configurations, BER and eye diagram analysis were done for 240km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 3.55dB and 8dB, for post-compensating configuration the gain of the EDFA's are 8dB and 3.55dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 100Gb/s 11 channels NRZ format with all compensating configurations are shown in Figure 3.50. For all compensating configurations BER is less than equal 10^{-9} up to 240km. As shown in this figure, BER values of post- compensating configuration is better compared to symmetrical compensating configuration. Pre- compensating configuration represents the best case among all considered configurations.

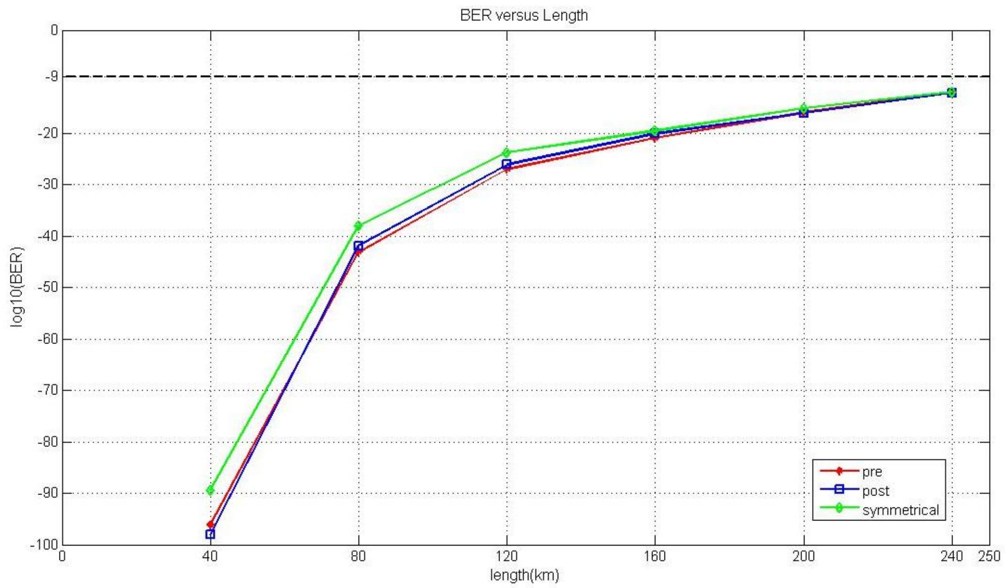


Figure 3.50 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.51. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 40km. As seen from this figure eye opening is good up to 240km.

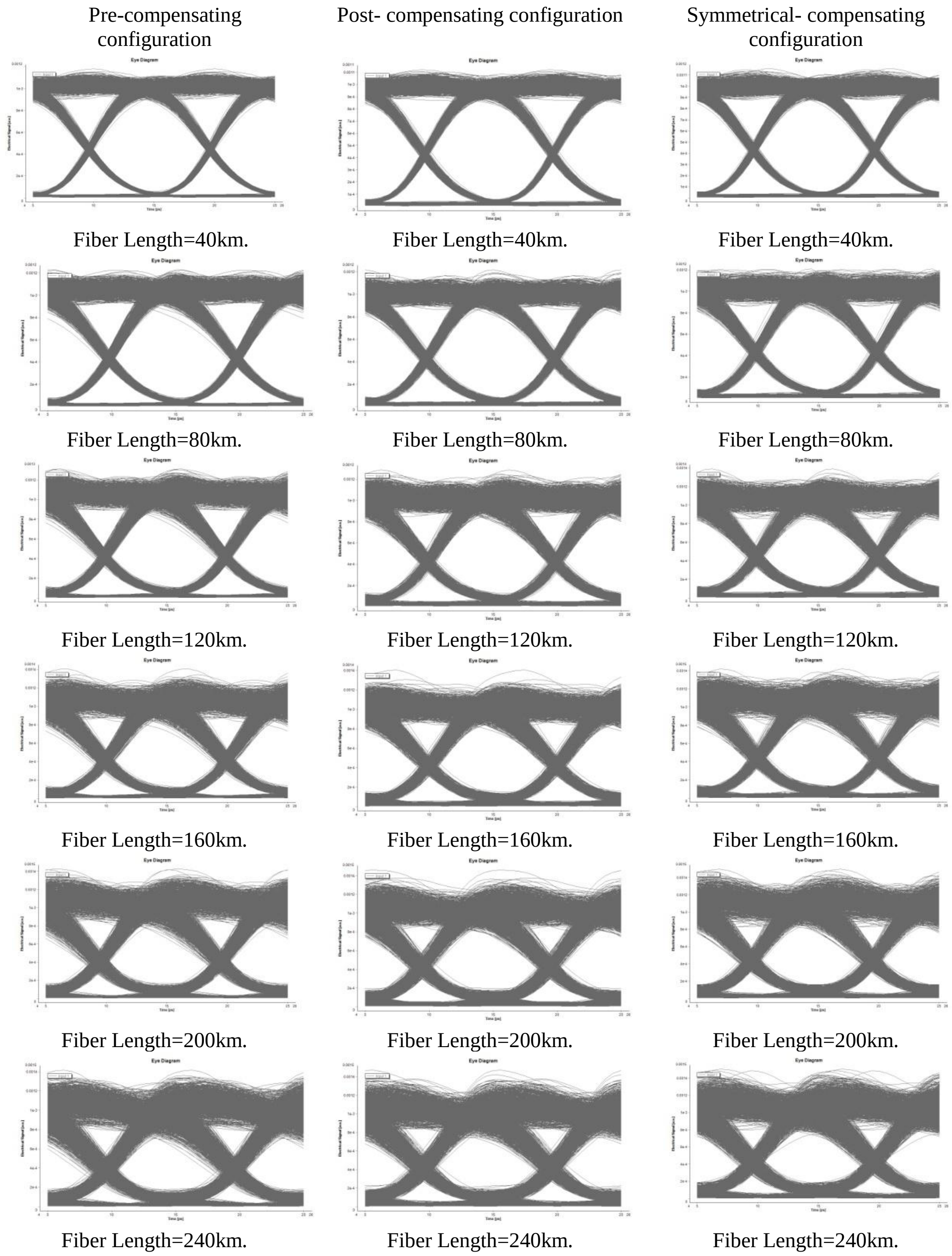


Figure 3.51 Eye diagrams of system for different fiber lengths; (a) Pre-compensating configuration, (b) Post-compensating configuration, (c) Symmetrical compensating configuration.

3.3.2.2 RZ Format

The simulation layouts for 11 channel 100Gb/s RZ format with pre-, post and symmetrical compensating configurations are same as 40Gb/s RZ format except the data rate, transmission fiber length, dispersion compensating fiber length and EDFA gain.

For pre- and post- compensating configurations transmission fiber length is 40km. and compensating fiber length is 7.1 km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers each length of 20km and two DCFs each length of 3.55km were used. In all configurations, BER and eye diagram analysis were done for 240km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 3.55dB and 8dB, for post-compensating configuration the gain of the EDFA's are 8dB and 3.55dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 100Gb/s 11 channels RZ format with all compensating configurations are shown in Figure 3.52. For all compensating configurations BER is less than equal 10^{-9} up to 200km. As shown in this figure, pre case is better compared to post case. Symmetrical compensating configuration represents the best case among all considered configurations.

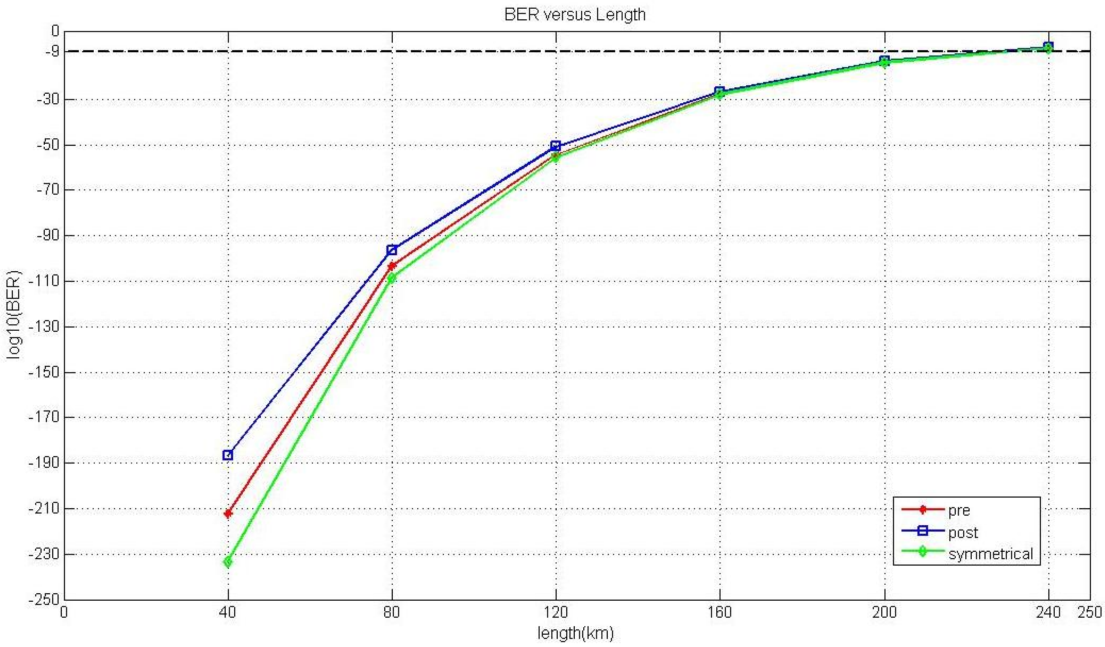


Figure 3.52 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.53. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 40km. As seen from this figure eye opening is good up to 200km.

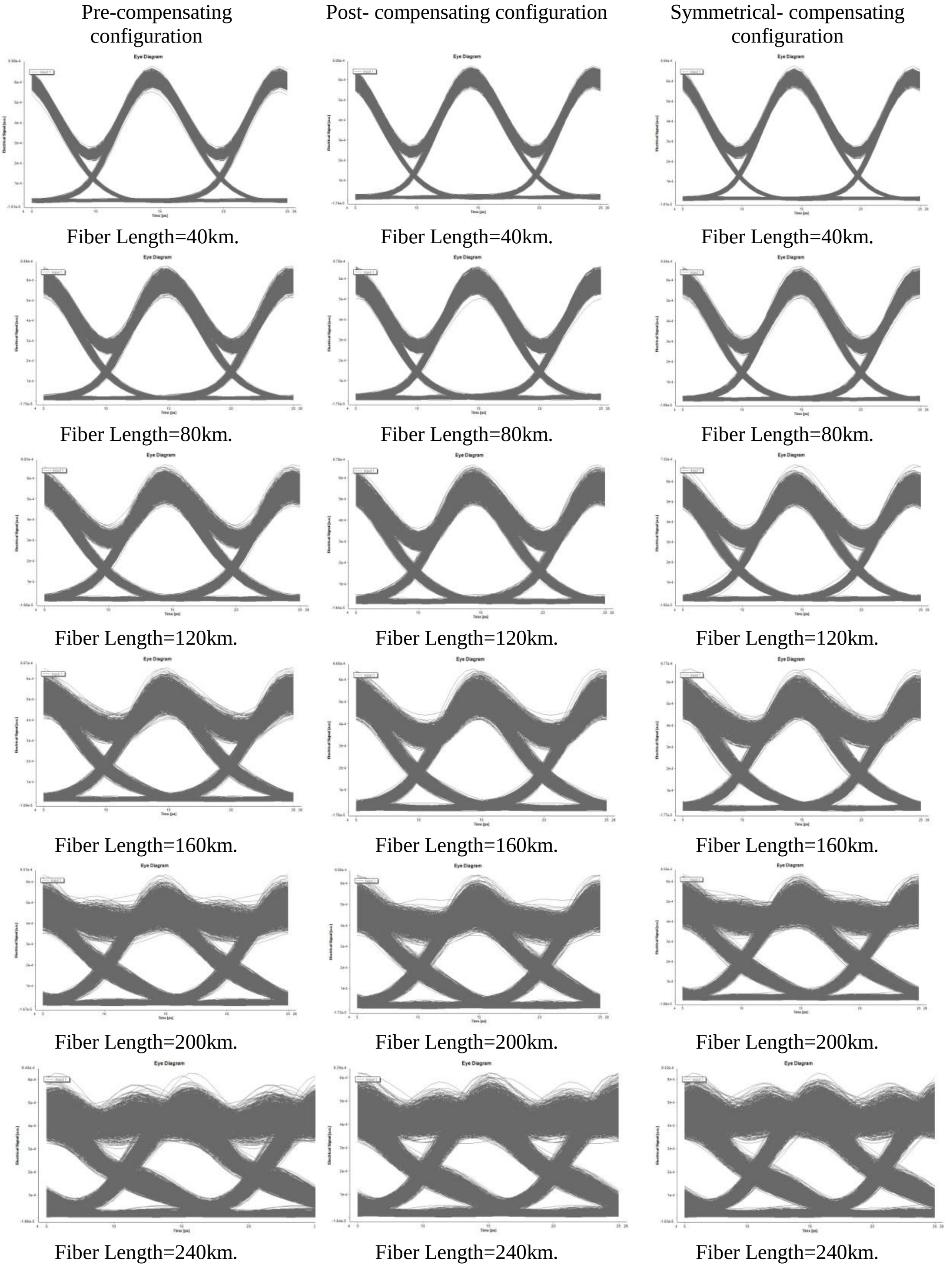


Figure 3.53 Eye diagrams of system for different fiber lengths; (a) Pre-compensating configuration, (b) Post-compensating configuration, (c) Symmetrical compensating configuration.

3.3.2.3 CRZ Format

The simulation layouts for 11 channel 100Gb/s CRZ format with pre-, post and symmetrical compensating configurations are same as 40Gb/s CRZ format except the data rate, transmission fiber length, dispersion compensating fiber length and EDFA gain.

For pre- and post- compensating configurations transmission fiber length is 40km. and compensating fiber length is 7.1 km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers each length of 20km and two DCFs each length of 3.55km were used. In all configurations, BER and eye diagram analysis were done for 240km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 3.55dB and 8dB, for post-compensating configuration the gain of the EDFA's are 8dB and 3.55dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 100Gb/s 11 channels CRZ format with all compensating configurations are shown in Figure 3.54. For all compensating configurations BER is less than equal 10^{-9} up to 120km. As shown in this figure, BER values of post- and pre- compensating configurations are nearly the same. Symmetrical compensating configuration represents the best case among all considered configurations.

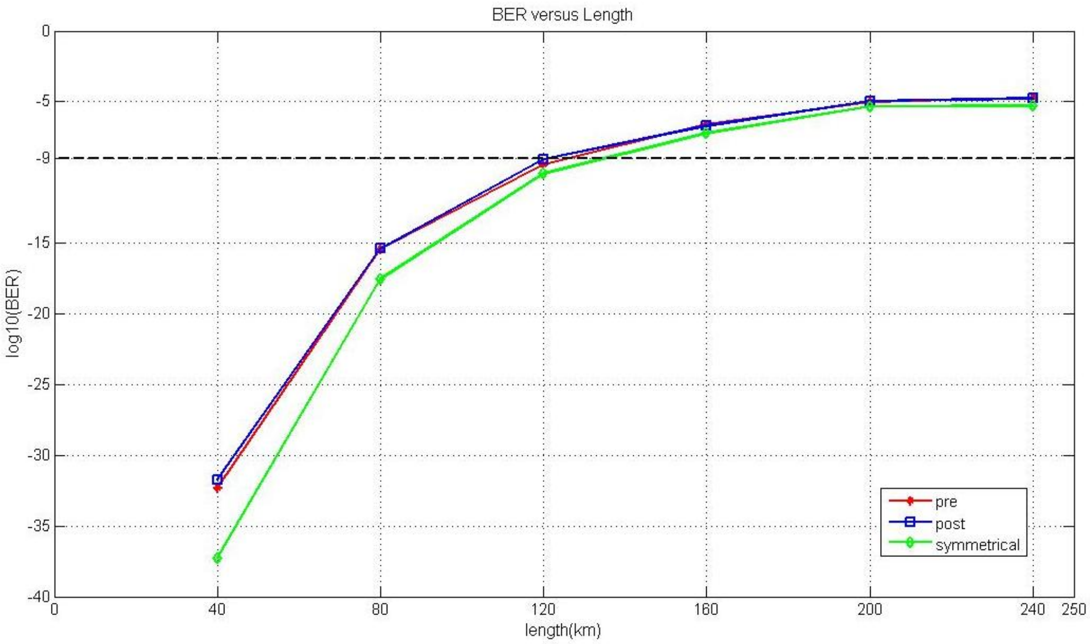


Figure 3.54 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.55. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 40km. As seen from this figure eye opening is good up to 120km.

Pre-compensating configuration | Post- compensating configuration | Symmetrical- compensating configuration

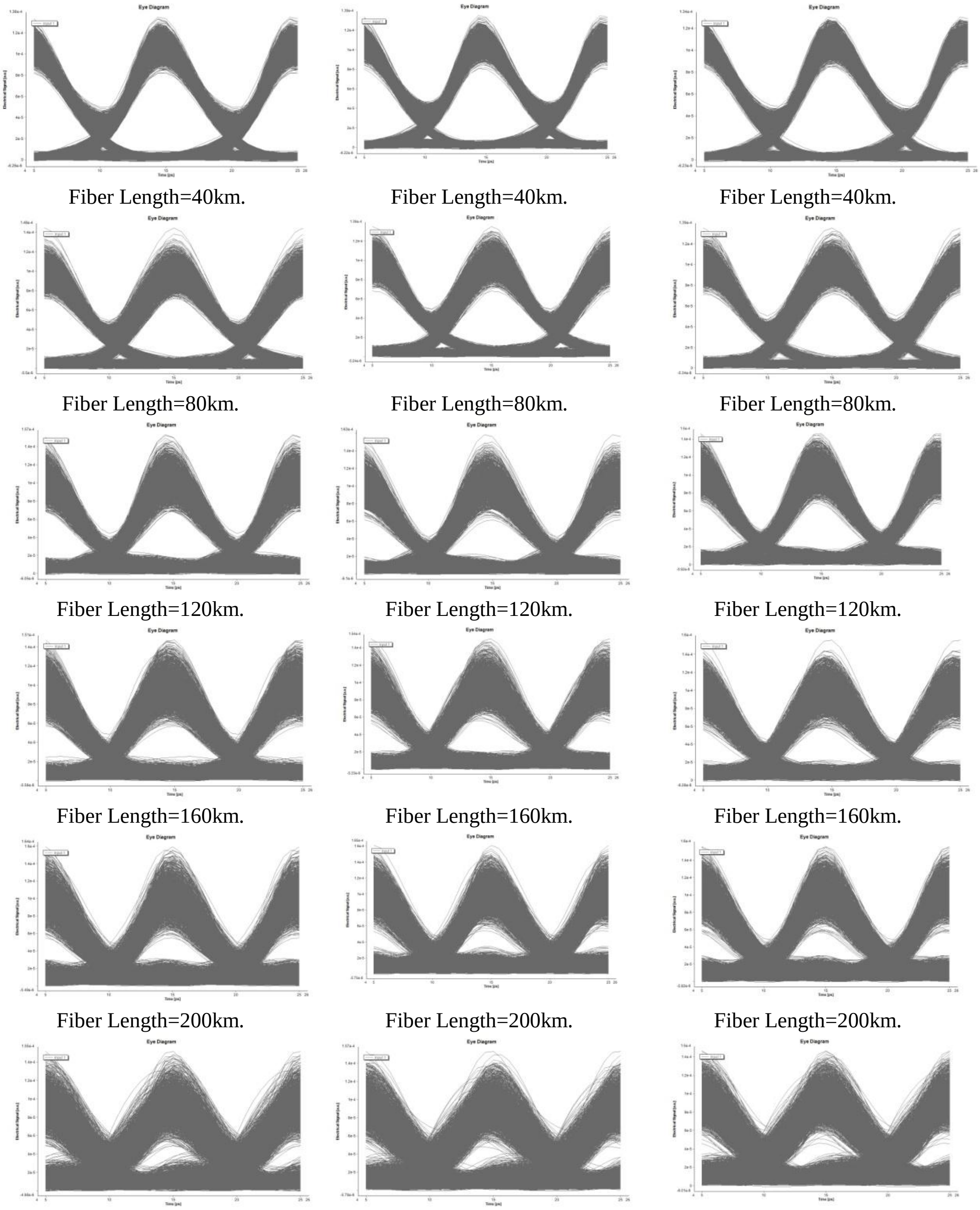


Figure 3.55 Eye diagrams of system for different fiber lengths; (a) Pre-compensating configuration, (b) Post-compensating configuration, (c) Symmetrical compensating configuration.

3.3.2.4 CSRZ Format

The simulation layouts for 11 channel 100Gb/s CSRZ format with pre-, post and symmetrical compensating configurations are same as 40Gb/s CSRZ format except the data rate, transmission fiber length, dispersion compensating fiber length and EDFA gain.

For pre- and post- compensating configurations transmission fiber length is 40km. and compensating fiber length is 7.1 km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers each length of 20km and two DCFs each length of 3.55km were used. In all configurations, BER and eye diagram analysis were done for 240km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 3.55dB and 8dB, for post-compensating configuration the gain of the EDFA's are 8dB and 3.55dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 100Gb/s 11 channels CSRZ format with all compensating configurations are shown in Figure 3.56. For all compensating configurations BER is less than equal 10^{-9} up to 200km. As shown in this figure, BER values of pre- compensating configuration is better compared to post-compensating configuration. Symmetrical compensating configuration represents the best case among all considered configurations.

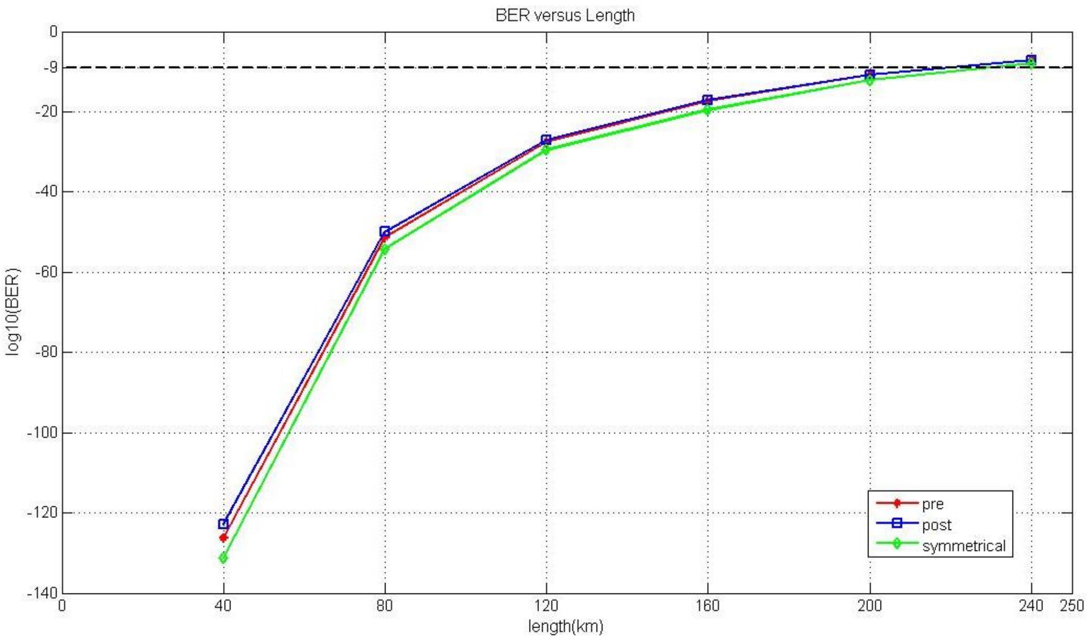


Figure 3.56 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.57. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 40km. As seen from this figure eye opening is good up to 200km.

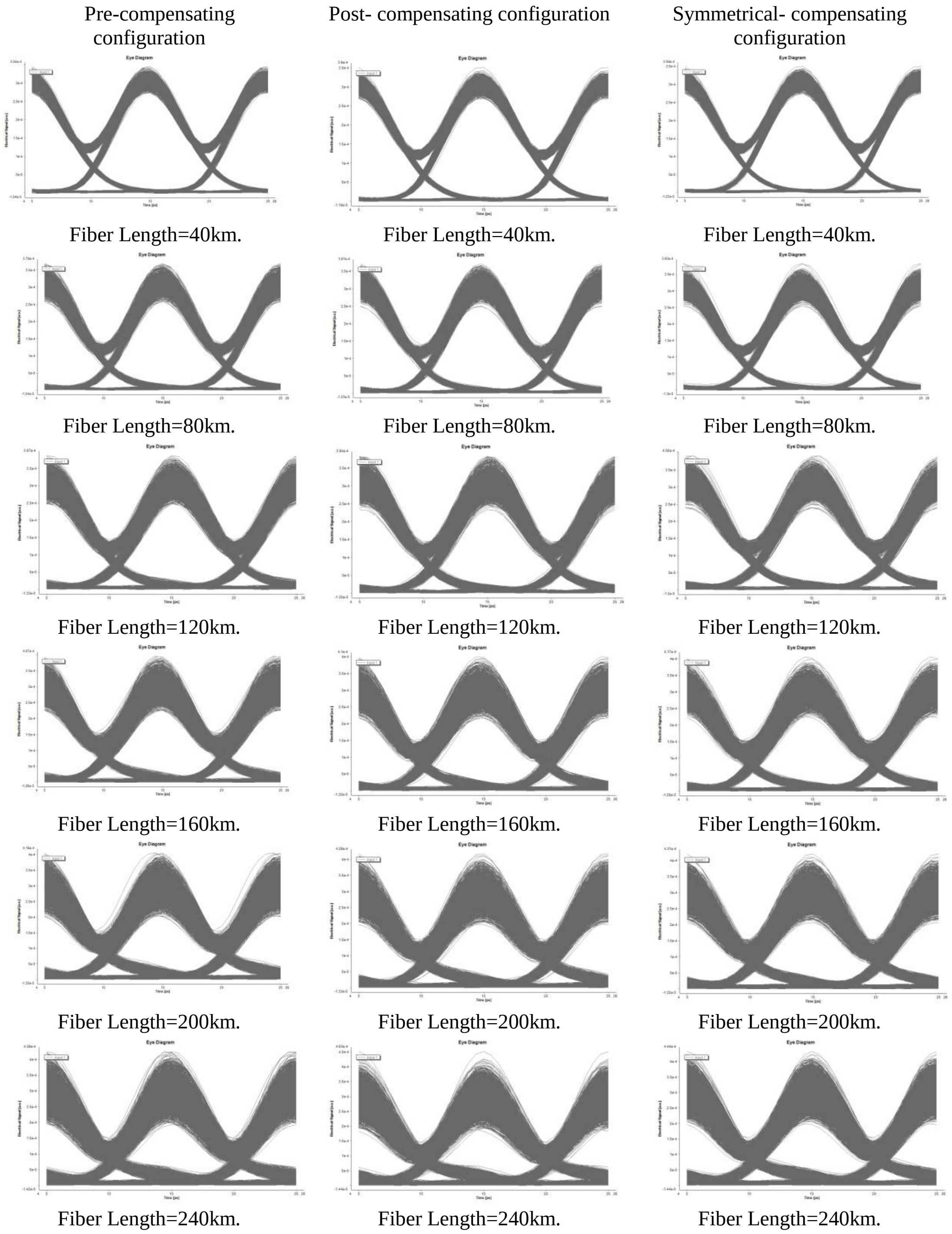


Figure 3.57 Eye diagrams of system for different fiber lengths; (a) Pre-compensating configuration, (b) Post-compensating configuration, (c) Symmetrical compensating configuration.

3.3.2.5 DPSK Format

The simulation layouts for 11 channel 100Gb/s DPSK format with pre-, post and symmetrical compensating configurations are same as 40Gb/s DPSK format except the data rate, transmission fiber length, dispersion compensating fiber length and EDFA gain.

For pre- and post- compensating configurations transmission fiber length is 40km. and compensating fiber length is 7.1 km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers each length of 20km and two DCFs each length of 3.55km were used. In all configurations, BER and eye diagram analysis were done for 240km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 3.55dB and 8dB, for post-compensating configuration the gain of the EDFA's are 8dB and 3.55dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 100Gb/s 11 channels DPSK format with all compensating configurations are shown in Figure 3.58. For all compensating configurations BER is less than equal 10^{-9} up to 240km. As shown in this figure, BER values of pre-and post- compensating configurations are nearly the same and are better compared to symmetrical case. Post compensating configuration represents the best case among all considered configurations.

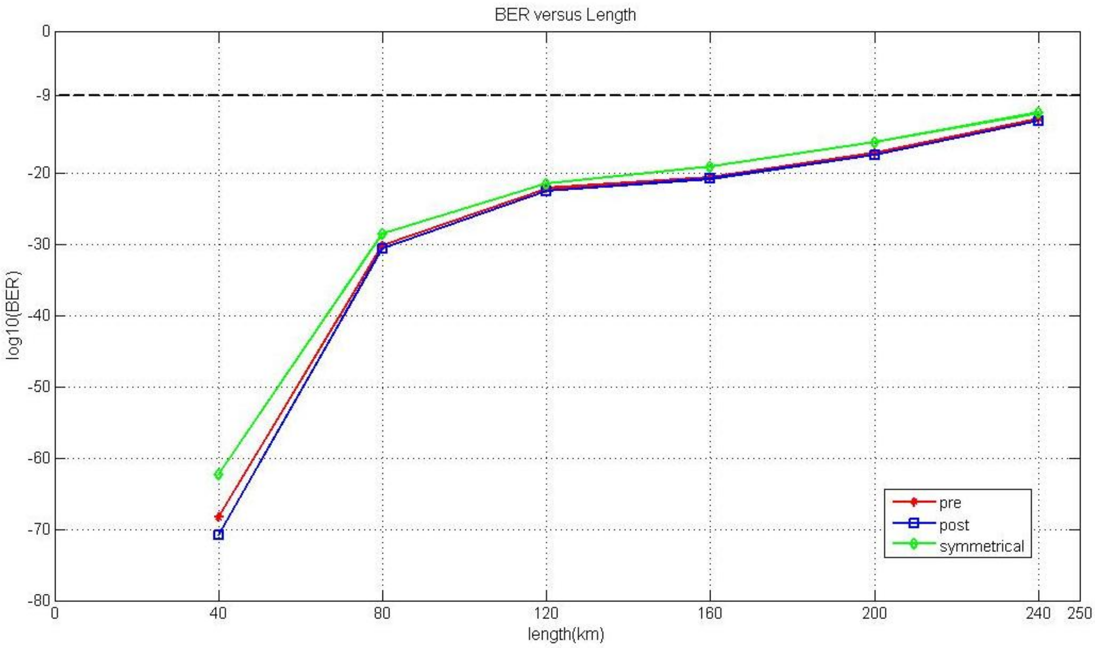


Figure 3.58 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.59. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 40km. For all compensating configuration eye opening is good up to 240km.

Pre-compensating configuration | Post- compensating configuration | Symmetrical- compensating configuration

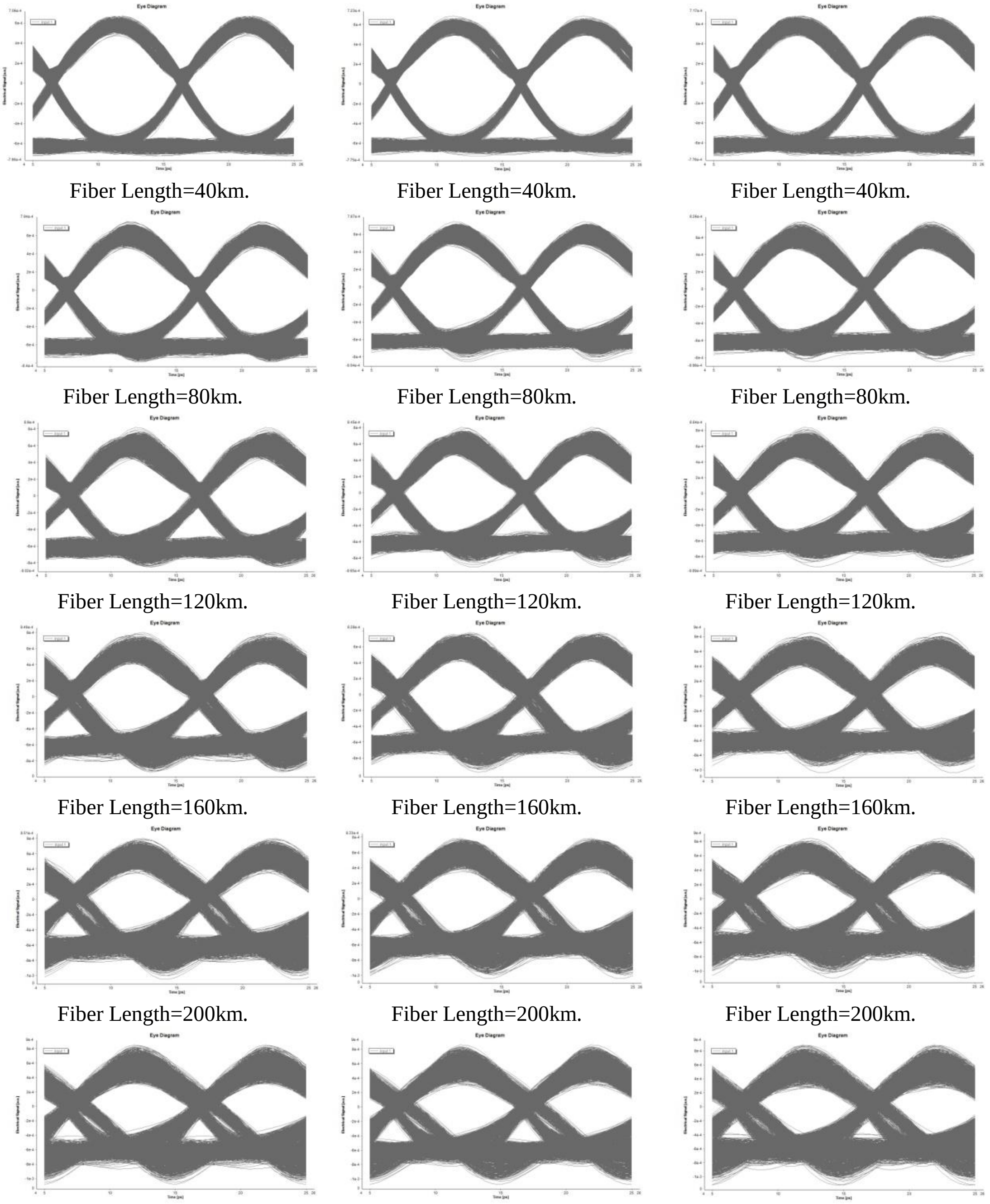


Figure 3.59 Eye diagrams of system for different fiber lengths; (a) Pre-compensating configuration, (b) Post-compensating configuration, (c) Symmetrical compensating configuration.

3.3.2.6 CSRZ DPSK Format

The simulation layouts for 11 channel 100Gb/s CSRZ DPSK format with pre-, post- and symmetrical compensating configurations are same as 40Gb/s CSRZ DPSK format except the data rate, transmission fiber length, dispersion compensating fiber length and EDFA gain.

For pre- and post- compensating configurations transmission fiber length is 40km. and compensating fiber length is 7.1 km evaluated using the Eq. (3.2) and Eq. (3.4). For symmetrical compensating configuration, two transmission fibers each length of 20km and two DCFs each length of 3.55km were used. In all configurations, BER and eye diagram analysis were done for 240km. fiber length.

For pre-compensating configuration, the gain of the EDFA's are 3.55dB and 8dB, for post-compensating configuration the gain of the EDFA's are 8dB and 3.55dB evaluated from Eq. (3.1) and Eq. (3.3).

The graph of BER versus Length for 100Gb/s 11 channels NRZ format with all compensating configurations are shown in Figure 3.60 For all compensating configurations BER is less than equal 10^{-9} up to 240km. As shown in this figure, BER values of pre-and post- compensating configurations are nearly the same. Symmetrical compensating configuration represents the best case among all considered configurations.

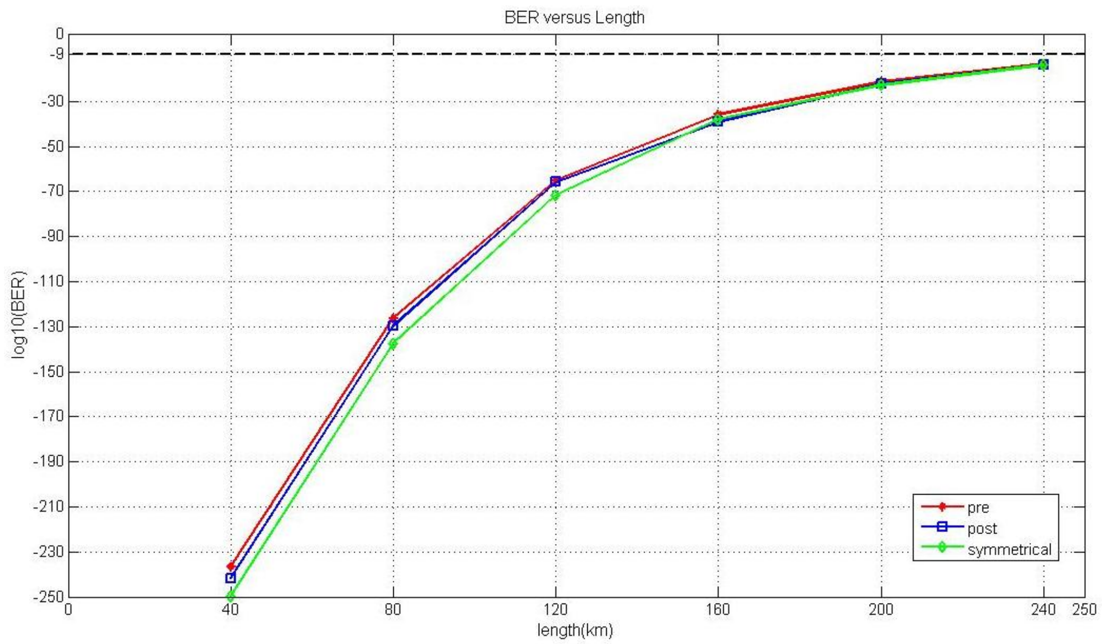


Figure 3.60 BER versus Length with all dispersion compensating configuration.

The eye diagrams of this system are shown in Figure 3.61. The eye diagrams show the eye opening of system for different fiber lengths. Each span is 40km. As seen from this figure eye opening is good up to 240km.

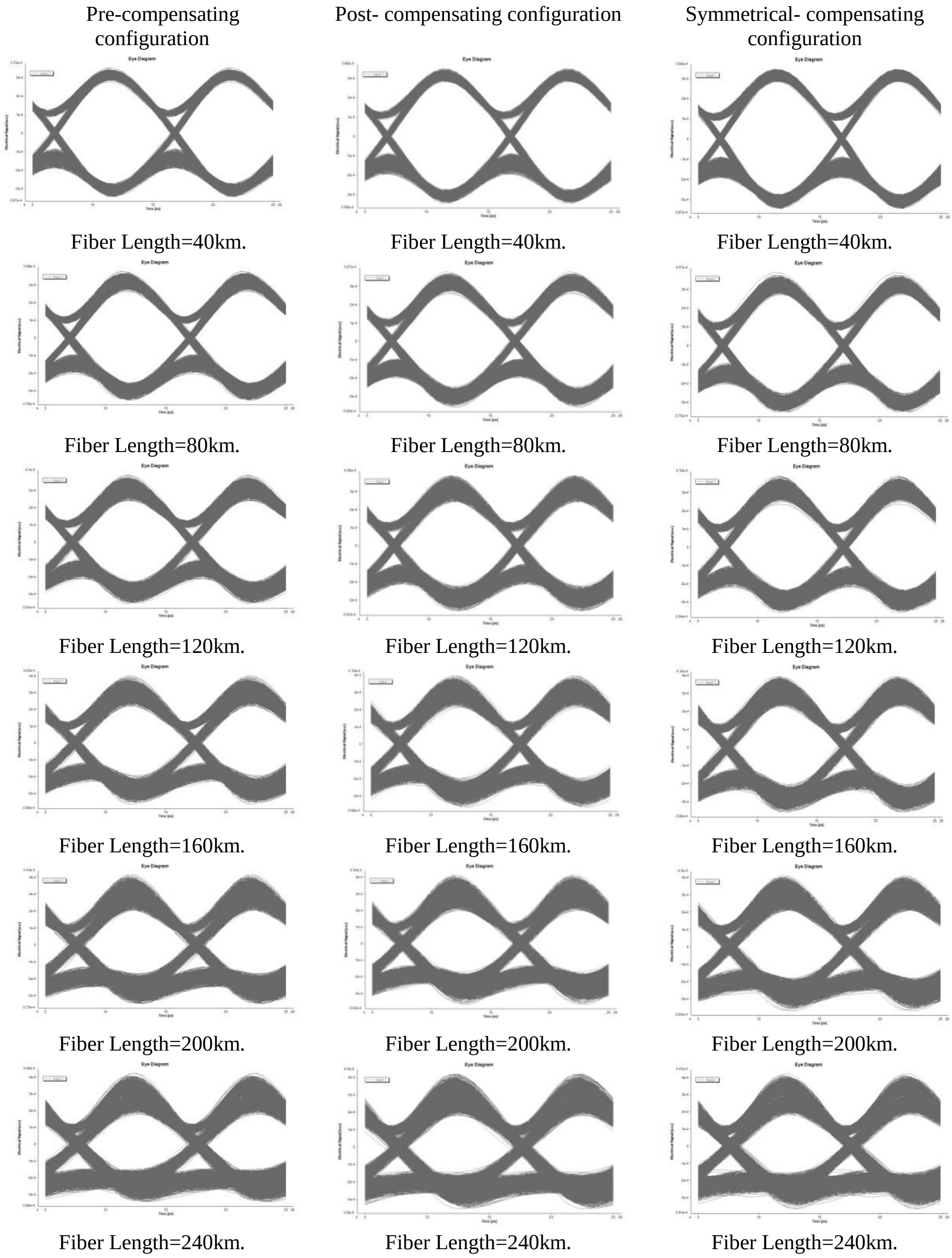


Figure 3.61 Eye diagrams of system for different fiber lengths; (a) Pre-compensating configuration, (b) Post-compensating configuration, (c) Symmetrical compensating configuration.

11 channels 100Gb/s for all modulation formats with pre- compensating configuration is shown in Figure 3.62. As shown in this figure, CSRZ DPSK modulation format represents the best case among all considered formats up to 240km. The performance of RZ is better compared to others up to 200km. CSRZ is good up to 200km. NRZ and DPSK also provide 240km. CRZ is the worst case.

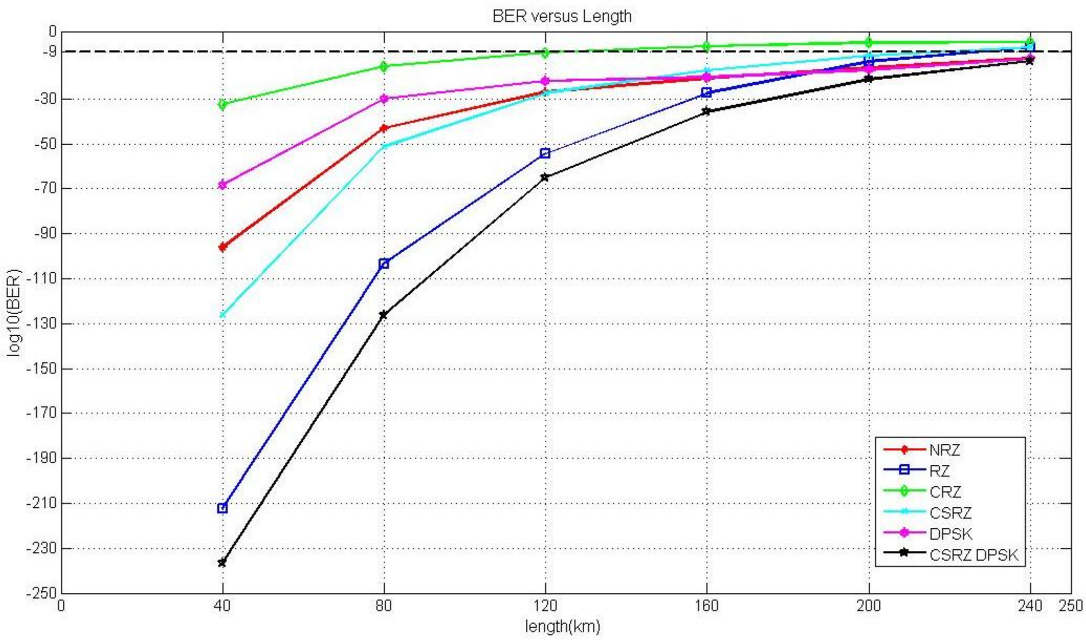


Figure 3.62 BER versus Length for 11 channels 100Gb/s system for all modulation formats with pre-compensating configuration.

Figure 3.63 shows the 11 channels 100Gb/s for all modulation formats with post-compensating configuration. As shown in this figure, CSRZ DPSK modulation format represents the best case among all considered formats up to 240km. The performance of RZ is better compared to others up to 200km. CSRZ is good up to 200km. NRZ and DPSK also provide 240km. CRZ is the worst case.

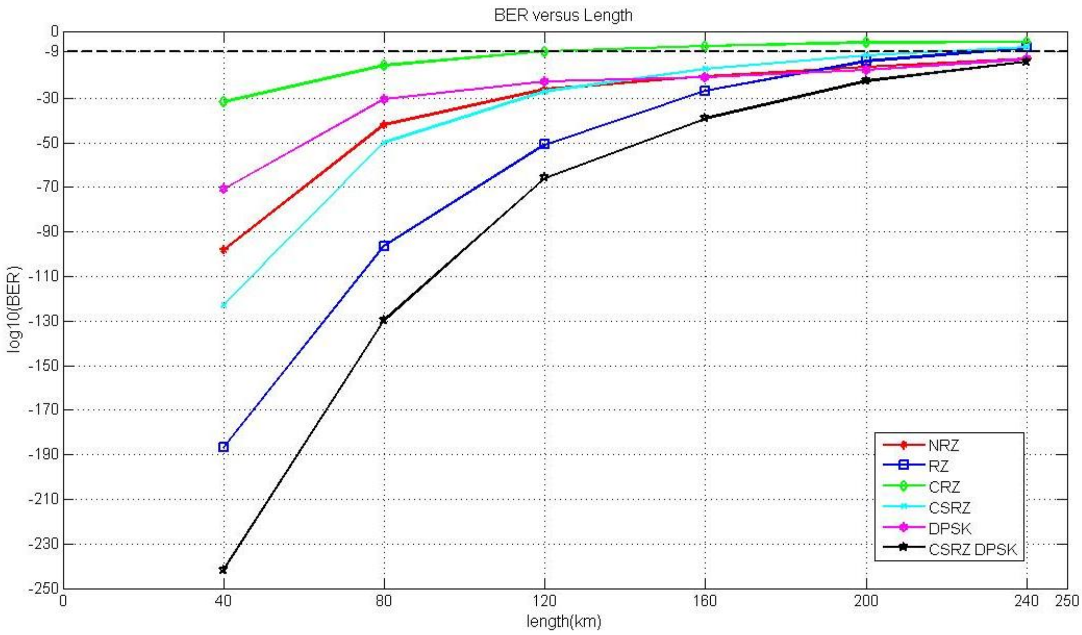


Figure 3.63 BER versus Length for 11channels 100Gb/s system for all modulation formats with post-compensating configuration.

11 channels 100Gb/s for all modulation formats with symmetrical compensating configuration is shown in Figure 3.64. As shown in this figure, CSRZ DPSK modulation format represents the best case among all considered formats up to 240km. The performance of RZ is better compared to others up to 200km. CSRZ is good up to 200km. NRZ and DPSK also provide 240km. CRZ is the worst case.

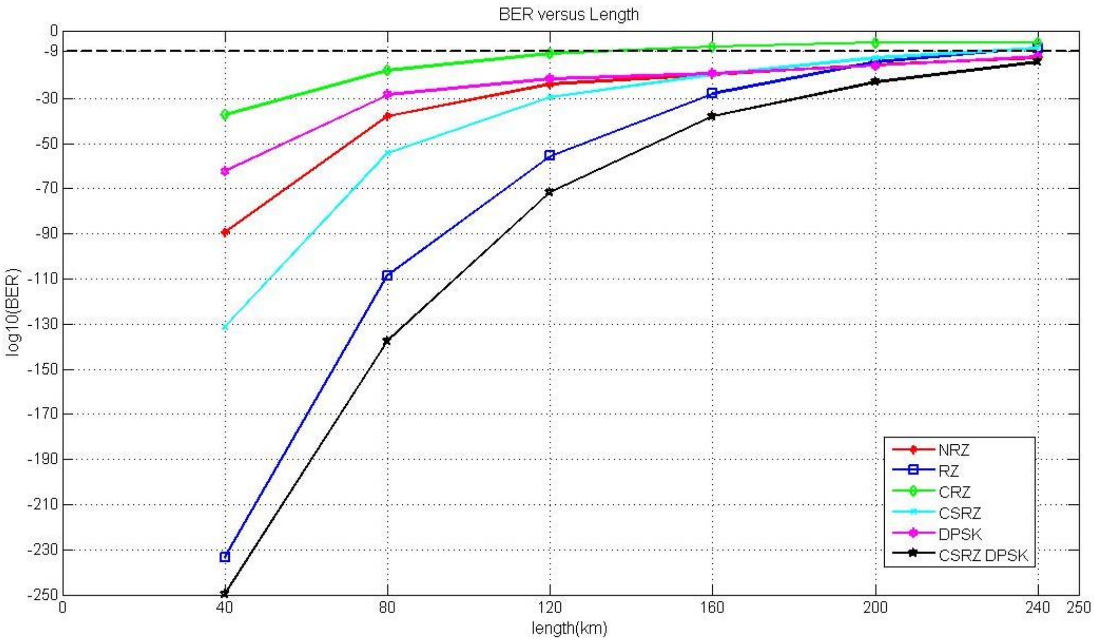


Figure 3.64 BER versus Length for 11 channels 100Gb/s system for all modulation formats with symmetrical compensating configuration.

Table 3.2 Performance of 40 Gb/s and 100Gb/s WDM Systems with all Modulation Formats and Compensating Configuration.

Modulation Format	40Gb/s						100 Gb/s					
	Single Channel			25 Channels			Single Channel			11 Channels		
	Compensating configuration	Transmission Length 12x80=960km	BER	Compensating configuration	Transmission Length 12x80=960km	BER	Compensating configuration	Transmission Length 6x40=240km	BER	Compensating configuration	Transmission Length 6x40=240km	BER
NRZ	**symmetrical**	**960km**	1.03E-18	symmetrical	480km	5.20E-11	**symmetrical**	**240km**	2.25E-11	**post**	**240km**	6.07E-13
	post	**960km**	1.30E-11	post	400km	1.80E-09	**post**	**240km**	1.09E-10	**symmetrical**	**240km**	9.81E-13
	pre	**960km**	3.64E-09	pre	240km	9.94E-09	**pre**	**240km**	1.92E-10	**pre**	**240km**	1.09E-12
RZ	**symmetrical**	**960km**	1.03E-25	**symmetrical**	**960km**	2.16E-11	symmetrical	200km	2.22E-17	symmetrical	200km	1.30E-14
	post	**960km**	4.44E-10	**pre**	**960km**	5.82E-09	post	200km	1.14E-16	pre	200km	3.27E-14
	pre	**960km**	2.16E-09	post	800km	1.98E-09	pre	200km	2.31E-16	post	200km	4.44E-14
CRZ	**symmetrical**	**960km**	1.35E-09	symmetrical	720km	4.67E-09	symmetrical	80km	2.22E-11	symmetrical	120km	8.66E-11
	post	800km	3.34E-09	pre	240km	6.33E-10	post	80km	7.34E-11	pre	120km	3.75E-10
	pre	720km	1.14E-09	post	240km	7.93E-10	pre	80km	7.81E-11	post	120km	8.77E-10
CSRZ	**symmetrical**	**960km**	2.57E-17	**symmetrical**	**960km**	2.02E-11	**symmetrical**	**240km**	2.65E-09	symmetrical	200km	7.24E-13
	post	**960km**	2.30E-10	post	640km	1.45E-09	**pre**	**240km**	6.37E-09	post	200km	1.39E-11
	pre	**960km**	2.40E-10	pre	640km	2.19E-09	**post**	**240km**	5.97E-09	pre	200km	1.57E-11
DPSK	**symmetrical**	**960km**	7.45E-15	post	800km	6.94E-09	**symmetrical**	**240km**	3.46E-12	**post**	**240km**	2.71E-13
	post	**960km**	3.84E-12	pre	720km	9.94E-09	**post**	**240km**	1.73E-11	**pre**	**240km**	4.36E-13
	pre	800km	4.26E-10	symmetrical	480km	7.29E-10	**pre**	**240km**	1.23E-11	**symmetrical**	**240km**	3.13E-12
CSRZ DPSK	**symmetrical**	**960km**	**1.13E-47**	**symmetrical**	**960km**	**8.83E-16**	**symmetrical**	**240km**	**8.88E-15**	**symmetrical**	**240km**	**1.02E-14**
	post	**960km**	1.12E-32	**post**	**960km**	8.71E-14	**post**	**240km**	2.41E-14	**post**	**240km**	2.28E-14
	pre	**960km**	1.26E-19	**pre**	**960km**	7.87E-13	**pre**	**240km**	1.51E-13	**pre**	**240km**	5.22E-14

As seen from the Table 3.2, for single channel 40Gb/s system all modulation formats with all compensating configuration provide transmission length of 960km. CSRZ DPSK modulation format with symmetrical compensating configuration represents better performance among all formats and configuration. Its BER value is 1.13E-47.

For 25 Channels with the same data rate, RZ with symmetrical and pre compensating configurations, CSRZ with symmetrical compensating configuration and CSRZ DPSK with all compensating configuration provide 960km. CSRZ DPSK modulation format with symmetrical compensating configuration represents better performance among all formats and configuration. Its BER value is 8.83E-16.

For single channel 100Gb/s system NRZ with all compensating configurations, CSRZ with all compensating configurations, DPSK with all compensating configurations and CSRZ DPSK with all compensating configuration provide transmission length of 240km. CSRZ DPSK modulation format with symmetrical compensating configuration represents better performance among all formats and configuration. Its BER value is 8.88E-15.

For 11 Channels with the same data rate, NRZ with all compensating configurations, DPSK with all compensating configuration, and CSRZ DPSK with all compensating configurations provide 240km. CSRZ DPSK modulation format with symmetrical compensating configuration represents better performance among all formats and configuration. Its BER value is 1.02E-14.

As a result for the entire system configuration, CSRZ DPSK modulation format with symmetrical compensating configuration represents better performance among all formats and configuration.

CHAPTER 4

CONCLUSION

Advanced modulation formats play an important role in the design of networks. In this dissertation, most used modulation formats were reviewed. NRZ, RZ, CRZ, CSRZ, DPSK, NRZ-DPSK, RZ-DPSK, and CSRZ-DPSK were been explained and compared. In order to compare and analysis the transmission performances of modulation formats computer simulation have been performed. The system performance was monitored by means of eye-diagram. For all systems BER versus fiber length were analyzed. Firstly single channel for different modulation formats were focused on.40Gb/s, 100Gb/s data rate were considered. Then, channel numbers were increased. For 40Gb/s data-rate, 25 channels were used with the channel spacing of 160GHz (1.28nm) and total capacity was 1Tb/s. For 100Gb/s data-rate, 11 channels were used with the channel spacing of 400GHz (3.2nm) and total capacity was 1.1Tb/s. In all cases, simulations were performed in the C-band (1530nm – 1565nm).

Different fiber types and different modulation formats could affect the system performance. In this simulations, Standard Single mode fiber (SSMF) was used.

In order to compensate the accumulated dispersion in the fiber different types of dispersion compensating configurations were considered. Pre-, post-, and symmetrical dispersion compensating configurations were applied each case. In these configurations, optical amplifiers after each fiber have been used to compensate for the span loss. The system performance has been monitored by means of eye-diagram. BER and system length graphs for all case analyzed. Symmetrical dispersion compensating configurations for majority of the modulation formats represents better performance among all compensating configuration because it is the combination of pre- and post- compensating configurations and provides the advantages of both of them. The performances of post- and pre- compensating configurations are nearly the same and post- case is slightly better compared to pre-case.

Chromatic dispersion and nonlinear effects of XPM, SPM and FWM are important constraints for long haul transmission optical system. These are the critical to the performance of the system. Modulation formats is the important method to reduce this linear and nonlinear impairments.

The effect of dispersion is increased while the bit rate increases. 40Gb/s system has better tolerance to dispersion than 100Gb/s system. For example single channel 40Gb/s system with symmetrical compensating configuration, the best performance, has BER value of 1.13E-47 at 960km. On the other hand, single channel 100Gb/s system with symmetrical compensating configuration, the best performance, has BER value of 8.88E-15 at 240km. In addition 25 channels 40Gb/s WDM system with symmetrical compensating configuration, the best performance, has BER value of 8.83E-16 at 960km. while 11 channels 100Gb/s CSRZ DPSK WDM system with symmetrical compensating configuration, the best performance, has BER value of 1.02E-14 at 240km. Therefore 40Gb/s system is simulated for the transmission length of 960km. and fiber span length of 80km, 100Gb/s system is simulated for the transmission length of 240km. and fiber span length of 40km. In simulations, maximum transmission length for single and 25 channels 40Gb/s systems are 960km., for single and 11 channels 100GB/s systems are 240km.

The nonlinear effects of the fiber are increased in multiple channels. The performance of single channel is better than 25 channels in 40Gb/s system. Similarly, the performance of single channel is better than 11 channels in 100Gb/s system. For example, the performance of single channel 40Gb/s CSRZ DPSK system with symmetrical compensating configuration, the best performance, has BER value of 1.13E-47 at 960km. On the other hand 25 channels of that system has BER value of 8.83E-16 at 960km. The performance of single channel 100Gb/s CSRZ DPSK system with symmetrical compensating configuration, the best performance, has BER value of 8.88E-15 at 240km. On the other hand 11 channels of that system has BER value of 1.02E-14 at 240km. FWM, SPM and XPM decrease the system performance in multiple channels systems. The single channel is affected by only SPM nonlinear effect. One way to manage with FWM is to use unequal channel.

Another, and very effective, way is fiber dispersion management method. This method is also effective for SPM and XPM.

In simulations for all configurations input power is 1.0E-3W. When the power is increased nonlinear effects are increased.

Most commercial systems use the NRZ modulation format. It is easy to implement, and less costly. The performance of 25 channels 40Gb/s RZ with all compensating configurations are better compared to 25 channels 40Gb/s NRZ but in 11 channels 100Gb/s system performance of NRZ is better than RZ. For example, 25 channels 40Gb/s NRZ with pre compensating configuration has BER value of 9.49E-9 at 480km. while RZ with pre configuration has BER value of 5.82E-9 at 960km. 11 channels 100Gb/s NRZ with pre compensating configuration has BER value of 1.09E-12 at 240km. while RZ with pre configuration has BER value of 3.27E-14 at 200km. Because RZ is more tolerant to nonlinearity than NRZ, however, suffers from a stronger signal degradation due to chromatic dispersion. 100Gb/s system is less tolerant to dispersion.

CSRZ is special form of RZ where the carrier is suppressed. The dispersion tolerance of CSRZ modulation can be improved due its reduced spectral width compared to RZ modulation. For example, single channel 100Gb/s CSRZ system with symmetrical compensating configuration has BER value of 2.65E-9 at 240km., while RZ has BER value of 2.22E-17 at 200km. In addition, carrier suppression reduces the efficiency of FWM in WDM systems.

DPSK is more tolerant to nonlinear effects. It has better resilience to XPM and FWM, as compared with intensity modulation formats. For example, 11 channels 100Gb/s DPSK system with post compensating configuration has BER value of 2.71E-13 at 240km., while NRZ has BER value of 6.07E-13 at 240km., RZ has BER value of 4.44E-14 at 200km.

CSRZ-DPSK exhibit superior transmission performance than simple DPSK. The CSRZ-DPSK pulses posses a RZ signal shape and due to the reduced spectral width, CSRZ-DPSK modulation shows an increased dispersion tolerance and it is more robust to nonlinear impairments than conventional RZ format. In all systems that simulated the performance of CSRZ DPSK is better than DPSK. For example, 11 channels 100GB/s with symmetrical compensating configuration has BER value of 1.02E-14 at 240km., while DPSK has BER value of 3.13E-12 at 240km.

As a result for all the systems considered in this dissertation, CSRZ DPSK modulation format with symmetrical compensating configuration represents better performance among all formats and compensating configurations. For single channel 40Gb/s BER value of CSRZ DPSK with symmetrical compensating configuration is 1.13E-47, for 25 channels 40Gb/s system BER value is 8.83E-16, for single channel 100Gb/s system BER is 8.88E-15, for 11 channels 100Gb/s system BER is 1.02E-14. The performance of CSRZ DPSK modulation format with other dispersion compensating configuration is also good.

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APPENDIX A

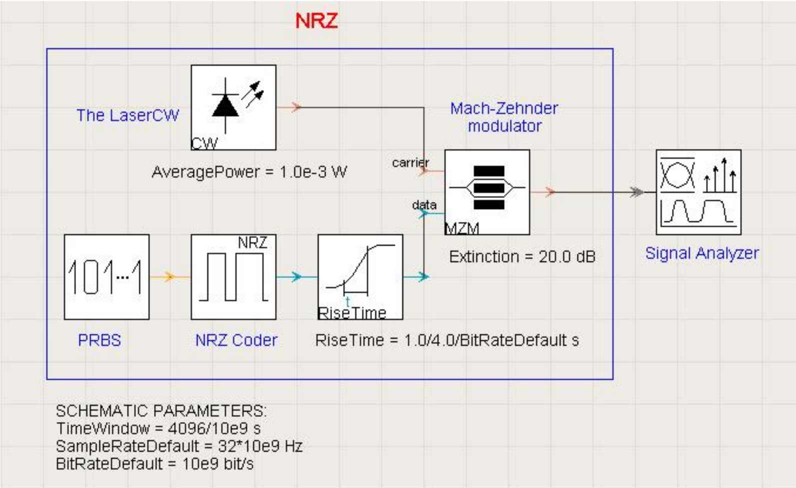


Figure A.1 Simulation set up of 10 Gb/s NRZ modulation.

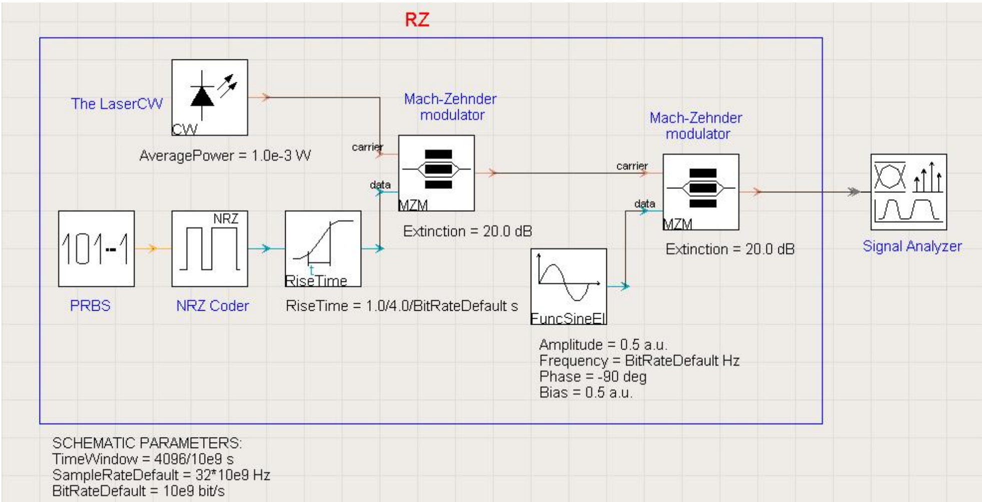


Figure A.2 Simulation set up of 10 Gb/s RZ modulation.

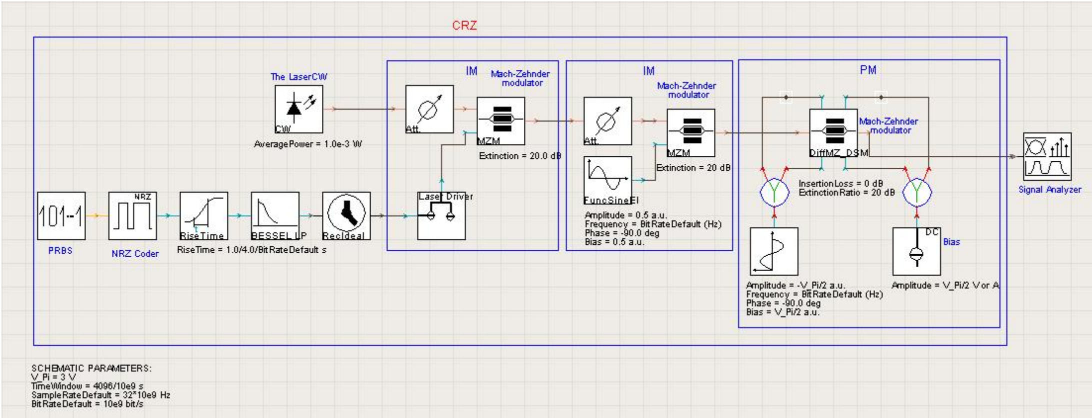


Figure A.3 Simulation set up of 10 Gb/s CRZ modulation.

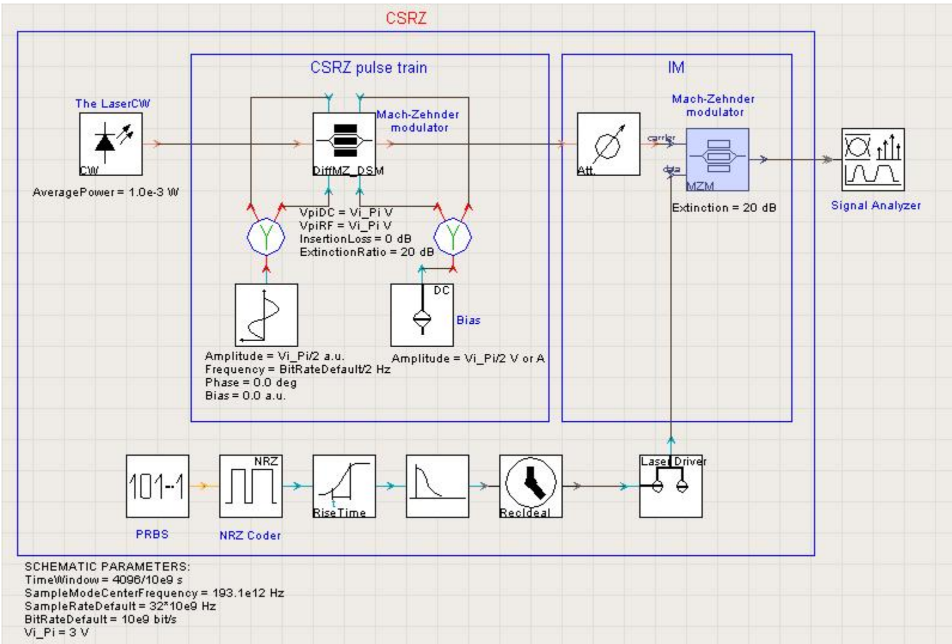


Figure A.4 Simulation set up of 10 Gb/s CSRZ modulation.

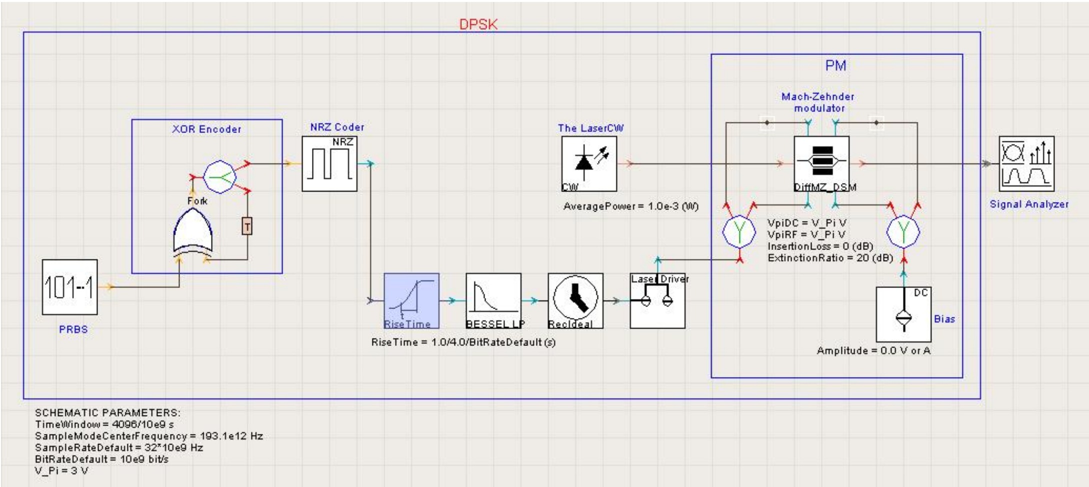


Figure A.5 Simulation set up of 10 Gb/s DPSK modulation.

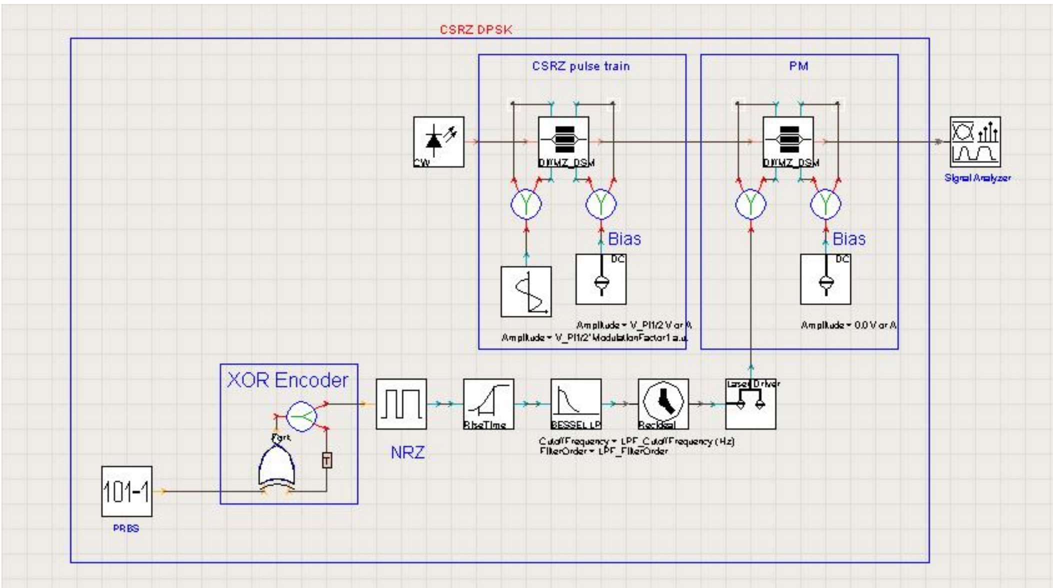
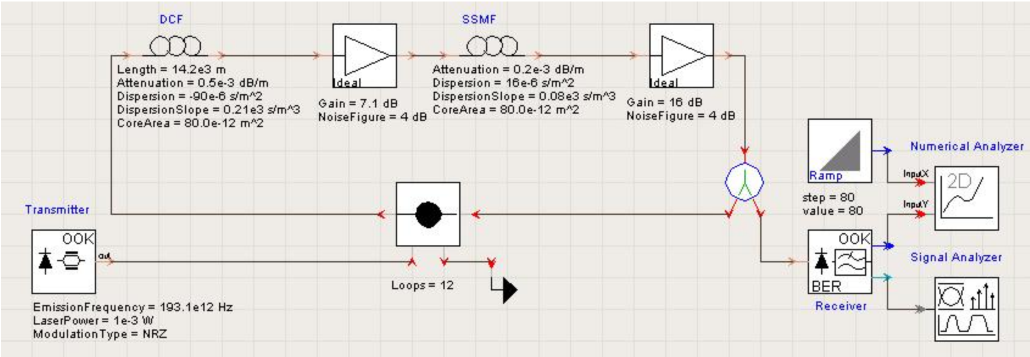


Figure A. 6 Simulation set up of 10 Gb/s CSRZ DPSK modulation.



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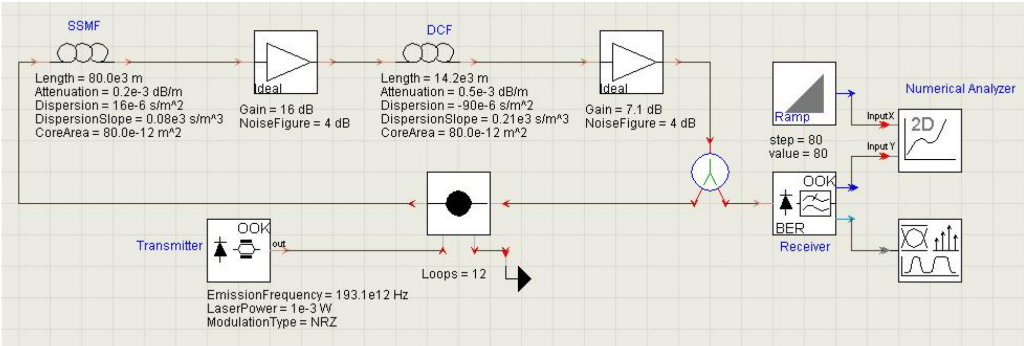
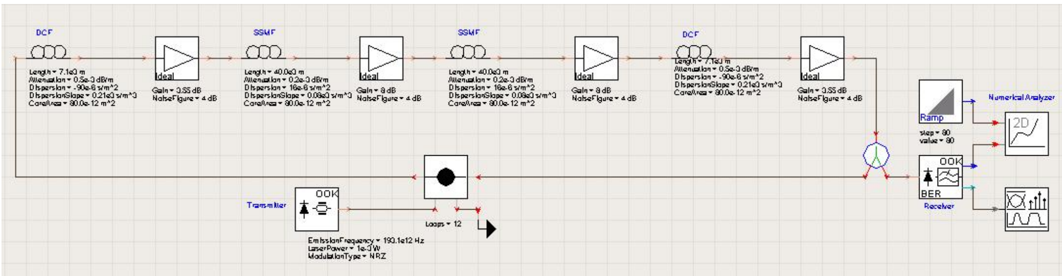
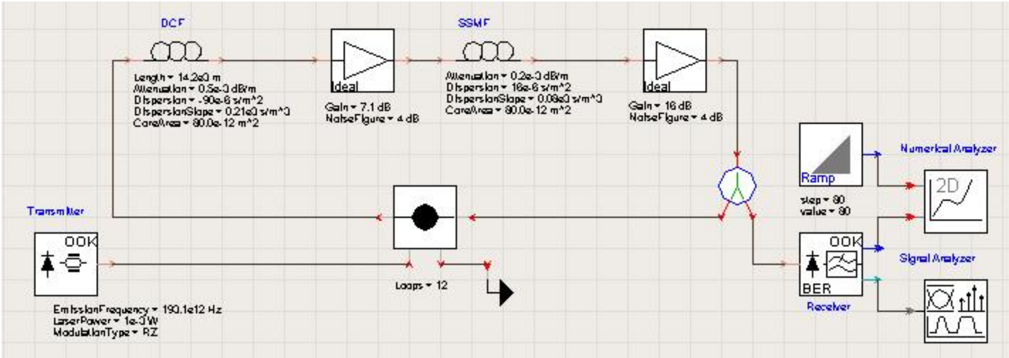


(b)

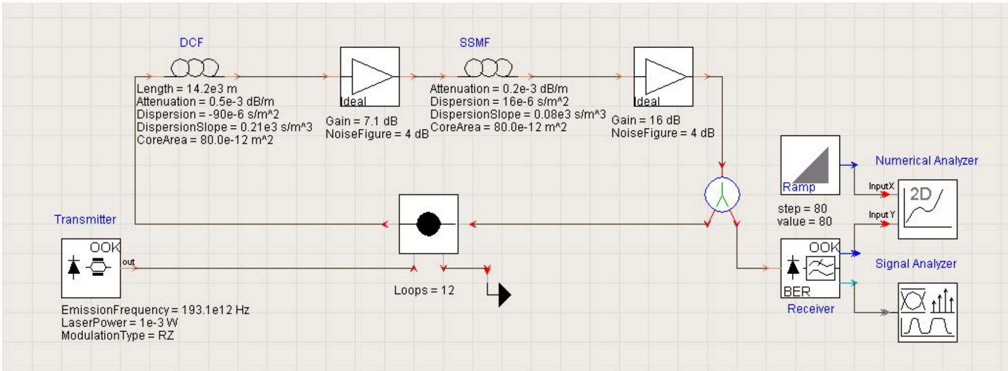


(c)

Figure A.7 Simulation set up of single channel 40 Gb/s NRZ (a) pre-compensating configuration, (b) post-compensating configuration, (c) symmetrical compensating configuration.



(a)



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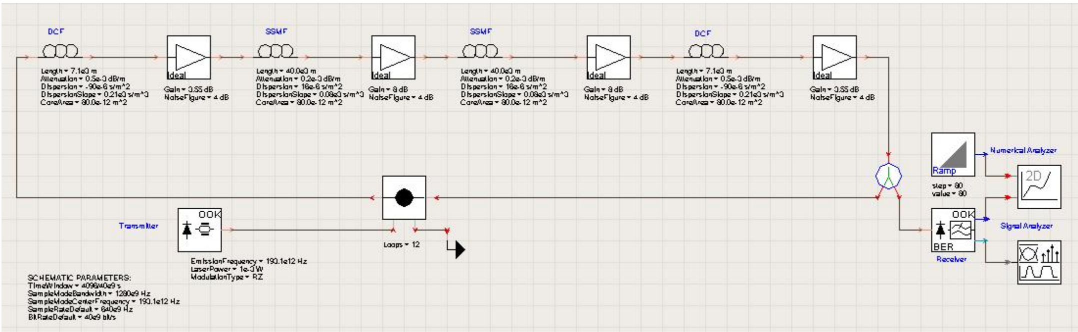
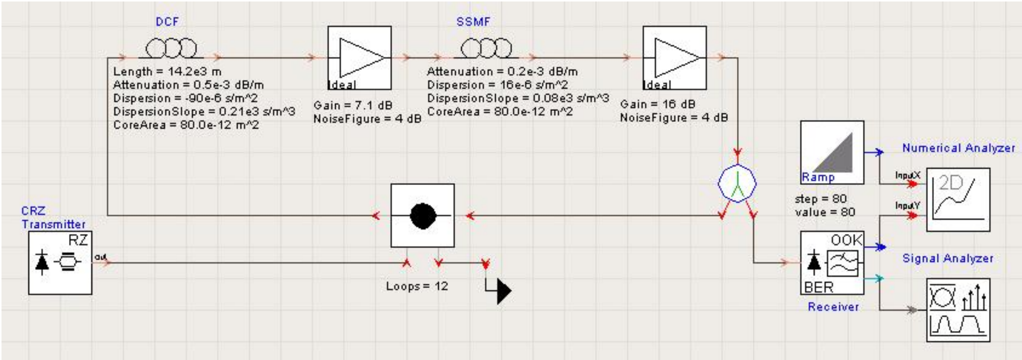


(c)

Figure A.8 Simulation set up of single channel 40Gb/s RZ (a) pre-compensating configuration, (b) post-compensating configuration, (c) symmetrical compensating configuration.



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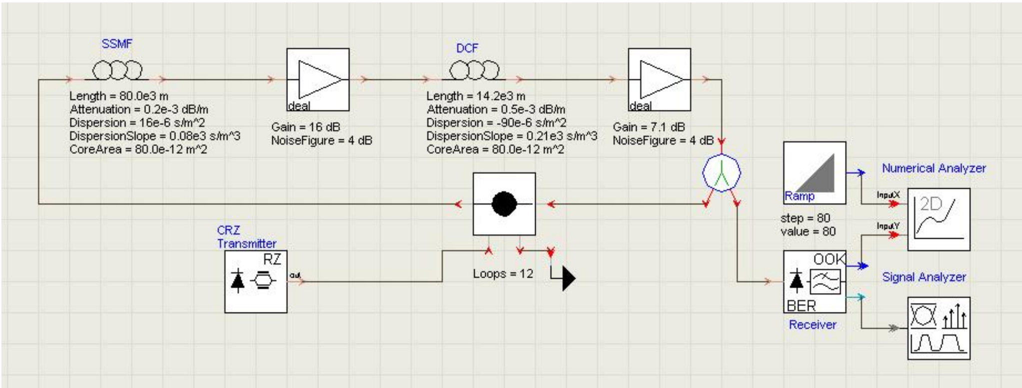

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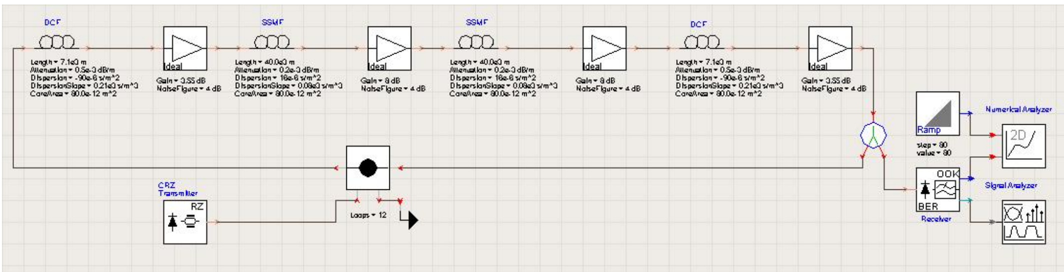
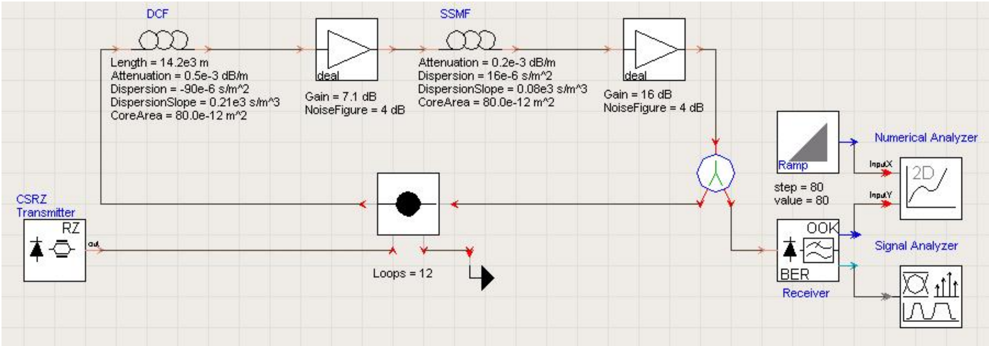


(c)

Figure A.9 Simulation set up of single channel 40Gb/s CRZ (a) pre-compensating configuration, (b) post-compensating configuration, (c) symmetrical compensating configuration.



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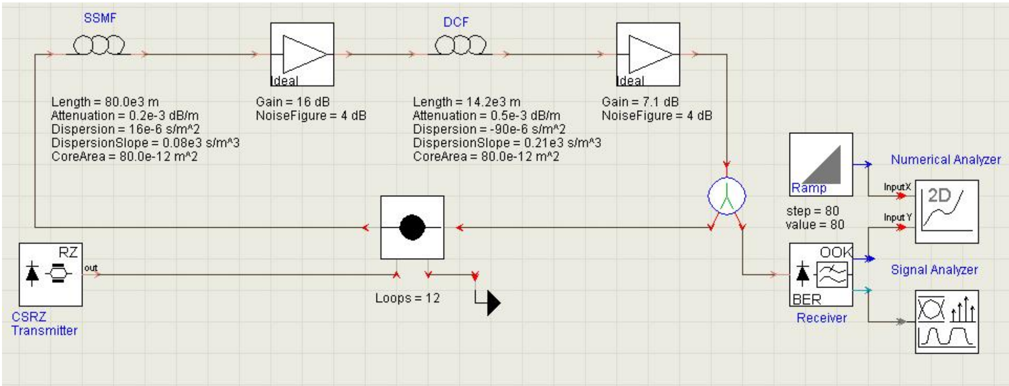

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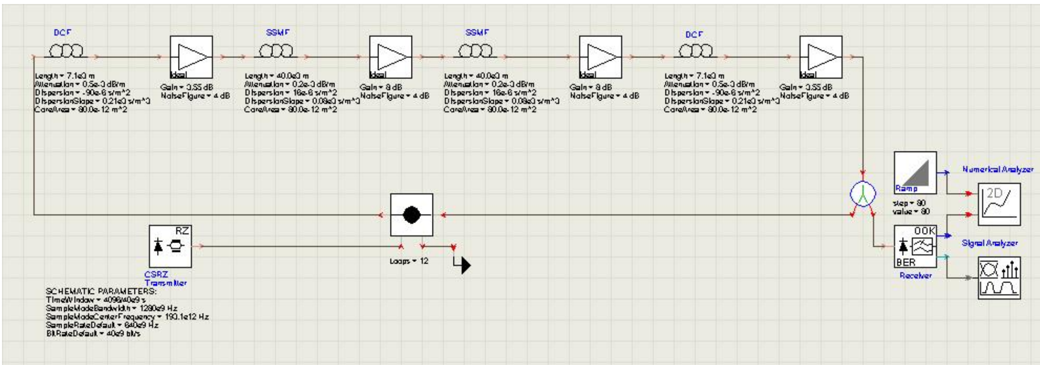
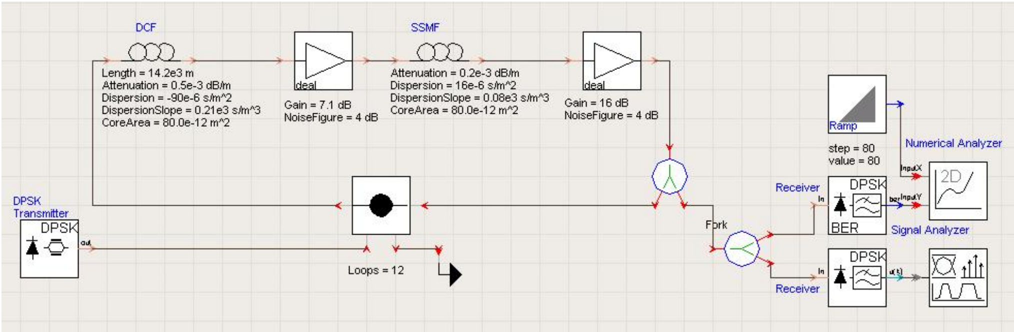


(c)

Figure A.10 Simulation set up of single channel 40Gb/s CSRZ (a) pre-compensating configuration, (b) post-compensating configuration, (c) symmetrical compensating configuration.



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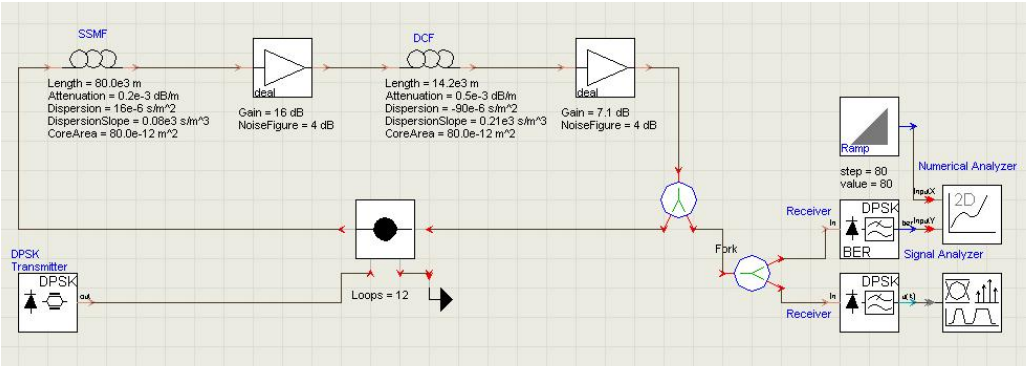

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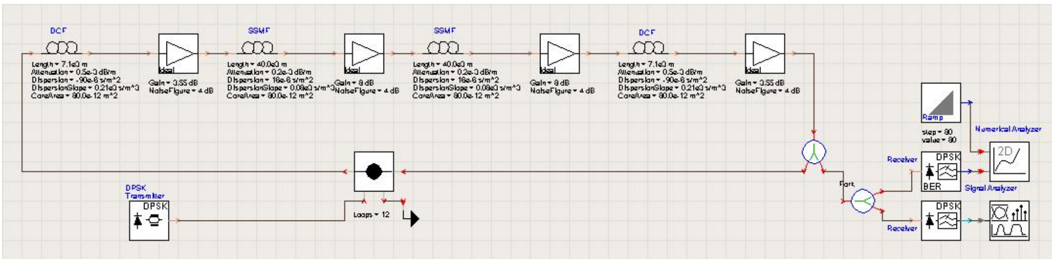
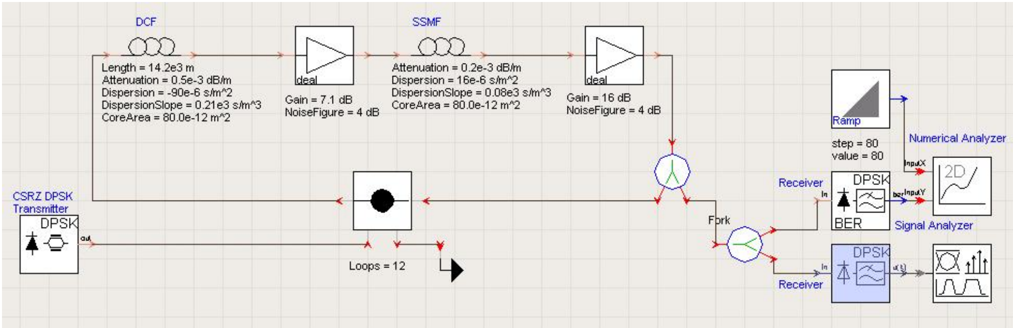
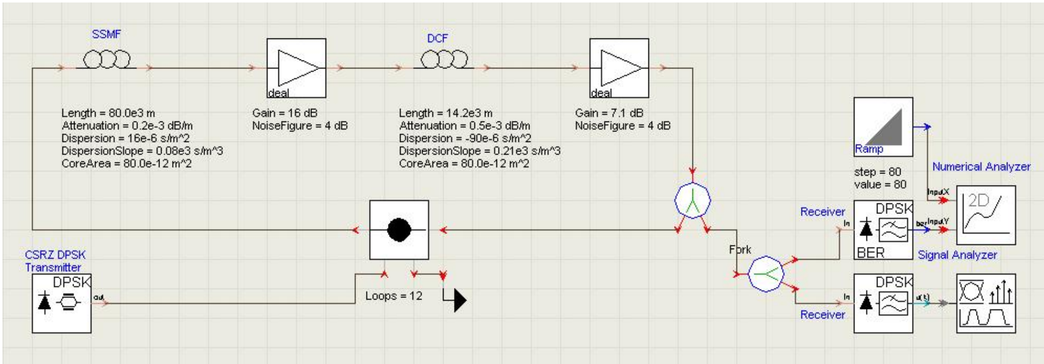


(c)

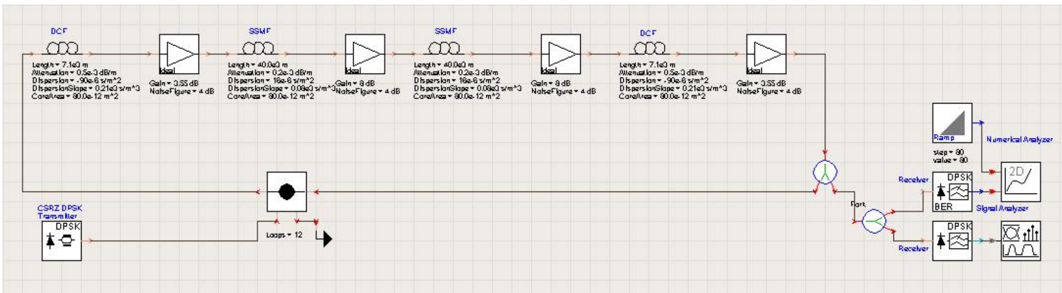
Figure A.11 Simulation set up of single channel 40Gb/s DPSK (a) pre-compensating configuration, (b) post-compensating configuration, (c) symmetrical compensating configuration.



(a)

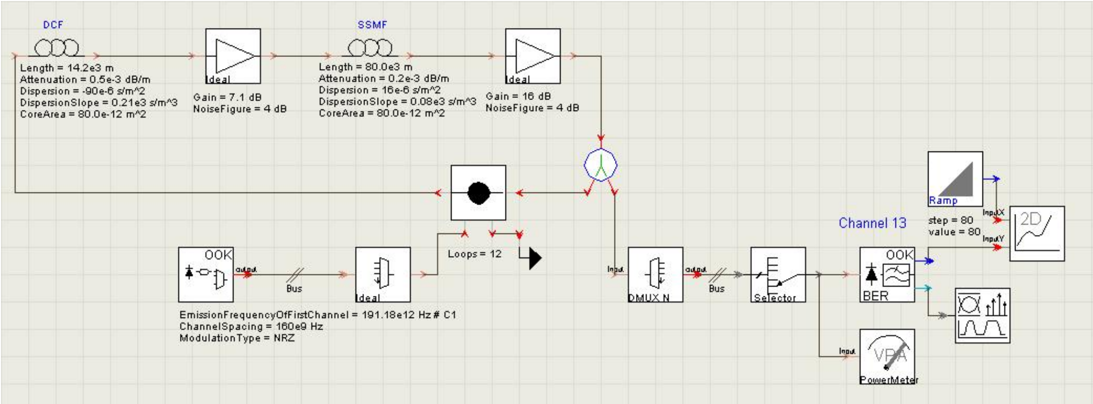


(b)

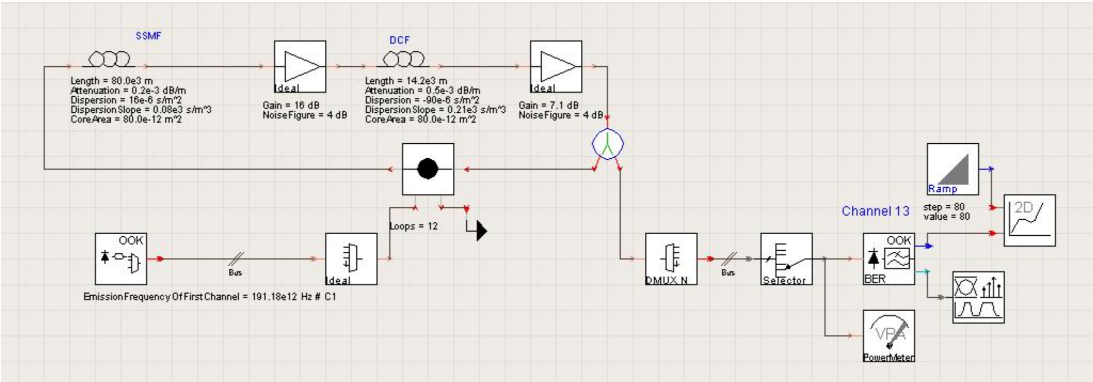


(c)

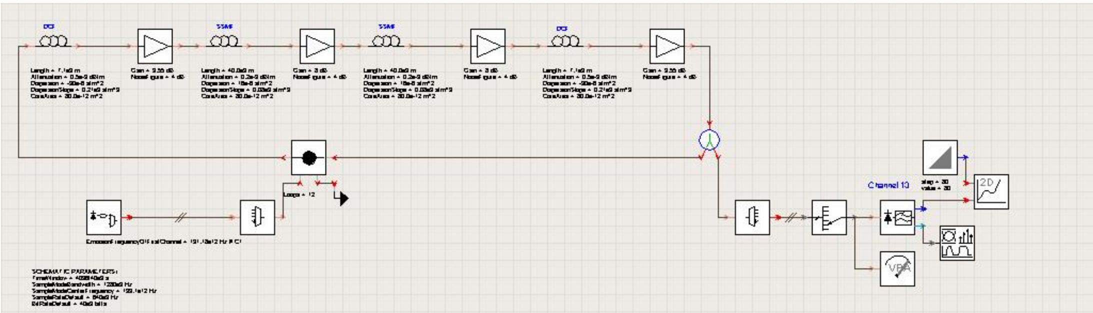
Figure A. 12 Simulation set up of single channel 40Gb/s CSRZ-DPSK (a) pre-compensating configuration, (b) post-compensating configuration, (c) symmetrical compensating configuration.



(a)

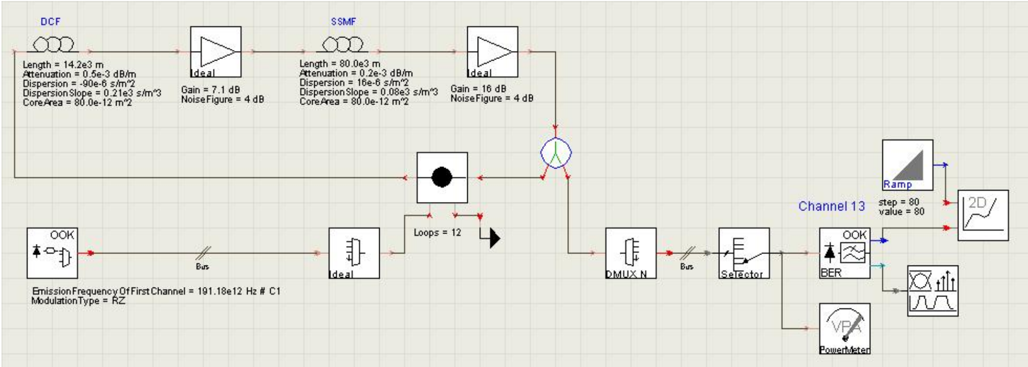


(b)

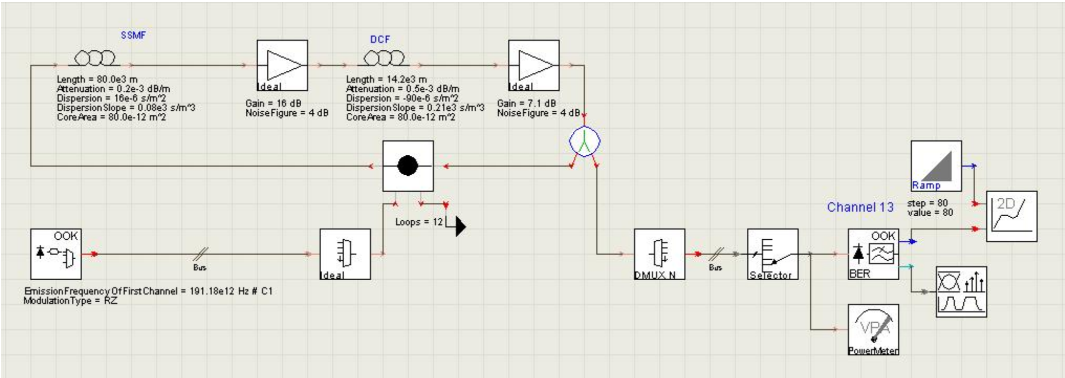


(c)

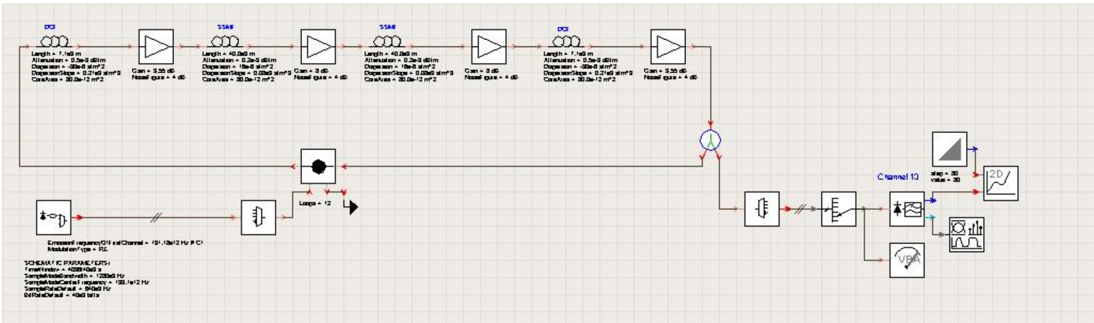
Figure A.13 Simulation set up of 25 channels 40Gb/s NRZ (a) pre-compensating configuration, (b) post-compensating configuration, (c) symmetrical compensating configuration.



(a)

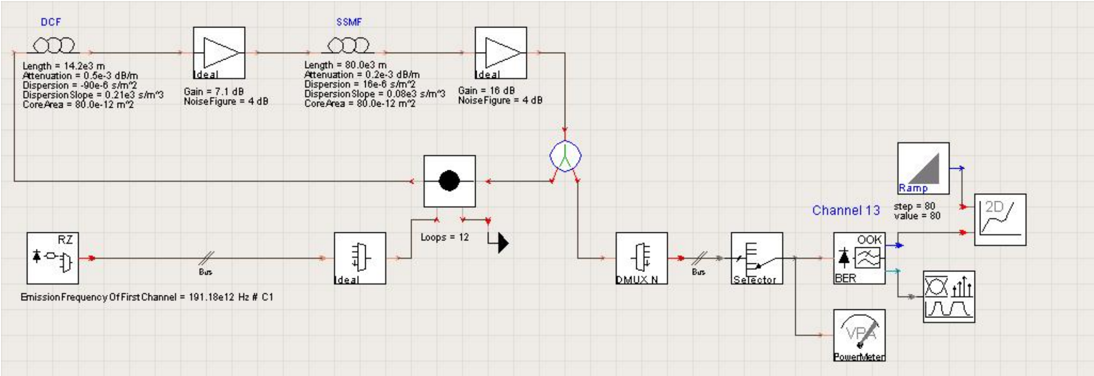


(b)

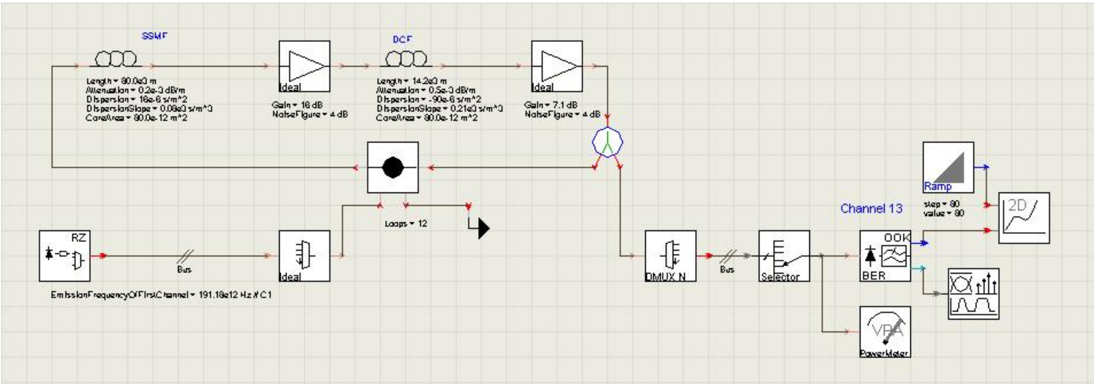


(c)

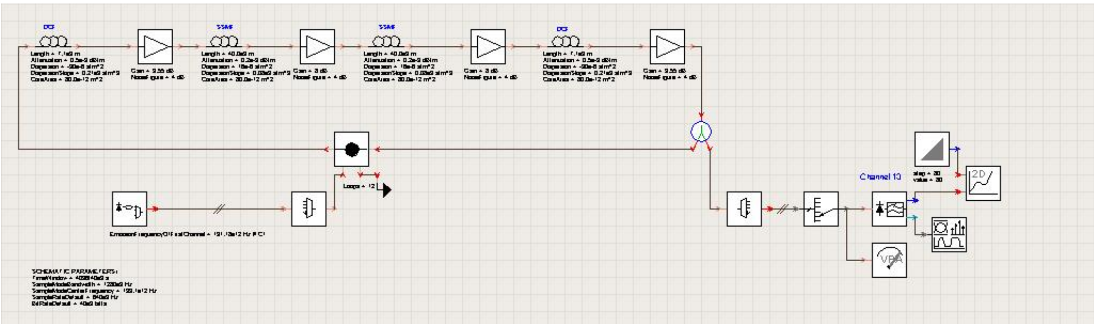
Figure A.14 Simulation set up of 25 channels 40Gb/s RZ (a) pre-compensating configuration, (b) post-compensating configuration, (c) symmetrical compensating configuration.



(a)

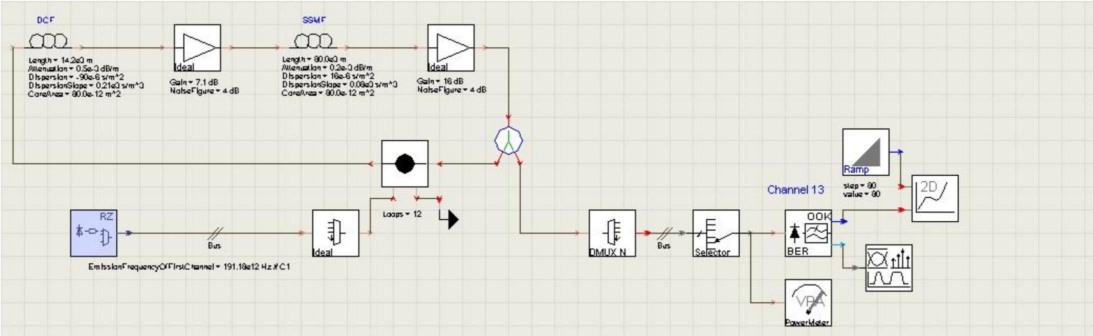


(b)

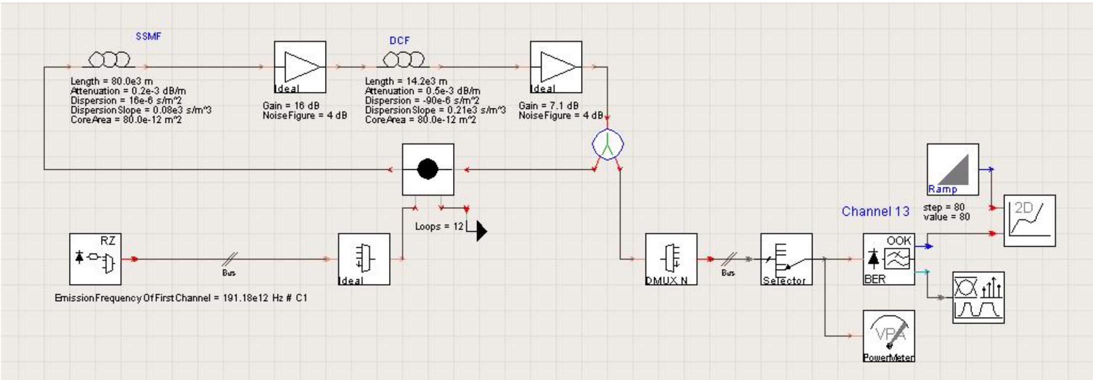


(c)

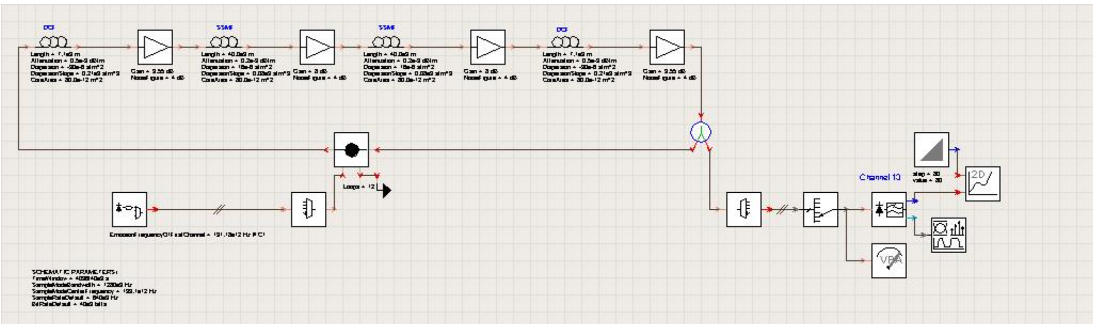
Figure A.15 Simulation set up of 25 channels 40Gb/s CRZ (a) pre-compensating configuration, (b) post-compensating configuration, (c) symmetrical compensating configuration.



(a)

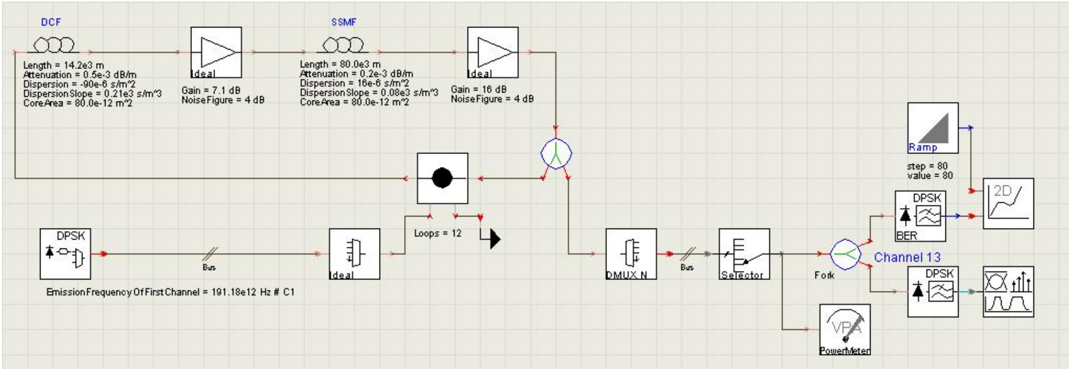


(b)

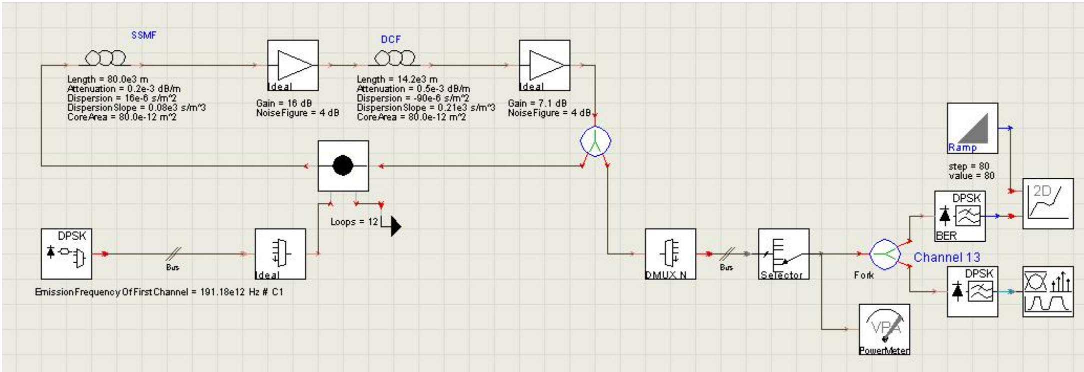


(c)

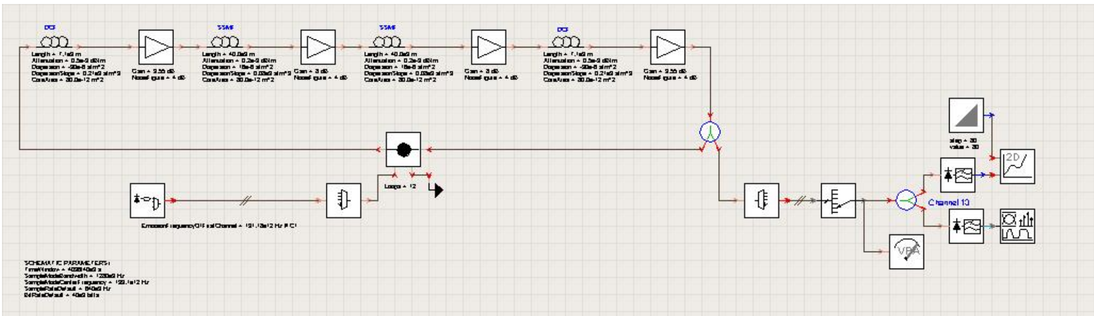
Figure A.16 Simulation set up of 25 channels 40Gb/s CSRZ (a) pre-compensating configuration, (b) post-compensating configuration, (c) symmetrical compensating configuration.



(a)

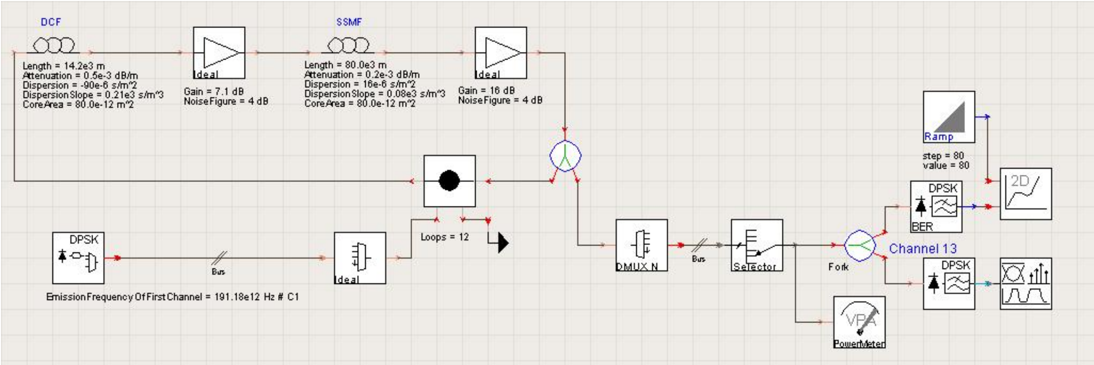


(b)

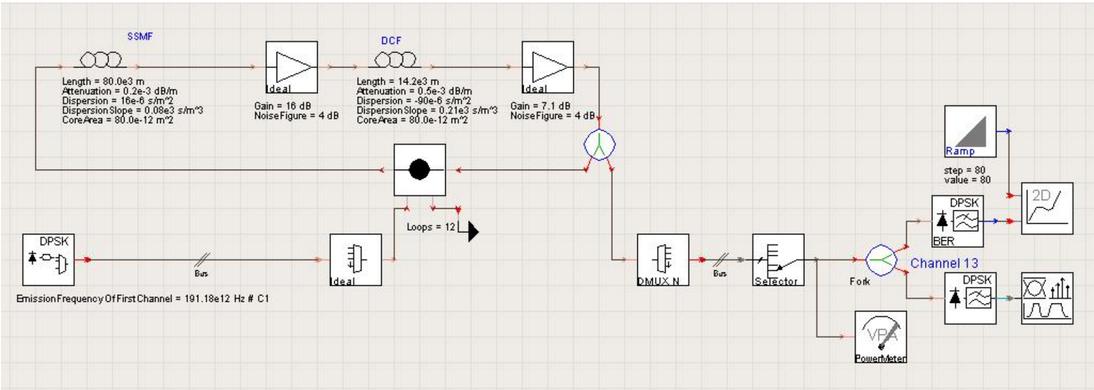


(c)

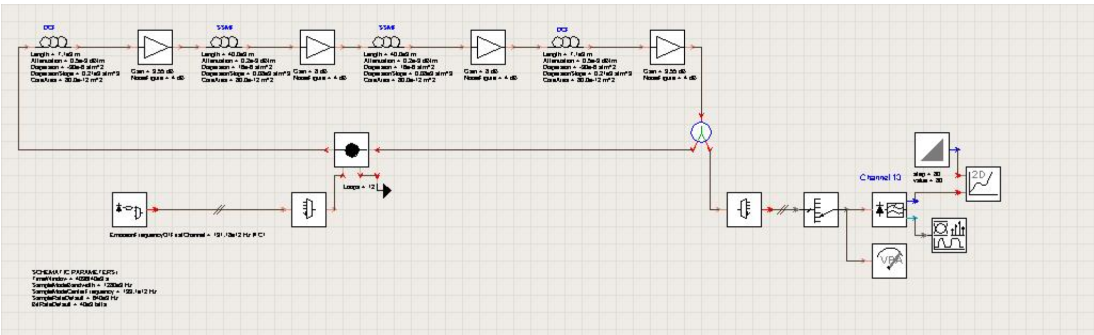
Figure A. 17 Simulation set up of 25 channels 40Gb/s DPSK (a) pre-compensating configuration, (b) post-compensating configuration, (c) symmetrical compensating configuration.



(a)



(b)



(c)

Figure A. 18 Simulation set up of 25 channels 40Gb/s CSRZ-DPSK (a) pre-compensating configuration, (b) post-compensating configuration, (c) symmetrical compensating configuration.

CURRICULUM VITAE

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EDUCATION

Degree	Institution	Year of Graduation
MS	METU Physics	2001
BS	METU Physics	1997
High School	Yahya Kemal Beyatlı Lisesi, Ankara	1992

WORK EXPERIENCE

Year	Place	Enrollment
2007-Present	STM Savunma Teknolojileri Mühendislik A.Ş	Systems Engineer Consultant
2003-2007	Maliye Bakanlığı Bütçe ve Mali Kontrol Genel Müdürlüğü	System Analysts
1997-2003	Başbakanlık Aile Araştırma Kurumu	System Analysts
1998-1999	Data Kontrol Bilgisayar Sanayi ve Ticaret Ltd. Şti.	Instructors
1997	METU Computer Center	Computer Operator

FOREIGN LANGUAGES

Fluent English, Basic Japanese

PARTICIPATED SCIENTIFIC MEETINGS AND CONGRESS

Elektronik Harp Konferansı — May 2009
Savunma Sanayi Müsteşarlığı, Ankara

Radar Sistemlerinde Mevcut Kabiliyetler Çalıştayı — March 2009
Savunma Sanayi Müsteşarlığı, Ankara

UZAL CBS 2008 II. Uzaktan Algılama ve Coğrafi Bilgi Sistemleri — Oct 2008
Erciyes Ü. Kayseri,
“Helikopterler için Engel Tespit ve Uyarı Sistemleri” (Paper presentation)

SPIE Defense & Security Conference — March 2008
SPIE, USA

6th National Optic Electro-Optic and Photonic Meeting — Dec 2004
Sabancı University, İstanbul

5th National Optic Electro-Optic and Photonic Meeting — Dec 2003
METU, Ankara

4th National Optic Electro-Optic Meeting — Dec 2002
TÜBITAK-UME, Gebze

3rd National Electro-Optic Meeting — Nov 2001
ASELSAN Electronic Industries Inc., Ankara
"Simulation on 4 x 2.5 Gbit/s WDM System." (Poster presentation)

TURKISH PHYSICAL SOCIETY 19th PHYSICS CONFERENCE — Sept 2000
Fırat University, Elazığ

HOBBIES

Tennis, Computer Technologies, Movies.