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Evaluation of impairment mitigations for optical fiber communications using dispersion compensation techniques

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ABSTRACT

This study discusses dispersion as a key issue influencing the performance of optical fiber communication technology. Poor bit rate, pulse broadening, and transmission distance restrictions are the outcomes. The dispersion correction method frequently employs fiber with dispersion compensation (DCF) and fiber Bragg grating (FBG). A model transmission system has been analyzed in light of numerous parameters using the Optic System 20.0 simulator. The DCF and FBG dispersion compensation methods are two that have been proposed. The Q-factor, BER, and eye height measured at the receiver end will be utilized as three metrics to describe the results of the two dispersion-correcting strategies. Additionally, the system's transmission performance will vary as a result of varied compensatory approaches. The DCF approach does not significantly increase system performance compared to the compensation technique. In addition, the properties of the optical fiber used for transmission in the system affect the characteristics of the FBG and the fiber used for the compensating process. It has been demonstrated that post-compensation, followed by symmetrical compensation, produces the best result. In addition, the transmission performance of the system with different compensation methods will be different, and the compensation technique will improve the system performance much better than the DCF technique. Moreover, the characteristics of the FBG and the fiber that is used for the compensation process depend on the characteristics of the optical fiber that is used for the transmission in system. It is shown that the symmetrical compensation performance is the best. Due to the nonlinear nature of propagation, system performance depends on power levels, followed by post-compensation.

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1. Introduction

Dispersion compensation plays an important role in fiber optics. Optical fiber communication is a way of transmitting information from one station to another by sending light pulses through an optical fiber having chromatic dispersion that distorts phase [1, 2]. These light pulses undergo modulation at the transmitter to carry the required information in the form of electromagnetic carrier wave. The advantages are realizable in an efficient manner if the dispersion which is the major enfeeblement in optical fibers, is compensated Dispersion in fiber optics is the phenomenon in which the velocity of a wave is dependent on its frequency i.e. when the phase velocity depends on the frequency. Techniques of compensating the chromatic dispersion. The simplest being the dispersion compensating fibers (DCFs) which loop of fiber inserted in line with the main fiber but with opposite chromatic dispersion as that of main fiber [3, 4]. Other technique called electronic dispersion compensation uses electronics in optics for the chromatic dispersion compensation [5–8]. Now a days the completely optical components like fiber Bragg gratings (FBGs) are also used for chromatic dispersion compensation by the recompression of the dispersed optical signal [9]. But the recent techniques of dispersion compensation involve the use of digital filters called low pass Bessel filters. These dispersive techniques required to maintain a good signal quality in fiber optics are discussed in this paper. The rest of the paper is organized as follows: In the next section the need for dispersion compensation is explained. Section 2 discusses the dispersion compensation using DCF. Sections 3 presents the FBG and an overview of developed methods of dispersion compensation. Section 4 presents the system design and Section 5 discusses the simulation results Section 6 presents the conclusion of this paper.

1.1 Dispersion compensation techniques

The major dispersion-process cause may be determined using the group velocity in its most frequent form; however, each type of dispersion has a unique origin. Dispersion phenomena can be shown in Fig.1. Consider a fiber cable that transmits optical signals in a variety of modes, each of which possesses all the spectral elements found in the wavelength band. Each spectral component propagates individually and undergoes a group delay as well as a distinct temporal delay. Group velocity is the rate at which a pulse's energy moves along a fiber. Therefore, signal dispersion occurs when the frequency components of a signal travel with distinct group velocities and reach their target at various times [10].

Types of dispersion techniques:

- Chromatic dispersion:

Optical pulses spread when they pass through a substance due to the wavelength dependence of light speed. Wavelength hardly slightly affects the speed of light. Because shorter wavelengths move more quickly than longer ones, pulses of different wavelengths arrive at different times. The widening and spreading of the pulse cause the signal to become distorted. often referred to as intramodal dispersion. Examples of it are waveguide chromatic dispersion and material types [11].

- Material dispersion:

It comes from the wavelength-dependent refractive index of the fiber's constituent material. The difference between the speed of light in a material and the speed of light in a vacuum is known as an element's refractive index. Different light wavelengths encounter changing refractive indices as a result of the material's fluctuating propagation velocities. Material dispersion is becoming more important in fibers with large core sizes and broad spectral ranges. It is recognized as one of the several types of chromatic dispersion. This dispersion is small at wavelengths about 1300 nm, as we'll see later [12].

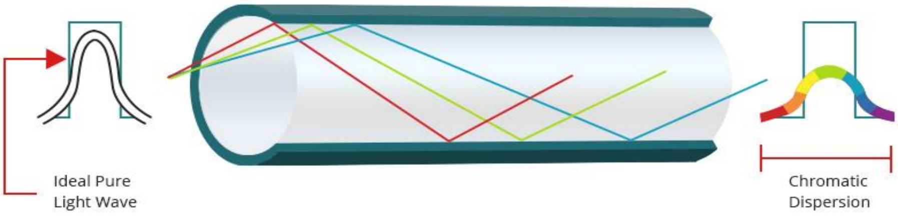


Figure1. Chromatic dispersion phenomena

- Intermodal dispersion

Numerous light modalities result in intermodal dispersion. Multiple independent "modes" of light, each with a somewhat different effective refractive index and speed, can flow through a multimode waveguide. The differing propagation constants of the modes cause them to move at varying speeds. In other words, because each mode travels through the fiber at a different velocity, the pulse spreads gradually. It is usually described as simply "modal" or "mode dispersion," although single-mode fibers lack it as well.

1.2 Dispersion compensation

1.2.1 Definition

Dispersion correction is a crucial strategy that can improve the efficiency and bandwidth of optical communication systems. Dispersion correction in optical communication systems refers to the techniques employed to thwart unwanted pulse spreading. Reducing the consequences of dispersion is what it entails.

1.2.2 Benefits:

• Better signal quality: By reducing the distortion and spreading of optical signals, dispersion correction methods can improve signal quality and speed up data transfer rates.

• Greater transmission distance: The maximum transmission distance of optical signals can be hampered by dispersion, which worsens signal quality. Dispersion correction systems can prolong transmission distance by reducing the effects of dispersion. Lower bit error rates (BER): Signal distortion brought on by dispersion might result in errors in the data delivered. Dispersion correction improves the system's overall reliability while reducing the BER.

2. Dispersion compensation techniques

2.1 Dispersion Compensation Fiber (DCF)

One of the most straightforward techniques for optical fiber dispersion correction. Its basic idea is to build an optical fiber link with certain characteristics and opposing dispersion, then connect it to the optical transmission fiber. When the positive dispersion cancels the negative dispersion or vice versa, the consequent dispersion of the optical fiber, as shown in the fig.2, will be erased. By following an SMF with positive dispersion with a DCF that has negative dispersion, the net dispersion should be zero [13].

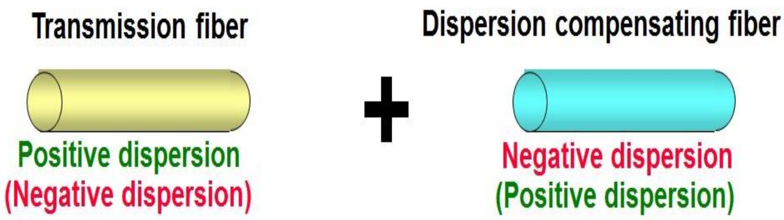


Figure 2. Dispersion Compensation Fiber (DCF).

2.2 Fiber Bragg Grating (FBG)

It is an optical fiber whose refractive index periodically varies along the fiber axis. It is a reflecting tool constructed of an optical fiber whose core refractive index varies with length. The grating will reflect the light as it passes through the fiber if the wavelength and modulation periodicity match [14]. FBGs may be used to account for dispersion by generating a wavelength-dependent phase delay with the opposite sign of the transmission fiber's dispersion. In order to do this, the device is chirped throughout its whole length, creating a structure known as a Chirped Fiber Bragg Grating (CFBG)

The structure of the FBG is influenced by both the refractive index and the grating period as shown if Fig.3. The grating period of a superstructure might be concentrated or scattered, uniform or graded. The two primary characteristics of the refractive index are offset and refractive index profile. Either a uniform or an apodictic refractive index profile is possible. Table 1. Illustrate the Comparison between dispersion compensation methods depending on the grating period of the fiber, Bragg gratings come in four main varieties:

• Uniforms grating: In this type of grating, the intervals are static.

• Chirping grating: Non-uniform grating is used in this.

• slanted grating: This grating is slanted but otherwise completed uniformly.

• Superstructures: These are uniformly arranged in this grating [15].

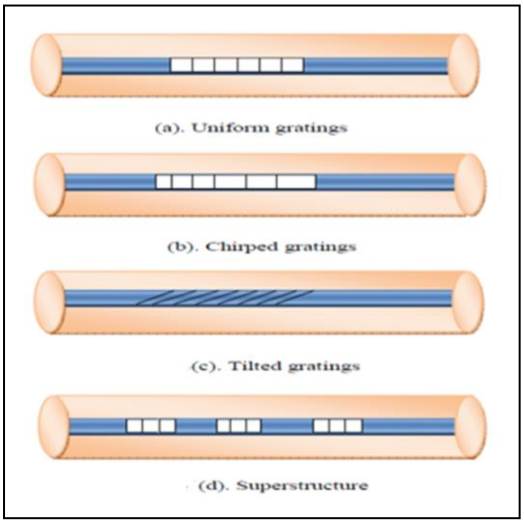


Figure 3. Fiber Bragg grating according to the grating period.

3. System design

The modelling program OPTISYSTEM 20.0 was used to analyze various CW laser wavelengths and data rates for DCF and FBG dispersion correction methods. This program replicates optical communication networks using a unique technique.

Here is the simulated schematic of the dispersion compensation fiber. Fig.4 shows the configuration of dispersion compensation fiber in optical communication system. In addition, the system parameters can be shown in table 2, table.3, table 4 and table 5 illustrate CW laser parameters, Transmission fiber parameters and dispersion compensation fiber parameters respectively.

The following are the values of the parts of the blocks used for the simulated dispersion compensation fiber diagram.

Table 1. Comparison between dispersion compensation methods

Characteristics	**DCF**	**FBG**
Band-width	Wide band 25 nm	Narrow band $0.2 - 6\ nm$
Fiber lengths	$16 - 25 km$	$15 - 20\ cm$
Construction	Complex	Simple
Negative-dispersions	$18\ to\ 30\ ps/nm/km$	$2500\ ps/nm/km$
Positive-dispersions	$-85\ to - 125\ ps/nm/km$	$-210\ ps/nm/km$
Dispersions	$18\ pm/km/nm$	$18\ pm/km/nm$
Bending-losses	$0.4 - 0.8\ dB/km$	$0.16\ dB/km$
Reflectancelosses	97.99 %	15 − 93 %
Attenuations	$0.9 dB/Km$	$0.4\ dB/km$
Nonlinear-effects	Some limitations	No
Insertio- losses	High	Low
Rate	High	Low

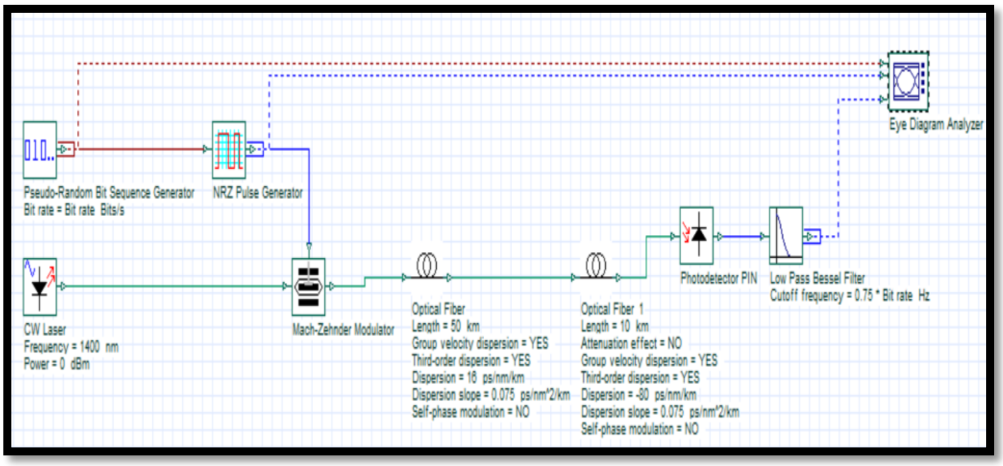


Figure 4. Block diagram of dispersion compensation fiber in Opti System

Table 2. Simulation parameter values.

Parameter	**Value**
Reference- bit rate	Yes
Bit rates	20 Gbit/sec
Sequence lengths	256 bits
Samples per bits	256

Table .3 CW laser parameter values.

Parameter	**Value**
Wavelength	1400-1650 nm by step = 25 nm
Power	0 dBm
Linewidth	1 MHz

Table .4 CW laser parameter values.

Parameter	**Value**
Wavelength	1400-1650 nm by step = 25 nm
Power	0 dBm
Linewidth	1 MHz

Table 4. Transmission fiber parameter values.

Table 5. Dispersion compensation fiber parameter values

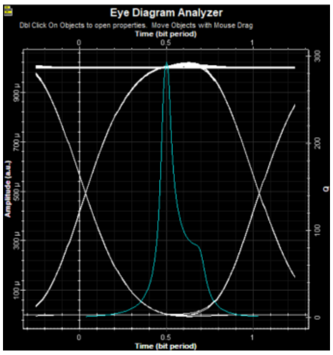
Parameter	Value
User defined reference wavelength	Yes
Reference wavelength	1550 nm
Length	10 km
Attenuation effect	No
Group velocity dispersion	Yes
Third-order dispersion	Yes
Dispersion data type	Constant
Dispersion	-80 ps/nm/km
Dispersion slope	0.075 ps/nm^2/km
Self-phase modulation	No

3.1 *Simulation results*

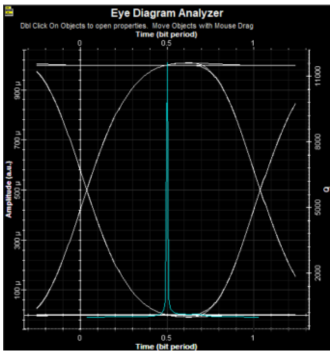
3.1.1 *Dispersion compensation fiber*

The effect of the dispersion compensation fiber on the performance of the optical fiber communication system can be shown in fig.5.The simulation results show the eye diagrams for different bit rates 2.5 Gbit/sec and 10 Gbit/sec. In addition, table 6 and table 7 illustrate the simulation results of the DCF for 2.5 and 10 Gb/s respectively.

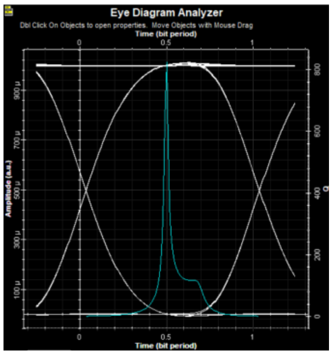
Eye diagram & Q-factor in DCF with B=2.5 Gbit/sec



Wavelength=1400 nm

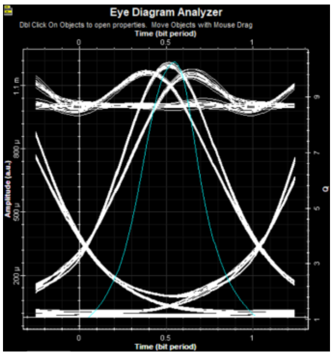


Wavelength=1550 nm

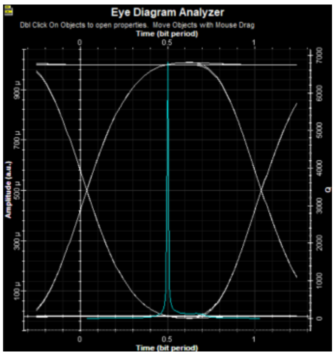


Wavelength=1650 nm

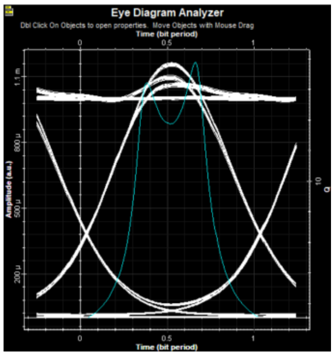
Eye diagram & Q-factor in DCF with B=10 Gbit/sec



Wavelength=1400 nm



Wavelength=1550 nm



Wavelength=1650 nm

Figure 5. Graph result of Dispersion Compensation Fiber.

Table .6 Dispersion compensation fiber parameter values

Parameter	Value
User defined reference wavelength	Yes
Reference wavelength	1550 nm
Length	10 km
Attenuation effect	No
Group velocity dispersion	Yes
Third-order dispersion	Yes
Dispersion data type	Constant
Dispersion	-80 ps/nm/km
Dispersion slope	0.075 ps/nm^2/km
Self-phase modulation	No

Table .7 Simulation results by DCF with bit rate = 10 Gbps.

Wavelength	Q-factor	BER	Eye height
1400	227.436	0	0.000986391
1425	322.332	0	0.0009900012
1450	493.699	0	0.00099264
1475	817.584	0	0.00099513
1500	1419.21	0	0.000995933
1525	3434.8	0	0.00099731
1550	11602.4	0	0.000997768
1575	3038.27	0	0.000997279
1600	1298.59	0	0.000995787
1625	907.105	0	0.00099508
1650	581.314	0	0.000993519

3.1.2 *Fiber Bragg Grating:*

The configuration of the fiber Bragg grating compensation techniques can be shown in figure 6. Moreover, the simulation results of the FBG dispersion compensation scheme can be shown in Fig.7. Table 8 and Table 9 show the simulation results for two different bit rates 2.5 Gb/s and 10 Gb/s respectively.

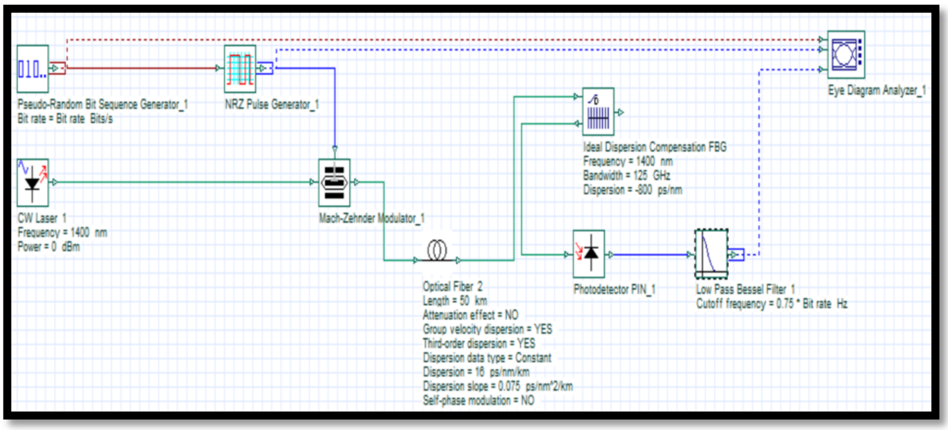


Figure 6. Block diagram of the fiber Bragg grating system in optical fiber communication system.

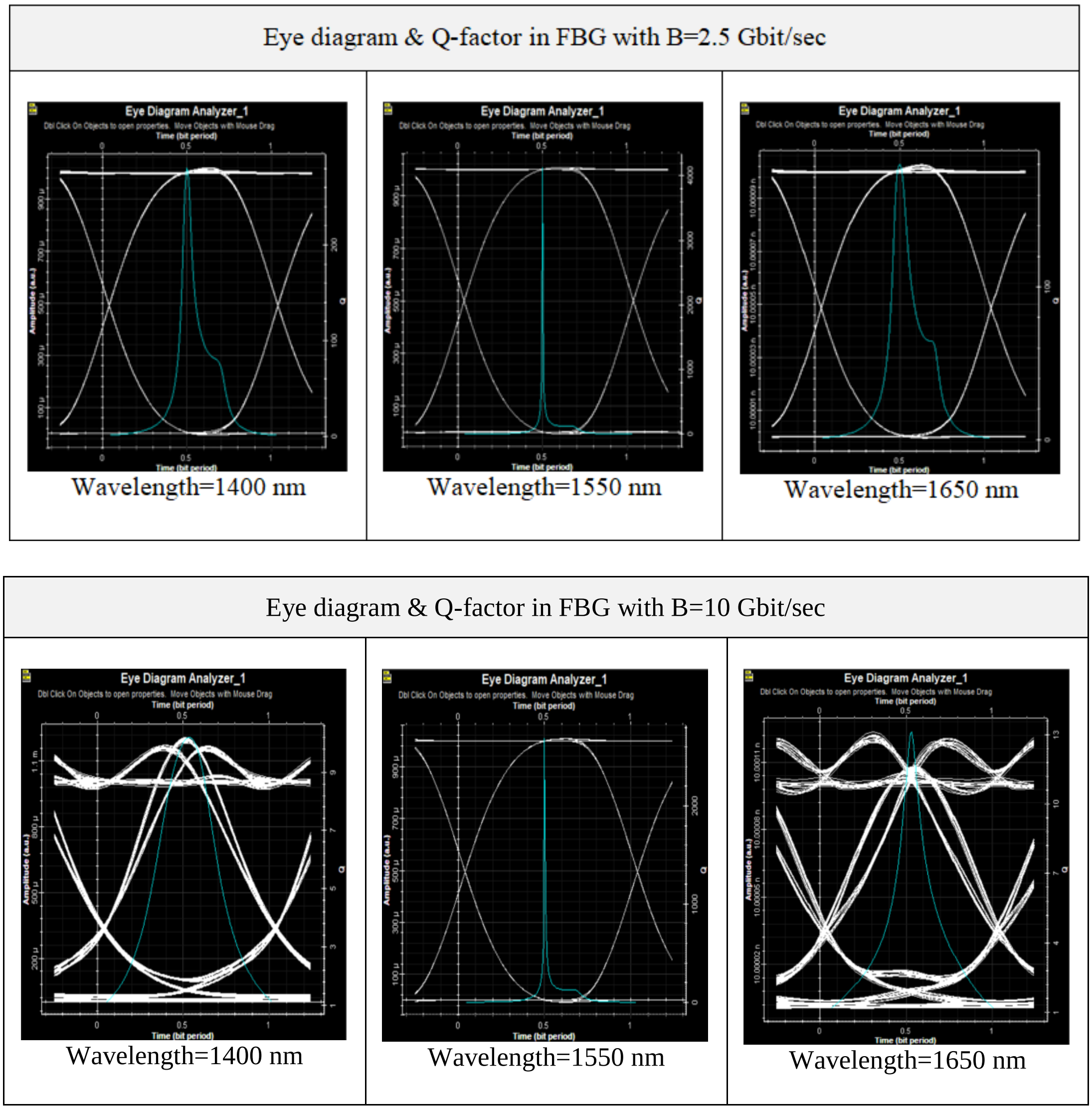


Figure .7 Graph result of Fiber Bragg Grating.

Table .8 Simulation results by FBG with bit rate = 2.5 Gbps.

Wavelength	Q-factor	BER	Eye height
1420	327.849	0	9.90025e-14
1430	248.679	0	9.89482e-14
1455	291.027	0	9.88902e-14
1480	274.733	0	9.88288e-14
1550	259.682	0	9.87643e-14
1555	245.766	0	9.86968e-14
1560	4226.97	0	0.00099757
1570	220.937	0	9.8553e-14
1675	179.856	0	9.84802e-14
1650	199.555	0	9.84054e-14
1655	189.976	0	9.83271e-14

Table .9 Simulation results by FBG with bit rate = 10 Gbps.

Wavelength	Q-factor	BER	Eye height
1400	10.3693	5.63168e26	7.44238e-14
1425	10.2606	2.16829e-26	7.43188e-14
1450	10.7023	4.81231e-27	7.42658e-14
1475	10.766	8.22373e-28	7.52231e-14
1500	11.1511	1.07455e-28	7.51739e-14
1525	11.2378	1.18623e-29	7.40707e-14
1550	2683.73	0	0.000996708
1575	11.7341	3.34553e-32	7.38921e-14
1600	12.4419	4.4805e-34	7.36286e-14
1625	13.3681	1.52509e-14	7.40715e-14
1650	13.1122	1.29582e-39	7.42658e-14

3.1.3 *Quality factor:*

The numerical tables and sophisticated graphics make it clear that there is a direct connection between the quality factor and the wavelengths. The performance is at its best between 1500 and 1600 nm, especially at the operating wavelength of 1550 nm, when the quality factor exhibits a conspicuous and considerable rise. However, the quality steadily deteriorates outside of this range. A measurement of 0 dBm using an optical power meter indicates 1 mille Watt of power. The unit dB expresses the difference between two dBm values.

Additionally, an inverse link between the quality factor and the data rate is shown by the advanced numerical tables. Although it performs satisfactorily in all situations, the quality factor shows a notable increase with lower data rates. This improvement is notably noticeable between 1500 and 1600 nm, particularly at the practical wavelength of 1550 nm. However, the quality factor steadily declines when the data rate reaches this range.

3.1.4 *Bit Error Rate*

- The Bit Error Rate (BER) and wavelengths have an inverse connection, according to analysis of the sophisticated numerical tables. The BER shows a clear and noticeable decline and performs at its best between 1500 and 1600 nm, especially at the operating wavelength of 1550 nm. Beyond this range, however, the bit error rate starts to progressively rise.
- A clear correlation between the Bit Error Rate (BER) and the data rate is also shown by the sophisticated numerical tables and graphs. While it performs satisfactorily in all scenarios, the BER noticeably rises at slower data rates. Particularly at the operating wavelength of 1550 nm, this impact is most pronounced in the range of 1500–1600 nm. But as the data rate rises over this threshold, the Bit Error Rate gradually rises.

3.1.5 *Eye diagram*

The sophisticated graphs and numerical tables show a clear correlation between the eye height and wavelengths. With optimal performance in the region of 1500–1600 nm, especially at the operating wavelength of 1550 nm, the eye height shows a clear and noticeable rise. Beyond this point, however, the eye height steadily declines.

Furthermore, the sophisticated numerical tables and graphs show a negative correlation between the data rate and the eye height. Although it displays acceptable performance in all situations, the eye height significantly improves at lower data rates. This improvement is notably noticeable between 1500 and 1600 nm, particularly at the practical wavelength of 1550 nm. However, the eye height steadily decreases as the data rate rises over this limit.

3.2 The impact of DCF and FBG positions on the system performance

The effects of the DCF and FBG situations will be evaluated in this section. The light source in use is a CW laser. With the help of an NRZ pulse generator, the required digital sequence is produced. The optical signal is produced by applying an electro-optical effect to the optical wave after it has exited the MZM. The global value is 10 GB/s, and the sequence length is set to 128 bits. 1550 nm window, average value of 0.20 dB/km. The configuration of the dispersion compensation fiber at different positions can be shown in the following figures. The fig.8 shows the block diagram when the FBG is unviable, whereas ,the Fig.9 ,Fig.10 and Fig.11 show the types of the dispersion compensation systems such as Pre-compensation, post compensation and symmetrical compensation systems.

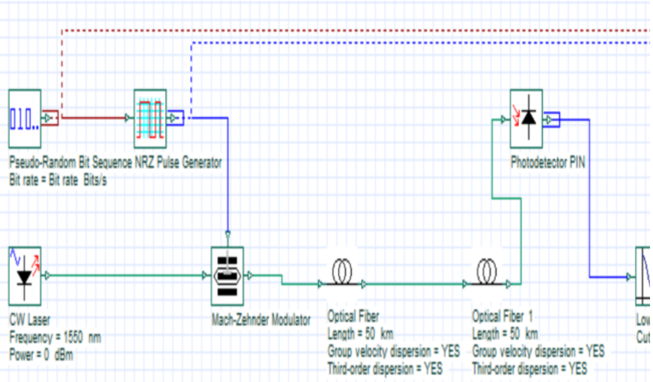


Figure 8. FBG is unavailable.

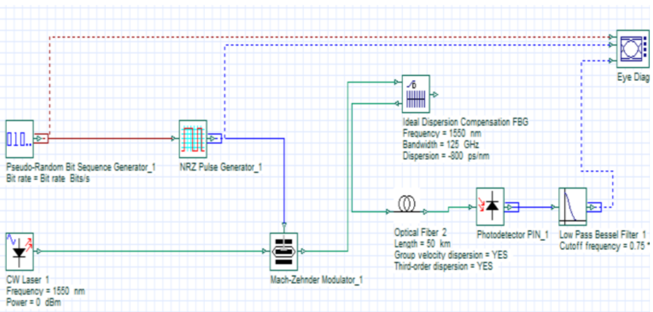


Figure 9. Pre-compensation system.

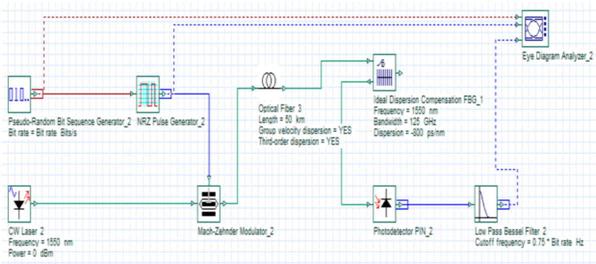


Figure 10. Post-compensation system.

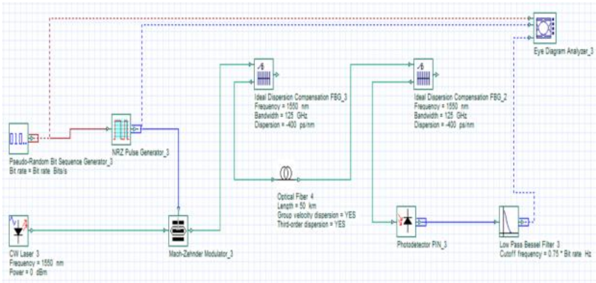


Figure 11. Symmetric compensation system.

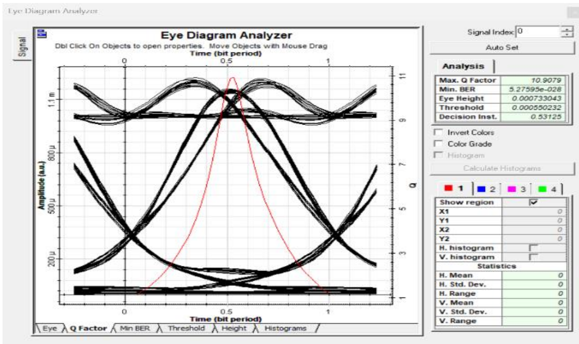


Figure12. Signal eye diagram before compensation

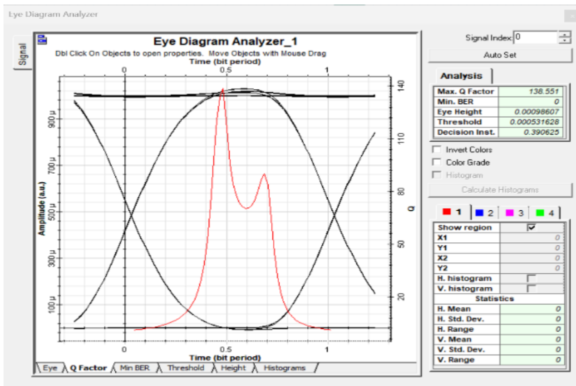


Figure 13. Post compensation signal eye diagram

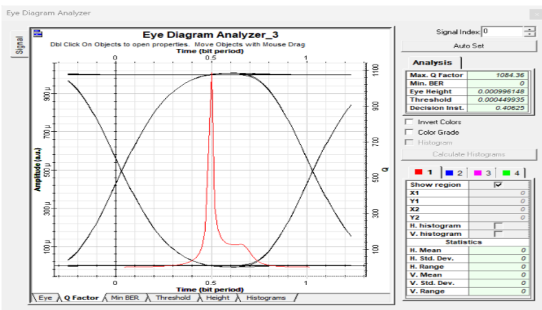


Figure 14. Symmetric compensation signal eye diagram

According to the simulation findings, the system without dispersion correction displays pulse interference, waveform distortion, and an illegible eye diagram as a result of signal transmission delay. However, the eye diagram becomes apparent and the waveform distortion is greatly decreased after correcting using a fiber Bragg grating (FBG). A deeper examination of the eye diagram opening condition finds that post-compensation comes in second to symmetrical compensation in terms of performance. the optical communication system is symmetrically compensated by two dispersion compensated fibers of negative dispersion against the standard fiber in between. Due to the nonlinear nature of propagation, system performance depends upon power levels.

3.3 Performance comparison of different compensation techniques

This study uses two well-known dispersion compensation techniques, DCF and FBG, in a variety of configurations (such as pre, post, and symmetrical). The FBG, DCF, FBG, and DCF) are taken into account for dispersion. In optical communication, compensation. The simulation results for different setups using various bit rates are shown in the previous diagrams.

Fig.12, Fig.13 and Fig 14 display a comparison of eye diagrams for two different techniques. In high data rate, uniform FBG has very low performance due to the regular dispersion of the gratings. As opposed to this, FBG performs better in above all others, both data speed FBG models. Analysing the results also allows us to using the DCF, we can deduce that the Q-factor is a vast improvement over the FBGs. If not for the decrease in SMF's positive dispersion a high a requirement for a negative dispersion coefficient is that DCF. There is a more nonlinear impact. FBG is hence greater.

The corresponding eye diagrams for the uniform FBG, FBG models with data rates of 2.5 Gbps and 10 are shown in Figure7. According to the 2.5 Gbps simulation results the optimum data rate symmetrical model Factor compare to all other models. In addition, model after compensation offers the best Q-factor unlike other models. Regarding to FBG techniques delivers the greatest results in both data rates.

The optical communication system is symmetrically compensated by two dispersion compensated fibers of negative dispersion against the standard fiber in between. Due to the nonlinear nature of propagation, system performance depends upon power levels.

4. Conclusion

The following points summarize the main conclusions regarding this research:

• The sophisticated graphs and numerical tables show a clear correlation between the eye height and wavelengths. With optimal performance in the region of 1500–1600 nm, especially at the operating wavelength of 1550 nm, the eye height shows a clear and noticeable rise. Beyond this point, however, the eye height steadily declines.

•Furthermore, the sophisticated numerical tables and graphs show a negative correlation between the data rate and the eye height. Although it displays acceptable performance in all situations, the eye height significantly improves at lower data rates. This improvement is notably noticeable between 1500 and 1600 nm, particularly at the practical wavelength of 1550 nm. However, the eye height steadily decreases as the data rate rises over this limit.

• There is an inverse relationship between the bit error rate (BER) and the wavelengths, with the bit error rate (BER) clearly and significantly decreasing and providing the best performance quality at the window (1500-1600 nm), especially at the operational wavelength (1550 nm), but gradually increasing once you cross this window.

• The bit error rate (BER) and data rate have a proportional relationship, which results in somewhat good performance in both cases, but it increases clearly and significantly at low data rates, as is evident from the best performance quality at window (1500-1600 nm), especially at length Operational waveform (1550 nm). However, after crossing this window, the bit error rate (BER) starts to rise gradually.

•The system's transmission performance will vary depending on the compensatory strategy selected. • The relationship between the eye height and the wavelengths is proportional, increasing clearly and significantly and giving the best performance quality at the window (1500-1600 nm), especially at the operational wavelength (1550 nm). The ocular diagram, waveforms, and system parameters are all displayed in great detail during the simulation. The pre-compensation, post-compensation, and symmetric supplement techniques are used in the simulation.

• The FBG compensation approach significantly enhances system performance over the DCF technique.

• The features of the optical fiber used in the compensating process affect the parameters of the FBG and the fiber used in that procedure. We believe that our method can be easily extended to a PAM-4 modulation format, which will be considered in our future works.

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