Design and Analysis of Hybrid Dispersion Compensation Techniques for 32×40Gbps DWDM Optical Transmission Systems

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Research Article

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Posted Date: May 19th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1653304/v1

Design and Analysis of Hybrid Dispersion Compensation Techniques for 32×40Gbps DWDM Optical Transmission Systems

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Abstract

In this article, the proposed modal evaluates the performance of 32×40Gb/s dense wavelength division multiplex (DWDM) optical transmission systems through hybrid dispersion compensation techniques which are Dispersion-Compensation-Fiber (DCF), DCF-FBG (Fiber Braggs Grating), OPC (Optical-Phase-Conjugation)-DCF, and OPC-DCF-FBG using Gaussian, Non-Return-to-Zero (NRZ) and Return-to-Zero (RZ) pulse generators. Performance of proposed modal is evaluated through single-mode fiber (SMF) length between 100-500km with an optimized length of DCF/FBG for low-cost optical transmission systems. The performance of the designed model is evaluated in terms of quality-factor (Q-factor), bit-error-rate (BER), eye diagrams, and cost analysis for all proposed combinations of dispersion compensation techniques. The quality factor and BER are also evaluated at different input power levels. It is found that the hybrid combination of OPC-DCF-FBG techniques having RZ pulse-generator gives the best performance with low cost for 500km long-haul optical transmission systems.

Keywords: Dispersion compensation fiber (DCF), fiber bragg grating (FBG), optical phase conjugation (OPC), non-return-to-zero (NRZ), return-to-zero (RZ), and single-mode fiber (SMF).

1. Introduction

A couple of years ago, two wires coaxial cables were used for transmitting data in the telecommunication industry, but these cables are limited in bandwidth. Therefore, coaxial cables are not able to transmit data at high speed. To overcome the requirement of bandwidth, optical fiber (OF) cable has been invented. Therefore, the demands of optical fibers have been increased due to high bandwidth and more data rates in the telecommunication industry [1]. To increase the data rates, a low-cost optical transmission system with dense-wavelength-division-multiplexing (DWDM) has been used. A DWDM system can transmit different wavelength signals for long-distance with the help of multiplexer and de-multiplexer that's used at the transmitter and receiver side in the optical transmission system. The multiplexer is used to collect different wavelength signals and transmit different wavelengths through a single channel and similarly, de-multiplexer is used to separate different wavelength signals [2-4]. Although considering these requirements it is found that when optical signals are transmitted for long distances, the optical signals are affected by attenuation and dispersion. To overcome the problem of attenuation, optical amplifiers are used like semiconductor optical amplifier (SOA), Raman amplifier (RA), and erbium-doped-fiber amplifier (EDFA) [3-6]. However, to eliminate the dispersion problem, dispersion compensation techniques such as DCF, FBG, OPC DCF-FBG, OPC-DCF, and OPC-DCF-FBG are suggested in previously reported work [3-15]. Among all these dispersion justifying techniques, the hybrid DCF-FBG, OPC-DCF, and OPC-DCF-FBG are the most efficient dispersion compensation techniques. In DCF, a special SMF having a negative dispersion coefficient is introduced to compensate for the effect of positive dispersion in an optical fiber transmission system [16]. A lot of researchers have explored the design of optical transmission characteristics, applications with an optimized length of DCF as a dispersion compensator [17-19]. It is concluded from literature, DCF technique is very reliable and easy to the upgrading of previously connected optical fiber transmission systems however it increases major nonlinear effects and cost of optical systems [20]. To overcome the encounters of the DCF process, Fiber Bragg Grating is advised to recompense dispersion in optical fiber links. Fiber Bragg Grating is immersed in major eminence for the approximation of dispersion compensation. So, FBG is considered as minor nonlinear effects and cost competence for optical transmission systems. Further, the uniform FGB reflects only a single wavelength; however, for dispersion compensation, it's needed to chirp the grating period of FBG beside its length to return all wavelength components along with its time-span [21, 22]. Moreover, a lot of researchers are concentrated on issues related to design, optimization of optical transmission systems using DC, FBG, DCF-FBG parameters, grating period/length, effective refractive index, and applying FBG to DWDM networks [23-29]. Recently, M. Chakkour et. al [30] were also design and compared the optical transmission system using FBG and FBG-EDFA techniques for 500km length of optical fiber but the capacity of the system is very less. Further, Shivin Aggarwal et. al [31] investigated the performance of a 32×10Gbps optical transmission system using different combined dispersion compensation techniques but data rates of the system is very less. In addition to DCF and FBG, the OPC module is also useful to overcome the nonlinear dispersion impairments due to group-velocity-dispersion (GVD) and self-phase-modulation (SPM) [32, 33]. Furthermore, the OPC was used to mitigate the effect of fiber non-linear impairments on optical modulation schemes by P. Minzioni et. al [34-36]. Furthermore, the fundamental restrictions of OPC system performance in CO-OFDM systems were studied by M. Morshed et. al [37, 38]. Therefore, it is clear from the literature; most of the researchers are focused on DCF, FBG, OPC, and DCF-FBG techniques as dispersion compensators [28-38]. Hence, the authors are working out on hybrid dispersion compensation techniques which are DCF-FBG, OPC-DCF, and OPC-DCF-FBG using Gaussian, non-return-to-zero, and return-to-zero pulse generators to design, evaluate, enhance, and compare the performance of proposed optical transmission systems. Then, we also compared the proposed model with previously reported optical transmission systems by researchers as dispersion compensation [2-4, 13, 28-31]. Finally, it can be observed that the presented work improves the performance of the proposed model by reducing dispersion and attenuation phenomena through hybrid dispersion techniques OPC-DCF-FBG and comparable to an expensive DCF, FBG, DCF-FBG and OPC-DCF techniques. The designed optical DWDM transmission configurations are modeled and simulated using an Opti-System simulator.

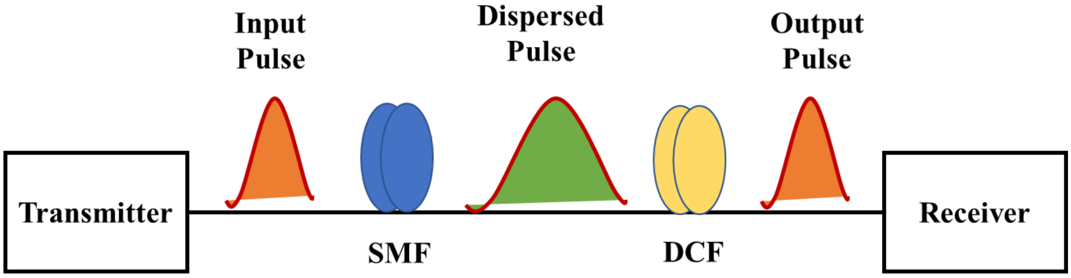


Fig.1: Basic principle of DCF techniques

2. Mathematical Modelling of Dispersion Compensation Techniques

2.1 Dispersion Compensation Fiber

When an optical signal is transmitted from transmitter to receiver for long-distance through SMF the dispersion problem occurs due to the nonlinearity of fiber. To overcome dispersion, positive dispersion coefficients of SMF around 17ps/nm-km and for DCF negative dispersion coefficients of -80 to -110ps/nm-km have been optimized and chosen in proposed model. Therefore, the DCF is connected with SMF in the optical transmission system to reduce the dispersion effects as shown in Fig.1. Hence, for perfect dispersion compensation, the proposed model should be satisfied by the following equations given as [12, 13]:

$$D_{SMF} * L_{SMF} + D_{DCF} * L_{DCF} = 0 \tag{1}$$

$$L_{DCF} = -L_{SMF}\left(\frac{D_{SMF}}{D_{DCF}}\right) \quad (2)$$

where, D_{SMF} = dispersion of SMF; D_{DCF} = dispersion of DCF L_{SMF} = length of SMF; L_{DCF} = length of DCF.

2.2 Fiber Bragg Grating

Fiber Bragg grating is designed with a small portion of an optical fiber that has a periodic variation in refractive index beside the length of optical fiber. Therefore, through FBG a particular wavelength signal can be reflected and the remaining wavelength signals can be transmitted. Hence, FBG works as a filter. However, an identical FBG has a constant refractive index along the length of optical fiber as can be illustrated in Fig.2. The reflected wavelength is known as Bragg's wavelength as given by equation [12, 13]:

$$\lambda_{Bragg} = 2 \cdot n_{eff} \cdot \Lambda \quad (3)$$

where, where λ_{Bragg}= Bragg's wavelength; n_{eff}= effective refractive index; and Λ= grating period of fiber.

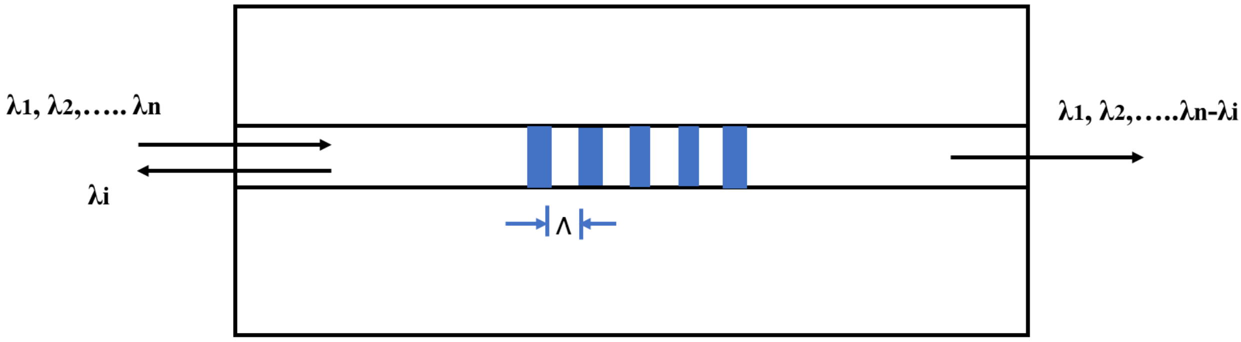


Fig.2: Schematic of uniform Fiber Bragg Grating

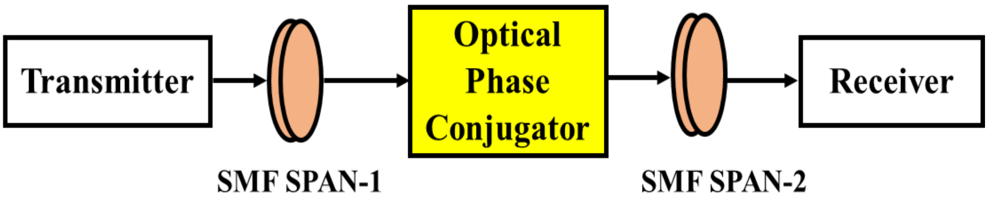


Fig.3: Basic principle of optical phase conjugation

2.3 Optical Phase Conjugation

The optical phase conjugation (OPC) technique is differing from DCF and FBG dispersion compensation techniques. OPC is a nonlinear dispersion-managed technique and it can compensate group-velocity-dispersion (GVD) and self-phase-modulation (SPM) simultaneously [14,15]. The basic concept of optical phase conjugation is illustrated in Fig.3. As can be seen in Fig.3, the optical phase conjugation module is placed between the middle of two identical SMF transmission links; therefore nonlinear dispersion impairments, before the OPC module (in the first span of transmission link) can be canceled by those generated after OPC module (in the second span of transmission link). Therefore, the OPC technique improves the nonlinear performance for long-haul optical transmission systems [38]. Further, to achieve the best compensation outcomes, the SMF span in both sides of OPC modules should be identical for long-haul transmission systems. Hence, the optical phase conjugation technique is known as midway optical phase conjugation or mid-span spectral inversion technique or output signal spectrum after the OPC module becomes the mirror image of the input spectrum [33]. Furthermore, the authors show mathematically how OPC can compensate for the problem of group-velocity dispersion. From the pulse propagation equation given by [14,15]:

$$\frac{\partial A}{\partial Z}+\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^2}=0 \tag{4}$$

where, A is the amplitude of optical pulse. Using the concept of OPC, author will take the complex conjugate of equation (4):

$$\frac{\partial A^*}{\partial Z}-\frac{i\beta_2}{2}\frac{\partial^2 A^*}{\partial t^2}-\frac{\beta_3}{6}\frac{\partial^3 A^*}{\partial t^2}=0 \tag{5}$$

By comparing equations (4) and (5) it is established that the GVD parameter β_2 is reversed for the phase-conjugated field of A^*. By the concept of OPC, dispersion holds in the first half-span of the SMF link which can be compensated in the second half-span of the SMF link [14,15]. The pulse-propagation equation (4) can be further solved with the help of Fourier transform as given by equation (6):

$$A(z,t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{A}(0,\omega)\exp\left(\frac{i}{2}\beta_2 z\omega^2-i\omega t\right)d\omega \tag{6}$$

Where, $\tilde{A}(0,\omega)$ is the Fourier transform of $A(0,t)$. Further, optical field before the OPC can be obtained by z = L/2 from equation (6):

$$A(L,t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{A}\left(\frac{L}{2},\omega\right)\exp\left(\frac{i}{4}\beta_2 L\omega^2-i\omega t\right)d\omega \tag{7}$$

The pulse spectrum before the OPC is given by:

$$\tilde{A}\left(\frac{L}{2},\omega\right)=\tilde{A}\left(0,\omega\right)\exp\left(\frac{i}{4}\beta_2 L\omega^2\right) \tag{8}$$

The optical field after the OPC is given by equation (9)

$$A^*(L,t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{A}^*\left(\frac{L}{2},\omega\right)\exp\left(\frac{i}{4}\beta_2 L\omega^2-i\omega t\right)d\omega \tag{9}$$

where, $\tilde{A}^*\left(\frac{L}{2},\omega\right)$ is the Fourier transform of $A^*\left(\frac{L}{2},t\right)$. The pulse spectrum after the OPC is given by:

$$\tilde{A}^*\left(\frac{L}{2},\omega\right)=\tilde{A}^*\left(0,-\omega\right)\exp\left(\frac{-i}{4}\beta_2 L\omega^2\right) \tag{10}$$

Put the value of equation (10) in equation (9)

$$A\left(L,t\right)=A^*\left(0,t\right) \tag{11}$$

Hence, equation (11) shows the input optical field is completely recovered except for the phase reversal induced by the OPC. Given the above analysis, the mechanisms of OPC along the SMF spans are increased optical transmission reach, more stable and insignificant temperature dependence effect. Hence, OPC is also the most appropriate technique for dispersion compensation. Therefore, the physical arrangement of DCF-FBG, OPC-DCF and OPC-DCF-FBG can be positioned at a different location in the proposed DWDM transmission system for dispersion compensation as shown in Fig.4. In section 3, we discussed the proposed 32×40Gb/s DWDM transmission model and evaluate its performance in terms of Q-factor, BER and eye diagrams for all proposed combinations for each channel through the above dispersion compensation techniques.

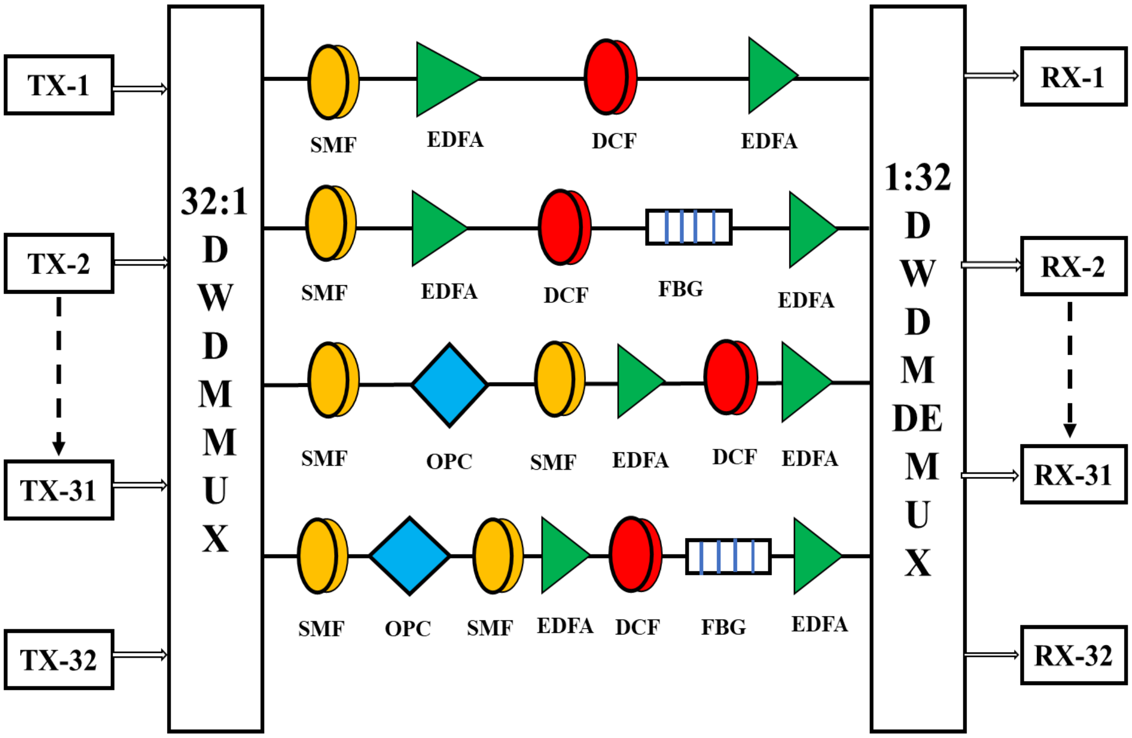


Fig.4: Proposed model for hybrid dispersion compensation techniques: DCF; DCF-FBG; OPC-DCF; and OPC-DCF-FBG.

3. Description of Proposed System

In the proposed model, 32×40Gbps optical transmission systems is designed through a hybrid module as dispersion compensator of DCF, DCF-FBG, OPC-DCF, and OPC-DCF-FBG using Gaussian, NRZ and RZ pulse generators. Designed systems are simulated via Opti-system simulator by changing the length of SMF and input power to examine in what manner hybrid dispersion compensator modules can change the performance of proposed systems. The fundamental simulation sketch of the proposed systems is shown in Fig.5. The proposed model is allocated into three segments which are the optical transmitter section, transmission link, and receiver section. The results related to the performance parameters of the proposed model are discussed in the results Section.

3.1 Optical Transmitter

Optical transmitter unit includes four blocks: Pseudo-Random Bit Sequence (PRBS), pulse generator (RN/NRZ/Gaussian), continuous-wave laser (CWL) and Mach-Zehnder (MZ) modulator. Optical transmitter is made by data source to produce pseudo-random bit sequence at bit rate of 40Gb/s where a binary signal is transmitted, pulse generator, to convert binary data into electrical pulse, CW laser and MZ modulator to modulate laser signal. MZ-modulator receives an electrical signal or optical signal and makes phase-shift between two signals if required and provide an optical-signal at the output. Extinction-ratio of the MZ-modulator is to be chosen 30dB. Central frequency of each channel is choosing from 193.1THz-to-196.2THz. Thirty-two continuous-wave laser sources are used for generating different optical signals and space between channels is kept 0.8nm (100GHz). The output power of each CW laser is optimized at 0dBm (performance evaluate between -2 to 2dBm).

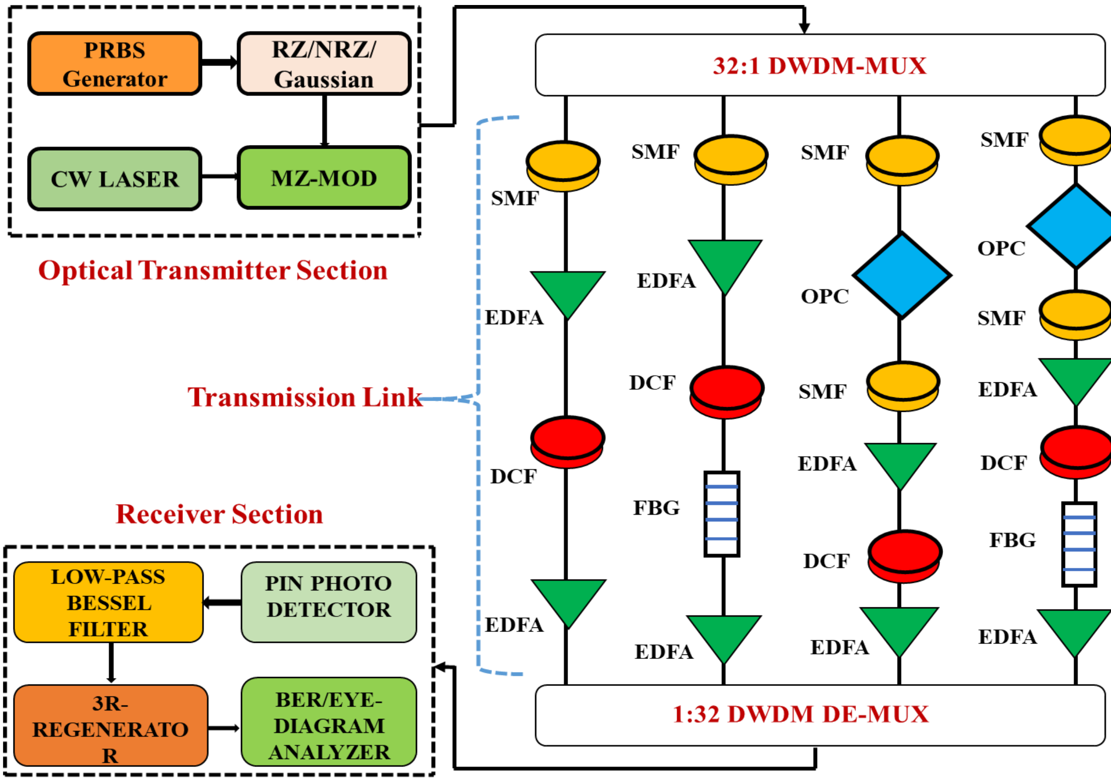


Fig.5: Proposed 32×40Gbps DWDM optical transmission systems to evaluate the performance of hybrid dispersion compensation techniques

Table 1: Components and simulated parameter values of the proposed model

Components	Parameters	Values
Data source	Data Rate	40Gbps
	Sample per bit	32
	Sequence length	256
	Total no. of channels	32
Pulse Generator	Gaussian, NRZ, RZ	Exponential
	Rise time	0.05bit
	Fall time	0.05bit
	Duty cycle	0.5
CW Laser	Output power	-2 to 2dBm
	Central frequency	193.1-196.2THz
	Channel spacing	0.8nm (100GHz)
MZ-Modulator	Extinction ratio	30dB
	Insertion loss	5dB
SMF	Length	50×N km (N=2,4,6,8,10)
	Dispersion	17ps/nm/km

	Attenuation loss	0.2dB/km
	Dispersion slop	0.075ps/nm^2/ km
	Differential Group delay	0.2ps/km
	Core effective area	70µm^2
	Reference wavelength	1550nm
DCF	Length	10.2×N km (N=2,4,6,8,10) for Gaussian and NRZ 8.5×N km (N=2,4,6,8,10) For RZ
	Dispersion	-83.4ps/nm/km for NRZ and Gaussian -100ps/nm/km for RZ
	Attenuation loss	0.5dB/km
	Differential Group delay	0.2ps/km
	Core effective area	22µm^2
	Reference wavelength	1550nm
EDFA amplifier	Gain	10-20dB
	Amplifier length	10m
	Noise figure	4 dB
PIN Photo-detector	Gain	2
	Sensitivity	-100dBm
	Dark current	10nA
	Responsivity	1A/W
	Error probability	10^{-9}
LPB Filter	Order	3
	Cut-off frequency	30GHz

3.2 Transmission Link Structures

The generated optical signals from the transmitter are combined over DWDM multiplexer (DWDM-MUX) and transmitted over SMF by considering four hybrid module/combinations of DCF, DCF-FBG, OPC-DCF and OPC-DCF-FBG as can be seen in Fig.5. This section is known as the transmission link. Therefore, the transmission link section is considered under investigation through different location falls of SMF-DCF, DCF-FBG, OPC-DCF and OPC-DCF-FBG as dispersion compensators. Hence, the optimized length of each span of SMF is 50×N km and DCFs are 10.2×N km for Gaussian, NRZ; 8.5×N km for RZ (where the number of loops is N=2, 4, 6, 8, 10). Further, the physical arrangement of SMFs, DCFs, FBGs, OPCs, and EDFAs are situated according to proposed schemes as shown in Fig.5.

3.3 Optical Receiver

In the receiver section, the output of DWDM de-multiplexer (DWDM DE-MUX) is given to PIN photodetector and pass-through low pass electrical Bessel filter. Further, the data pulse is provided to the 3R-Regenerator circuit where reshaping, retiming, and reamplification are to be accomplished. Then, BER/Eye analyzer is used for computing the bit-error-rate, quality-factor, and eye diagrams. Furthermore, all components and simulation parameters related to SMF, DCF, FBG, OPC and EDFA for the designed optical transmission systems are tabulated in Table1.

4. Results and Analysis

In this section, we are investigating the performance of hybrid dispersion compensation for 32×40Gbps DWDM optical transmission systems through diverse DCF, DCF-FBG, OPC-DCF and OPC-DCF-FBG modules. To explore the performance of proposed systems by varying length of SMF and input power with optimized simulated parameters values as given in Table1. Accordingly, simulations are accomplished via proposed compensation schemes having Gaussian, NRZ, and RZ pulse generators. The output results are measured in terms of quality-factor (Q-factor), bit-error-rate (BER) and eye-diagrams via BER analyzer. For better optical transmission systems, the values of Q-factor and BER must be $Q>10^6$ and $BER<10^{-9}$, respectively.

4.1. Performance Effect by Gaussian Pulse Generator

The variations of Q-factor versus length of SMF between different dispersion compensation schemes are plotted in Fig.6 using Gaussian pulse generator. It can be observed that by increasing the length of SMF with an optimized range of 100-500km, the Q-factor of OPC-DCF-FBG dispersion compensation module have been obtained the maximum Q-factor among DCF, DCF-FBG, OPC-DCF and OPC-DCF-FBG schemes. Further, the variations of BER vs. length of SMF have also been plotted for different dispersion compensation techniques as shown in Fig.7. It has been clear from Fig.7 that the OPC-DCF-FBG technique gives the minimum BER for 100-500km length of SMF. Furthermore, the quality factor and BER performance between 100-500km lengths through proposed dispersion compensation techniques using Gaussian pulse generator are calculated at 0dBm input power as indicated in Table 2. It has been found from Table 2 that the OPC-DCF-FBG technique gives the best performance compared to DCF, DCF-FBG and OPC-DCF dispersion compensation techniques.

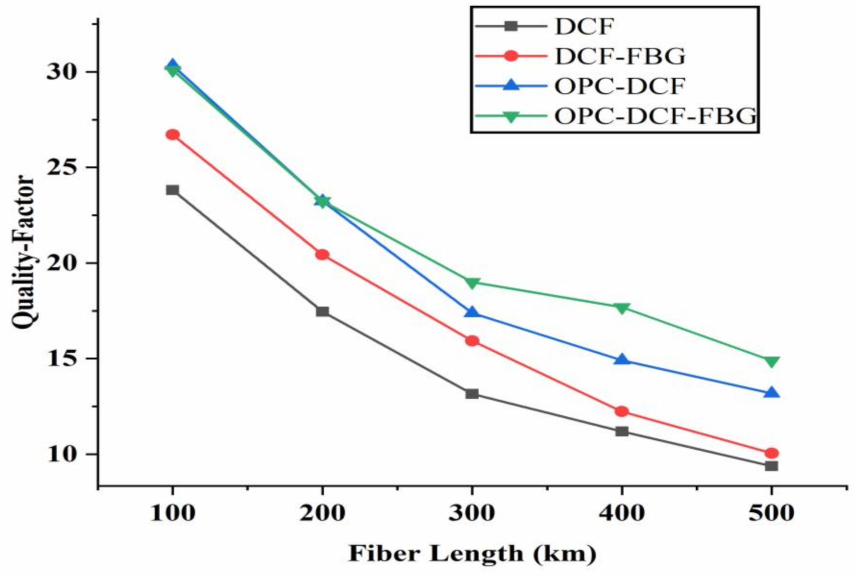


Fig.6: Variations of Q-factor vs. length of SMF through Gaussian pulse generator

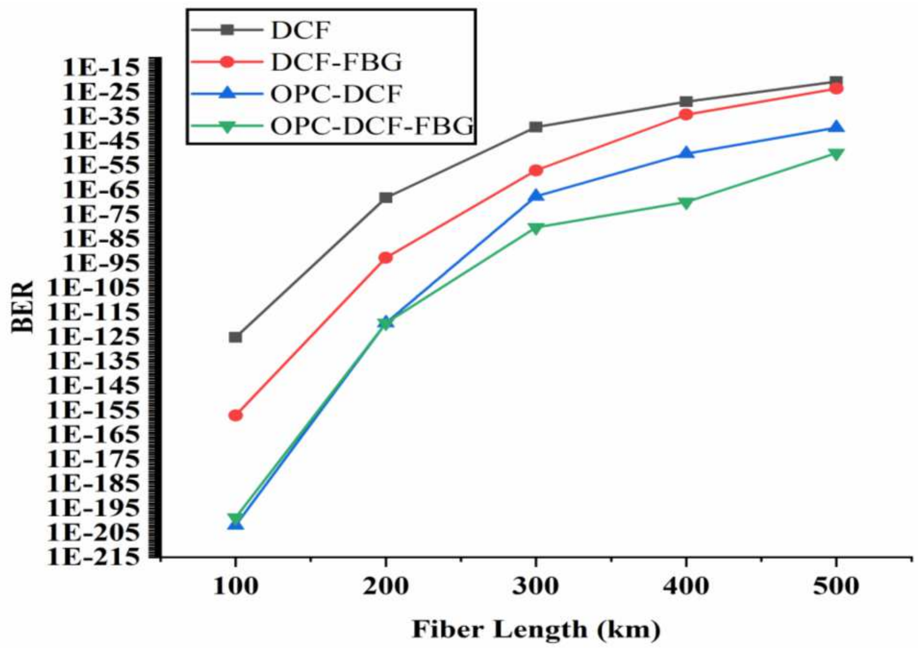


Fig.7: Variations of BER vs. length of SMF through Gaussian pulse generator

Table 2: Q-factor and BER are measured for different lengths of SMF with Gaussian pulse generator at 0dBm input power

SMF Length	100km		200km		300km		400km		500km	
Dispersion Compensation Techniques	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER
DCF	23.81	7.50e-126	17.46	8.31e-069	13.15	5.01e-040	11.19	1.49e-029	09.38	2.35e-021
DCF-FBG	26.71	8.82e-158	20.43	2.53e-093	15.93	1.11e-057	12.23	6.88e-035	10.05	2.95e-024
OPC-DCF	30.33	1.16e-202	23.24	4.97e-120	17.39	2.90e-068	14.91	8.41e-051	13.18	3.38e-040
OPC-DCF-FBG	**30.10**	**1.43e-199**	**23.23**	**5.69e-120**	**19.00**	**5.06e-081**	**17.69**	**1.39e-070**	**14.89**	**1.17e-050**

Further, the effect of Q-factor versus input power variations is shown in Fig.8 for an optimized SMF length of 500km. It can be observed that the calculated values of Q-factor are almost constant for DCF and DCF-FBG techniques but Q-factor is increased at optimized 0dBm input power for OPC-DCF and OPC-DCF-FBG techniques. Similarly, the variations of BER versus input power for 500km length of SMF with Gaussian pulse generator are shown in Fig.9. It can also be observed that the value of BER is almost constant for DCF and DCF-FBG techniques however BER is decreased at optimized 0dBm input power for OPC-DCF and OPC-DCF-FBG techniques. Therefore, OPC-DCF-FBG dispersion techniques give the best Q-factor and minimum BER for the 500km length of SMF as compared to DCF, DCF-FBG and OPC-DCF dispersion techniques.

It can also be seen from Fig.8-9, when input power is increased, Q-factor is also increased however BER is decreased for OPC-DCF-FBG techniques. Furthermore, the Q-factor and BER for 500km length of SMF via proposed dispersion compensation techniques with Gaussian pulse generator at different input powers are calculated as indicated in Table 3. It is found from Table 3, the OPC-DCF-FBG technique gives the best performance as compared to reaming reporting dispersion compensation techniques.

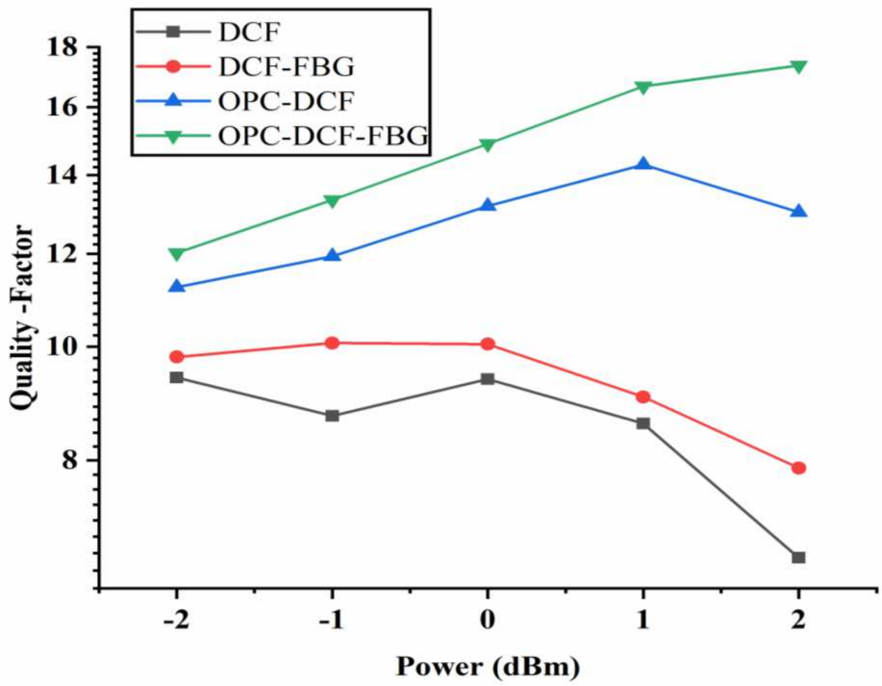


Fig.8: Variations of Q-factor vs. power for 500km length of SMF with Gaussian pulse generator

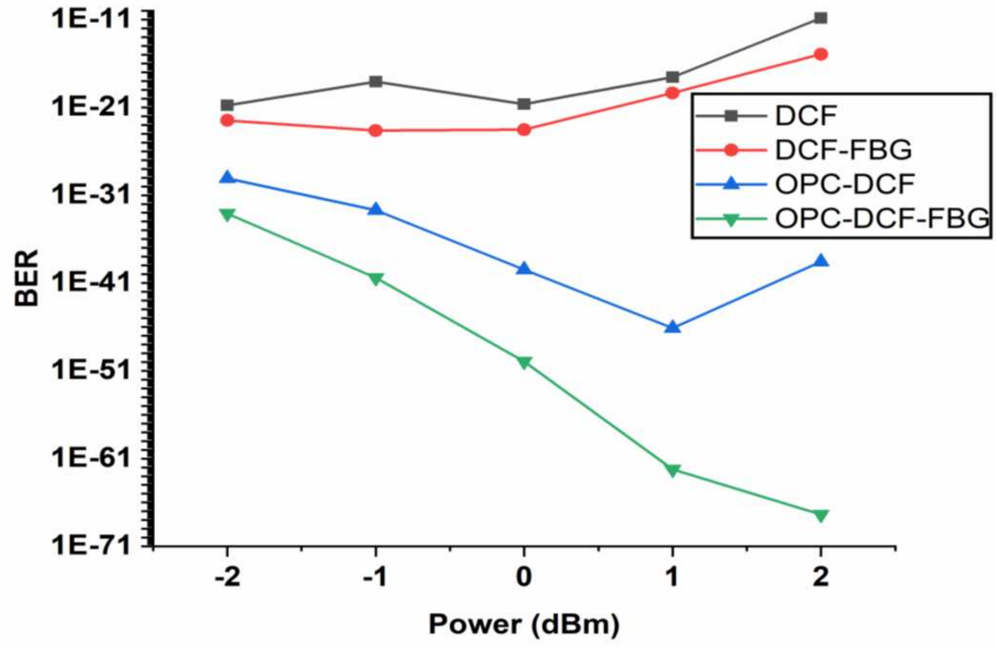


Fig.9: Variations of BER vs. power for 500km length of SMF with Gaussian pulse generator

Table 3: Q-Factor and BER for 500km length of SMF with Gaussian pulse generator at a different input power

Techniques	DCF		DCF-FBG		OPC-DCF		OPC-DCF-FBG	
Power (dBm)	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER
-2	9.41	1.72e-021	9.80	3.32e-023	11.24	8.06e-030	12.02	8.26e-034
-1	8.73	8.25e-019	10.07	2.29e-024	11.94	1.99e-033	13.34	4.09e-041
0	**9.38**	**2.35e-021**	**10.05**	**2.95e-024**	**13.18**	**3.38e-040**	**14.89**	**1.17e-050**
1	8.60	2.89e-018	9.06	4.41e-020	14.29	7.08e-047	16.67	6.13e-063
2	6.61	1.55e-011	7.88	1.16e-015	13.02	2.62e-039	17.36	4.38e-068

Furthermore, the eye patterns of received signals are obtained by eye-analyzer for different hybrid dispersion compensation techniques with Gaussian pulse generator at 0dBm input power as shown in Fig.10. It can be observed that the OPC-DCF-FBG technique gives the batter eye-opening as compared to eye patterns obtained via DFC, DCF-FBG and OPC-DCF dispersion compensation techniques.

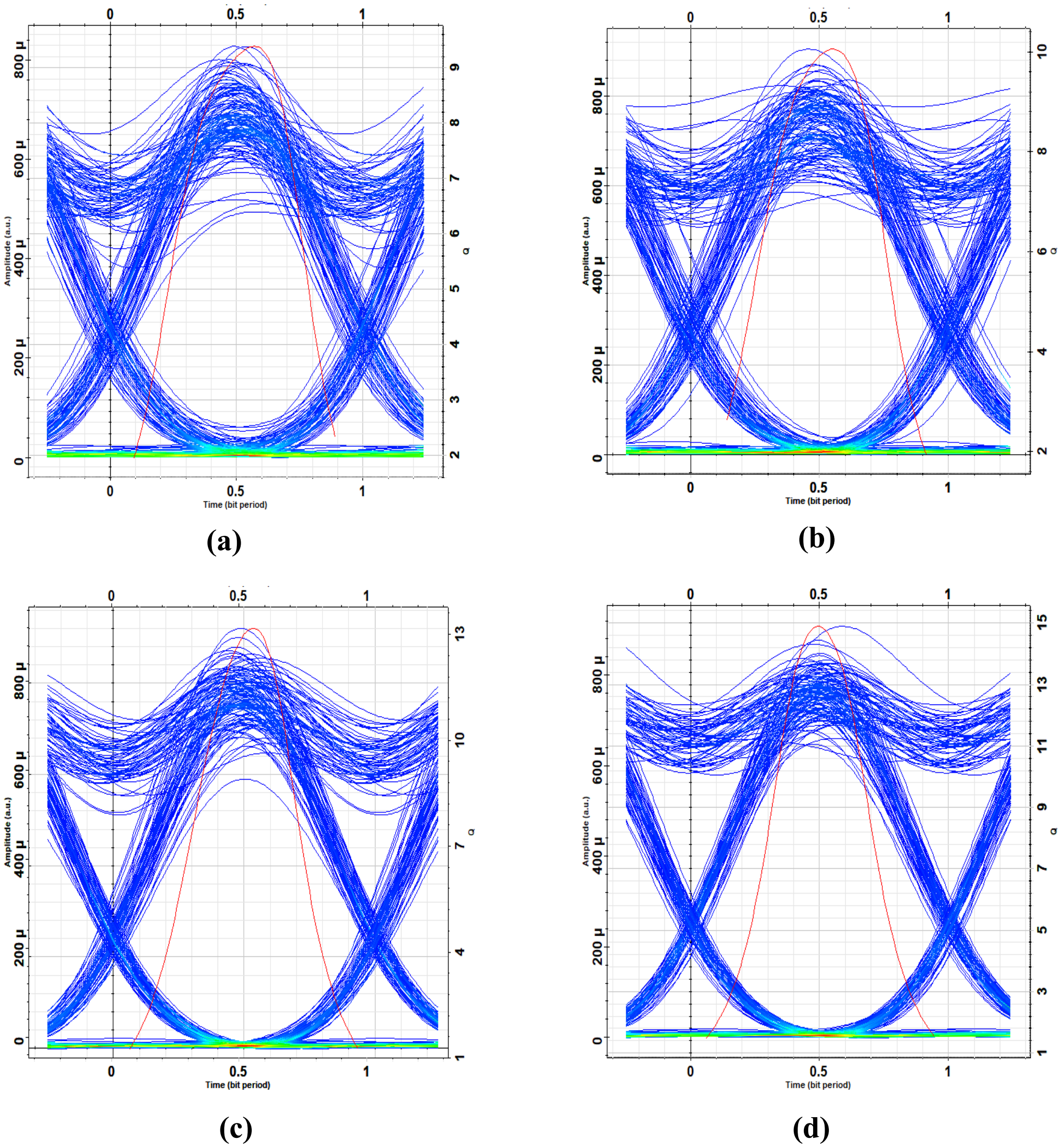


Fig.10: Eye-diagrams for different dispersion compensation techniques via Gaussian pulse generator at 500km length of SMF: (a) DCF only; (b) DCF-FBG; (c) OPC-DCF; (d) OPC-DCF-FBG.

4.2. Performance Effects by NRZ Pulse Generator

The deviations of Q-factor versus length of SMF among different dispersion compensation schemes are machinated in Fig.11 using NRZ pulse generator. It can be observed that as the length of SMF is increasing from 100-500km, the obtained range of Q-factor is 16-25.54 via OPC-DCF-FBG dispersion compensation module, which is higher than DCF, DCF-FBG, and OPC-DCF schemes. However, obtained Q-factor is less than to Gaussian pulse generator. Further, the variations of BER vs. length of SMF have also been plotted for proposed dispersion compensation techniques as shown in Fig.12. It has been clear from Fig.12 that the OPC-DCF-FBG technique gives acceptable BER for 100-500km length of SMF. Furthermore, Q-factor and BER performance through proposed dispersion compensation techniques using NRZ pulse generator are calculated and summarized at 0dBm input power as indicated in Table 4. It has been found from Table 4 that the OPC-DCF-FBG technique gives optimum performance compared to DCF, DCF-FBG and OPC-DCF dispersion compensation techniques.

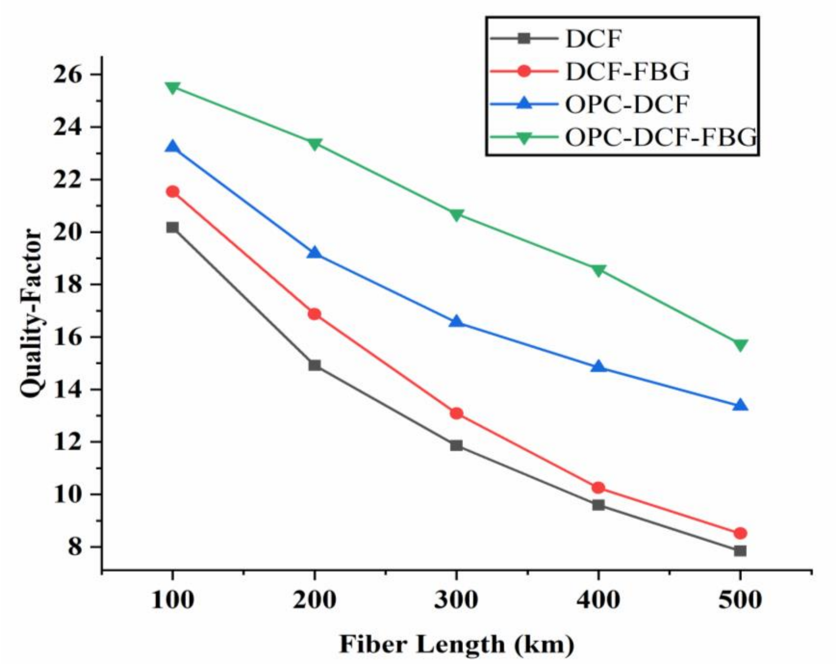


Fig.11: Variations of Q-factor vs. length of SMF through NRZ pulse generator

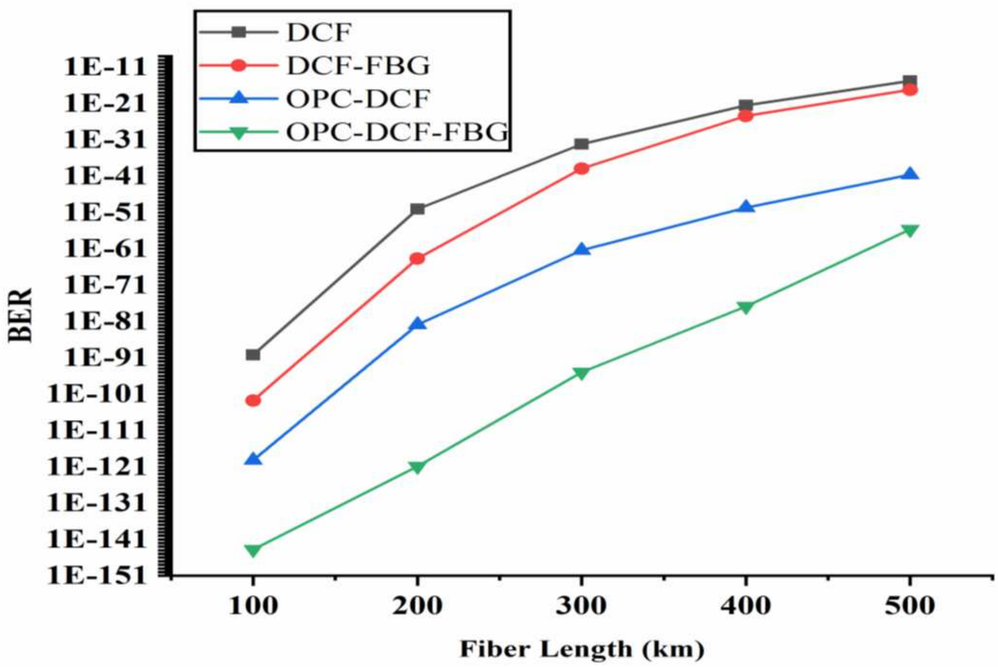


Fig.12: Variations of BER vs. length of SMF through NRZ pulse generator

Table 4: Q-factor and BER are measured for different lengths of SMF with NRZ pulse generator at 0dBm input power

SMF Length	100km		200km		300km		400km		500km	
Dispersion Compensation Techniques	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER
DCF	20.17	6.14e-091	14.92	7.96e-051	11.86	6.50e-033	9.59	3.22e-022	7.84	1.67e-015
DCF-FBG	21.54	1.76e-103	16.87	2.19e-064	13.09	1.24e-039	10.25	3.83e-025	8.51	5.72e-018
OPC-DCF	23.23	6.53e-120	19.18	1.41e-082	16.55	4.40e-062	14.84	2.13e-050	13.37	2.60e-041
OPC-DCF-FBG	**25.54**	**1.67e-144**	**23.39**	**1.27e-121**	**20.69**	**1.07e-095**	**18.58**	**1.31e-077**	**15.73**	**2.41e-056**

Further, the effect of quality factor versus input power deviations is shown in Fig.13 for the optimized SMF length of 500km. It can be observed that the calculated values of Q-factor are almost constant for DCF and DCF-FBG techniques, but Q-factor is increased from 13.37-15.73 at optimized 0dBm input power for OPC-DCF and OPC-DCF-FBG techniques. Similarly, the effect of BER versus input power for 500km length of SMF with NRZ pulse generator is shown in Fig.14. It can be observed that the value of BERs is almost constant for DCF and DCF-FBG techniques however BER is decreased at optimized 0dBm input power for OPC-DCF and OPC-DCF-FBG techniques. Therefore, OPC-DCF-FBG dispersion techniques give batter Q-factor and minimum BER for 500km length of SMF as compared to DCF, DCF-FBG and OPC-DCF dispersion techniques. It can also be seen from Fig.13-14 when input power is increased, Q-factor is also increased but BER is decreased for OPC-DCF-FBG techniques. Moreover, Q-factor and minimum BER for 500km length of SMF via proposed dispersion compensation techniques with NRZ pulse generator at different input powers are given in Table5. It is found from the Table5, combined OPC-DCF-FBG technique gives optimum performance compared to other reporting dispersion compensation techniques.

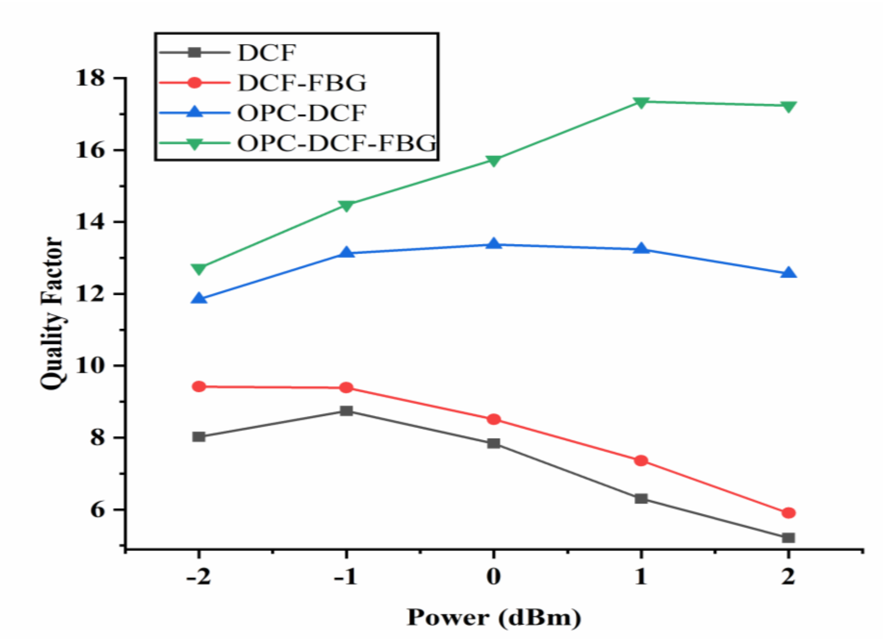


Fig.13: Variations of Q-factor vs. power for 500km length of SMF with NRZ pulse generator

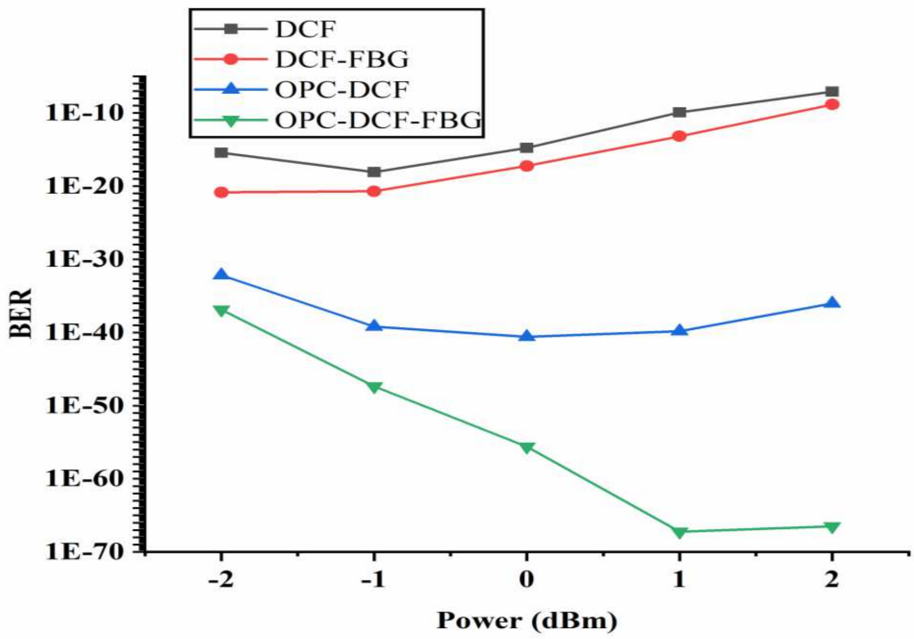


Fig.14: Variations of BER vs. power for 500km length of SMF with NRZ pulse generator

1 **Table 5:** Q-Factor and BER for 500km length of SMF with NRZ pulse generator at a different input power

Techniques	DCF		DCF-FBG		OPC-DCF		OPC-DCF-FBG	
Power (dBm)	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER
-2	8.02	3.57e-016	9.42	1.37e-021	11.85	6.59e-033	12.72	1.30e-037
-1	8.74	8.44e-019	9.39	1.98e-021	13.13	6.03e-040	14.48	4.25e-048
0	**7.84**	**1.67e-015**	**8.51**	**5.72e-018**	**13.37**	**2.60e-041**	**15.73**	**2.41e-056**
1	6.30	1.17e-010	7.36	6.59e-014	13.24	1.44e-040	17.35	5.70e-068
2	5.21	8.05e-008	5.90	1.46e-009	12.56	9.22e-037	17.24	3.32e-067

Moreover, Figure 15 shows the received eye-patterns through eye-analyser for different hybrid dispersion compensation techniques with NRZ pulse generator at 0dBm input power. It can be observed that the OPC-DCF-FBG techniques give better eye-opening as compared to eye-patterns obtained using DCF, DCF-FBG and OPC-DCF dispersion compensation techniques.

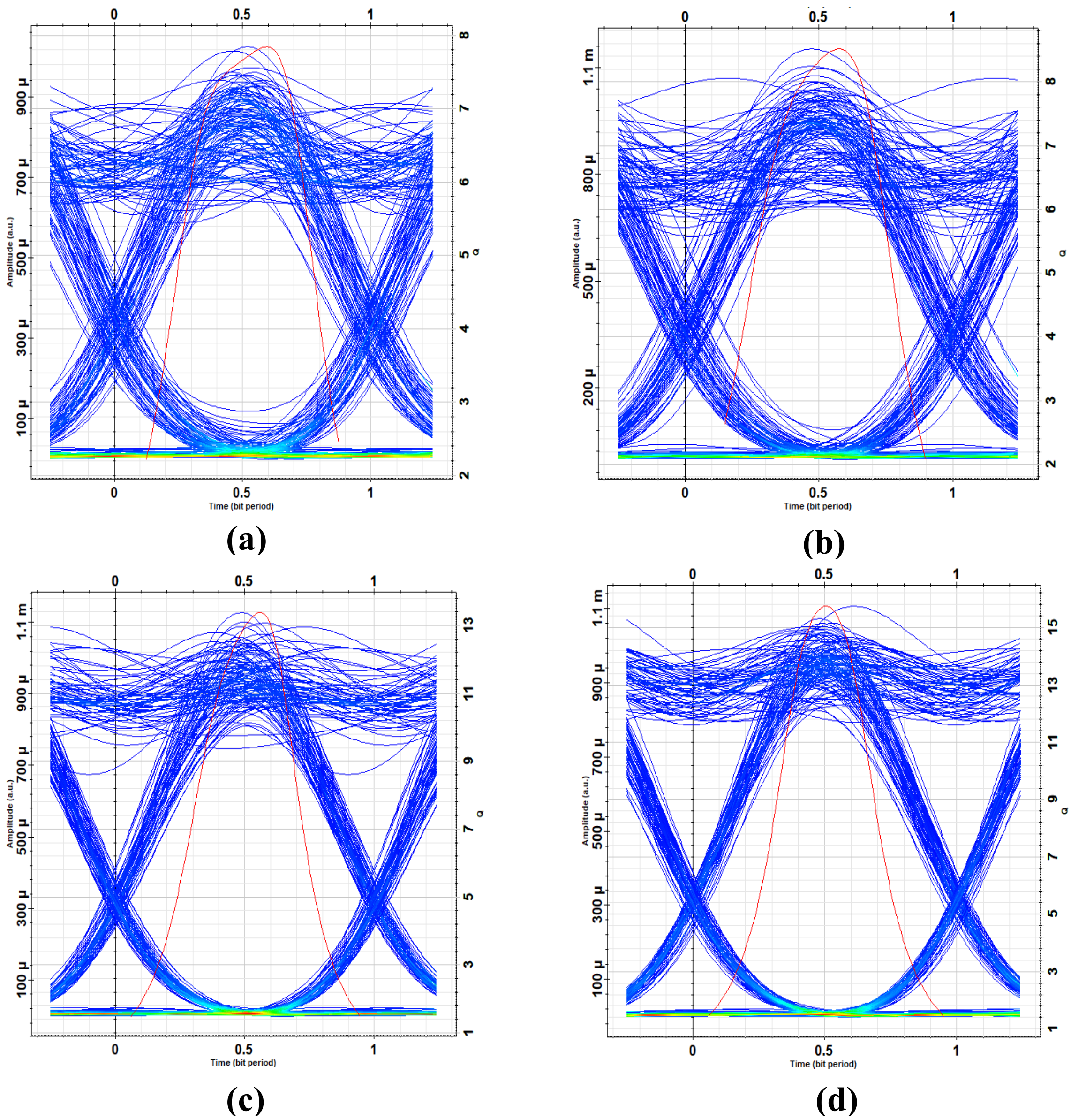


Fig.15: Eye-diagrams for different dispersion compensation techniques via NRZ pulse generator at 500km length of SMF: (a) DCF only; (b) DCF-FBG; (c) OPC-DCF; (d) OPC-DCF-FBG.

4.3.Performance Effect by RZ Pulse Generator

The quality factor and bit-error-rate are affected by varying the length of SMF in the proposed systems. The variations of Q-factor versus length of SMF among different hybrid dispersion compensation schemes are schemed in Fig.16 via RZ pulse generator. It can be observed that the length of SMF is increasing from 100-500km; attained range of Q-factor is 15.71-25.86 through OPC-DCF-FBG dispersion compensation module which is greater than the DCF, DCF-FBG and OPC-DCF schemes. The acquired Q-factor is also greater than to Gaussian and NRZ pulse generators. Further, the variations of BER vs. length of SMF also scheme for proposed compensation techniques as shown in Fig.17. It is clear from Fig.17; all four dispersion techniques give adequate BER for 100-500km length and are BER<10^{-9}. Furthermore, Q-factor and BER performance through proposed dispersion compensation techniques using RZ pulse generator are summarized in Table 4. It is found from Table 6 that the OPC-DCF-FBG hybrid dispersion technique gives optimum performance compared to DCF, DCF-FBG and OPC-DCF techniques.

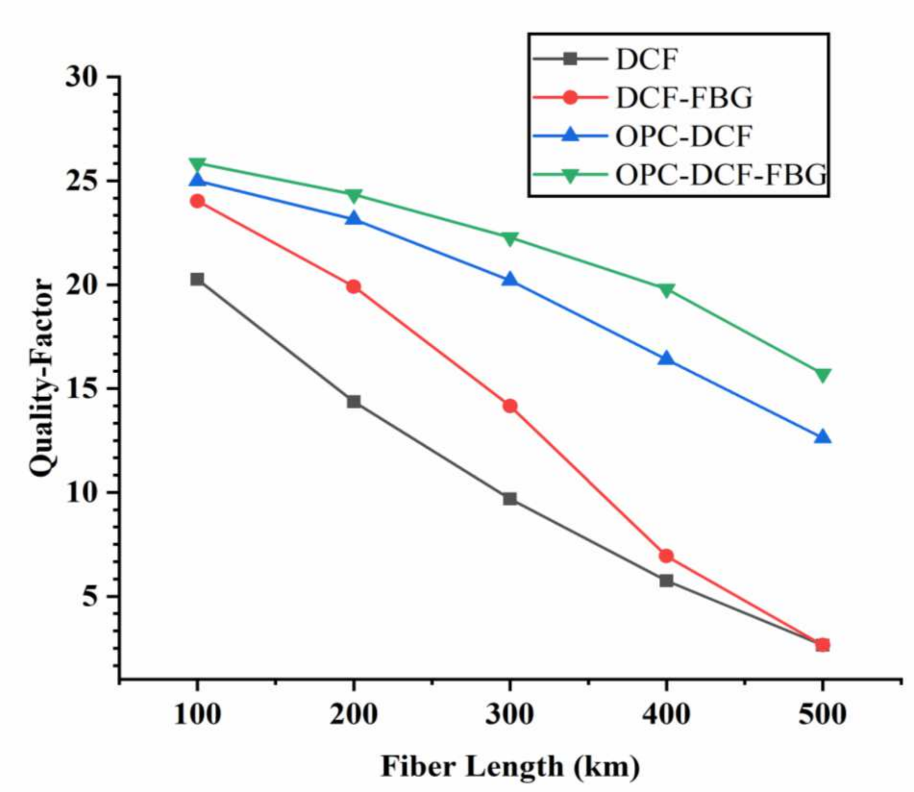


Fig.16: Variations of Q-factor vs. length of SMF through RZ pulse generator

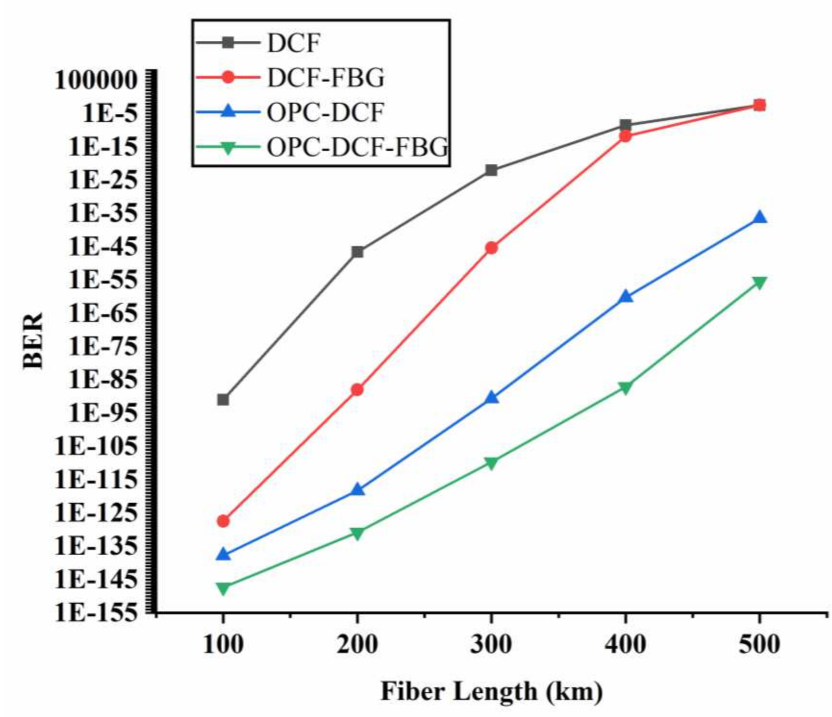


Fig.17: Variations of BER vs. length of SMF through RZ pulse generator

Table 6: Q-factor and BER are measured for different length of SMF with RZ pulse generator at 0dBm input power

SMF Length	100km		200km		300km		400km		500km	
Dispersion Compensation Techniques	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER
DCF	20.25	1.01e-091	14.36	2.52e-047	9.69	9.57e-023	5.75	3.13e-009	2.64	0.0035
DCF-FBG	24.03	3.74e-128	19.91	1.00e-088	14.16	4.52e-046	6.93	1.55e-012	2.65	0.0034
OPC-DCF	25.00	1.91e-138	23.14	5.68e-119	20.21	2.52e-091	16.40	5.24e-061	12.63	4e-037
OPC-DCF-FBG	**25.86**	**5.12e-148**	**24.35**	**1.57e-131**	**22.27**	**2.13e-110**	**19.80**	**8.17e-088**	**15.71**	**3.76e-056**

Further, the effects of Q-factor vs. input power variations are shown in Fig.18 for the optimized 5000km length of SMF. It is observed that the Q-factor for DCF and DCF-FBG techniques are almost the same and the Q-factor decreases as power is increased. However, the Q-factor for OPC-DCF and OPC-DCF-FBG techniques is increasing from 12.63-15.71 at optimized 0dBm input power. Similarly, the effect of BER vs. input power variations for all four dispersion schemes having RZ pulse generators are shown in Fig.19. It can be observed that the values of BERs are almost constant for both DCF and DCF-FBG techniques; however, BER is very less at optimized 0dBm input power for OPC-DCF and OPC-DCF-FBG techniques. After optimized input power level, the BERs are increased for OPC-DCF and OPC-DCF-FBG schemes. Therefore, OPC-DCF-FBG dispersion technique gives batter Q-factor and minimum BER for 500km length of SMF at optimized 0dBm input power as compared to DCF, DCF-FBG and OPC-DCF techniques. Further, calculated Q-factor and minimum BER for 500km length of SMF via proposed dispersion compensation techniques having RZ pulse generator at different input power levels are summarized in Table 7. It is found from Table 7, combined OPC-DCF-FBG technique gives the finest performance compared to other reporting dispersion compensation techniques.

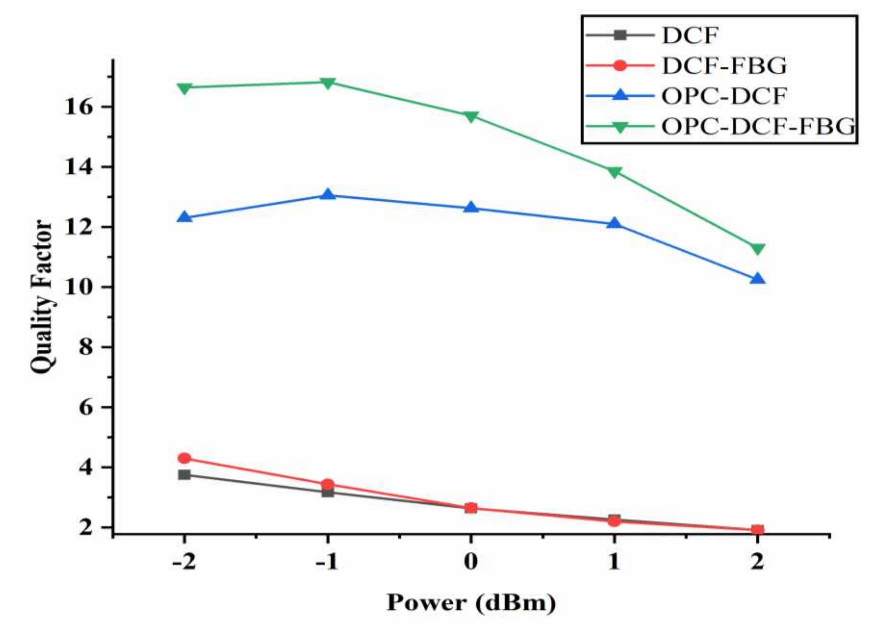


Fig.18: Variations of Q-factor vs. power for 500km length of SMF with RZ pulse generator

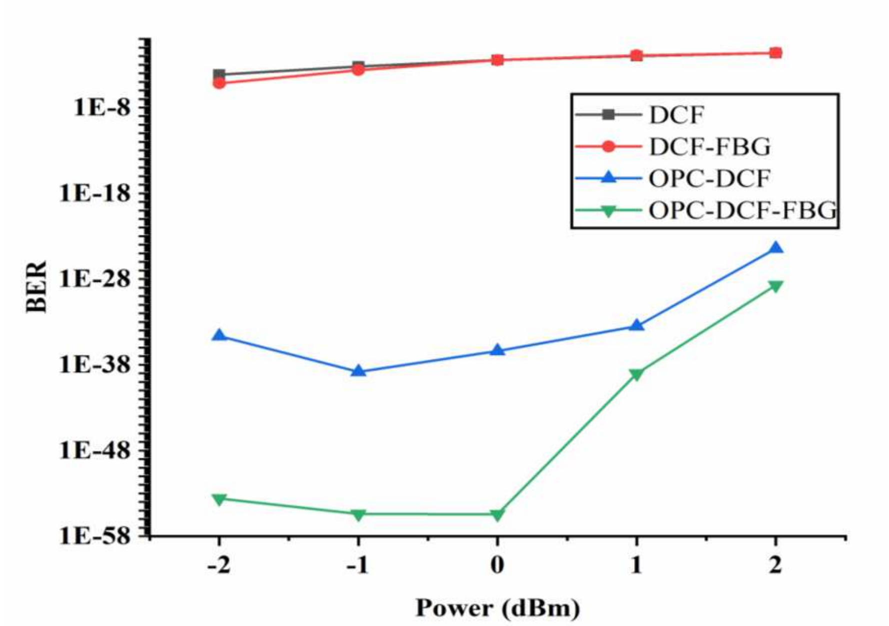


Fig.19: Variations of BER vs. power for 500km length of SMF with RZ pulse generator

Table 7: Q-factor and BER for 500km length of SMF with RZ pulse generator at different input power

Techniques	DCF		DCF-FBG		OPC-DCF		OPC-DCF-FBG	
Power (dBm)	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER
-2	3.75	6.78e-005	4.30	6.79e-006	12.31	2.27e-035	16.65	2.63e-054
-1	3.17	0.0006	3.44	0.00024	13.06	1.55e-039	16.83	4.01e-056
0	**2.64**	**0.0035**	**2.65**	**0.0034**	**12.63**	**4e-037**	**15.71**	**3.76e-056**
1	2.26	0.010	2.20	0.012	12.10	3.10e-034	13.86	9.44e-040
2	1.91	0.024	1.91	0.024	10.25	3.66e-025	11.31	1.93e-029

Moreover, the Eye-diagrams of received signals is accomplished through Eye-analyser for different hybrid dispersion compensation techniques with NRZ pulse generator at 0dBm input power as shown in Fig.20. It can be observed from Fig.20; Eye-patterns for DCF and DCF-FBG are more attenuated and dispersed. However, OPC-DCF and OPC-DCF-FBG techniques give very less dispersed and clear eye-opening. Hence, OPC-DCF-FBG technique gives the finest eye-opening when compared with DCF, DCF-FBG and OPC-DCF dispersion compensation techniques.

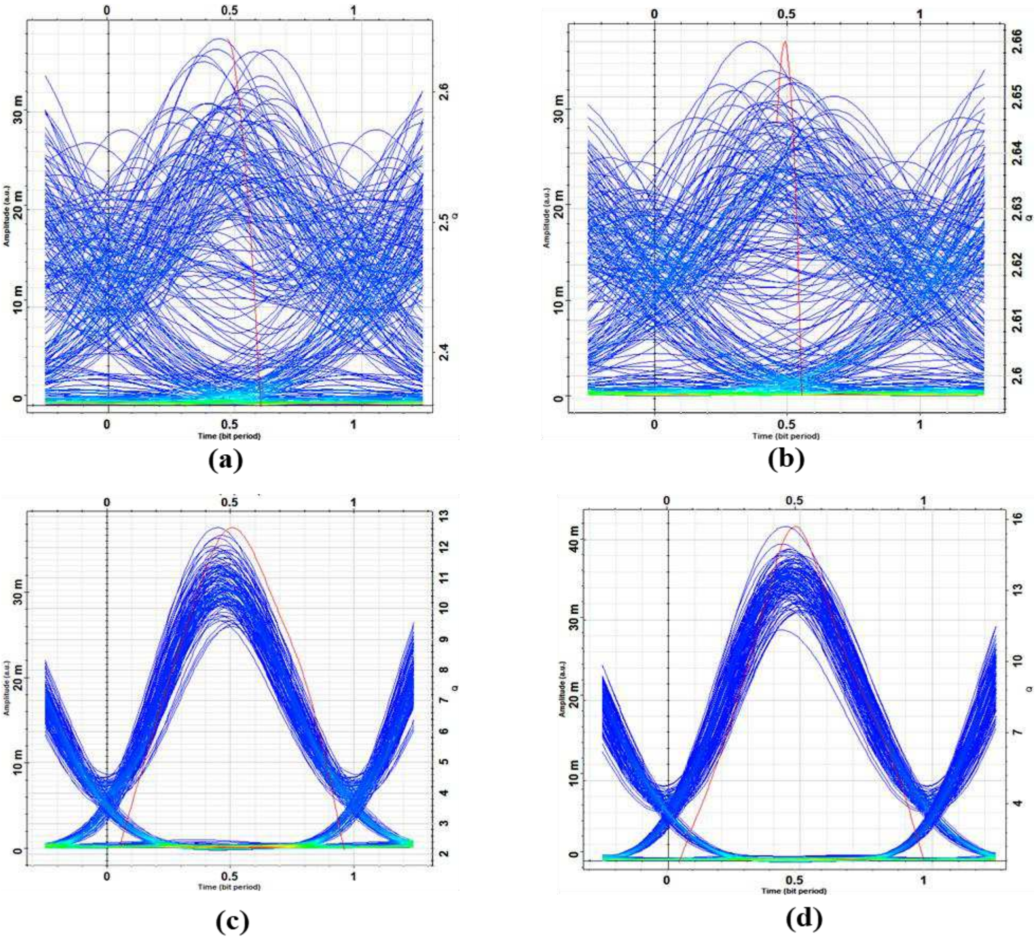


Fig.20: Eye-diagrams for different dispersion compensation techniques via RZ pulse generator at 500km length of SMF: (a) DCF only; (b) DCF-FBG; (c) OPC-DCF; (d) OPC-DCF-FBG.

5. Comparitive Performance and Cost Analysis of Discussed Techniques

Performance investigations of all deliberated techniques are compared based on the fineness of Eye-shape, Q-factor and BER through each pulse generator. We also discussed cost evaluation for DCF and hybrid techniques. Comparative analysis of Q-factor against all four dispersion compensation techniques for different pulse generators is shown in Fig.21. It can be observed from Fig.21, that identical Q-factors are attained for both DCF and DCF-FBG techniques. However, the Q-factor increases up to 12.36 for OPC-DC and it is further increased for OPC-DCF-FBG up to 15.71 using RZ pulse generator. Similarly, the Q-factors for all four dispersion techniques are attained identical with slight variations for Gaussian and NRZ pulse generators. Further, the comparative analysis of BER against all dispersion compensation techniques is plotted in Fig.22 for different pulse generators. It can be seen from Fig.22, using RZ pulse generator, DCF and DCF-FBG techniques BER are not below the threshold level of 10^{-9}. However, the BER for OPC-DCF and OPC-DCF-FBG techniques achieved below the threshold level. Similarly, the BER for Gaussian/NRZ pulse generator are also attained in acceptable range but minimum BER is attained for OPC-DCF-FBG through RZ pulse generator. Therefore, OPC-DCF-FBG using RZ pulse generator gives best performance in terms of maximum Q-factor and minimum BER for 500km length of SMF.

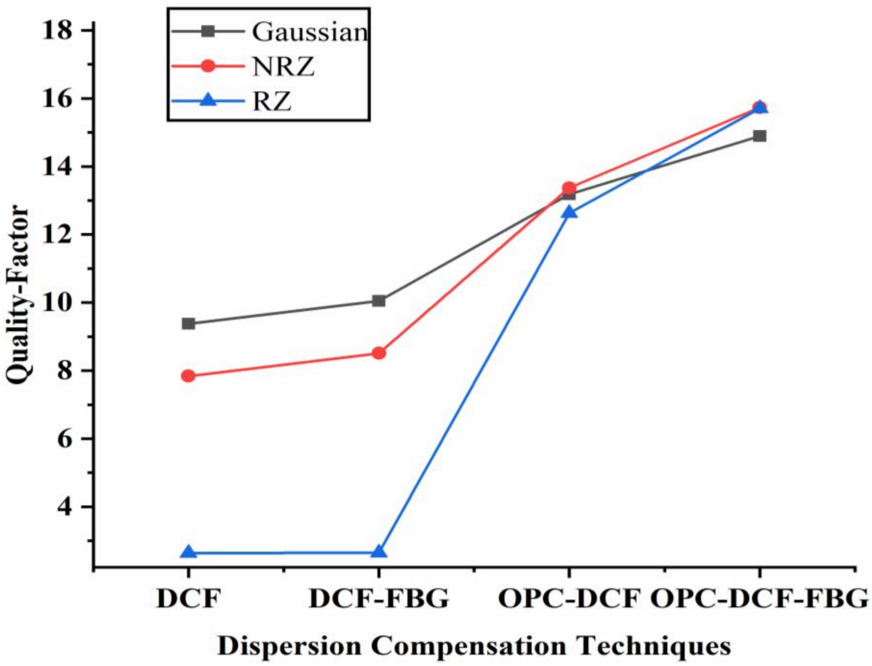


Fig.21: Comparative analysis of Q-factor vs. dispersion compensation techniques for different pulse generators.

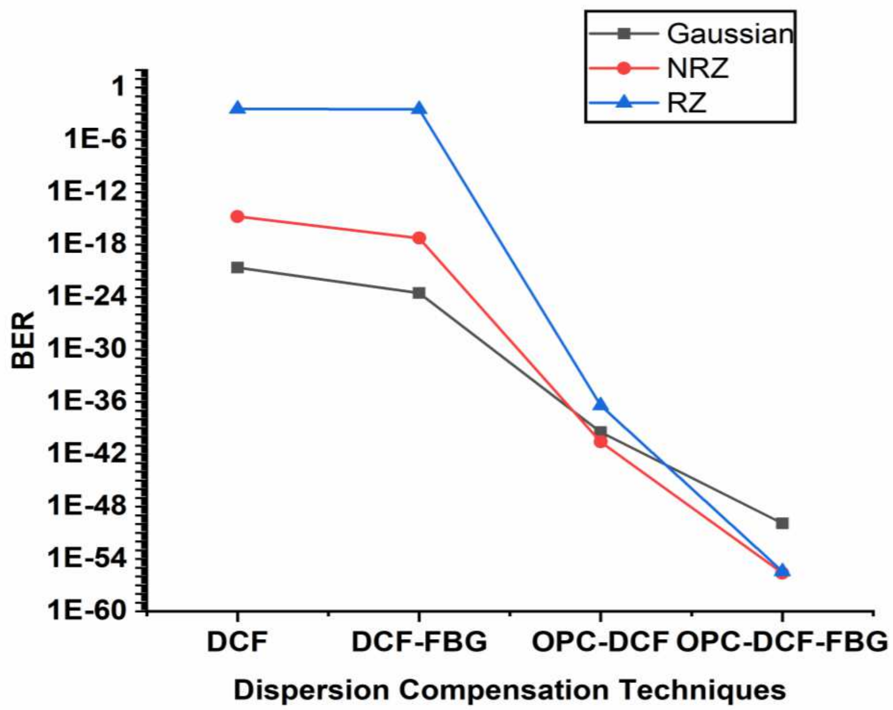


Fig.22: Comparative analysis of BER vs. dispersion compensation techniques for different pulse generators.

Table 8: Comparative performance analysis of dispersion compensation techniques using different pulse generator modules at 500km length of SMF

Modulation Scheme	**Gaussian**		**NRZ**		**RZ**	
Dispersion Techniques	**Q-Factor**	**BER**	**Q-Factor**	**BER**	**Q-Factor**	**BER**
DCF	9.38	2.35e-021	7.84	1.67e-015	2.64	0.0035
DCF-FBG	10.05	2.95e-024	8.51	5.72e-018	2.65	0.0034
OPC-DCF	13.18	3.38e-040	13.37	2.60e-041	12.63	4e-037
OPC-DCF-FBG	**14.89**	**1.17e-050**	**15.73**	**2.41e-056**	**15.71**	**3.76e-056**

In view of above all discussed techniques, we have further focus and analyses the comparive performance only for OPC-DCF-FBG technique using different pulse generators in terms of Q-factor and BER vs. different fiber length are plotted in Fig.23 and Fig.24, respectively. The comparative performance analysis of different pulse generators for OPC-DCF-FBG dispersion technique at different length of SMF are summarized in Table 9.

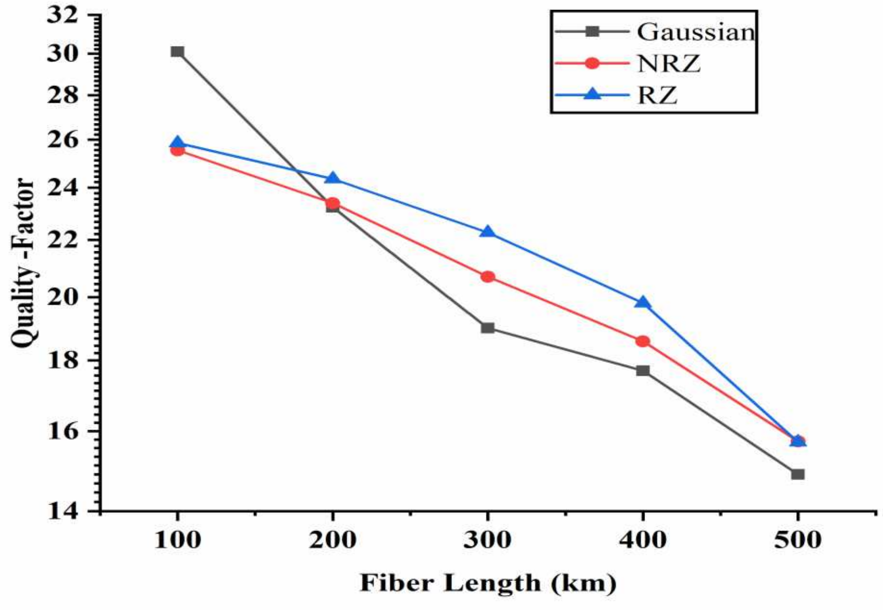


Fig.23: Comparative analysis of OPC-DCF-FBG technique using different pulse generators in terms of Q-factor vs. fiber length

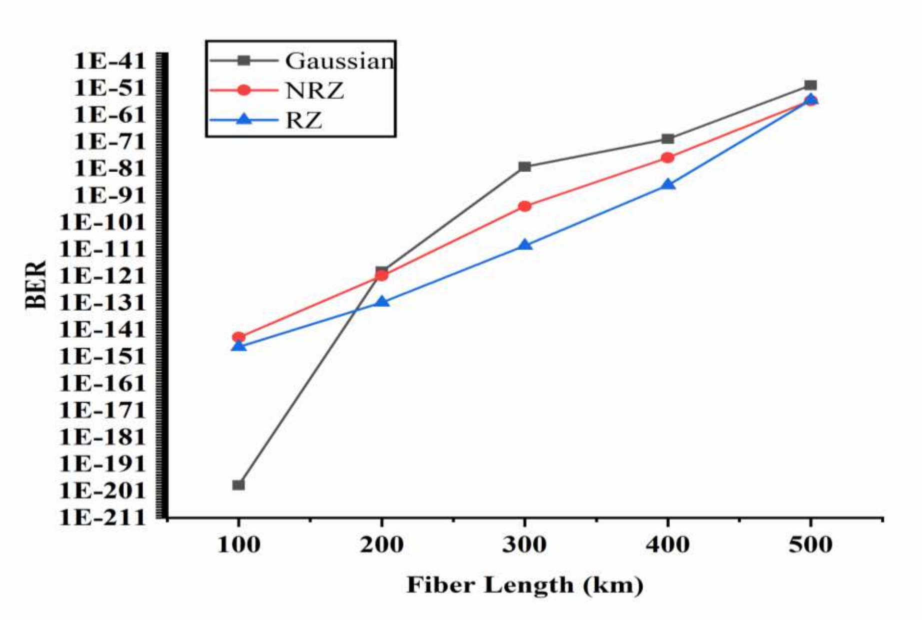
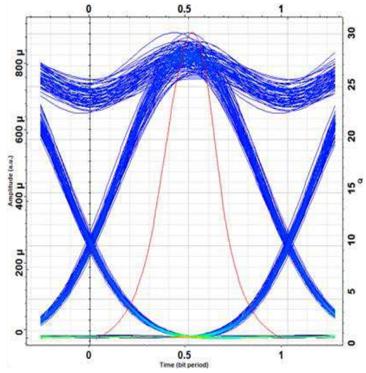


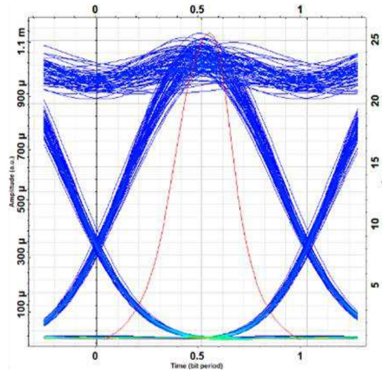
Fig.24: Comparative analysis of OPC-DCF-FBG technique using different pulse generators in terms of BER vs. fiber length

Table 9: Comparative performance analysis of different pulse generators for OPC-DCF-FBG dispersion technique at different length of SMF

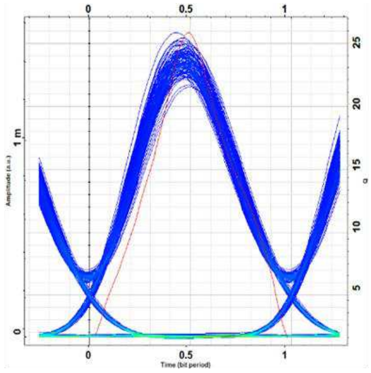
SMF Length	**100km**		**200km**		**300km**		**400km**		**500km**	
Modulation Schemes	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER	Q-Factor	BER
Gaussian	30.10	1.43e-199	23.23	5.69e-120	19.00	5.06e-081	17.69	1.39e-070	14.89	1.17e-050
NRZ	25.54	1.67e-144	23.39	1.27e-121	20.69	1.07e-095	18.58	1.31e-077	15.73	2.41e-056
RZ	**25.86**	**5.12e-148**	**24.35**	**1.57e-131**	**22.27**	**2.13e-110**	**19.80**	**8.17e-088**	**15.71**	**3.76e-056**


Amplitude (a.u.)
Time (bit period)
Q

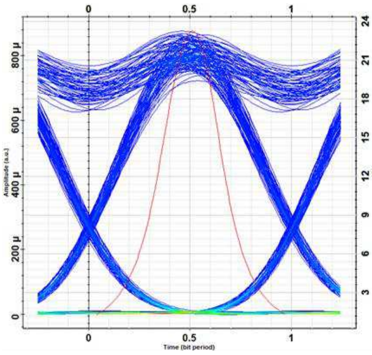
(a)


Amplitude (a.u.)
Time (bit period)
Q

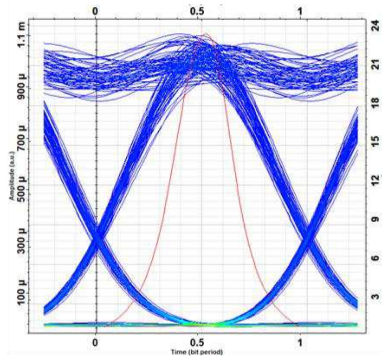
(b)


Amplitude (a.u.)
Time (bit period)
Q

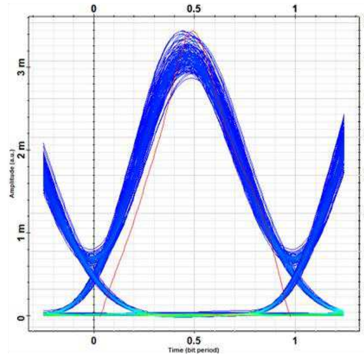
(c)


Amplitude (a.u.)
Time (bit period)
Q

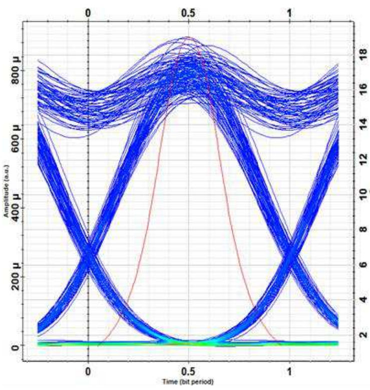
(d)


Amplitude (a.u.)
Time (bit period)
Q

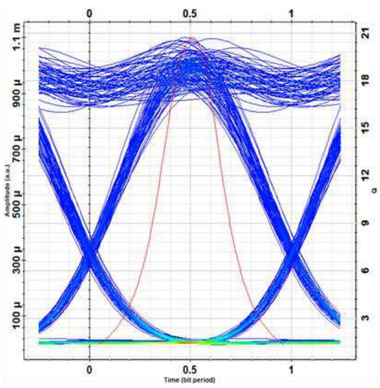
(e)


Amplitude (a.u.)
Time (bit period)
Q

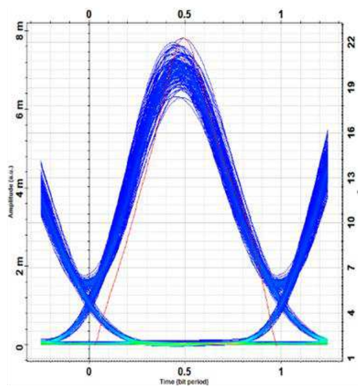
(f)


Amplitude (a.u.)
Time (bit period)
Q

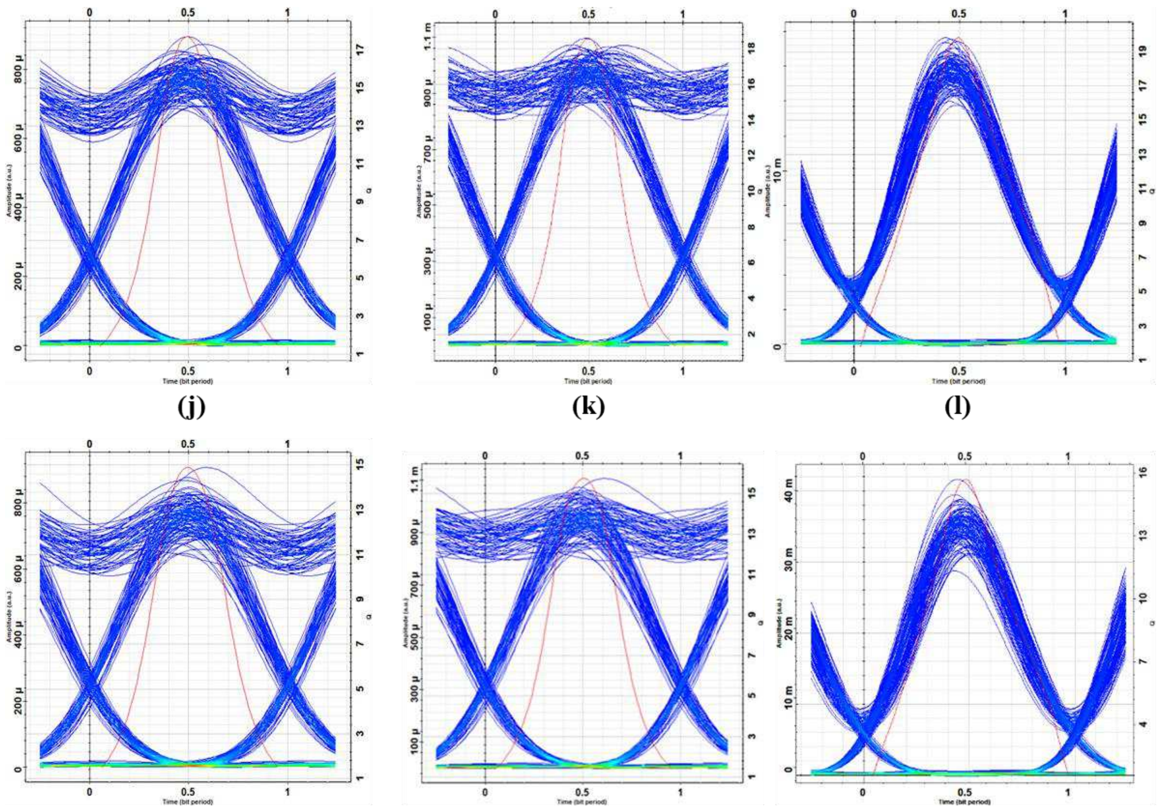
(g)


Amplitude (a.u.)
Time (bit period)
Q

(h)


Amplitude (a.u.)
Time (bit period)
Q

(i)



(j) (k) (l)

(m) (n) (o)

Fig.25: Eye-patterns for OPC+DCF+FBG joint techniques through Gaussian, NRZ and RZ pulse generators, respectively at different length of SMF: **(a-c)** for 100km; (d-f) 200km; (g-i) 300km; (j-l) 400km; (m-o) 500km.

Further, the eye patterns for 100-500km length of SMF with pulse generators of Gaussian, NRZ and RZ by OPC-DCF-FBG dispersion compensation technique are shown in Fig.25. Furthermore, comparative performance analysis of all discussed dispersion compensation techniques using different pulse generator modules for different lengths of SMF at 0dBm input power is summarized in Table 8-9. When we can discuss Table 8-9, these are summarized the performance parameters reading of simulated model through DCF, DCF-FBG, OPC-DCF and OPC-DCF-FBG Techniques. It is observed that the DCF, DCF-FBG and OPC-DCF technique achieves slightly distorted or fair eye shape as discussed earlier in Fig.10, 15, 20 and 25 but low Q-Factor, as well as higher BER, is obtained. However, the OPC-DCF-FBG provides a more perfect eye shape, a maximum Q-Factor of 15.71, and a minimum BER. Further, the DCF, DCF-FBG, OPC-DCF and OPC-DCF-FBG with Gaussian/NRZ give a good eye shape but such performance is achieved with more length of DCF about 102km. Therefore, the performances of all discussed techniques with Gaussian/NRZ are more expensive.

Furthermore, the cost analysis of the proposed optical transmission system is carried out by 50×Nkm=500km length of SMF, where no. of loops N=10 and length of DCF is optimized by

10.2×Nkm=102km, where no. of loop N=10 with the dispersion of −83.4ps/nm/km for Gaussian and NRZ but for RZ pulse generator, optimized length of DCF is 8.5×Nkm=85km, where no. of loop N=10 with the dispersion of -100ps/nm/km having costs of $3 per meter [40]. Hence, the OPC-DCF-FBG dispersion compensation technique with RZ pulse generator reduces the cost about 70% compared to DCF, DCF-FBG, OPC-DCF and OPC-DCF-FBG with Gaussian/NRZ and we can save 17km length of DCF [39]. Therefore, it is clear from the above analysis; the OPC-DCF-FBG technique gives an approximate identical performance with NRZ and RZ pulse generators. However, the optimized length of DCF is 102km for NRZ pulse generator but for RZ pulse generator it chooses 85km. Therefore, a proposed optical transmission system gives the low-cost optimal performance through OPC-DCF-FBG technique having RZ pulse generator. Furthermore, Table 10 concise the comparative investigation of proposed work with similar research efforts reported earlier [2-4, 13, 28-31].

Table 10: Comparison of proposed work with previous research work reported by researchers

References	Work done	Achievement	Performance	Conclusion
[2] 2013	Investigated pre, post and symmetric compensations	Different length of SMF for 96×10Gbps system	Q-factor 16.2dB for 132km length of SMF using NRZ	Shorter reach, low performance, low cost
[3] 2017	Investigated DCF-FBG compensation	100km length of SMF for 10Gbps system	Q-factor, PWRP for 100km length of SMF using NRZ	Low cost but short reach, moderate performance
[4] 2018	Investigated pre, post and symmetric compensations	150km length of SMF for 4×8Gbps system	Q-factor 33.77dB using symmetric with RZ	Shorter reach, low capacity, high cost
[13] 2019	Investigated DCF-FBG compensation	150km length of SMF with 30km length of DCF and 45mm CFBG for 8×10Gbps system	Q-factor 17 for CFBG with RZ techniques	Moderate reach, high capacity, low cost
[28] 2019	Investigated OPC-DCF, OPC-FBG and DCF-FBG	180km length of SMF for 8×2.5Gbps system	Q-factor 8.70dB using OPC-FBG	Shorter reach, low capacity
[29] 2020	Investigate OPC-DCF	40km Length of SMF for 8×120Gbps system	Q-factor 26.2dB using OPC-DCF	Shorter reach, high cost
[30] 2020	Investigated FBG and FBG-EDFA	500km length of SMF for 16×10Gbps system	Q-factor 6dB using FBG-EDFA	Low cost, long reach, but less capacity
[31] 2021	Investigated FBG-DCF, OPC-DCF and FBG-DCF-OPC	300km length of SMF with 51.2km length of DCF, 32×10Gbps system	Q-factor 17.7dB using FBG-DCF-OPC-EDFA	Longer reach, low capacity, low cost
Proposed Work	Investigated DCF, DCF-FBG, OPC-DCF and OPC-DCF-FBG	50×Nkm length of SMF with 8.5×Nkm length of DCF for RZ and 10.2×Nkm for NRZ and Gaussian. Where no. of loops N= (2, 4, 6, 8, 10) for 32×40Gbps system	Q-factor 15.71dB with RZ modulation format using OPC-DCF-FBG for 500km length of SMF, Ref. as Table [9]	Longer reach, High capacity, low cost

6. Conclusions

This paper emphasized the performance of 32×40Gbps DWDM optical transmission system using different dispersion compensation techniques of DCF, DCF-FBG, OPC-DCF and OPC-DCF-FBG with Gaussian, NRZ and RZ modulation formats. The proposed system is designed for different length of SMF and DCF/FBG length are optimized by 50×N, for number of loops are N=2, 4, 6, 8, 10. Performance of proposed system is investigated in terms of Q-factor, BER and eye-diagrams. It is found that the OPC-DCF-FBG dispersion technique with Gaussian, NRZ, RZ pulse generators achieved the Q-factors of 14.89, 15.73 and 15.71, respectively at 0dBm input power for 500km length of SMF. The achieved Q-factors of NRZ and RZ pulse generators are approximately identical but optimized length of DCF used with NRZ, RZ pulse generators are 102km and 85km, respectively. Therefore, OPC-DCF-FBG dispersion technique with RZ pulse generators gives the best performance with low cost as compared to DCF, DCF-FBG and OPC-DCF dispersion compensation techniques.

Declarations

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests

Financial interests: Author Rajkumar Gupta and M.L.Meena declare they have no financial interests.

Data Availability

The datasets generated during and/or analyzed during the current study are not publicly available due to [this is my Ph.D work, but are available from the corresponding author on reasonable request.].

Code Availability

The proposed work is implemented on optisystem 7.0 software. This is simulation software. The simulation models are not publicly available because this is my Ph.D work, but are available from the corresponding author on reasonable request.

Author Contributions

Both authors contributed to the study conception and design. Data collection, manuscript writeup and analysis were performed by both authors.

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