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Performance Evaluation of Chromatic and Polarization Dispersion of Fiber Optic Transmission Link in Broadband Communication

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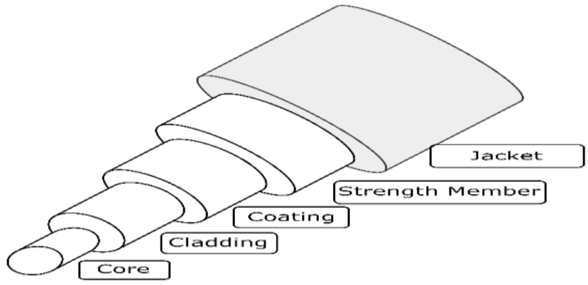
Abstract: This study involved a quantitative evaluation of the performance of dispersion and polarisation of light in a fibre optic link for broadband communication. The dispersion that occurs in the transmission of a signal over a 120 km separation at 100 Gbps was studied, and uniform chirped fibre Bragg grating dispersion compensation was adopted using three particular setups: pre-dispersion compensation, Post-Dispersion Compensation, and Mixed dispersion compensation procedures. Optical fibre is a medium consisting of slender glass or plastic strands that enables high-speed data transmission across a wide frequency range, spanning up to 25 GHz, and this is achieved without signal amplification. However, as data rates and transmission distances escalate, challenges stemming from nonlinearities and dispersion intensify, impacting overall performance. This study is devoted to tackling these challenges through the deployment of Fibre Bragg Gratings (FBGs) in three distinct configurations: pre-dispersion compensation, Post-Dispersion Compensation, and Mixed dispersion compensation. Its principal objective is to correct dispersion in a 120 km transmission operating at 100 Gbps. The results obtained from each of the three compensation methods, employing the Optisystem simulation application software, were then analysed using key performance metrics such as Bit Error Rate (BER), Quality Factor (Q-Factor), and received power to identify the best compensation method, with the ultimate aim of significantly enhancing signal transmission performance. Post-compensation of UFBG exhibits the best performance, with the highest quality factor, the lowest BER, and the lowest power requirements among the three compensation techniques. Hence, UFBG Post-compensation is recommended to mitigate chromatic and polarization dispersions in fibre optic transmission systems. The findings of this work will provide valuable information for the design and manufacture of fibre optic transmission equipment for long-haul data communication systems.

Keywords: Optical Fiber, High-Speed Data Transmission, Dispersion, Fiber Bragg Gratings

I. INTRODUCTION

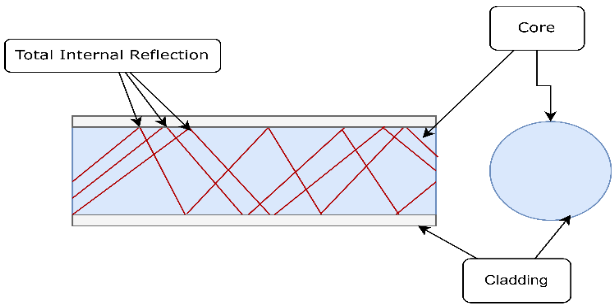
Optical fibre, often referred to as fibre-optic cable, is a vital component of modern communication systems. Comprising slender strands of glass or plastic [1]. It plays a crucial role in transmitting data across an extensive frequency range, exceeding 25THz, and covering considerable distances [2]. The fundamental structure of an optical fibre, as depicted in Figure 1, consists of four key components: the core, cladding, coating, and strength member.



[Fig.1: Structure of Optic Fibre] [2]

The operation of optical fibres hinges on transmitting data through light pulses that travel within the slender fibre strands [3]. The fibre core, as thin as a human hair, is surrounded by a cladding layer with a lower refractive index, causing light to bend inward due to the phenomenon of total internal reflection as depicted in Figure 2. This effect ensures containment within the core, preventing dispersion [4]. Finally, an outermost layer, the coating, serves as protection against damage and moisture for the fibre optics.

The versatility of optical fibres is demonstrated through a range of applications, including internal data transmission, telecommunications, and medical imaging, as illustrated in Figure 3. They outperform traditional copper wires in several key aspects, such as offering longer transmission distances, a higher bandwidth, immunity to electromagnetic interference, and minimal signal loss [5]. These qualities make optical fibres an ideal choice for broadband communication. As a result, the introduction of fibre optics has led to a revolution in long-distance communication methods.



[Fig.2: Operation of Optic Fibres] [4]

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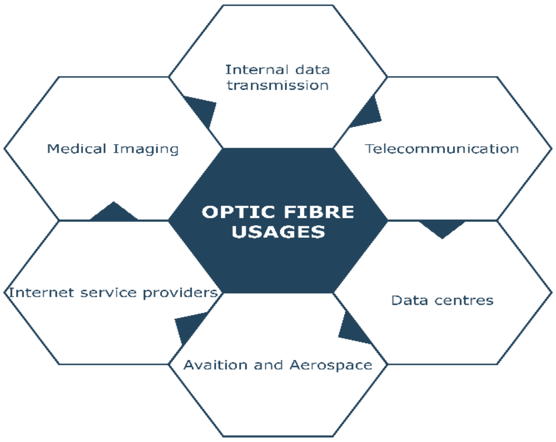
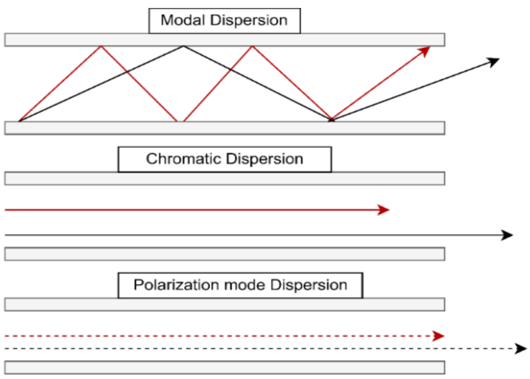


[Fig.3: Applications of Fibre Optics] [6]

Fibre optic transmission systems are susceptible to three significant types of dispersions [6], namely modal dispersion, polarization mode dispersion (PMD) [7], and chromatic dispersion, as illustrated in Figure 4 [8]. Modal dispersion arises from the different paths and modes light pulses can take [9], causing variations in signal arrival times and potentially leading to signal smearing. PMD results from variations in light wave speeds with different polarisation orientations, which impact signal quality, especially in high-speed transmission. Chromatic dispersion, on the other hand, is rooted in the diverse speeds of various light wavelengths within the fibre, potentially causing signal degradation due to variations in arrival times. The collective impact of these dispersions can lead to signal distortion and reduced signal quality in fibre optic transmission systems.



[Fig.4: Dispersion Mode in Fibre Optics] [Error! Reference source not found.]

The evolution of fibre optic transmission systems, designed to support higher data rates across extended distances, has introduced challenges related to the compromised performance of transmission media. This degradation is manifested in the form of nonlinearities and dispersion, and it has a substantial impact on the efficiency of optical fibre transmission. A particularly critical concern arises from residual Chromatic Dispersion (CD), which becomes a limiting factor, especially in the context of high-speed systems. Addressing and mitigating CD is pivotal in ensuring the continued success of advanced fibre optic communication.

Effectively addressing this challenge requires the development of innovative solutions that enhance the Chromatic Dispersion (CD) tolerance of high-speed systems, alongside the provision of cost-effective and adaptable compensation methods for Polarisation Mode Dispersion (PMD). This necessitates the advancement of more dynamic and precise PMD and CD compensation techniques. Embracing cutting-edge approaches in this regard will not only overcome the limitations posed by transmission media degradation but also enable optimal performance in fibre optic transmission systems. By doing so, we ensure reliable and efficient data transfer even over extended distances, meeting the ever-growing demands of modern communication networks.

This study aims to assess the influence of polarisation mode and chromatic dispersion on the performance of optical fibre transmission links in the context of broadband communication. In recent years, significant advancements have been made in optical transmission systems, with transmission capacities exceeding one petabit per second (1 Pbps). However, as these systems have evolved to handle higher data rates and longer distances, nonlinearities and dispersion have emerged as substantial constraints, impacting the effectiveness of transmission links and, consequently, the overall performance of broadband communication systems.

II. MATERIALS AND METHODS

This involves experimental study, simulation, and data analysis.

A. Experimental Study

The experimental study involves establishing an optical fibre transmission link system within a laboratory setting to assess link performance under diverse conditions of chromatic and polarisation mode dispersions. To achieve this, the following steps are taken:

Link Setup for the Construction of a Fibre Optic Transmission Link Utilising Standard Single-Mode Fibre as the Medium.

Dispersion Introduction, which involves inducing chromatic and polarisation mode dispersion into the transmission link by manipulating factors such as fibre length and twisting angle.

Performance Measurement, for the evaluation of transmission link performance through the utilization of a range of performance metrics, including eye diagrams, signal-to-noise ratios, and bit error rates.

Performance Comparison, involving a comparative analysis of transmission link performance in two scenarios. One is without compensation techniques for polarization and chromatic mode dispersion, while the other incorporates these compensation techniques.

By executing the steps, the experimental study provided valuable empirical insights into the ramifications of dispersions and the influence of compensation techniques on the performance of optical fibre transmission links.

B. Simulation

This was achieved using OptiSystem 7.0 software. This is a robust tool for simulating and analyzing optical communication systems. The simulation process involves the following stages:

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Designing a Model. That is, constructing a model of the fibre optic transmission link utilising the capabilities of OptiSystem software.

Dispersion Introduction, where polarization and chromatic mode dispersion were incorporated into the transmission link model to mimic real-world scenarios accurately.

Effect Evaluation, for assessing the influence of dispersions by varying their performance effects. This assessment will be based on key parameter evaluation metrics, including eye diagrams, signal-to-noise ratios, and bit error rates.

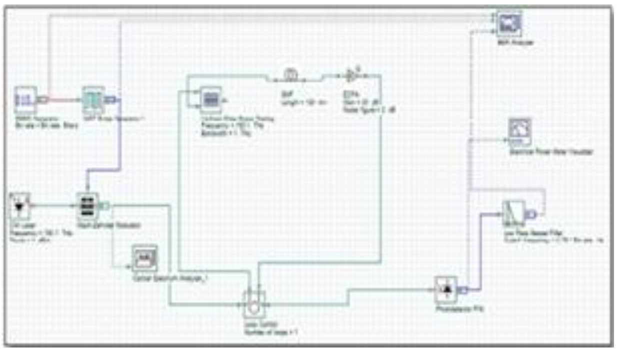
Performance Comparison involves contrasting the performance of the transmission link model under two conditions: one without compensation techniques for polarization mode dispersion and chromatic mode dispersion, and another with these compensation techniques.

By following the steps, the impact of dispersions and the efficacy of compensation techniques on the performance of fibre optic transmission links in broadband communication were observed.

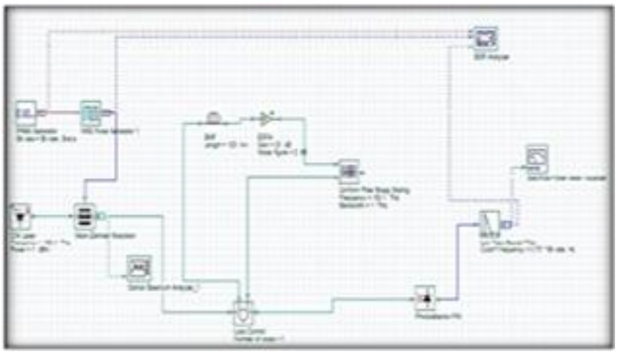
i. Simulation Setup

The accomplishment of dispersion compensation using Uniform Fibre Bragg Gratings (UFBGs) as the dispersion compensator, employing OptiSystem 7.0 software, was implemented. The focus is on a single-channel scenario, and simulation setups are conducted at both the transmitter and receiver ends.

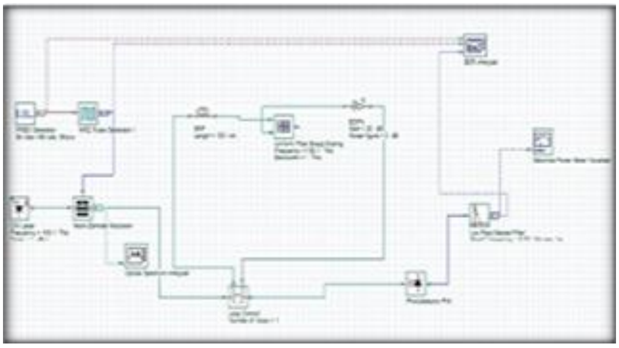
At the transmitter segment, a pseudo-random binary sequence (PRBS) generator was used to create consistent irregular bit patterns. A Mach-Zehnder modulator, where one input followed a non-return-to-zero (NRZ) modulation format and the other input was from a continuous-wave laser acting as a light source, was employed. The modulated optical signals were transmitted through the optical channel at a rate corresponding to 100 Gbps, with input power ranging from 1 dBm to 10 dBm. The simulations were conducted at a frequency of 193.1 THz. The received signals were directed to a pin detector, which serves as a transducer by converting optical signals into electrical signals. The position of the UFBG was adjusted to observe its impact on data transmission pulses and bandwidth. This adjustment was made in three configurations: pre-compensation, post-compensation, and mixed compensation. An erbium-doped fibre amplifier (EDFA) was integrated into the model to mitigate attenuation, placed after each instance of the UFBG. The simulation circuits for the three specific setups of UFBG (pre-compensation, post-compensation, and mixed-compensation) are illustrated in Figures 5, 6, and 7, respectively.



[Fig.5: Simulation Circuit for Pre-Compensation Using Uniform Fibre Bragg Grating]



[Fig.6: Simulation Circuit for Post-Compensation Using Uniform Fibre Bragg Grating]



[Fig.7: Simulation Circuit for Mix Compensation Using Uniform Fibre Bragg Grating]

The evaluation primarily revolves around observing the Q-factor and bit error rate (BER) to determine the most suitable design among the three. The parameters for UFBG and simulation details are outlined in Tables 1 and 2, respectively.

Table 1: Parameters Used for UFBG Simulation

Value (Unit)	Parameter Measured
120km	Length of Fibre
-100dB	Noise Threshold
0.99	Reflectivity
500GHz	Sample Rate

Table 2: General Parameters Used in Simulation

Value (Unit)	Parameter Measured
100Gbps	Bit Rate
1THz	Bandwidth
30dB	Extinction Ratio
6.4THz	Sample Rate
1-10dBm	Power
20dB	Gain
2dB	Noise
193.1THz	Frequency

C. Data Analysis

The data gathered from both simulation and experimental studies were analyzed utilizing statistical methods, aimed at elucidating the impact of polarization and chromatic mode dispersion on optical fibre transmission link performance by employing the following procedure:

Performance Metrics Evaluation. This assessment evaluates performance metrics within each scenario, followed by a comparative analysis of the outcomes.

Optimal Compensation Technique Identification, for recognition of the most effective compensation techniques for mitigating polarisation and chromatic mode dispersion effects in optical fibre transmission links.

Factor Identification is used to determine the factors that influence the efficiency of compensation techniques.

The validation process involves a validation procedure that cross-references simulation outcomes with experimental findings to confirm the reliability of the results.

Hence, a comprehensive understanding of the interplay between dispersions, compensation techniques, and the performance of optical fibre transmission links is attained.

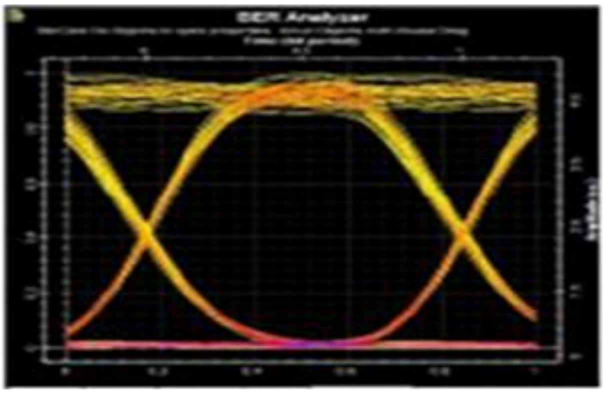
III. RESULT AND DISCUSSION

The analysis of the UFBG for Pre-compensation, Mix Compensation, and Post-compensation was conducted based on key performance metrics, including the Q-factor, BER, eye height, and received power.

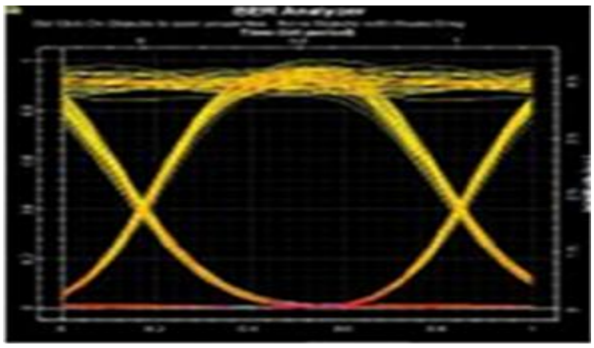
Figures 8, 9, and 10 illustrate the eye charts for Pre-, Post-, and Mix compensations, each employing the UFBG. Notably, the input power is set at 10 dBm in these eye diagrams, as this power level demonstrates distinct schemes of the UFBG showcasing the maximum Q-factor and minimal BER in comparison to other power levels ranging from 1 dBm to 10 dBm.

Tables 3, 4 and 5 provide a detailed breakdown of BER, Q-factor, received power, and eye heights across the three schemes at varying power levels. These Tables offer a comprehensive overview of the performance characteristics observed in each compensation setup, providing valuable insights into the effects of dispersion compensation using UFBG under different conditions.

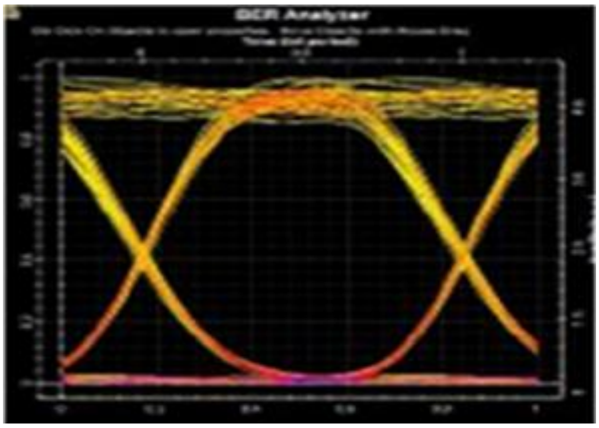
From Tables 3, 4, and 5, it is observed that post-dispersion compensation has the highest quality factor and the lowest BER, indicating a desired and optimal compensation technique condition.



[Fig.8: UFBG Pre Compensation]



[Fig.9: UFBG Post Compensation]



[Fig.10: UFBG Mix Compensation]

Table 3: Results of Inputs from 1dBm to 10dBm for Pre-Compensation of FBG

Input Power (dB)	Max. Q Factor	Min. BER (Gbps)	Eye Height (m)	Threshold	Received Power
1	7.86135	1.78E-12	0.000301	0.000291	1.26E
2	9.13437	3.02E-20	0.000412	0.000319	1.89E
3	10.5549	2.18E-26	0.000555	0.000354	2.90E
4	12.1228	3.56E-34	0.000737	0.000398	4.49E
5	13.8473	5.75E-44	0.000969	0.000441	7.01E
6	15.7283	4.15E-56	0.001263	0.000504	1.10E
7	17.7594	6.10E-71	0.001637	0.000561	1.74E
8	19.9478	6.47E-89	0.002112	0.00065	2.74E
9	22.2657	3.25E-11	0.002714	0.000763	4.33E
10	24.7116	3.18E-13	0.003477	0.000838	6.86E

Table 4: Results of Inputs from 1dBm to 10dBm for Post-Compensation of UFBG

Input Power (dB)	Max. Q Factor	Min. BER (Gbps)	Eye Height (m)	Threshold	Received Power
1	10.5753	1.56E-26	0.00036	0.0001132	1.09E
2	11.913	4.04E-33	0.0004752	0.0001343	1.73E
3	13.369	3.55E-41	0.0006205	0.0001531	2.73E
4	14.9508	5.97E-51	0.0008056	0.00018449	4.32E
5	16.663	9.12E-63	0.00104	0.0002099	6.85E
6	18.512	6.11E-77	0.00133935	0.00023831	1.09E
7	20.5079	6.61E-94	0.001718	0.0002698	1.72E
8	22.6786	2.55E-11	0.002197	0.0002909	2.72E
9	25.028	1.04E-13	0.002805	0.00033431	4.31E
10	27.54	1.95E-16	0.00357	0.0003932	6.84E

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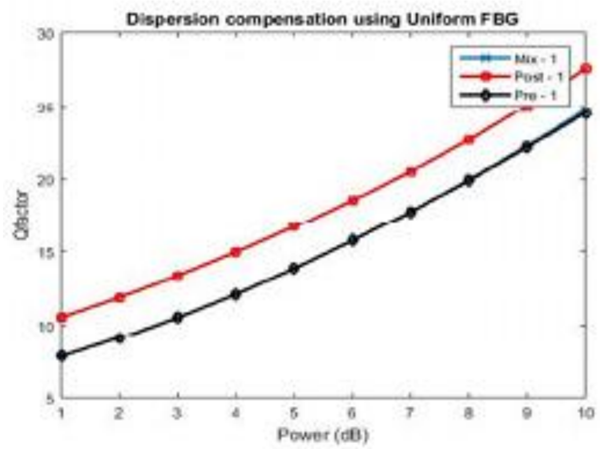
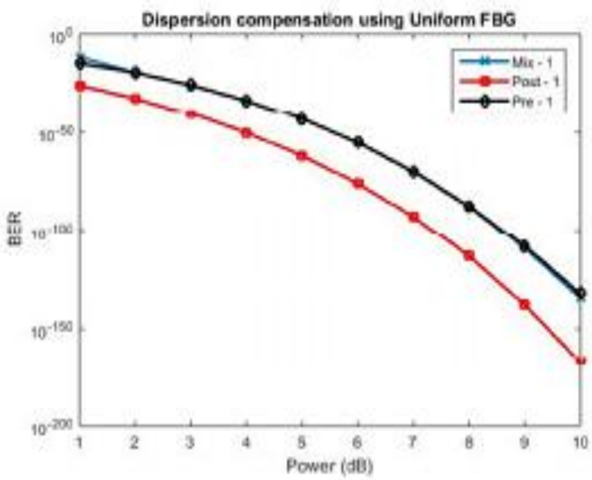
Table 5: Results of Inputs from 1dBm to 10dBm for Mix Compensation of UFBG

Input Power (dB)	Max. Q Factor	Min. BER (Gbps)	Eye Height (m)	Threshold	Received Power (dB)
1	7.86036	1.79E-15	0.000301	0.000291	1.75E
2	9.13275	3.07E-20	0.000413	0.000319	2.52E
3	10.5523	2.24E-26	0.000555	0.000354	3.72E
4	12.1191	3.72E-34	0.000737	0.000397	5.58E
5	13.8391	6.43E-44	0.000969	0.000441	8.49E
6	15.7154	5.08E-56	0.001263	0.000502	1.30E
7	17.7315	1.02E-70	0.001638	0.000581	2.02E
8	19.8949	1.86E-88	0.002112	0.000644	3.15E
9	22.1653	3.02E-10	0.002715	0.000752	4.93E
10	24.5084	4.73E-13	0.003477	0.000819	7.75E

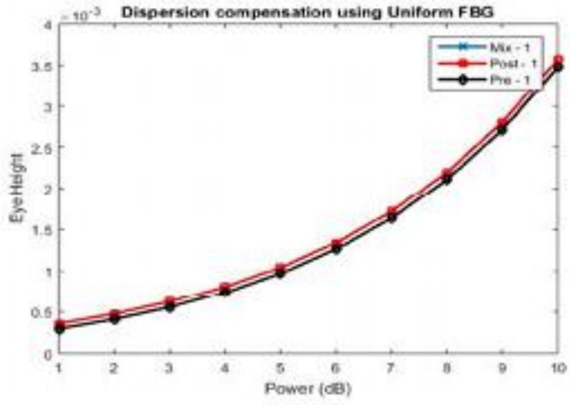
By analysing all the graphs shown in Figures 11, 12, 13, and 14, it is clear that Post-compensation of UFBG shows the best performance at 100 Gbps for a 120 km range. Again, pre- and mix compensations overlapped in Figures 10 through 14. In Figure 11, UFBG Post-compensation exhibited the highest quality factor of the three compensation techniques.



[Fig.11: Q-Factor Against Input Power Plot]

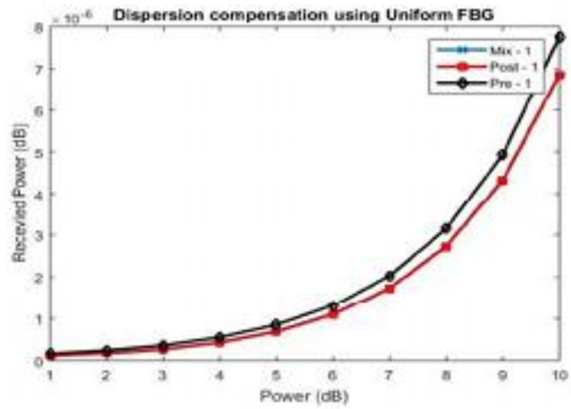


[Fig.12: BER Against Input Power Plot]



[Fig.13: Eye Height Against Input Power Plot]

Figure 12 shows that Post-compensation UFBG has the lowest error rates, while the eye plots (Figure 13) are closely related; however, post-compensation has a slightly lower eye height per dB than pre- and Mixed compensations. Additionally, Post-compensation received the lowest power compared to Pre- and Mix compensations, which were again overlapped.



[Fig.14: Received Power Against Input Power Plot]

IV. CONCLUSION

This work investigated the performance of adaptive optical fibre compensation design techniques, which involve compensation and monitoring modules, and is expected to produce experimental results in an optical fibre transmission system operating at 40Gbps CSRZ format. Optical fibre is a vital component of modern communication systems, comprising slender strands of glass or plastic that transmit data across an extensive frequency range, exceeding 25 GHz, and cover considerable distances. However, fibre optic transmission systems are susceptible to modal, polarisation and chromatic dispersions. Hence, three different compensation techniques were identified and investigated to mitigate chromatic and dispersion effects in the fibre optic transmission medium. These are Pre-compensation, post-compensation, and Mixed compensation methods, utilising uniform fibre Bragg Gratings (UFBGs) as the dispersion compensator, and employing OptiSystem 7.0 software. The focus is on a single-channel scenario, and simulation setups are conducted at both the transmitter and receiver ends.

The results of the investigation suggested that when analysed using key performance metrics such as BER, Q-factor, and power requirement, Post-compensation of UFBG shows the best performance at 100Gbps for a 120km range, while pre- and Mixed compensations overlap. Furthermore, UFBG Post-compensation exhibited the highest quality factor, the lowest BER, and the lowest power requirements among the three compensation techniques.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/Competing Interests:** Based on my understanding, this article does not have any conflicts of interest.
- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it was conducted without any external influence.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

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