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Performance Analysis of Gaussian Apodized Fiber Bragg Grating (GA-FBG) Dispersion Compensator for a Long Haul Optical Fiber Link



Abstract: This examination gives a complete analysis of the GA-FBG, a generally involved grating for dispersion compensation across a 150 kilometer optical link, from each point. The essential objective of this study is to distinguish how long the GA-FBG can work as an independent dissemination reimbursement gadget and how well it acts in various compensation settings. In this review, the GA-FBG is utilized as an option in contrast to the exorbitant Dispersion-Reimbursing Fiber inside the association to give a more safe optical link. The investigation delves into three specific compensation methods and studies the GA-FBG grating boundaries in light of the relative abundance of real imperatives associated with a Fiber Bragg Grating (FBG) in the design phase. Using a Piece Blunder Rate analyzer to examine the streamlined links' exhibition highlights allows us to evaluate their productivity. Results show that the GA-FBG exhibits a common dispersion compensation adequacy when the link's channel boundaries are tuned. Using gearbox over distances easily exceeding 500 km, the balanced compensation strategy delivers a remarkable Q-factor respect. Utilizing OptiSystem programming, we validate the proposed system's functional viability. The results of our study indicate that the GA-FBG is capable of efficiently counteracting dispersion, leading to an optical link that is both more economical and effective, with significant potential for extended transmission ranges.

Keywords: Gaussian Apodization, Long-haul optical link, Fiber Bragg grating (FBG), Dispersion compensation, Chromatic dispersion

I. INTRODUCTION

In single-mode fibers (SMF), the test of chromatic dispersion turns out to be more articulated over long distances, prompting inter-symbol interference (ISI) that compels the capacity to accomplish high piece rates, in this manner representing a significant obstruction to long-separate optical transmission [1, 2]. In spite of the way that chromatic dispersion doesn't turn out as expected at the Zero-Dispersion Frequency (ZDW=1300 nm), the 1550 nm frequency window stays the favored decision for optical transmission because of its little transfer speed [3, 4]. Notwithstanding, dispersion inside this 1550 nm range stays a critical test [4], handling one of the central concerns with accomplishing long-haul optical transmission in SMF. Fiber Bragg Grating (FBG) and Dispersion Compensating fiber (DCF) are two regularly involved techniques for relieving dispersion; both can be joined with conventional single-mode fibers (CSMF) [4]. It has been determined that DCF is more efficient than FBG, even though previous research [4-8] has mostly concentrated on using DCF and FBG for distribution revision. Negative dispersion results from the DCF-adjusted refractive index allowing longer wavelength components to travel faster [9]. On top of that, the DCF provides reliable dispersion adjustment for various phantom components [5]. Regardless, increasing dispersion compensation in long-haul links requires increasing the DCF's length, which in turn increases costs and limits the DCF's use to shorter transmission distances [5]. While suitable peeping and apodization tactics can improve FBG's display, it has shown to be less effective than DCF [8]. The optimum passband can be mirrored by FBG by selecting the appropriate grating length and twitter rate, as confirmed in [10]. Consequently, a crucial and extensive research area is finding the optimal tweeting and apodization systems for designing dispersion correction modules. The Gaussian-Apodized-FBG (GA-FBG) is one of the Apodized-FBG types that has recently emerged as a practical approach to long-haul link dispersion adjustment [8]. This approach supposedly achieves high reflectivity levels while effectively concealing side curves, according to the research [5]. According to this research, a GA-FBG could be used as a dispersion compensator for an optical link that runs 150 km at a piece rate of 10 GB/s.. Full investigation and optimization of the suggested module has been carried out for all three types of compensation: pre-, post-, and even compensation. In addition, the review delves into how the module's presentation is impacted by four distinct peeping strategies: direct, square root, cubic root, and quadratic.

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Changing the grating lengths and convincing the refractive records to build the quality variable (Q-factor) considers the assessment of the module's ascribes. For additional investigation at expanded transmission removes, the arrangement with the most elevated Q-factor is picked to make a practical and proficient dispersion compensator for long-haul optical organizations.

With regards to gearbox distances surpassing 500 km and empowering really long reach gearbox with FBG as the main dispersion compensation unit, the even compensation mode accomplishes a sensible Q-factor.

II. METHODOLOGY: PRINCIPLE OF OPERATION

A type of optical fiber link, FBG consolidates gratings—regularly distributed variants in refractive record—as shown in Figure 1. The grating length (L_g) is the length of fiber cut with gratings, while the grating period (Λ) is the span between two gratings. At the Bragg wavelength (λ_B), which is impacted by the compelling refractive record, light passing through FBG is linked.

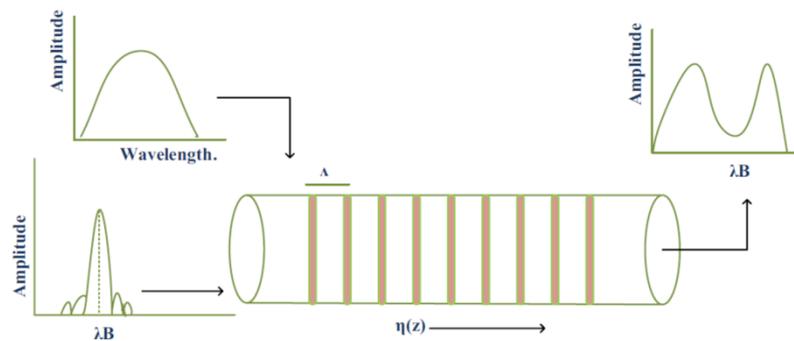


Fig. 1 Schematic diagram of a FBG [3]

A FBG can be categorized as Uniform or Chirped FBG (CFBG) depending on whether the grating duration is kept constant or varied. In contrast to CFBG, which is designed for a wider reflection band, uniform gratings reflect narrower bands, rendering them impractical for high piece rates. In order to alter the reflection range and enable a wider reflection band, CFBG is a type of peeping-profile non-uniform grating design. Some CFBG tweeting profiles are nonlinear, while others are straight. The most common nonlinear types are quadratic, square root, and cubic root. In [11], the tweeting profiles are shown in Table 1 as points, with ' Λ_0 ' representing the focal grating time frame, ' z ' the propagation pivot, and ' C ' the trill rate.

Table 1: Chirping Profiles

Linear chirping	$\Lambda(z) = \Lambda_0 \left[\frac{z}{L_g} - \frac{1}{2} \right]_C$
Square root chirping	$\Lambda(z) = \Lambda_0 \left[\sqrt{\frac{z}{L_g}} - \sqrt{\frac{1}{2}} \right]_C$
Cubic root chirping	$\Lambda(z) = \Lambda_0 \left[\sqrt[3]{\frac{z}{L_g}} - \sqrt[3]{\frac{1}{2}} \right]_C$
Quadratic chirping	$\Lambda(z) = \Lambda_0 \left[\left(\frac{z}{L_g} \right)^2 - \left(\frac{1}{2} \right)^2 \right]_C$

By fitting the twittering profile of the FBG, it becomes conceivable to tweak the grating's unearthly reaction to meet the exact necessities of a given application. As framed in [8], the focal grating time of a FBG can be determined utilizing the accompanying recipe:

$$\Lambda_0 = \lambda_B / 2 \cdot \eta_{eff} \tag{1}$$

The first grating period will be approximately 533.2 nm when the operating wavelength is 1552.52 nm and the effective refractive index (η_{eff}) is 1.45. By following this method, one may simply ascertain the grating variances for different chirping profiles. One needs to calculate the chirp rate, which is the amplitude of the grating period change along the grating length, in order to get the linear-chirping profile ($\Lambda(z) = \Lambda_0 + [Z/L_g - 1/2]C$) for a 30 mm FBG grating. Common ways to measure this variance include the initial grating period in percentage and unit duration. As an example, the grating period varies by 0.1 percent of the beginning period for every millimetre of grating length when the chirp rate is 0.1% per mm. Take the 30-millimeter grating length as an example; the calculations would take into consideration a 0.5-percent increase in grating period.

To calculate the chirp rate C , we use the following formula:

$$C = \frac{\Delta\Lambda}{\Lambda_0 \times L_g} \tag{2}$$

In our case, $\Delta\Lambda$ is 2.67 nm, which is 0.5% of the original grating period or $0.005 \times 533.2 \text{ nm} = 2.67 \text{ nm}$, and it represents the fluctuation in the grating period across the length of the grating. At the conclusion of the 30 mm grating, the new grating period would be 535.87 nm, according to the formula $\Lambda_0 + \Delta\Lambda = 535.87 \text{ nm}$. We may approximate the chirp rate (C) to be around $C \approx 1.67 \times 10^{-7} / \mu\text{m}$ by plugging the values of $\Lambda_0 = 533.2 \text{ nm}$ and $L_g = 30 \text{ mm} = 30,000 \mu\text{m}$ into Equation (2).

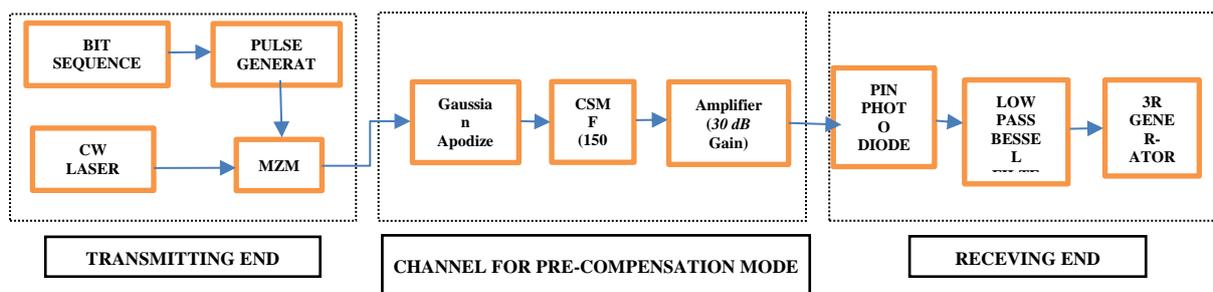
Additionally, as light passes through a CFBG, the components with higher wavelengths undergo a longer round-trip time compared to those with lower wavelengths. This phenomenon serves to mitigate chromatic dispersion, which is a prevalent problem in conventional single-mode fibers. The effectiveness of the FBG in compensating for dispersion is detailed in [11] as follows:

$$D_{\text{FBG}} = \frac{1}{C(\Delta\Lambda)} \left\{ 1 - \frac{\lambda}{\eta_{\text{eff}}} \left(\frac{d\eta_{\text{eff}}}{d\lambda} \right) \right\}; \tag{3}$$

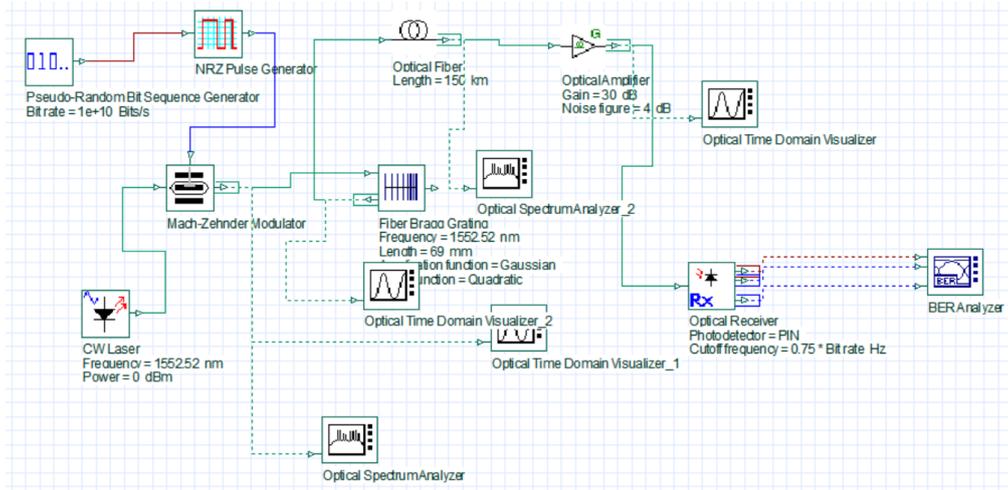
In Equation (3) the term C represents velocity of light and λ denotes the optical wavelength.

III. PROPOSED SIMULATION SET-UP

For an optical link length of 150 km, this review introduces a GA-FBG as a specific dispersion compensator. We evaluate the GA-FBG's performance in three distinct compensation modes—Pre-compensation, Post-compensation, and Even—by means of four distinct chirping strategies. The intended structure is implemented using OptiSystem programming. With the pre-compensation option selected, Figure 2 shows the suggested link model and reproduction arrangement. The components of the transmitter and collector are illustrated in detail in the cited figures. A 150 km CSMF, a 30 dB speaker, and a GA-FBG make up the Dispersion Compensation Module in the Channel portion. Prior to being communicated through the SMF, the GA-FBG is configured to reduce the line's unusual width. An extraterrestrial effort to lessen chromatic dispersion is made when the speaker gain is chosen according to the length of the SMF.



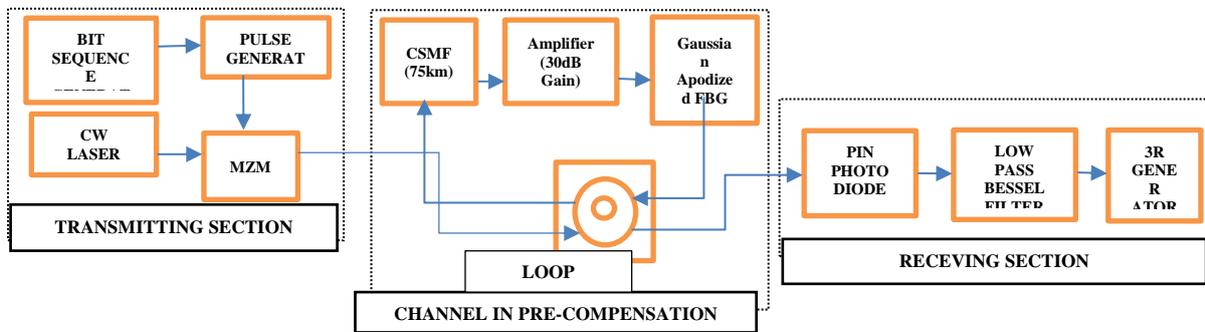
(a) In pre-compensation mode, the suggested link model



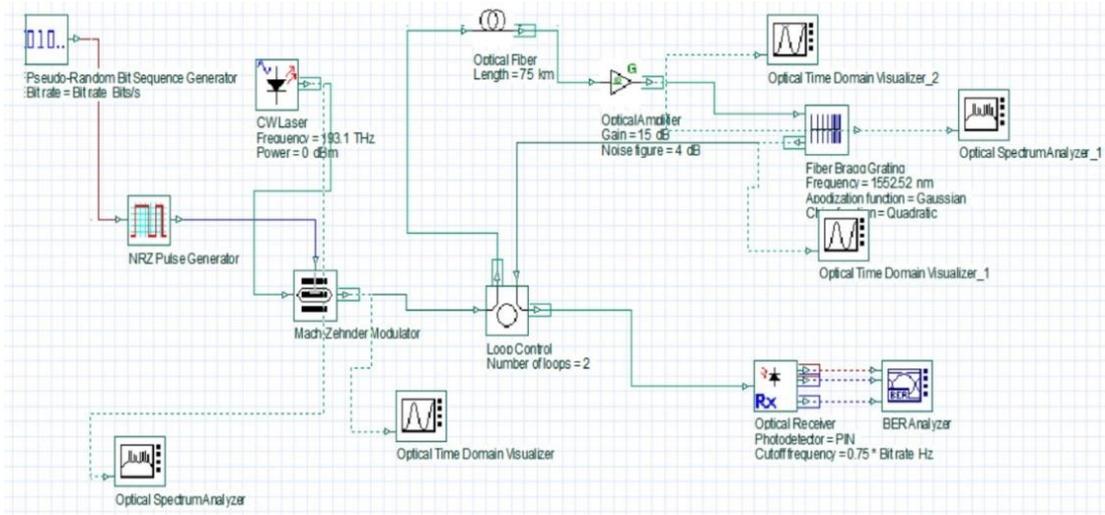
(b) Pre-Compensation Mode Simulation Setup

Fig. 2 Proposed link model and simulation setup in Pre-Compensation Mode

As shown in Figure 3, the reproduction arrangement and proposed connection model are displayed in balanced compensation mode. The dispersion adjustment module is inserted into the channel after every 75 km segment and is structured like a circular. To cover the entire 150 km length, the circle is used twice. Inside each circle, after every 75 km portion, a 15 dB speaker is set up in series with SMFs. The duration of the SMF determines the change in the speaker's gain. After every 75 km stretch, gearbox can resume after signal dispersion correction in even mode. This intended correction for dispersion narrows the sign's sensitivity to intersymbol interference (ISI) and prepares it for the next transmission phase by limiting its otherworldly width.



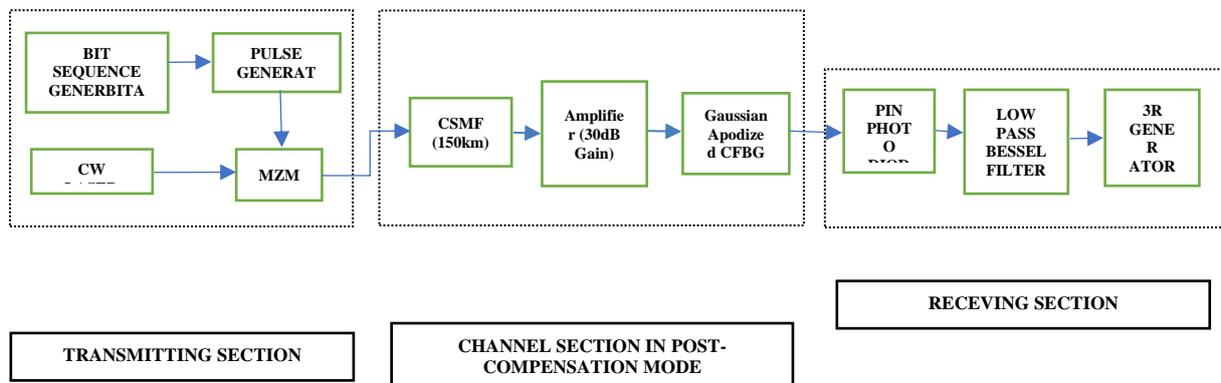
(a) Proposed link symmetrical-compensation mode



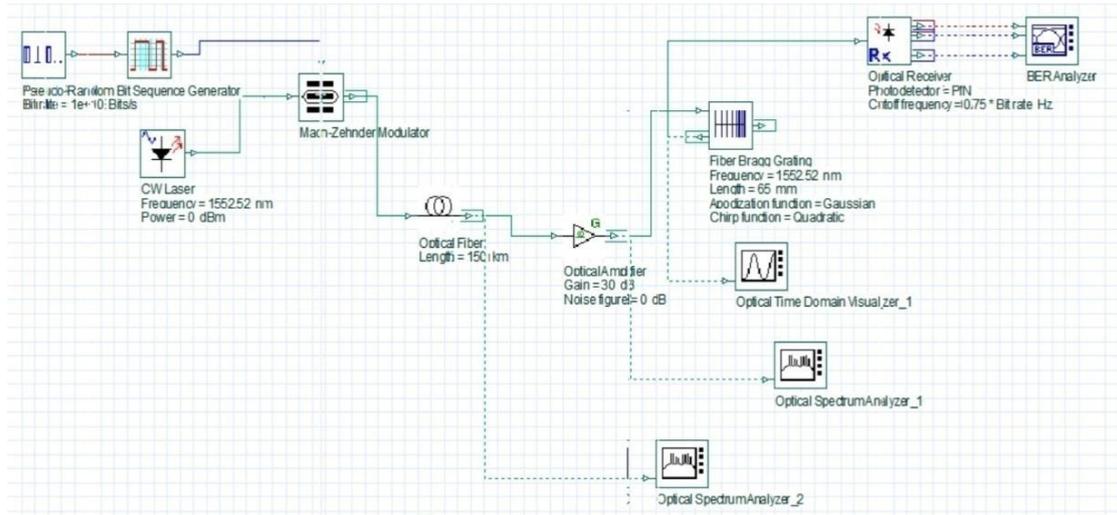
(b) Altering the Simulation Settings to Use Symmetrical Compensation

Fig. 3 Proposed link model and simulation setup in Symmetrical-Compensation Mode

After the adjustment, Figure 4 shows the suggested network model and the setup for the simulation. Following the SMF and the amplifier on the receiver side is where you'll find the GA-FBG in this configuration. The signal undergoes dispersion as it travels through the SMF, but the GA-FBG uses negative dispersion to compensate for this. The length of the CSMF is used to control the amplifier's gain. Each graphic describing the simulation configurations contains the parameters used for running the simulation in each mode. A data rate of 10 Gbps is used for all types of transmission.



(a) The post-compensation phase of the suggested link model



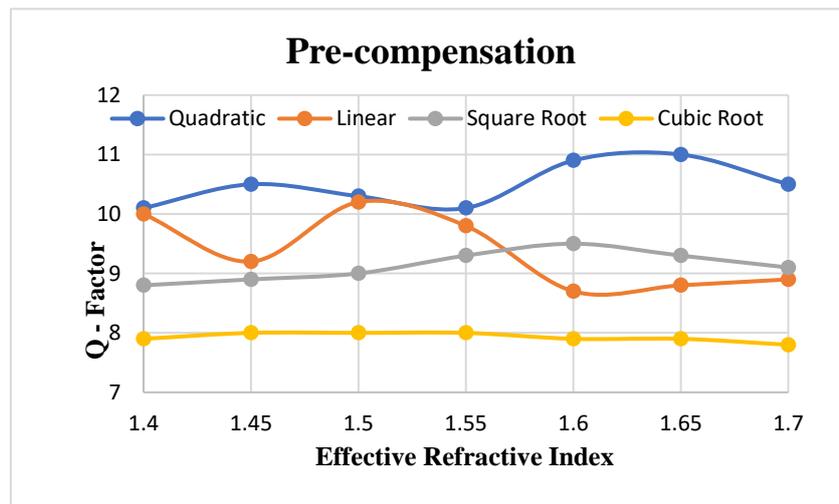
(b) The simulation setup in the post-compensation mode

Fig. 4 Proposed link model and simulation setup in Post-Compensation Mode

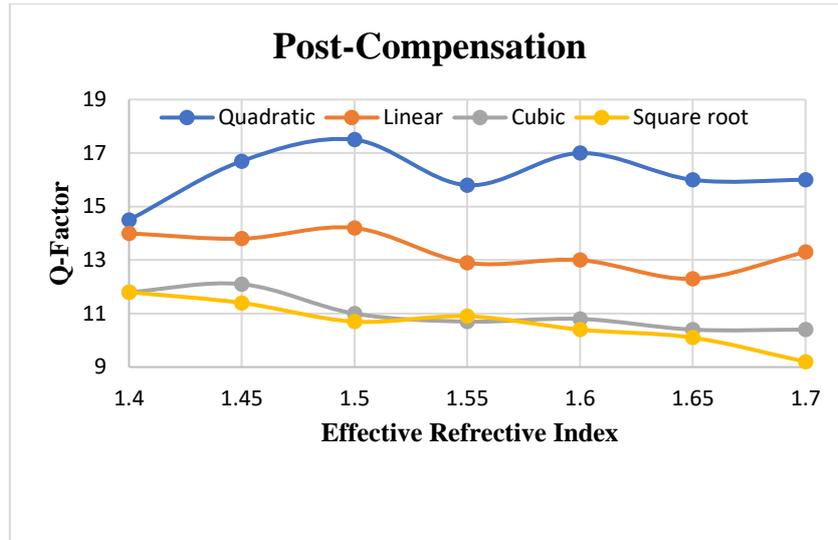
4. RESULTS AND DISCUSSION

We evaluate the display of each link and highlight on the FBG using various Twitter tactics, and then use metrics like Q-factor, BER, and Eye Graph to determine the likelihood of the compensation modes. For an optical link to be reasonable for correspondence applications, its Q-factor should be 6.8 or more [7]. To achieve the highest possible Q-factor, the cutoff points η_{eff} and L_g are modified directly. The variations in the greatest Q-factor esteem for modifications in the strong refractive rundown are shown in Figures 5a-c for the Pre-, Post-, as well as symmetrical compensation modes.

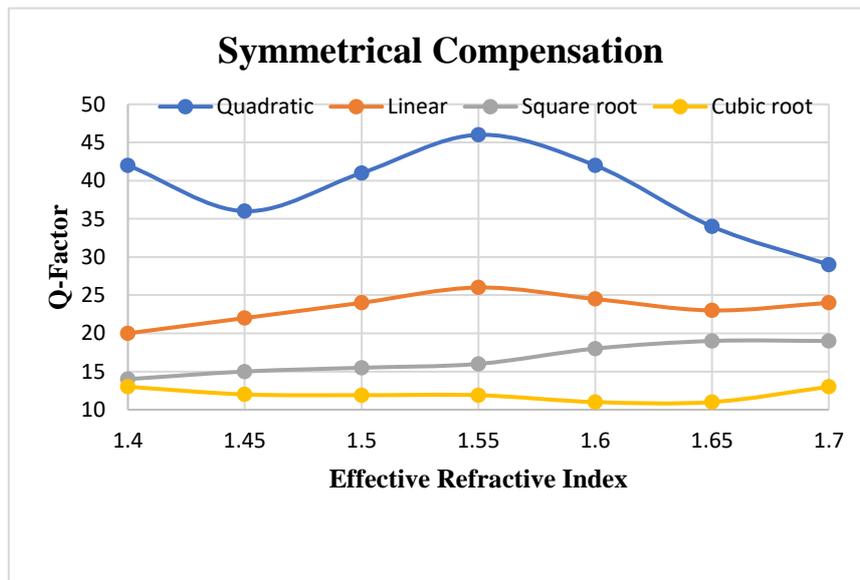
Several dispersion correction strategies for a 100 km optical link operating at 10 Gbps were proposed and evaluated in the study reported in [13]. The following PWRP is 75.15 while using a Direct Chirped Tanh FBG as the only dispersion compensator. Using DCF as a distribution the board unit increased the PWRP to 96.36, but it also increases the system's expense.



(a) Effect of Chirping Techniques on Q-Factor with n_{eff} in Pre-compensation mode



(b) How Chirping Techniques Affect the Q-Factor While n_{eff} after receiving reimbursement



(a) How Chirping Impacts Q-Factor Utilising n_{eff} under the symmetry-compensation setting

Fig. 5 Impact of Chirping Methods on Q-Factor in Relation to n_{eff} with different compensating schemes

For a long-haul optical link of 300 km, scientists investigated a crossbreed dispersion change system that joined DCF and FBG in [14]. A 52 km long DCF was expected to accomplish the most elevated Q-factor worth of 8.50, which expanded the system's expense. Different dispersion compensating techniques for SMF were almost analyzed in research works [15]. In spite of the fact that DCF is the most utilized Album strategy generally, the examination found that FBGs give better execution because of their more modest size, tunability, and negligible consideration misfortunes. Nonetheless, it is vital for redesign the limits as indicated by the particular system necessities.

Dispersion correction devices for 10 Gbps NRZ transmission systems over 100 km single-mode fibre lines were evaluated in the study published in [12]. The dispersion compensation units that were assessed included hybrid methods that combine DCF with fibre Bragg grating (FBG), direct, square root, block root chirped Tanh apodized FBGs, and a variety of others. We achieved the maximum power loss rate (PWRP) of 86.66% for a 100 kilometre optical network. For a single optical channel running at 10 Gbps piecewise, researchers examined different

compensating strategies in [16]. The Q-factor reached an extremely low 10.08 when using DCF and 4.83 while using FBG in a 100 kilometre link.

The impact of dispersion on optical correspondence and methods to verify it using appropriate dispersion compensation mechanisms were investigated in [17]. At 80 km gearbox distance, the maximum Q-factor was 6.936. A 150 kilometre optical link using GA-FBG as the primary dispersion adjustment unit is the subject of the current evaluation. Without DCF, the dispersion compensation unit can achieve a maximum Q-factor of 46.24 in balanced mode and 17.48 in post-compensation mode over a 150 km optical link. In addition, effective gearbox lengths more than 500 km are considered in balanced compensation mode. The post-compensation mode also provides an optical link that is simple, intelligent, and productive, with a PWRP of 68.22%. A PWRP of 78.17% is achieved in even compensation mode.

The data show that, at least when using GA-FBG as the primary dispersion compensation unit, the quadratic trilling process achieves the best performance in all three forms of compensation. To work with a linkage of the different looking methodologies utilized, Table 2 shows the most noteworthy raised Q-factor values accomplished for every technique in every mode. Notwithstanding other basic attributes, the table additionally incorporates the ideal grating still up in the air through broad testing to expand the quality component.

Table 2: Q-Factor with optimized value of η_{eff} and L_g in various modes

Max. Q-factor	η_{eff}	Compensation Mode	Chirping Scheme	L_g (mm)
46.24	1.55	Symmetrical	Quadratic chirping	37
26.26	1.55	Symmetrical	Linear chirping	47
18.43	1.7	Symmetrical	Square root chirping	31
17.48	1.5	Post	Quadratic chirping	65
14.12	1.5	Post	Linear chirping	94
13.04	1.4	Symmetrical	Cubic root chirping	31
12.19	1.45	Post	Cubic root chirping	81
11.64	1.4	Post	Square root chirping	94
11	1.65	Pre-	Quadratic chirping	68
10.27	1.5	Pre-	Linear chirping	88

In the evaluation of the links stated before, the Q-factor values are exceptionally high, which is consistent with an optical link's construction. For an efficient and uncomplicated 150 kilometre optical link, a post-compensation Q-component of 17.48 is sufficient. In addition, the Q-factor value of 46.24 is quite unusual for the even compensation mode. It should be noted that the link plan is challenging because twice as many FBGs and enhancers are used than in the pre- and post-compensation modes. In addition, if there are more passive components in the network, the amount of added misfortune could escalate. On the other hand, this strategy takes into account the high Q-factor in order to implement very long gearbox lengths that would be impossible to achieve using other modes. For longer transmission distances, the balanced compensation mode (Quadratic peeping approach) exhibits more variation in Q-factor, as seen in Figure 6. It proves that the suggested dispersion compensation module, when operated in balanced mode, provides excellent dispersion compensation for transmission lengths above 500 km and is a perfectly reasonable approach for extremely long-distance transmission hyperlinks.

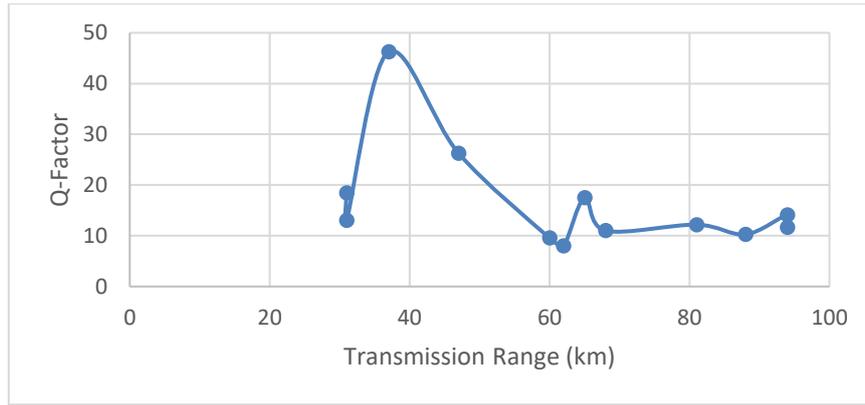
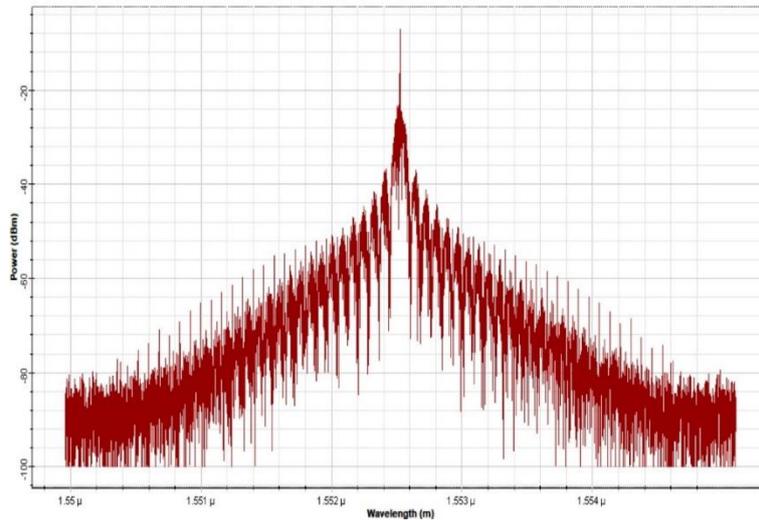
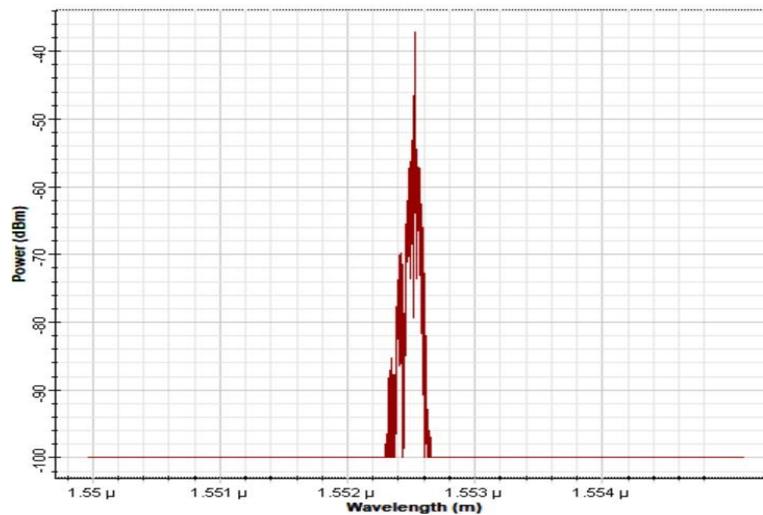


Fig. 6 Variation in Q-In symmetrical-compensation mode, the factor with transmission length

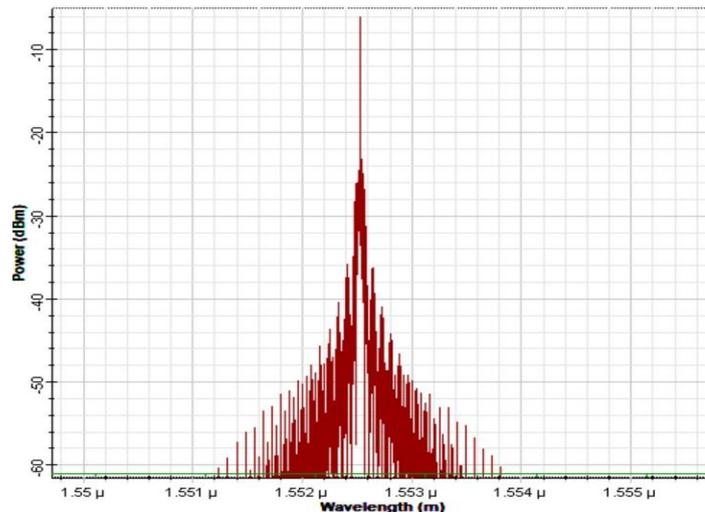
The result spectra of the sent and received signals in all compensatory modes were also examined in addition to the BER, as illustrated in Figure 7(a)–(d). By assessing the dispersion and sign quality when the compensation system is in operation, Optical Spectrum Analysis (OSA) definitively portrays the performance of the dispersion compensation system. Figured out as an OSA, it validates the reproduction outcomes by contrasting the optical sign's purposefully eerie content with the reproduced results.



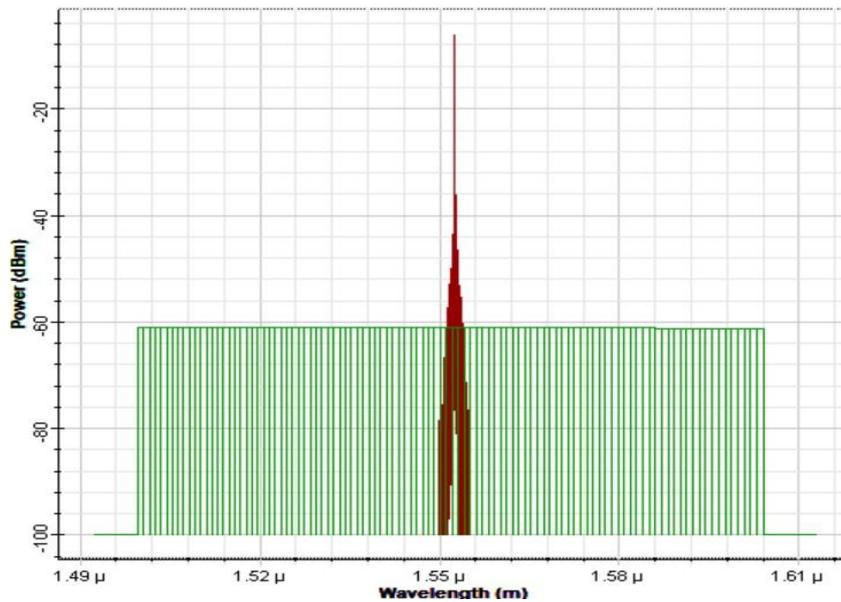
(a) Transmitted Pulse



(b) Pulse output while in mitigation mode



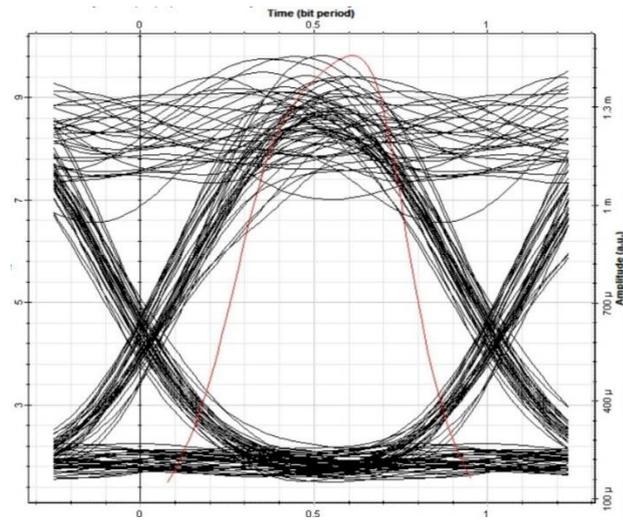
(b) Reset to post-compensation performance



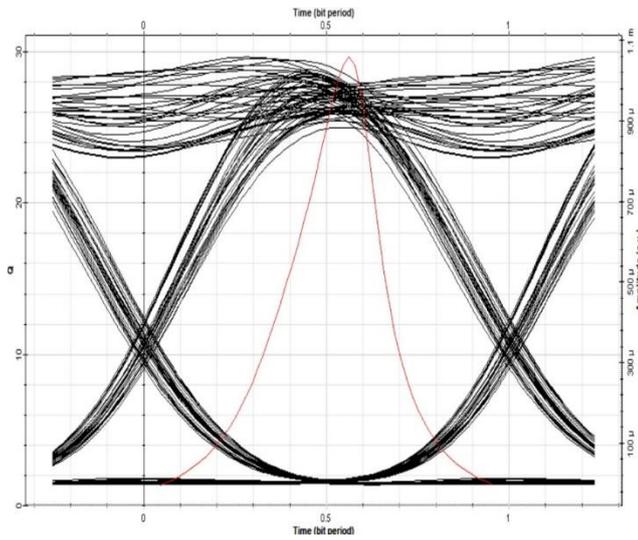
(b) Output Pulse in Symmetrical-compensation mode

Fig. 7 Pulse configuration in various compensation modes

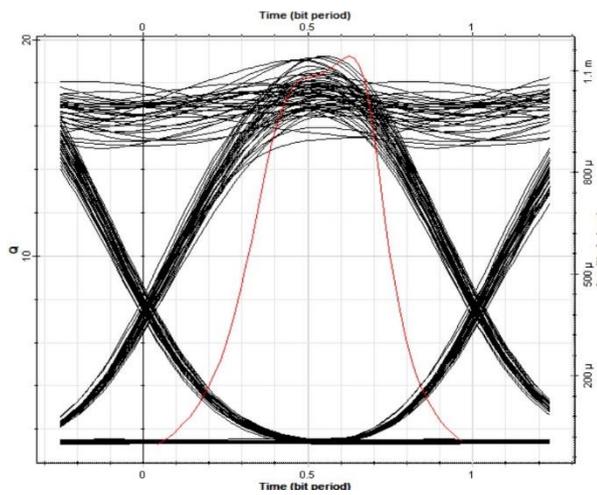
Figures 8 (a)-(c) likewise show the link's eye graph after the three remedy modes utilize the quadratic twittering technique for dispersion compensation. All of the compensatory modes have suitably wide eye-openings, as per the schematics, however the even (symmetrical) mode beats the others. The accompanying formulae, as portrayed in [12], can be utilized to compute the pulse width reduction percentage (PWRP) across different modes: Accomplishing 61.11% in pre-compensation mode, 78.17% in even compensation mode, and 68.15% in post-compensation mode.



(a) The pre-compensation eye diagram



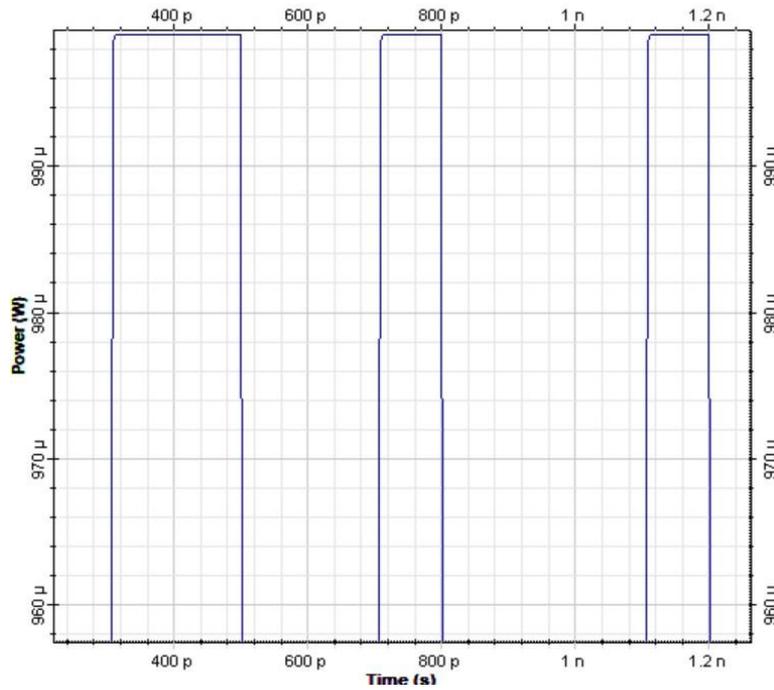
(a) Eye-diagram in symmetrical-compensation mode



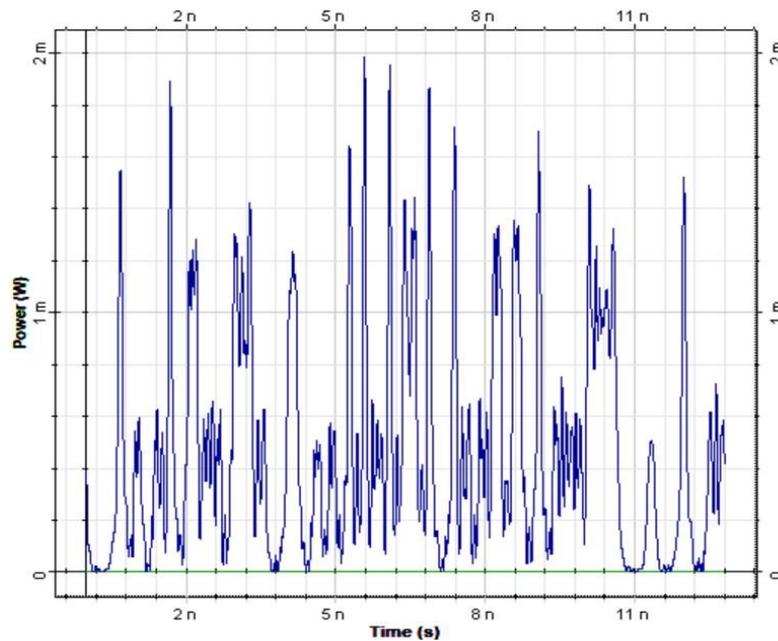
(b) Eye-diagram in post-compensation mode

Fig. 8 Eye-diagrams in various compensation modes

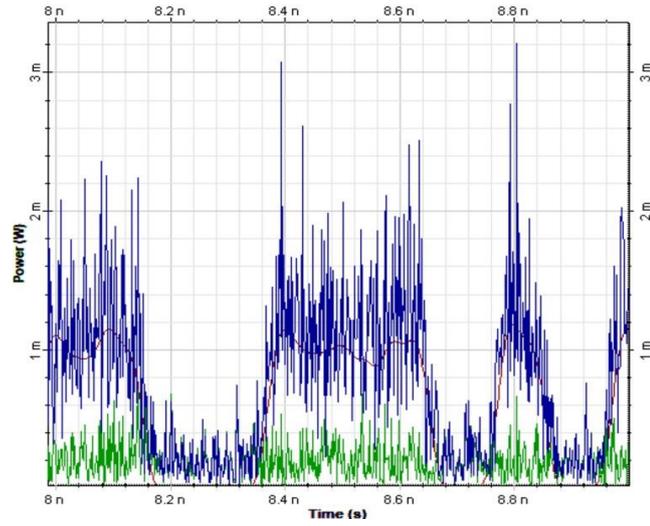
Figure 9 (a)–(e) shows the temporal domain of the optical signals before and after compensation in all three compensation modalities. We can measure the amount of dispersion impacting the signal by looking at its form. The transmitted signal with a pulse width of 100 ps is shown in Figure 9 (a). Figure 9 (b) shows that the result signal is distorted and unrecognisable without dispersion modification. As seen in Figure 9 (c), the resulting pulse in pre-compensation mode is highly distorted despite its great amplitude. In contrast, the optical result pulses in the post- and symmetrical compensation modes, as seen in Figure 9 (d) and (e), respectively, exhibit distinguishable and equitable pulse shapes. A pulse width reduction percentage (PWRP) of 61.11% in the pre-compensation mode, 78.17% in the symmetrical-compensation mode, and 68.15% in the post-compensation mode can be determined using the calculations provided in [12].



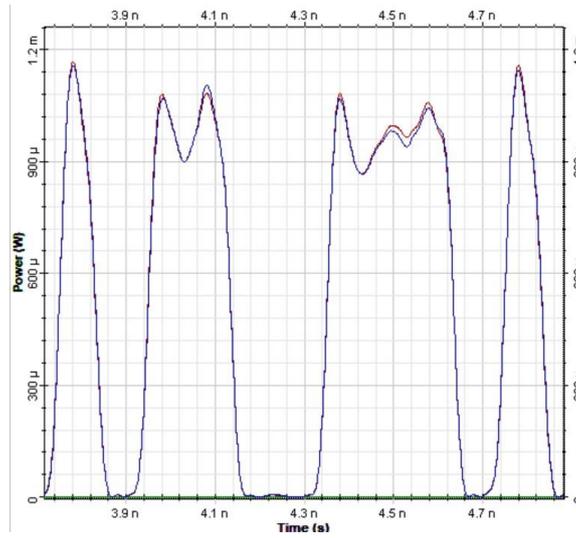
(a) Transmitted Pulse



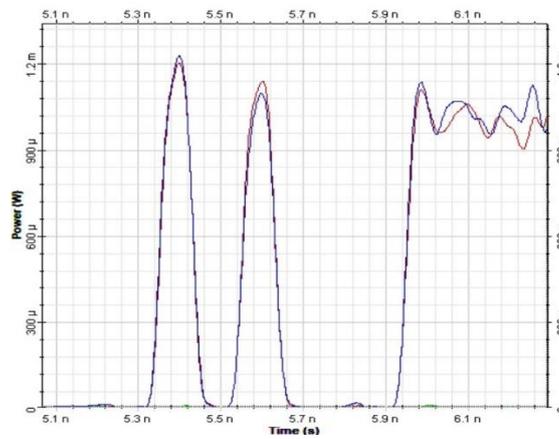
(b) Uncompensated Pulse



(c) Pre-compensated Pulse



(d) Symmetrically-compensated pulse



(e) Post-compensated Pulse

Fig. 9 Pulses in various compensation modes

5 CONCLUSIONS

This study assessed the effectiveness of various chirping methods used in Gaussian Apodized FBG for dispersion management across three different compensation modes. The outcomes exhibited that the Quadratic twittering strategy reliably outperformed different methods in all modes, especially in the balanced compensation mode which showed prevalent execution. Improvement of the Q-factor was accomplished through changes in FBG grating boundaries, accomplishing most extreme upsides of 11, 17.48, and 46.24 in the pre-, post-, and even compensation modes, separately. Notwithstanding its complicated construction and high addition misfortunes, the balanced mode succeeded in execution. Meanwhile, a direct and economical solution for supervising dispersion in a 150 kilometre optical link was proposed by using the quadratic tweeting method in the post-compensation mode. These findings are critical for optical communications dispersion compensation strategy advancement.

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