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Erbium-Doped Fiber Amplifier (EDFA) Dispersion Compensation Technique For Multimode Fiber

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***Abstract*— This study examines the efficacy of employing an Erbium-doped fiber amplifier (EDFA) as a dispersion compensation technique for multimode fiber in a transmission system. The investigation involved conducting simulations using the OptiSystem software to comprehensively analyze the performance of the EDFA dispersion compensation technique. Pertinent parameters, namely the input power of the optical signal, the length of the EDFA, the number of EDFA units deployed, and the length of the multimode fiber, were systematically varied during the simulations. The results obtained from the study indicate that the EDFA dispersion compensation technique effectively mitigates the dispersion experienced in the multimode fiber, leading to a marked enhancement in the quality of the transmitted optical signal. Specifically, notable reductions in the bit error rate (BER) and considerable improvements in the quality factor (Q-factor) of the optical signal were observed. The findings strongly suggest that EDFA constitutes a promising and viable approach to ameliorate the effect of dispersion in the performance of multimode fiber transmission systems. The implications of this research are vital, as it can significantly contribute to the advancement of high-speed optical communication networks reliant on multimode fiber. Such developments in the field hold the potential to enhance the overall efficiency and reliability of optical communication systems, thereby fostering advancements in modern-day communication technology.**

Keywords*— *EDFA; dispersion; multimode fiber; OptiSystem; Q-factor; BER.

I. INTRODUCTION

Multimode fibers are extensively employed in local area networks, server farms, and short-distance communication networks due to their affordability and easy installation [1]. However, their transmission range and capacity are limited by factors such as bandwidth, attenuation, and dispersion [2]. To address these limitations, various strategies have been devised, including the incorporation of optical amplifiers like the erbium-doped fiber amplifier (EDFA) [3].

Optical networking is a communication method that facilitates the transfer of information between diverse telecommunications networks using light-encoded signals. These networks encompass long-distance national, global, and continent-wide systems, as well as local-area networks (LAN) and wide-area networks (WAN) covering metropolitan and suburban regions [4]. Optical networking is preferred over coaxial cables for high-speed transmission of large data volumes due to its ability to achieve ultrahigh bandwidth. It relies on optical amplifiers, LEDs or lasers, and wavelength division multiplexing (WDM) to achieve its capabilities [5].

Wavelength division multiplexing (WDM) is a fiber-optic communication technique that enables the utilization of multiple light wavelengths (or colors) to convey signals through the same medium. Consequently, a single fiber can support numerous channels operating at different light wavelengths. Fiber-optic communication systems employ simple light pulses to transmit data through glass strands, conveying data in either serial form with characters or parallel form with bits. Leveraging WDM innovation is an effective means to integrate multiple networks into a unified structure [6].

While the benefits of using EDFA to enhance performance in single-mode fibers have been demonstrated, its effectiveness in multimode fibers remains uncertain [3]. Therefore, the objective of this research is to investigate the impact of the EDFA compensation approach on the channel capacity, dispersion, and attenuation performance of multimode fibers.

II. METHODOLOGY

The proposed system employs four 5GB/s transmitters, which are multiplexed into a unified transmission over a distance of 2km through multimode fiber. Subsequently, demultiplexing of the signal takes place. To mitigate the adverse impacts of dispersion and attenuation within the network's channel segment, which comprises multimode fiber

(MMF), Erbium-doped fiber amplifiers (EDFAs) are strategically integrated. The EDFAs serve to amplify the transmitted signal's power while concurrently minimizing the effects of intermodal dispersion. A visual representation of the network is presented in the block diagram provided in figure 1.

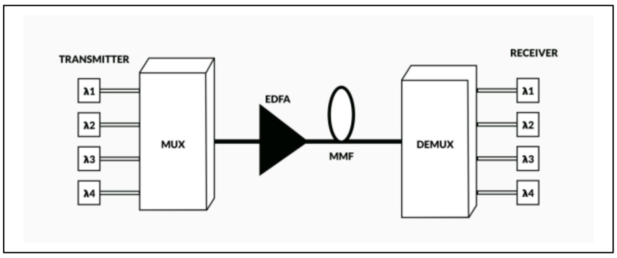


Fig. 1. Block diagram of the WDM network

A. Simulative design of the network using Optisystem

The system is composed of three main components: the transmitter, the channel, and the receiver. Within the transmitter, there exists a Mach-Zehnder modulator, a Continuous Wave (CW) laser, a pseudo-random bit sequence generator, and an NRZ generator. The Mach-Zehnder modulator converts the electrical input into optical signals, while the CW laser emits a continuous and stable light beam with consistent output power. The pseudo-random bit sequence generator generates a binary sequence of seemingly random bits (comprising pulses of 0s and 1s), which are subsequently transmitted to the NRZ Pulse generator. The NRZ Pulse generator encodes the electrical signal into a series of non-return to zero pulses.

The channel segment consists of two integral elements: the Erbium-doped fiber amplifier (EDFA) and multimode fiber (MMF). The EDFA serves to amplify the transmitted signal's power and alleviate the effects of intermodal dispersion, while the MMF facilitates the transmission of optical signals. The receiver component incorporates an optical receiver and a Bit Error Rate (BER) analyzer. Upon reception, the optical signal is demultiplexed using a Wavelength Division Multiplexing (WDM) Demux. The 20 Gbps optical connection bandwidth is multiplexed onto an optic fiber line in 5 Gigabits per second increments using a WDM Mux.

In summary, the system's transmitter section utilizes a Mach-Zehnder modulator, a CW laser, a pseudo-random bit sequence generator, and an NRZ generator to encode the electrical input into optical signals. The channel component employs an EDFA and MMF to ensure signal amplification and dispersion mitigation. Finally, the receiver section includes an optical receiver and a BER analyzer, along with WDM Demux, to demultiplex the received optical signal for analysis.

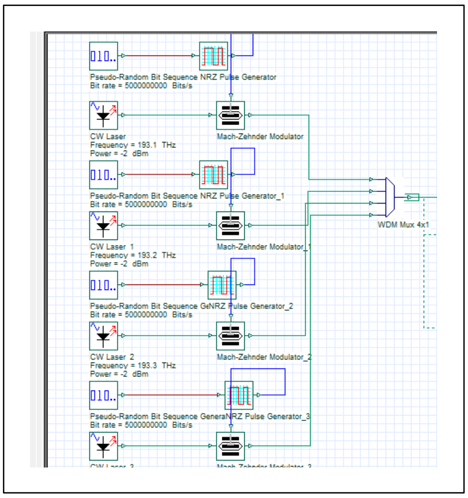


Fig. 2. Transmitter section

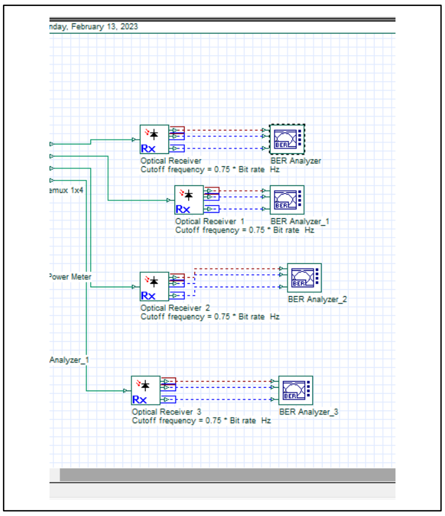


Fig. 3. Receiver section

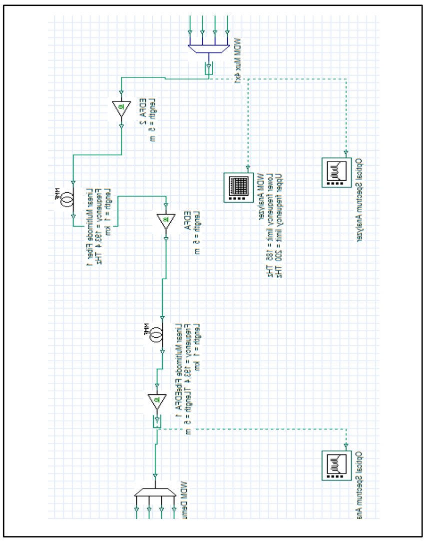


Fig. 4. Channel

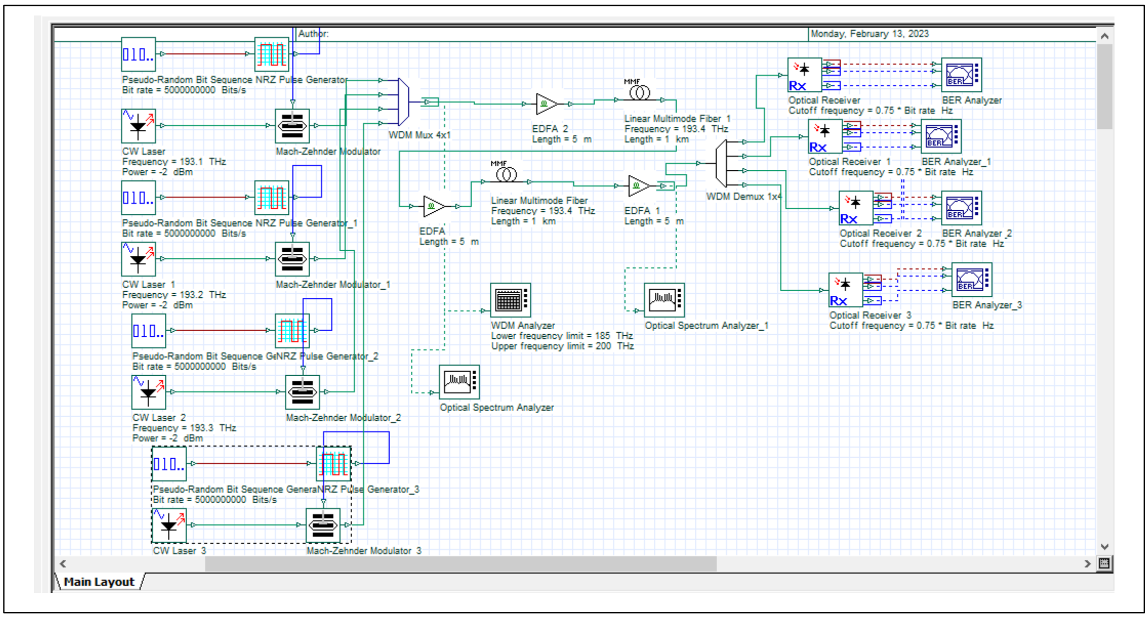


Fig. 5. Full WDM network

B. *Simulation parameters*

$$Po = P_T - P_R \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where; P_R = Receiver sensitivity

P_T = Transmitter power

P_o = Power Budget

$$Margin = P_o - P_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where Pi = Total link losses (i.e MMF attenuation + slice losses + Amplifier loss)

Using equation (1) for power budget analysis,

$$P_T = -2dB \ (given) \ and \ PR = -28 \ dB \ (given)$$

$$P_o = -2-(-28) = 26 \ dB$$

If the loss in the MMF fiber = Attenuation (dB/km) * Total distance (km)

Line loss at a distance of 2km at 6dB/km attenuation = 2*6 = 12dB

Using equation (2)

$$Margin = P_O - P_i = 26 - 12 = 14 \ dB$$

Table I and table II shows the different optical parameters from simulative design imputed into the network for simulation.

TABLE I. PARAMETERS FOR SIMULATION 1

Transmit power	-2dB
Receiver sensitivity	-28dB
End to End parameter	20GPS
End to End distance	2 km
Min required BER	e^{-09}
MMF attenuation at 193.4 THZ	6 dB / km
MMF Chromatic dispersion coefficient	-100 ps/nm/km
Power Budget	26dB
Margin	14

Post compensation parameters

$$PT = -2dB \ and \ PR = -28 \ dB$$

$$PB = -2-(-28) = 26dB$$

If the loss in the MMF fiber = Attenuation (dB/km) * Total distance (km)

Line loss at a distance of 2km at 6 dB/km attenuation = 2*6 = 12dB

$$Pi = (2*6) + 3(0.1*0.005) + 3*0.1 = 12.3dB$$

Using equation (2)

$$Margin = 26 - 12.3 = 13.7dB$$

TABLE II. PARAMETERS FOR SIMULATION 2

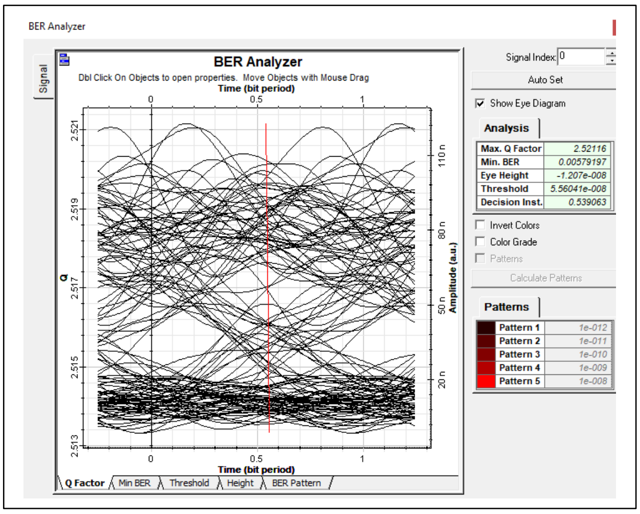
Transmit power	-2dB
Receiver sensitivity	-28Db
End to End parameter	20GPS
End to End distance	2.015 km
Min BER	e-09
MMF attenuation at 193.4 THZ	6 dB / km
MMF Chromatic dispersion coefficient	-100 ps/nm/km
EDFA length	5m
EDFA loss at 1550nm	0.1dB/m
Power Budget	26dB
Margin	13.7dB
Splice loss	0.1dB

III. RESULTS AND DISCUSSION

The simulations were carried out in two phases, phase one without EDFA and the second phase when the EDFA was integrated. Figure 6 shows channel 1 without EDFA. Upon integrating the EDFA into the system, the simulation results demonstrate a notable improvement in the Q factor, accompanied by an exceptionally low BER. The Q factor characterizes the characteristics of the distortion pulse, and it is inversely correlated with the BER. The simulations presented eye diagrams illustrating the BER and Q factor. To optimize the strength of the transmitted signal and mitigate the effects of intermodal dispersion, the EDFA was operated in the saturation region. The outcomes in figures 7, 9 11 and 13 unequivocally showcased a significant enhancement in the performance of the multimode fiber when utilizing the EDFA. In comparison to fiber without the EDFA, the BER experienced a considerable reduction. Table 3 shows the BER values and Q factor values before and after introduction of the EDFA to the channel while figures 6 -13 as well are the corresponding eye diagrams.

TABLE III. Q FACTOR AND BER BEFORE AND AFTER COMPENSATION WITH EDFA

Before			After	
SN	Q factor	BER	Q factor	BER
1	2.52116	$5.79197e^{-003}$	13.7467	$2.26114\ e^{-043}$
2	3.2363	$6.02442\ e^{-004}$	11.6728	$7.33912\ e^{-032}$
3	4.15134	$1.62285\ e^{-005}$	10.1493	$1.3047\ e^{-024}$
4	4.25489	$1.02455\ e^{-005}$	11.1216	4.0506^{-029}



Signal Index: 0

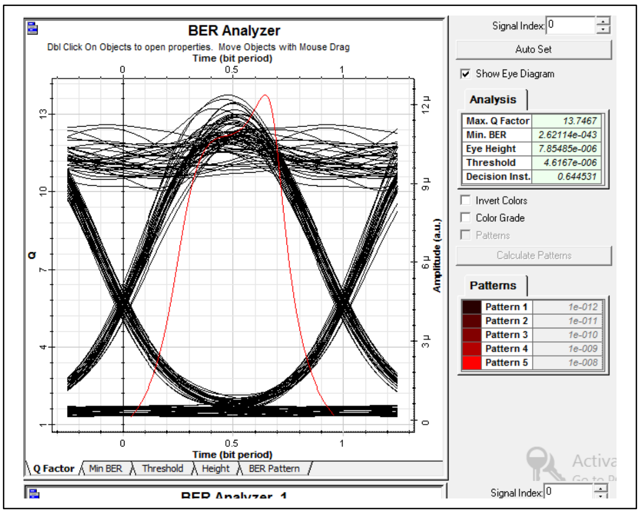
☑ Show Eye Diagram

Max. Q Factor	2.52116
Min. BER	0.00579197
Eye Height	-1.207e-008
Threshold	5.56041e-008
Decision Inst.	0.539063

☐ Invert Colors
☐ Color Grade
☐ Patterns

Pattern 1	1e-012
Pattern 2	1e-011
Pattern 3	1e-010
Pattern 4	1e-009
Pattern 5	1e-008

Fig. 6. Channel 1 Eye Diagram before EDFA



Signal Index: 0

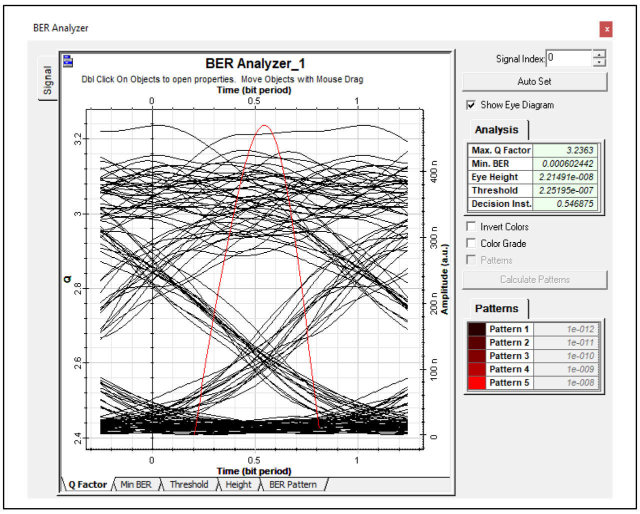
☑ Show Eye Diagram

Max. Q Factor	13.7467
Min. BER	2.62114e-043
Eye Height	7.85485e-006
Threshold	4.6167e-006
Decision Inst.	0.644531

☐ Invert Colors
☐ Color Grade
☐ Patterns

Pattern 1	1e-012
Pattern 2	1e-011
Pattern 3	1e-010
Pattern 4	1e-009
Pattern 5	1e-008

Fig. 7. Channel 1 Eye Diagram after EDFA



Signal Index: 0

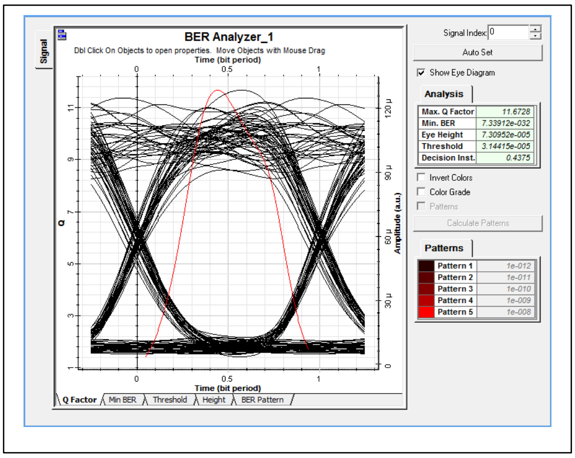
☑ Show Eye Diagram

Max. Q Factor	3.2363
Min. BER	0.000602442
Eye Height	2.21491e-008
Threshold	2.25195e-007
Decision Inst.	0.546875

☐ Invert Colors
☐ Color Grade
☐ Patterns

Pattern 1	1e-012
Pattern 2	1e-011
Pattern 3	1e-010
Pattern 4	1e-009
Pattern 5	1e-008

Fig. 8. Channel 2 Eye Diagram before EDFA



Signal Index: 0

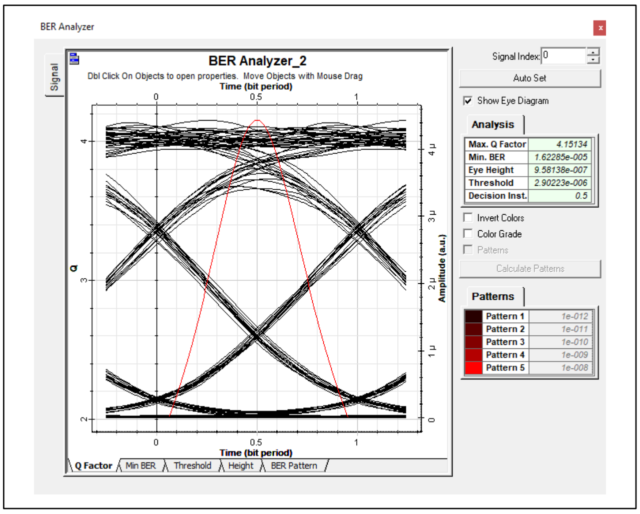
☑ Show Eye Diagram

Max. Q Factor	11.6728
Min. BER	7.33912e-032
Eye Height	7.30952e-005
Threshold	3.14415e-005
Decision Inst.	0.4375

☐ Invert Colors
☐ Color Grade
☐ Patterns

Pattern 1	1e-012
Pattern 2	1e-011
Pattern 3	1e-010
Pattern 4	1e-009
Pattern 5	1e-008

Fig. 9. Channel 2 Eye Diagram after EDFA



Signal Index: 0

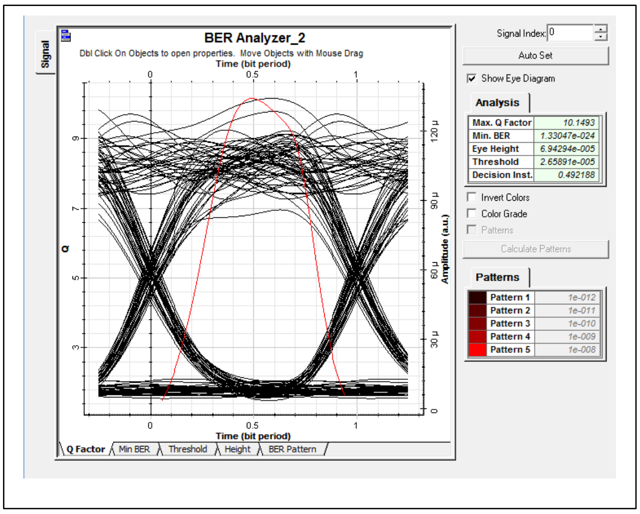
☑ Show Eye Diagram

Max. Q Factor	4.15134
Min. BER	1.62285e-005
Eye Height	9.58138e-007
Threshold	2.90223e-006
Decision Inst.	0.5

☐ Invert Colors
☐ Color Grade
☐ Patterns

▇	Pattern 1	1e-012
▇	Pattern 2	1e-011
▇	Pattern 3	1e-010
▇	Pattern 4	1e-009
🟥	Pattern 5	1e-008

Fig. 10. Channel 3 Eye Diagram before EDFA



Signal Index: 0

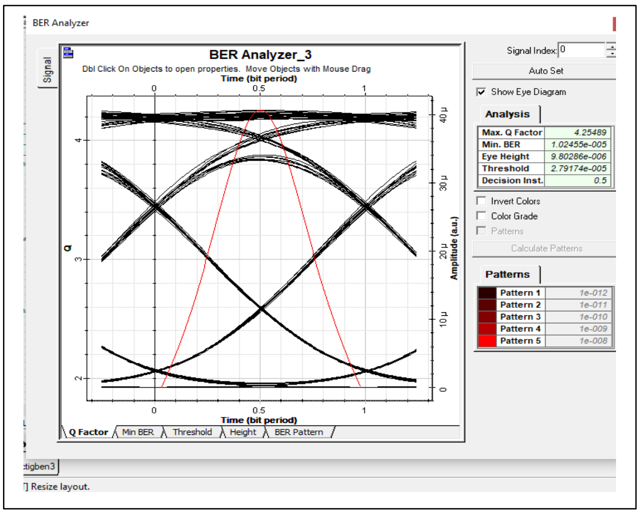
☑ Show Eye Diagram

Max. Q Factor	10.1493
Min. BER	1.33047e-024
Eye Height	6.94294e-005
Threshold	2.65891e-005
Decision Inst.	0.492188

☐ Invert Colors
☐ Color Grade
☐ Patterns

▇	Pattern 1	1e-012
▇	Pattern 2	1e-011
▇	Pattern 3	1e-010
▇	Pattern 4	1e-009
🟥	Pattern 5	1e-008

Fig. 11. Channel 3 Eye Diagram after EDFA



Signal Index: 0

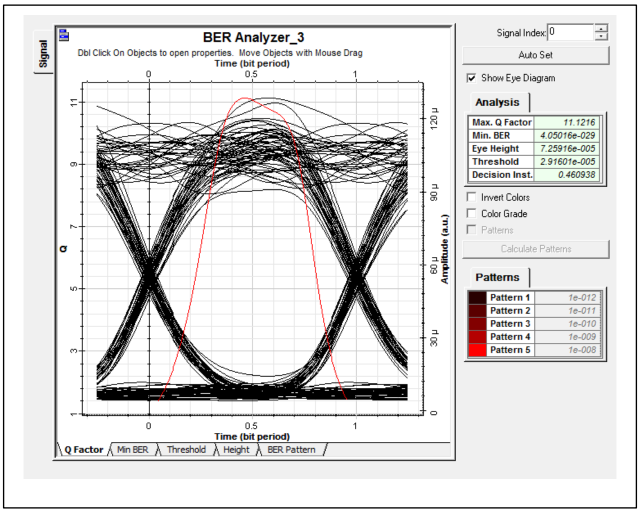
☑ Show Eye Diagram

Max. Q Factor	4.25489
Min. BER	1.02455e-005
Eye Height	9.80286e-006
Threshold	2.79174e-005
Decision Inst.	0.5

☐ Invert Colors
☐ Color Grade
☐ Patterns

▇	Pattern 1	1e-012
▇	Pattern 2	1e-011
▇	Pattern 3	1e-010
▇	Pattern 4	1e-009
🟥	Pattern 5	1e-008

Fig. 12. Channel 4 Eye Diagram before EDFA



Signal Index: 0

☑ Show Eye Diagram

Max. Q Factor	11.1216
Min. BER	4.05016e-029
Eye Height	7.25916e-005
Threshold	2.91601e-005
Decision Inst.	0.460938

☐ Invert Colors
☐ Color Grade
☐ Patterns

▇	Pattern 1	1e-012
▇	Pattern 2	1e-011
▇	Pattern 3	1e-010
▇	Pattern 4	1e-009
🟥	Pattern 5	1e-008

Fig. 13. Channel 4 Eye Diagram after EDFA

It should be acknowledged, however, that while EDFAs have proven effectiveness in addressing intermodal dispersion in multimode fibers, their performance diminishes with increasing fiber length, particularly when accounting for intermodal dispersion. Consequently, precise calibration of the amplification settings becomes crucial. In summary, the incorporation of EDFAs can substantially enhance the performance of multimode fibers by compensating for intermodal dispersion, providing a cost-effective means to achieve this improvement.

Furthermore, the EDFA's influence on optical communication systems' Signal-to-Noise Ratio (SNR) can yield both favorable and unfavorable consequences. When appropriately designed and implemented, the EDFA has the capability to boost signal strength, enhance SNR, and mitigate the impact of noise and distortion, thereby improving the overall BER and system performance.

In optical communication systems, the SNR plays a critical role in shaping the waveforms of the Bit Error Rate (BER) analyzer. The BER analyzer waveform, which charts the error rate of a digital communication system against the received signal power, is significantly affected by the SNR.

A low SNR amplifies the significance of the received signal's noise level, leading to a more erratic and unstable BER analyzer waveform. In such cases, fluctuations in received signal power can cause unpredictable and challenging-to-correct random bit errors due to elevated noise levels. Conversely, a high SNR results in a more predictable and consistent BER analyzer waveform, as the noise level is relatively low compared to the signal power. Consequently, a smooth and consistent curve with increasing received signal power is more likely to result in a decreasing error rate.

IV. CONCLUSION

Various methods exist to counteract dispersion in multimode fiber, including the implementation of graded-index fibers, mode scramblers, or mode converters. However, the employment of an erbium-doped fiber amplifier (EDFA) has emerged as a widely favored and efficient approach for addressing dispersion in long-haul transmission systems. EDFAs are esteemed for their broad amplification spectrum, which allows accommodation for diverse modes, and their relatively flat gain profile. These characteristics render EDFAs well-suited for mitigating overall dispersion in multimode fiber, ensuring uniform amplification of all modes and minimizing distortion arising from mode-dependent losses. In conclusion, the utilization of EDFA as a dispersion compensation technique in multimode fiber proves to be a valuable strategy that aids optical communication systems in circumventing the limitations of multimode fiber, thereby extending their operational range.

Notwithstanding the advantages offered by EDFA, certain challenges remain to be addressed, such as the necessity for high-resolution dispersion maps and the potential impact of nonlinear effects. Further research endeavors are warranted to unlock the full potential of dispersion compensation in multimode fiber systems. Additionally, it is crucial to acknowledge that dispersion compensation necessitates high-performance digital signal processing hardware, which can incur considerable costs. Therefore, future investigations should carefully examine the cost-benefit trade-off of employing EDFA in multimode fiber systems to discern the balance between the expenses associated with EDFA implementation and the benefits derived in terms of augmented capacity and extended reach.

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