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Performance Impact of Post- Chromatic Dispersion Compensation Techniques for High-Speed DWDM over Long-Haul Communication Systems

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This paper presents the comparison performance of an eight channels of DWDM optical transmission system proposed for various data rates 10Gbs, 20Gbs, 30Gbs, and 40 Gbs respectively. The findings of this study are based on an analytical approach and numerical simulations conducted using OptiSystem software version.7. In the first study of simulation, a fixed optical transmission length at 100 km of Single Mode Fiber (SMF) and 20.93 km of dispersion compensation fiber (DCF) used as post-compensation configuration has been considered. And in the second study of simulation, the optical transmission distance has been varied from 100 km to 220 km respectively. It is known, the main factors limiting to transmit high speed data and aim to reached long-haul distance are the chromatic dispersion, attenuation, and non-linearities.

To overcome these impairments many studies suggested techniques namely DCF and fiber bragg grating (FBG). In this work, these dispersion compensation techniques are combined in a serial configuration and treated as a single hybrid DCF–FBG compensation module, implemented in a post-compensation scheme after the transmission fiber. Furthermore, integrated the Erbium doped fiber amplifiers (EDFA) in order to upgrade optical system capacity to reach transmission distance up to 200 km and transmission data rate up to 40 Gb/s. Eye diagram, maximum signal quality factor (Q), minimum bit error rate (BER) are the major interesting performance parameters for measuring the efficiency of the DWDM system proposed using two dispersion compensation configurations: a DCF-only module and a hybrid serial DCF–FBG module. The results indicate a significant enhancement in system performance when the hybrid DCF–FBG module is utilized, compared with the DCF-only module, for the four simulated data rates. For a data rate of 40 Gb/s over 100 km of SMF, the obtained Q-factor reaches 16.97 ($\mathrm{BER} = 5.955 \times 10^{-65}$) when the hybrid DCF–FBG scheme is employed, compared with a Q-factor of 14.76 ($\mathrm{BER} = 1.191 \times 10^{-49}$) achieved using the conventional DCF technique. The optimized transmission distance for the 40 Gb/s signal is found to be 170 km when the hybrid DCF–FBG compensation approach is applied. Furthermore, in comparison with previously reported studies, the results obtained from the two proposed optical system designs clearly outperform those reported in earlier published works, as will be demonstrated in the simulation results section.

Keywords: DWDM system, DCF, FBG, Hybrid DCF-FBG, Optisystem software

1 Introduction

Due to its fast data rate, broad bandwidth, and reasonably priced, optical fiber technology has gained popularity in the telecommunications sector as a reliable alternative to optical communication lines[1].

DWDM systems are being used to boost data transmission capacity and make effective use of optical fiber networks[2, 3].

Typically, the transmission in an optical DWDM system is primarily affected by the differences in core and cladding refractive indices, which cause various wavelength signals to flow through an optical fiber at different rates. As a result, optical signals that have traveled a great distance through fiber overlap. And will give pulse broadening results in transmitted signal known by chromatic dispersion (CD) and losses can be introduced as the OF distance increased which at the receiver end provide an error signal[4]. Thus, the main characteristics influencing DWDM optical networks are dispersion, non-linearity, and attenuation.

An erbium doped fiber amplifier (EDFA) is proposed to address the attenuation issue. Because it operates on the low loss at 1550 nm wavelength window of silica-based fiber, EDFA is the most often used optical amplifier (OA) to amplify optical signals[5]. Appropriate power levels can also help prevent nonlinear-effects.

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The main problem limiting high-speed, long-distance optical fiber communication is dispersion[6, 7].

Such as, increasing the transmission distance is the primary objective of communication systems. One of the most serious constraints on long-distance transmission systems is fiber chromatic dispersion. Dispersion compensation devices, such as chirped fiber bragg grating (CFBG) or dispersion compensating fiber (DCF)[8, 9], are required to overcome dispersion effect and thereby reduce the nonlinear distortion if the fiber transmission length exceeds several tens of kilometers. Dispersion effect can result in unacceptable levels of distortions that eventually cause errors. Other dispersion correction methods employ optical phase conjugators (OPCs), negative dispersion fibers (NDFs), and reverse dispersion fibers (RDFs) as dispersion compensating devices.

In both single-channel and multiple-channel optical communication systems, the dispersion management strategy is essential for obtaining an error-free signal[10]. The implementation of the dispersion management strategy must maintain the signal's optical shape while compensating for dispersion.

DCF and FBG are the most often used dispersion management strategies[6, 7, 11, 12]. DCF has many benefits, including uniform dispersion compensation for many spectral components, efficient dispersion compensation, and the possibility to modify an existing system[13]. It is the best choice for dispersion management in optical communication systems[12], especially WDM networks. However, in order to achieve stronger dispersion compensation in long-haul lines, the DCF's length must be expanded, which raises costs and limits its use to short-distance transmissions.

On the other hand, it has been demonstrated that FBG is less successful than DCF, even though using the right chirping and apodization techniques can increase its effectiveness[14]. The FBG represents the intended passband by choosing the appropriate grating length and chirp rate. Investigating the best chirping and apodization techniques is therefore necessary[15].

Furthermore, as demonstrated[15, 16, 17], the authors have examined the performance of hybrid DCF-FBG. The results indicate that using DCF-FBG in an optical channel is more efficient than using DCF or FBG alone in reducing the effect of pulse broadening, improving the Q-factor, and lowering the BER performance of optical systems.

In this study, a comparative performance analysis between two dispersion compensation management strategies, namely DCF and hybrid DCF–FBG is proposed. As presented in the results section, significant performance improvements are observed when employing the hybrid DCF–FBG configuration compared with the use of DCF alone with SMF fiber type.

2 Chromatic Dispersion

There are three types of dispersion phenomenon are: chromatic dispersion, polarization dispersion, intermodal dispersion. In this study, we have interested only by the chromatic dispersion that limiting greatly the performance of optical communication system[6, 7].

Although the group velocity (GV) in its most common form can be used to identify the primary dispersion-process source, each type of dispersion has a distinct origin.

Figure 1 illustrates dispersion phenomena. Think of a fiber line that can send optical signals in multiple modes, each of which has all of the wavelength band's spectral constituents.

Every spectral component propagates independently and experiences both a clear temporal delay and a group delay. The speed at which the energy of a pulse travels through a fiber is known as group velocity (GV). Consequently, when a signal's frequency components travel with different group velocities and arrive at their destination at different times, signal dispersion takes place[1, 13].

The dispersion is related to the second derivative of the propagation constant (β):

$$D = \frac{-2\pi c}{\lambda^2} = \frac{1}{c}\left(2\frac{dn_e}{d\omega} + \omega\frac{d^2n_e}{d\omega^2}\right) \quad ...(1)$$

where c is the light velocity in the vacuum, λ is the wavelength, ω is the frequency, and n_e is the effective index.

The propagation constant can be written in terms of the free space wave number and the effective index:

$$\beta = k_0 n_e = \frac{\omega}{c} n_e = \frac{2\pi}{\lambda} n_e \quad ...(2)$$

and the effective index as

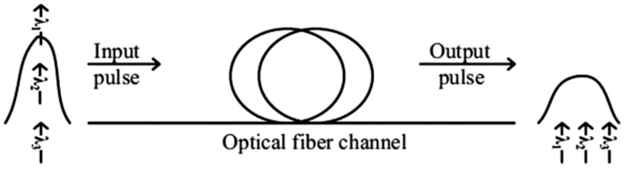


Fig. 1 — Phenomenon of chromatic dispersion[18]

$$n_e = \Delta n_e + n_0 \qquad \text{...(3)}$$

where Δn_e is the effective index difference, and n_0 is the refractive index of the cladding.

Therefore, the Chromatic dispersion is the combination of two distinct dispersions: material dispersion (MD) and waveguide dispersion (WD) defined by the following equations:

$$D = \frac{-2\pi c}{\lambda^2}\frac{d^2 k_0 \Delta n_e}{d\omega^2} + \frac{-2\pi c}{\lambda^2}\frac{d^2 k_0 n_0}{d\omega^2}$$

$$D = D_{waveguide} + D_{material} \qquad \text{...(4)}$$

3 Methods and Materials

3.1 Techniques to overcome the Chromatic Dispersion (CD)

3.1.1 Dispersion Compensation Fiber (DCF) Technique

Group velocity dispersion (GVD), which consists of material and waveguide dispersion resulting from slightly different group velocities associated with different spectral components of the signal, is the main type of dispersion occurring in single mode fibers (SMF) because chromatic dispersion limits the performance of SMF.

The Dispersion, D is related to GVD parameter β_2 and it is defined by the following equation[19]:

$$D = -\frac{2\pi c}{\lambda^2}\beta_2 \qquad \text{...(5)}$$

which c is the speed of light, λ is the signal wavelength.

The transmission length is limited by the dispersion that has accumulated throughout the fiber's length. The following formula provides the limiting transmission distance, L:

$$L < (16|\beta_2|B^2)^{-1} \qquad \text{...(6)}$$

where B is the bitrate, relatively large GVD of standard SMF thus limit the performance of communication system.

A DCF is a type of fiber made up of refractive index profiles that can be constructed so that the waveguide dispersion coefficient and total material dispersion are proportionate to a conventional fiber but have the opposite sign. An extended wavelength band can be used to accomplish this.

Concatenating the two fiber types (SMF and DCF) in the same optical channel transmission can then reverse the pulse spread that a conventional fiber introduced. Dispersion compensating fiber (DCF) is a fiber that has a reversed dispersion coefficient usually between (-70 to -90 ps/nm.km) and in our proposed the DCF applied in the simulation process has -80 ps/nm.km.

For optical signal propagating across the SMF and DCF segments at L transmission distance, the pulse propagation equation is as follows[1]:

$$S(L,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{S}\,(0,\omega)e^{\left(\frac{i}{2}\beta\omega^2 L - i\omega t\right)}d\omega \qquad \text{...(7)}$$

$\tilde{S}(0,\omega)$ is Fourier transform of pulse amplitude $S(0,t)$ and β is GVD parameter, which is reltaed to dispersion.

Dispersion induced deficiency of optical signal is cause by the phase aspect, $e^{\left(\frac{1}{2}\beta\omega^2 L\right)}$, which can be acquired by signal during it transmit through the optical fiber. If the length of two fiber segments L_{SMF}, L_{DCF} are due to SMF and DCF, respectively then from the Eq.(7):

$$S(L,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{S}\,(0,\omega)e^{\left(\frac{1}{2}\omega^2\,(\beta_{SMF}L_{SMF}+\beta_{DCF}L_{DCF}) - i\omega t\right)}\mathrm{d}\omega \qquad \text{...(8)}$$

where, overall length of fiber segment is

$$L = L_{SMF} + L_{DCF}$$

And β_{SMF}, β_{DCF} are GVD parameters for the segments of fiber length L_{SMF} and L_{DCF} , respectively.

The original pulse shape can be recovered by selecting DCF since the ω^2 term vanishes.

Thus, in addition to DCF, the ideal dispersion compensation condition is as follows:

$$\beta_{SMF}L_{SMF} + \beta_{SMF}L_{DCF} = 0 \qquad \text{...(9)}$$

or

$$D_{SMF}L_{SMF} + D_{DCF}L_{DCF} = 0 \qquad \text{...(10)}$$

Based on the above analysis. The DCF component is more stable, has a wide bandwidth, and is suitable for WDM applications,

Therefore, as illustrated in Fig. 2, the management of DCF with SMF can be positioned in the suggested optical communication DWDM (used as post-compensation method) and given by:

3.1.2 Fiber Bragg Grating (FBG) Technique

As illustrated in Fig. 3, FBG is a kind of optical fiber link that combines gratings, which are variations in the refractive record that are regularly spaced. The distance between two gratings is known as the grating period (Λ), whereas the grating length (Lg) is the length of fiber cut with gratings. Light traveling

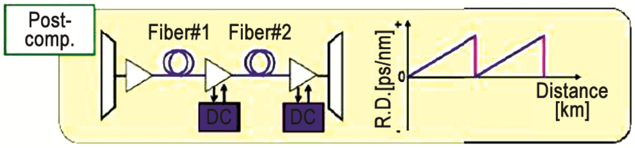


Fig. 2 — Post-Compensation techniques using DCF[20]

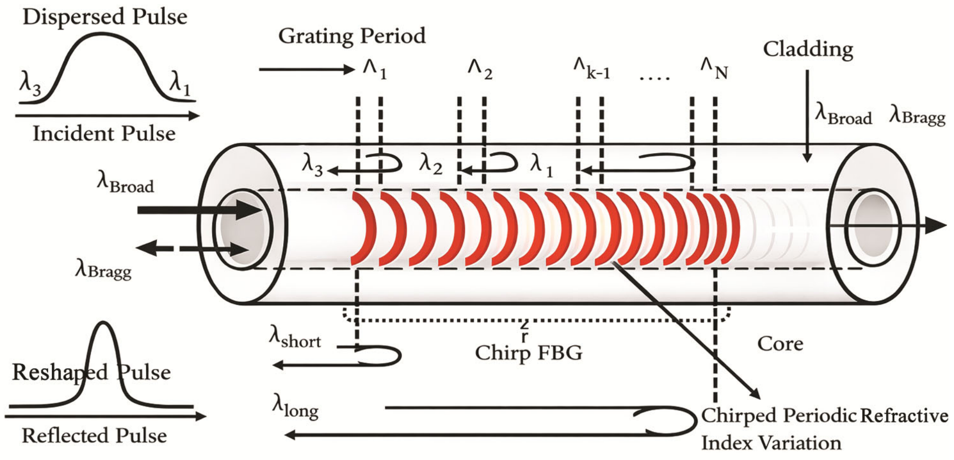


Fig. 3 — Non uniform fiber Bragg gratings[19]

through FBG is connected at the Bragg wavelength (λ_B), which is affected by the compelling refractive record.

Different frequency components of the incident beam are reflected as a result of the Bragg wavelength changing over the grating length[13].

$$\lambda_B = 2\bar{n}\,\Lambda \qquad \ldots(11)$$

i λ_B (*the Bragg wavelength*) The specific wavelength of light that is reflected by the fiber Bragg grating. It is the central wavelength of the reflected spectrum.

ii $\bar{n}$ (*Effective refractive index*) The average effective refractive index of the core mode in the optical fiber where the grating is inscribed.

iii Λ (*Grating period*) The distance between successive changes in the refractive index in the grating (i.e., the spacing of the grating structure inside the fiber).

The grating dispersion Dg is expressed as:

$$D_g = \frac{2n}{c\,(\Delta\lambda)} \qquad \ldots(12)$$

n represents the average mode index, c is the speed of light, and $\Delta\lambda$ is the grating bandwidth. The negative dispersion of the compensation fiber is higher than DCF.

In this paper, LCFBG (Linearly Chirped Bragg Grating) is used as a hybrid with DCF, with the LCFBG component inserted after each output port of the DEMUX at the receiver side. So, chirped gratings are a special case of a grating. These kinds of gratings can be achieved by altering the refractive index of the core along the inscribed section of the fiber, the spatial grating period, or occasionally both. The spectrum of wavelengths that are reflected is obtained[21]:

$$\Delta\lambda_{chirp} = 2n_{eff}(\Lambda_L - \Lambda_s) = 2n_{eff}\Delta\Lambda_{chirp} \qquad \ldots(13)$$

where $\Delta\lambda_{chirp}$ is the difference between λ_L and λ_S , the longest and shortest reflected wavelengths respectively, While, n_{eff} is the average effective refractive index of the fiber core. For a linearly chirped fiber Bragg grating (LCFBG), The representation of the grating period would be:

$$\text{where } \Lambda(z) = \Lambda_0 - \left[\left(z - \frac{L_g}{2}\right)/L_g\right]\Delta \qquad \ldots(14)$$

For Eqs. (13) and (14), A distinct area of the grating will reflect each wavelength. As a result, the time delay will vary for each wavelength.

A linearly chirped fiber Bragg grating (LCFBG) having the reflection time delay $\tau(\lambda)$ as a function of wavelength is given[22].

$$\tau(\lambda) = \frac{(\lambda-\lambda_s)}{(\lambda_L-L_s)}\frac{2n_{eff}L_g}{c}\ \lambda_s \le \lambda \le \lambda_L \qquad \ldots(15)$$

where c is the speed of light in space and L_g is the grating length. The rate of change of time delay $\tau(\lambda)$ with the wave length gives the dispersion $D(\lambda)$ as[22]

And, In the simulation setup for LCFBG component as Apodization function, the Uniform type which it is defined by: $A(Z) = 1$

4 Description of simulation model WDM

Figures 4 and 5 present the architecture of the proposed DWDM optical transmission system composed of eight channels operating at data rates of 10, 20, 30, and 40 Gb/s. The Non-Return-to-Zero (NRZ) modulation format is used to convert the generated binary data into electrical signals, which are

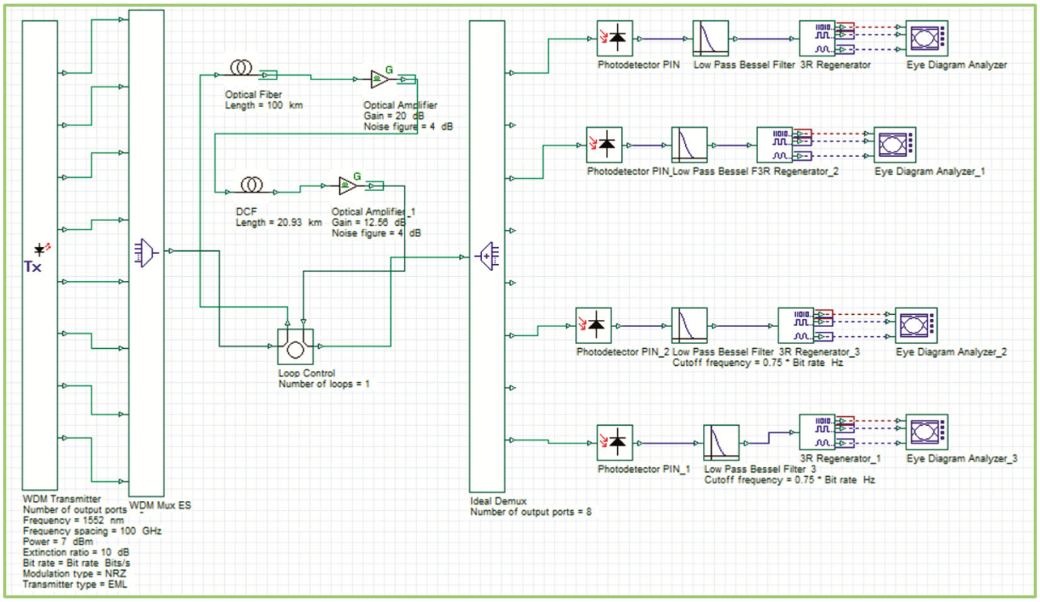


Fig. 4 — Design of optical system DWDM proposed using DCF post-dispersion compensation scheme

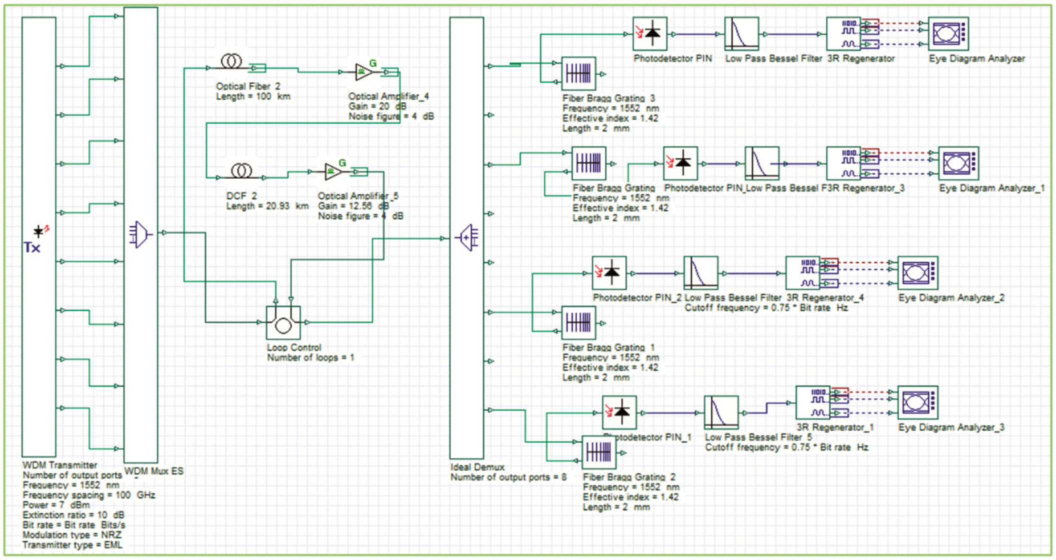


Fig. 5 — Design of optical system DWDM proposed using hybrid DCF and linearly chirped FBG post- dispersion compensation scheme

transmitted at different optical power levels to determine the optimal launch power ensuring acceptable received signal quality. The multiplexed signals propagate through a 100 km single-mode fiber (SMF) link with an attenuation coefficient of 0.2 dB/km, while optical amplifiers are employed to compensate for fiber losses.

To mitigate chromatic dispersion (CD), a DCF of 20.93 km length with a dispersion coefficient of −80 ps/nm/km is introduced. This length calculated using Eq. (10), effectively compensates the dispersion accumulated in the 100 km SMF section characterized by 16.75 ps/nm/km.

The signal weakened by the DCF fiber (having attenuation of 0.6 dB/km) is then corrected by placing another optical amplifier after the DCF. After that, the eight output ports on the demutiplexer component are used to reconstitute the signal on the received side. The PIN photodiode detects these received eight pulses. And about the second designed optical system a linearly chirped FBG is integrated before the photodiode PIN (hybrid DCF/FBG proposed as serial module) in aims to improve the performance of optical transmission system proposed as mentioned in the section of simulation results.

In the two designed systems, a PIN photodetector is used at each outport of demultiplexer to convert the optical signals received to an electrical signal. And a low pass Bessel filter is applied to these electrical signals. The output of this latest component is matched to an Eye Diagram Analyzer, which is used to visualize the signal's metrics including eye opening, maximum Q-factor and BER (Bit Error Rate) performance.

For the second designed optical model (DCF + FBG), the appropriate DCF length was selected to compensate the positive chromatic dispersion introduced by the SMF. In addition, the parameters of the linearly chirped FBG component particularly the grating length and effective refractive index were carefully optimized to further mitigate the residual chromatic dispersion of the SMF and reduce signal distortion at the receiver.

Table 1 summarizes the complete set of parameters for the proposed optical system, including the WDM configuration, channel specifications, and receiver-side parameters. Table 2 lists the simulated parameters of the proposed FBG compensator, including optimized values of the effective refractive index and grating length. Table 3 presents the optical fiber (OF) length, dispersion-compensating fiber (DCF) length simulated. And, the corresponding EDFA gain for each transmission distance considered.

5 Simulation Results and Analysis

5.1 Q Performance of DWDM Optical System Proposed (Without DCF and FBG) by Varying the Optical Power Transmission

Figure 6 presents the Q-factor performance of the proposed DWDM optical system. This result first highlights the detrimental impact of CD on the quality of the received signal. And secondly, emphasizes the necessity of dispersion compensation techniques such as DCF and FBG integrated within the transmission link. The obtained Q-factor values range from approximately 2.8 to 2.55 over a transmitted optical power varying from 1 dBm to 12 dBm. These results clearly indicate that the performance of the proposed DWDM system is significantly degraded in the absence of DCF and FBG dispersion compensation schemes.

5.2 Q Performance of DWDM Optical System Proposed by Varying the Optical Power Transmission

The simulation results presented in Fig. 7 demonstrate that for each data rate the optimal Q-factor is achieved at a specific optical power level. Beyond this optimum, a gradual degradation in system performance is observed for both dispersion compensation schemes. This decline is attributed to the onset of fiber nonlinear effects, which

Table 1 — Parameters of the simulation

Component used	Parameters	Values simulated
WDM transmitter	Number of channels	8
	Frequency of (chan1)	193.16 THz
	Fre quency of (chan8)	193.86 THz
	Frequency spacing	100 GHz
	Power transmitted	0 dBm to 12 dBm
	Data rate	(10, 20, 30, 40) Gbs
	Capacity system	(80, 160, 240, 320) Gbs
Optical channel transmission	SMF	
	Attenuation	0.2 dB/km
	Dispersion	16.75 ps/nm.km
	DCF	0.6 dB/km
	Attenuation	-80 ps/nm.km
	Dispersion	
Receiver side	Photodiode PIN	
	Responsivity	1 A/W
	Dark current	10 A

Table 2 — Parameters of FBG simulated

parameters	Simulated values
Apodization function	Uniform
Chirp function	Linear
Modulation AC	0.0001
Linear parameter	0.0001
For 10 Gbs	
Effective index	1.45
Length	5 mm
For 20 Gbs	
Effective index	1.46
Length	2 mm
For 30 Gbs	
Effective index	1.42
Length	2 mm
For 40 Gbs	
Effective index	1.57
Length	1 mm

Table 3 — The lengths of optical transmission channel and optical gains correspond

SMF length (Km)	100	120	140	160	180	200	220
DCF length (km)	20.937	25.125	29.312	33.5	37.687	41.875	46.062
Total length (km)	120.937	145.125	169.312	193.5	217.687	241.875	266.062
Gain1 (dB) (SMF)	20	24	28	32	36	40	44
Gain2 (dB) (DCF)	12.562	15.075	17.5872	20.1	22.612	25.125	27.637

deteriorate signal quality as the launched optical power increases.

A significant performance enhancement is observed when the hybrid DCF–FBG configuration module is employed. The integration of the Fiber Bragg Grating in series with DCF effectively improves the overall system performance across all investigated data rates. This improvement arises from the intrinsic capability of the FBG to selectively reflect and filter wavelengths, thereby contributing to dispersion compensation without introducing additional fiber length.

Further optimization of the hybrid configuration was achieved through careful adjustment of the FBG length and effective refractive index, as presented in the optimized parameters of Table 2. Although the Q-factor naturally decreases with increasing data rate for both system architectures, the hybrid DCF–FBG scheme consistently maintains superior signal integrity compared with the conventional DCF-only approach. Overall, the results confirm that the hybrid DCF + FBG dispersion compensation strategy provides improved power tolerance and enhanced transmission performance, making it a promising solution for high-speed DWDM optical communication systems.

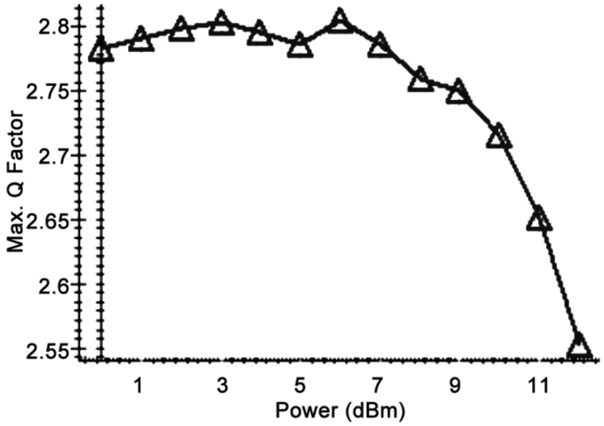


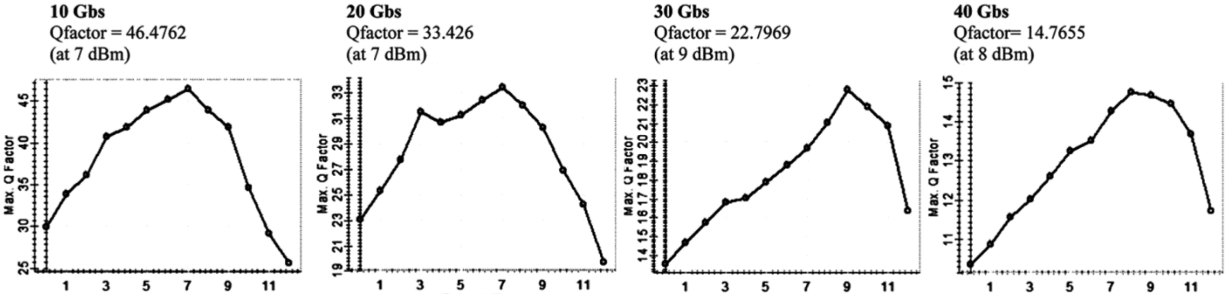
Fig. 6 — Q-factor performance of DWDM system proposed without DCF and FBG compensators

5.3 Eye Diagram Results of DWDM Optical System Proposed by Varying the Data Rate in Optimized Power

The following results of Fig. 8 presents eye diagrams provided in the simulation process and numerical performance (Q-factor and BER performance) resulting for an 8-channel DWDM system using the two dispersion compensation techniques: DCF alone (Dispersion Compensating Fiber) and DCF + FBG (Fiber Bragg Grating). The comparison is done at four different data rates: 10, 20, 30, and 40 Gbps respectively

The quality of the received optical signal is visually evaluated using the eye diagrams. A more "open" eye corresponds to better signal quality, less ISI (Inter Symbol Interference), and lower BER (Bit Error Rate). A closed or distorted eye indicates signal degradation, more noise, and higher BER.

(a) with DCF

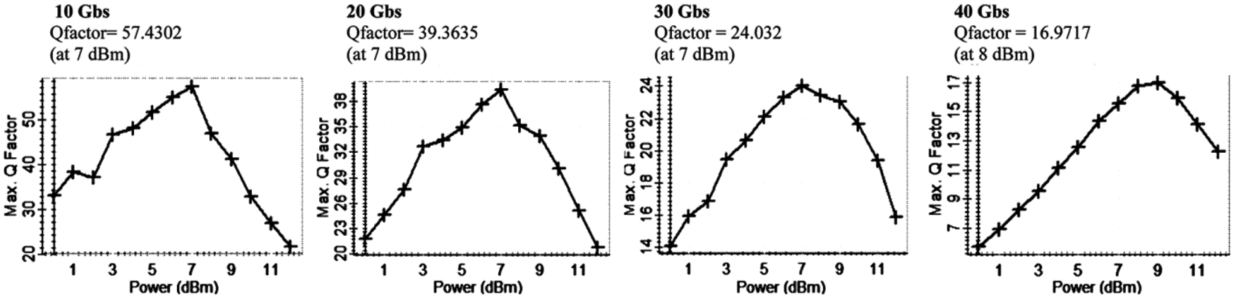

10 Gbs Qfactor = 46.4762 (at 7 dBm)

20 Gbs Qfactor = 33.426 (at 7 dBm)

30 Gbs Qfactor = 22.7969 (at 9 dBm)

40 Gbs Qfactor= 14.7655 (at 8 dBm)

(b) with DCF-FBG


10 Gbs Qfactor= 57.4302 (at 7 dBm)

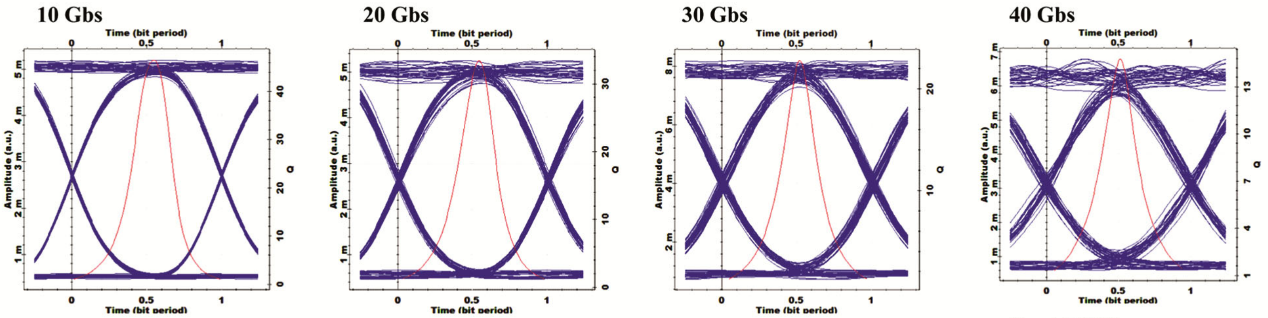
20 Gbs Qfactor= 39.3635 (at 7 dBm)

30 Gbs Qfactor = 24.032 (at 7 dBm)

40 Gbs Qfactor = 16.9717 (at 8 dBm)

Fig. 7 — Q-factor vs power for DWDM optical system proposed in different data rates using two dispersion compensation techniques (a) with DCF; and (b) with hybrid DCF-FBG

(a) With DCF



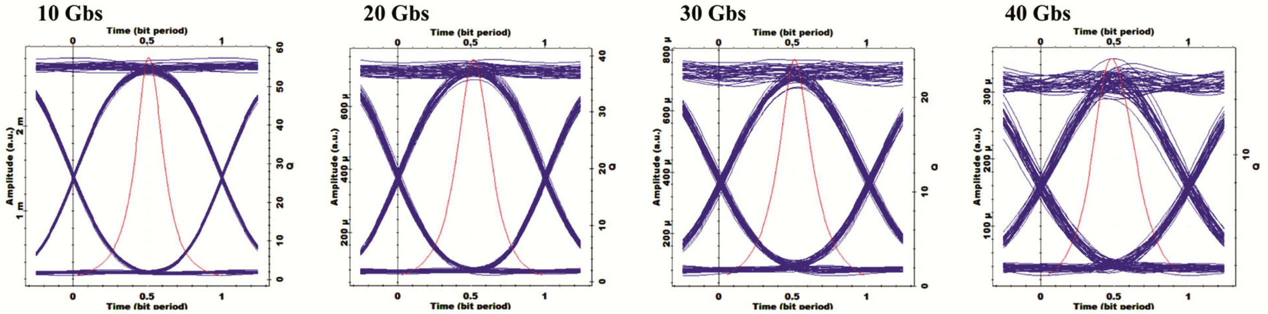
Q = 46.4762
BER = 0 (2.645^{e}-325)

Q = 33.426
BER = 2.645^{e}-245

Q = 22.7969
BER =2.407^{e}-115

Q = 14.7655
BER = 1.191^{e}-49

(b) With DCF-FBG



Q = 57.4304
BER = 0

Q = 39.3635
BER = 0

Q = 24.032
BER = 6.026^{e}-128

Q = 16.9717
BER = 5.955^{e}-65

Fig. 8 — Eye diagram results at the received signals for DCF and DCF-FBG in different data rates and 100 Km optical fiber length

5.3.1 As Analysis of Performance Comparison at Different Data Rates

i At low data rates (10 Gbs)

Both methods DCF and DCF-CFBG effectively manage dispersion, but DCF+CFBG improves the signal margin which the eye diagrams are more open than with DCF only, suggesting better compensation of dispersion effects., and making the system more robust. Both configurations show BER = 0, but DCF+FBG achieves higher Q-factors (up to 57) vs DCF only (~46).

ii At 20 Gbps data rate

With DCF only eye diagrams start to show degradation (narrower eye opening). With DCF + FBG: Improvement is noticeable, the eyes are more open than with DCF alone. About Q-factor and BER: with DCF only: Q-factors drop (~33), BER ranges from extremely low to zero. With DCF+FBG module: Higher Q-factors (~39), BER significantly reduced. It can be seen that, as data rate increases, dispersion effects become more pronounced. Adding FBG to DCF improves dispersion compensation, leading to better eye openings and lower BER.

iii At 30 Gbps and 40 Gbps

It has been observed in Eye Diagrams results simulated that both methods show acceptable eye opening which the two designed systems continue to maintain their effectiveness mitigating against to the chromatic dispersion. But applied dispersion compensation model of DCF+FBG in optical channel transmission the results still provide clearer, less distorted eyes compared to DCF alone. And the Q-factors metric has continued to decrease. BER have been increased with DCF only; the DCF+FBG mitigates this degradation somewhat. Therefore, for high data rates (30–40 Gbps), even advanced compensation techniques struggle fully to eliminate impairments. So, DCF+FBG remains superior and have given accept performance as recommended in optical communication where Q> 6 and BER < 10^{e}-9.

5.4 Q and BER Performance of Four Channels from DWDM Optical System Proposed

Table 4 compares the Q-factor and BER performance for four channels (channels 1, 4, 6, and 8) respectively have been chosen from the eight channels DWDM system introduced. The results have

Table 4 — Q-factor and BER performance of the four channels selected from 8-DWDM system proposed

Data rate	Dispersion Compensation technique	Performance	Channel 1 (193.16 THz)	Channel 3 (193.36 THz)	Channel 6 (193.66 THz)	Channel 8 (193.86 THz)
10 Gbs	With DCF	Q	46.4762	35.8998	37.6925	42.1238
		BER	0	1.43^{e}-282	3.013^{e}-311	0
	With DCF+FBG	Q	57.4302	54.0634	53.2637	53.5837
		BER	0	0	0	0
20 Gbs	With DCF	Q	33.426	23.3078	26.6291	31.8211
		BER	2.645^{e}-245	1.758^{e}-120	1.520^{e}-156	1.583^{e}-222
	With DCF+FBG	Q	39.3635	30.505	36.6235	37.7864
		BER	0	9.854^{e}-205	5.412^{e}-294	8.469^{e}-313
30 Gbs	With DCF	Q	22.7969	17.6384	17.3697	16.6434
		BER	2.407^{e}-115	5.963^{e}-70	6.857^{e}-68	1.683^{e}-62
	With DCF+FBG	Q	24.032	25.8522	24.9006	24.8948
		BER	6.026^{e}-128	1.105^{e}-147	3.459^{e}-137	4.018^{e}-137
40 Gbs	With DCF	Q	14.7655	12.3712	11.5658	10.5681
		BER	1.191^{e}-49	1.796^{e}-35	2.977^{e}-31	2.092^{e}-26
	With DCF+FBG	Q	16.9717	16.8040	16.8572	16.4342
		BER	5.956^{e}-65	1.003^{e}-63	4.227^{e}-64	4.977^{e}-61

been taken for different data rates (10, 20, 30, 40 Gb/s) studied.

i Performance at 10 Gb/s with DCF, Q-factor values are very high (ranging from 35 to 46) indicating excellent system performance. And the BER values confirming error-free transmission.

With DCF + FBG, Q-factor is even higher (from 53 to 57), suggesting improved system robustness. BER remains at zero. Both configurations ensure error-free performance at 10 Gb/s. Adding FBG further optimizes signal quality.

ii Performance at 20 Gb/s with DCF, Q-factor decreases significantly compared to 10 Gb/s the results achieved were (from 23 to 33). BER is extremely low but not zero; it ranges from 1.758e-120 to 2.645e-245. With DCF + FBG, Q-factor improves the results have been between (30 to 39). BER drops dramatically to extremely low levels (e.g.,0 and 8.469e-313).

Performance degrades at higher bit rates due to increased chromatic dispersion and nonlinearities. The combination of DCF and FBG helps mitigate these effects, improving Q-factor and reducing BER further.

iii Performance at 30 Gb/s: With DCF, Q-factor drops further (16.6434 to 22.7969), indicating weaker signal integrity. BER is still very low but worsening (from 1.683e-62 to 2.407e-115). With DCF + FBG, Q-factor improves to (24.032 to 25.8522), these results showing that FBG helps recover some quality. BER also improves compared to DCF alone.

The degradation trend continues with increased data rate. FBG remains beneficial but cannot fully compensate for all impairments at 30 Gb/s.

iv Performance at 40 Gb/s: With DCF, Q-factor is significantly reduced (10.5681 to 14.7655). BER increases sharply (from 2.092e-26 to 1.191e-49). With DCF + FBG, Q-factor nearly doubles in some channels (up to 16.9717), BER improves (from 4.977e-61 to 5.956e-65).

Even in high-speed rate, the two systems suggested shows an accepted performance and inferior performance introduced compared to transmit low data rate.

In all results given, compared to the numerical values obtained by DCF alone, where there was a gap between the values of the four channels, we have seen an improvement in dispersion compensation in all results provided by the addition of the FBG compensator. This is evident in the results obtained in the four channels, where the numerical values are closer to one another. Thus, FBG is more effectiveness againt to reduced equaly the chromatic dispersion for all channels of DWDM system proposed.

5.5 Q and BER Performance of The DWDM Optical System Proposed by Varying the Optical Fiber Length

In the following Fig. 9, the performance of Dispersion Compensating Fiber (DCF) and hybrid DCF with Fiber Bragg Grating (FBG) in a DWDM model is compared for various data rates (10G, 20G, 30G, 40G). The comparison is based on two key

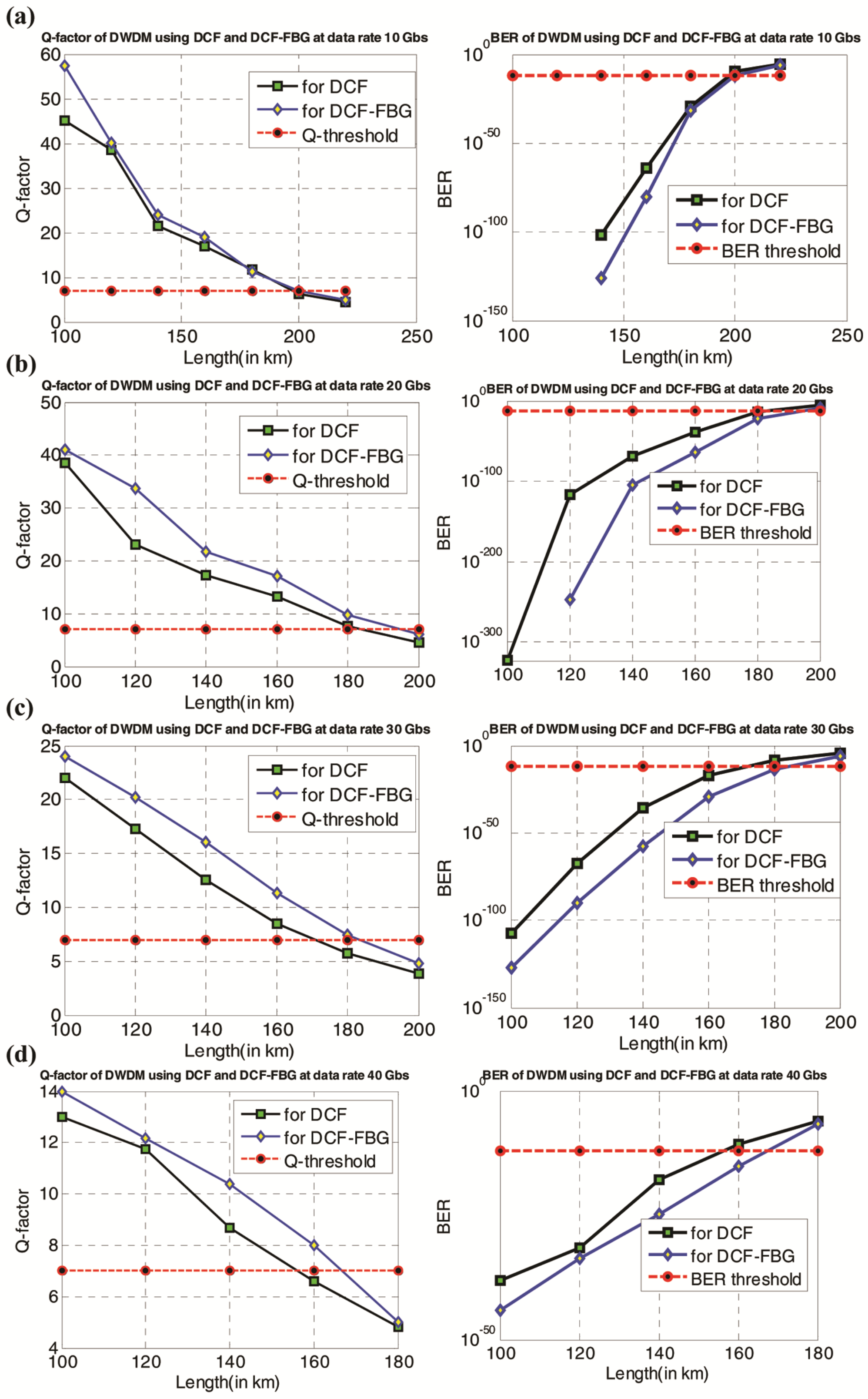


Fig. 9 — Q and BER performance for DWDM optical system using DCF and hybrid DCF-FBG at different optical fiber lengths (a)10 Gbs (b) 20 Gbs (c) 30 Gbs; and (d) 40 Gbs

performance metrics: Q-factor (indicating signal quality) and BER (indicating transmission accuracy).

In each subfigure, the optical transmission length is increased from 100 km to 220 km. The distance shown on the x-axis represents only the length of the SMF (excluding the length of DCF), which increases correspondingly as the SMF length is increased, as described in Table 3.

As common observation from these results provided in all figures given.

i In the Q-Factor curves: it can be seen that the Q-factor decreases with increasing distance for both DCF and DCF+FBG approaches. And the hybrid technique DCF+FBG consistently offers higher Q-factor compared to DCF alone across all data rates. At higher data rates (30Gbs, 40Gbs), the degradation in Q-factor is more rapid, but hybrid DCF+FBG module still maintains better performance in the proposed DWDM optical transmission system.

ii In the BER curves: it is observed that the BER performance increases with distance, as expected due to dispersion and attenuation. The combination technique DCF+FBG shows lower BER than DCF alone at all data rates and distances. For higher data rates (30G, 40G), the BER increases significantly with distance, especially for DCF-only configuration.

As detailed analysis about the comparison presented in different data rates simulated.

i About data rate 10 Gbps ($8 \times 10\, Gbs$ DWDM Optical system)

The results of Q-factor provided starts around 57 for DCF+FBG vs ~45 for DCF. Then, the Q-factor have decreased slightly beyond 200 km. Furthermore, curves of BER performance simulated DCF+FBG stays below the BER threshold longer. DCF shows a sharp BER increase near 200 km. So, at 10 Gbps, DCF is acceptable, but hybrid DCF+FBG improves system margin and robustness.

ii About data rate 20 Gbps ($8 \times 20\, Gbs$ DWDM Optical system)

From the Q-factor curves, it is observed that applying the hybrid DCF + FBG scheme maintains the Q-factor above the threshold value of 7 over longer transmission distances. In contrast, when only DCF is used, the Q-factor drops below the threshold (7) before a transmission length of 180 km. And in BER results introduced, DCF+FBG remains under BER threshold longer. But DCF rises performance BER above acceptable BER before (~180 km).

These results indicate that the hybrid DCF + FBG solution enables longer-distance transmission at 20 Gbps with improved signal quality and reduced error rates

iii About data rate 30 Gbps ($8 \times 3\,0\, Gbs$ DWDM Optical system)

In the Q-Factor curves**,** both compensation dispersion technique (DCF and DCF+FBG) the Q results curves degrade faster. While the combination DCF+FBG maintains Q > threshold longer (up to ~180 km). In the BER results given: DCF curve crosses BER threshold much faster compared to the technique DCF+FBG that maintains acceptable BER up to ~180 km.

Thus, the DCF+FBG is crucial for preserving the quality of received signals, and the DWDM optical system under study continues to show better performance at 30 Gbps.

iv About data rate 40 Gbps ($8 \times 40\, Gbs$ DWDM Optical system)

The Q-Factor starts low (~14 for DCF+FBG) and drops quickly. And with DCF the Q-factor falls below threshold very early. For the BER results DCF reaches high BER within (150 km to 160 km). Then, the DCF+FBG extends usable distance up to ~160 km. As can be shown, DCF by itself is insufficient for the simulated system's performance at 40 Gbps. While the remainder provides acceptable performance for a distance of up to 160 km, DCF+FBG extends system performance.

As a result, Hybrid DCF+FBG provides notable gains in BER and Q-factor at all data speeds. As data rate rises, the performance difference worsens, making DCF+FBG essential for high-speed DWDM systems. In addition to effectively compensating for chromatic dispersion, this hybrid technique probably reduces other limitations such as filtering effects or nonlinearities.

About summarized results of maximum transmission length reached in proposed model design for the data rates simulated will presented in the Table 5.

5.6 Comparative Performance Analysis Between Our Proposed Work with Results of Other Similarly Previous Studies

From the following Tables 6-9, the performance of the proposed 8-channels DWDM system has

Table 5 — The optimized length of optical transmission channel (without considered the length of DCF) for the two proposed models of DWDM

Data rate	10 Gbs		20 Gbs		30 Gbs		40 Gbs	
Disp comp technique	with DCF	with DCF-FBG	with DCF	With DCF-FBG	With DCF	With DCF-FBG	With DCF	With DCF-FBG
L_max reached	200 km	200 km	180 km	~ 200 km	170 km	180 km	< 160 km	> 160 km

Table 6 — Comparative performance for results of our proposed work (8 × 10 DWDM) and similar previous studies

Parameters	Proposed work		Ref [19] [2019]		Ref [23] [2018]	Ref [24] [2022]	Ref [25] [2021]	Ref [26] [2018]
Disp comp technique	With DCF	With DCF-FBG	With DCF	With CFBG	DCF	DCF	DCF-FBG	CFBG
Disp comp model	Post-comp		Post-comp		Post-comp	Symm-comp	Post-comp	Post-comp
DWDM (Channels number)	8 Channels		8 Channels		8 Channels	16 Channels	32 Channels	8 Channels
Spacing channels	100 GHz		100 GHz		-	100 GHz	25 GHz	-
Data rate	10 Gbs		10 Gbs		10 Gbs	10 Gbs	10 Gbs	10 Gbs
Coding type	NRZ		RZ		RZ	RZ	NRZ	RZ
SMF length (km)	100 km		150 km		86 km	150 km	300 km	80 km
DCF (in Km)	20.93 km		15 km		14 km	17 km	51.6 km	-
FBG length (mm)	-	5 mm	-	45 mm	-	-	-	10 mm
Q factor	46.4762	57.4304	9.6050	12.7412	15.07	18.27	10	30
BER	0	0	3.775^{e}-13	1.63383^{e}-37	1.142^{e}-51	6.70^{e}-75	1^{e}-25	-

Table 7 — Comparative performance for results of our proposed work (8 × 20 DWDM) and similar previous studies

Parameters	Proposed work		Ref [19] [2019]		Ref [24] [2022]	Ref [27] [2015]	
Disp-comp technique	With DCF	With DCF-FBG	With DCF	With CFBG	DCF	DCF	
Disp-comp-model	Post-comp		Post-comp		Symm-comp	Post-comp	
DWDM (Channels number)	8 channels		8 channels	8 channels	16 Channels	32 channels	
Spacing channels	100 GHz		100		100 GHz	100 GHz	
Data rate	20 Gbs		10 Gbs		10 Gbs	40 Gbs	20 Gbs
Coding type	NRZ		RZ		RZ	NRZ	
SMF_length (km)	100 km		150 km		150 km	80 km	
DCF length (km)	20.93 km		15 km		17 km	16 km	
FBG_length (mm)	-	2 mm	-	45 mm	-	-	-
Q	33.426	39.3635	9.6050	12.7412	18.27	9.5	11.5
BER	2.645^{e}-245	0	3.775^{e}-13	1.63383^{e}-37	6.70^{e}-75	1^{e}-22	1^{e}-30

been compared for different data rates (10, 20, 30, 40 Gbps) with results from different previous studies.

In each table, the performance of Q and BER is presented for the dispersion compensation techniques proposed in this study as DCF and hybrid DCF-FBG with these techniques that have studied in similar of our work and other technique such as FBG when it have studied only. In other works, published previously, in this comparison an attempt has been made to choice from literature a similar work of our studied. From the dispersion compensation techniques, the coding type applied, and the transmission parameters such as the number of channels of DWDM, spacing channels, and fiber length.

According to comparison results, the two suggested DWDM design models perform better than the findings in comparable systems that have been previously published, with the exception of one system that used DPSK (of 40 Gbs from 8-DWDM), which performed better than our results, which are displayed in Table 8.

Table 8 — Comparative performance for results of our proposed work (8 × 30 DWDM) and similar previous studies

Parameters	Proposed work		Ref [28] [2010]	Ref [29] [2016]	Ref [30] [2020]	Ref [27] [2015]	
Disp-comp technique	With DCF	With DCF-FBG	With DCF	With DCF	DCF	DCF	
Disp-comp-model	Post-comp		Mix-comp	Symm-comp	Symm-comp	Post-comp	
DWDM (Channels number)	8 channels		8 channels	8 channels	16 Channels	32 channels	
Spacing channels	100 GHz		80 GHz	200 GHz	100 GHz	100 GHz	
Data rate	30 Gbs		40 Gbs	40 Gbs	40 Gbs	40 Gbs	20 Gbs
Coding type	NRZ		DPSK	NRZ	RZ	NRZ	
SMF_length (km)	100 km		160 km	125 km	100 km	80 km	
DCF length (km)	20.93 km		-	25 km	20 km	16 km	
FBG_length (mm)	-	2 mm	-	-	-	-	-
Q	22.7969	24.032	31	10.0276	13.5768	9.5	11.5
BER	2.407^{e}-105	6.026^{e}-128	-	4.217^{e}-24	2.708^{e}-42	1^{e}-22	1^{e}-30

Table 9 — Comparative performance of our proposed work (8 × 40 DWDM) and similar previous studies

Parameters	Proposed work		Ref [28] [2010]	Ref [29] [2016]	Ref [30] [2020]	Ref [27] [2015]		Ref [31] 2024
Disp-comp technique	With DCF	With DCF-FBG	With DCF	With DCF	DCF	DCF		DCF-FBG
Disp-comp-model	Post-comp		Mix-comp	Symm-comp	Symm-comp	Post-comp		Post-comp
DWDM (Channels number)	8 Channels		8 Channels	8 Channels	16 Channels	32 Channels		32 Channelss
Spacing channels	100 GHz		80 GHz	200 GHz	100 GHz	100 GHz		
Data rate	40 Gbs		40 Gbs	40 Gbs	40 Gbs	40 Gbs	20 Gbs	40 Gbs
Coding type	NRZ		DPSK	NRZ	RZ	NRZ		RZ
SMF_length (km)	100 km		160 km	125 km	100 km	80 km		300 km
DCF length (km)	20.93 km		-	25 km	20 km	16 km		51 km
FBG_length (mm)	-	1 mm	-	-	-	-	-	-
Q	14.7655	16.9717	31	10.0276	13.5768	9.5	11.5	13.25
BER	1.191^{e}-49	5.955^{e}-65	-	4.217^{e}-24	2.708^{e}-42	1.10^{e}-22	1^{e}-30	1.27^{e}-40

6 Conclusion

Simulation results demonstrate that chromatic dispersion severely limits system performance without compensation. While, DCF significantly improves signal integrity. However, the proposed hybrid DCF–FBG configuration consistently outperforms DCF alone in terms of Q-factor, BER, eye-diagram quality, and transmission reach.

At optimized power levels, the hybrid approach achieved substantial performance gains across all data rates simulated (10, 20, 30, 40) Gbs, maintaining Q-factors well above the acceptable threshold (Q > 6) and extremely low BER values, even at 40 Gb/s. Moreover, the hybrid scheme extends the maximum achievable transmission distance and enhances robustness against chromatic dispersion-induced impairments.

Overall, the results confirm that the hybrid DCF–FBG module provides an efficient, scalable, and high-performance chromatic dispersion compensation solution for high-speed DWDM systems, making it a strong candidate for next-generation long-haul optical communication networks.

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