Design and analysis of a soliton-based WDM system for performance enhancement of long-haul communication

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The worldwide need for reliable and high-speed internet services over long distances is experiencing a steady escalation due to the growing user base. In response to this increasing demand, there exists an imperative need for rapid advancements in the technologies used in optical communication systems. The evolutionary regime of fiber optics has yielded broadband connections, making uninterrupted, high-speed internet access feasible over extensive geographical spans. Dispersion adversely affects the system's transmission capacity, thereby reducing the available bandwidth. Solitons provide an efficient solution for counteracting the attenuation caused by dispersion. The current study aims to determine the efficiency of a 16-channel WDM system, operating at distinct bit rates (10, 20, and 40 Gbps), and using a dispersion compensation fiber (DCF). The system evaluation was performed using the bit error rate (BER) and quality (Q-factor). Based on the observations obtained, it can be inferred that an acceptable BER value is achievable at a transmission distance of 1500 km at higher data rates.

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1. Introduction

The long-haul optical transmission system's overall capacity is the focus of ongoing research and development projects. The expansion of telecommunications markets and the widespread popularity of the internet have led to a stronger need for greater capacity in communication systems [1]–[3]. Consequently, wavelength division multiplexing (WDM) communication systems that use optical fiber for networking and telecommunication purposes have grown in popularity as solutions for high-speed networks [4]. In a single-mode fiber, the optical transmission method WDM multiplexes signals of various wavelengths to produce data rates surpassing hundreds of gigabits per second [5]. However, long-distance high-speed WDM systems have limitations due to several flaws such as signal attenuation and fiber losses. Dispersion, which is the spreading of optical pulses as they pass through the fiber, has a substantial impact on these systems' transmission capacities [6]. The various velocities of the frequency components within the channel cause this dispersion. Consequently, dispersion reduces the bandwidth, degrades the peak power, and widens the optical pulses, thus restricting the channel's transmission capacity [7]. To overcome this limitation, effective dispersion management techniques are required to efficiently transmit data from the transmitter to the receiver. One such solution for dispersion issues in optical fibers is the use of optical solitons [8], [9]. As a result, emerging technologies are being developed to address the challenges of WDM technology and meet the growing demands for higher transmission capacity in optical communication systems [10], [11].

The ultimate constraint on the maximal transmission distance within fiber-optic communication systems originates from the effects of fiber losses. In the context of long-range systems, the approach to overcome this loss constraint has conventionally entailed the deployment of optoelectronic repeaters. These devices convert optical signals into electrical currents and subsequently regenerate those using transmitters [11]. However, when dealing with night wake systems that employ wavelength-division multiplexing (WDM), the use of such regenerators becomes intricate and financially burdensome. The role of in-line amplifiers has evolved because they directly enhance the optical signal without the need for electric conversion. These amplifiers boost the signal power simultaneously and reduce attenuation [12], [13]. Fiber attenuation, which is the main cause of signal power depletion over distances, is effectively countered by these amplifiers. In addition, fiber non-linearities contribute to signal power level depletion.

Optical amplifiers have become widely deployed in long-distance connections, including transcontinental and submarine links, to extend the power budget and minimize the number of connectivity points. To improve the performance of long-distance optical systems, they have been developed to limit the effects of attenuation and dispersion [14]. To combat the problems caused by wavelength division multiplexing (WDM), other amplifier types have been developed, including fiber Raman amplifier (FRA) and erbium-doped fiber amplifier (EDFA). Each amplifier's type has benefits and drawbacks. Based on the appropriate selection of pump wavelength and power, the Raman amplifier operates on the concept of stimulated Raman scattering (SRS), which enables the amplification of signals at different wavelengths. The number and wavelength of the pumps can be varied to broaden the Raman amplifier's spectrum. The signal and pump wavelengths of the Raman amplifier are different, and the power is transmitted from shorter to longer wavelengths [15]. An efficient pump laser and high pump power are required for Raman amplifiers.

The semiconductor optical amplifier functions similar to the laser cavity. It has a wide amplification bandwidth and offers amplification in the 1310–1550 nm wavelength range. However, it is constrained to 10 Gbps, relies on polarization, has a high noise figure, and results in signal interference. Smaller networks often use SOAs because of their lower strength and severe signal distortion The EDFA transmits high pump power to the signal and provides amplification in the 1550 nm optical window. For ultra-long-distance transmission, EDFA's high dynamic range and low noise figure make it an effective solution. Hybrid optical amplifiers are designed to boost the bandwidth and maximize transmission speed. Over a transmission distance of 50 km, a uniform gain across 90.5 nm was acquired by combining Raman and EDFA amplifiers in a hybrid design. Different configurations of the SOA, EDFA, and Raman amplifiers are connected in either a series or parallel function as hybrid amplifiers [16], [17]. Although this work is straightforward to use, the guard band of the coupler introduces a neglected wavelength and lowers the amplifiers' noise figure. Without the use of couplers, a broad spectrum can be achieved in a series form. The placement of hybrid optical amplifiers in various configurations, including post, pre, and symmetric, is explored to examine their functionality. In contrast to the pre-and symmetrical power compensation approaches. Research has revealed that the approach of compensating after amplification performs better in terms of ber, received power, and eye closure. They discovered that increasing signal input power increases both the ber and eye closure penalty.

An innovative strategy for channel allocation, rooted in the concept of the optical Golomb ruler (OGR), was introduced [18] and successfully decreased the four-wave mixing (FWM) effect while retaining bandwidth effectiveness. Their approach permits wavelength division multiplexing (WDM) systems to allocate channels unevenly, resulting in decreased FWM. To determine how well a hybrid optical amplifier performs in 40 Gbps systems. In comparison to back-to-back values, they discovered that the hybrid pre-amplifier considerably decreases the power penalty of the system by 3.2 dB. The higher efficiency of hybrid preamplifiers is related to the fact that they are built to function as a noise limiter when operating in the saturated domain.

By adjusting the distance from 20 to 200 km, we investigated the efficiency of the power output, i.e., bit error rate (BER), Q-factor, and eye-opening [13], [15]. They discovered that at a distance of 100 km, the SOA-EDFA combination offers significant output power, a tolerable Q-factor, and the lowest BER and maximum eye-opening. A length of Raman fiber spanning 10 km results in a greater Q value and output power, according to their investigation into the effect of Raman fiber length on the hybrid optical amplifier (Raman-EDFA) at a transmission distance of 100 km.

In a single-mode fiber, when multiple solitons move together, the nearby soliton pulses temporarily affect the position of each other due to the fiber's nonlinearity. To prevent this interference, solitons need to be spaced far apart, but this reduces the data rate of the communication system. The main limitation of soliton-based transmission systems is the interaction between neighboring solitons, which reduces transmission capacity. Dispersion Compensation is an emerging solution to enhance soliton transmission performance. In this study, an 8, 16, and 32-channel WDM system is designed with a bit rate of 40 Gbps and a channel spacing of 100 GHz. Dispersion Compensated Fiber (DCF) is used to counteract dispersion caused by soliton interactions and other losses in the fiber. The system's quality (Q-factor) and error rate (BER) are analyzed using VPI simulation software, and performance is evaluated for different transmission distances.

There are five sections in this paper. Section 2 describes the modeling of optical solitons. In Section 3, a comprehensive description of the optical simulation setup is presented. Comparative outcomes for BER and Q-factor for different transmission distances and received optical power are discussed in Section 4 and the conclusion is presented in Section 5 with a summary of the findings.

2. Optical soliton model

Soliton pulses propagate across the optical fiber when both the SPM and GVD are precisely balanced. Group velocity dispersion is the term used to describe how the optical frequency or wavelength affects the group velocity of light in a transparent medium. It causes group delay, resulting in different wavelengths of an optical pulse traveling at different velocities through the fiber [19]. This pulse broadening leads to inter-symbol interference (ISI) as the pulses overlap. Self-phase modulation, on the other hand, is a non-linear optical phenomenon resulting from the interaction of light and matter. The change in the refractive index of the medium due to ultra-short pulses leads to a phase shift and a change in the pulse's frequency spectrum. SPM arises from the impact of the fiber's refractive index on its intensity. This occurs because the pulse's high-intensity region has a higher refractive index, which causes a positive refractive index gradient and a phase change. The term SPM refers to the phenomenon of this alteration of the pulse's optical phase, which is dependent on the refractive index profile.

The length of the fiber medium (L) in the physical context should exceed both the dispersion length ((L_D) and the length associated with non-linearity (L_{NL}) to maintain the characteristics of soliton pulses. The Non-linear Schrodinger equation (NLS) governs how optical pulses go along a fiber. With the use of soliton perturbation theory, the analytical resolution of the interaction among Schrodinger solitons within a system featuring distributed losses has been achieved. The focus of the theoretical investigation has been on the coupled nonlinear Schrodinger equations, which emulate the propagation of solitons in birefringent fibers. By introducing SPM and GVD, the Nonlinear Schrodinger equation (NLSE) can be normalized [20].

$$\frac{i\partial A}{\partial \varepsilon} - \frac{s}{2}\frac{\partial^2 A}{\partial \tau^2} + N^2|A|^2 A = 0 \qquad (1)$$

where, A=U/√Z, s = sgn (β_2), ε = z/L_D and τ = t/$\tau_0{}^2$. Equation (1) can be adjusted by setting the parameter N^2, which represents the ratio of the dispersion length (L_D) to the nonlinearity length (L_{NL}), as follows:

$$P^2 = \frac{L_D}{L_{NL}} = \frac{\gamma Z_0{}^2 T_0{}^2}{|\beta_2|^2} \qquad (2)$$

P stands for the soliton order, P_0 for the incident pulse's peak power, and T_0 for its width in the equation given. Equation (1) can be written as follows for s = -1, indicating the medium shows anomalous group velocity dispersion (GVD):

$$\frac{i\partial a}{\partial \varepsilon} - \frac{1}{2}\frac{\partial^2 a}{\partial \tau^2} + |a|^2 a = 0 \qquad (3)$$

The solution of the soliton can be achieved by solving Equation (3) directly and introducing the normalized amplitude a = -PA, giving the following results:

$$a\,(0, \tau) = P\ \mathrm{sech}\,(\tau) \qquad (4)$$

This suggests that pulses with a hyperbolic secant (sech) profile can produce basic solitons. The effects of dispersion and non-linearity cancel each other out when the non-linearity length and dispersion length are equal. Therefore, only the effects of GVD and SPM offset each other if the pulse form has a hyperbolic secant profile [8], [20].

The soliton period (P_0), which is the distance of the nonlinear medium where the preservation of the shape of higher-order solitons is governed by the equation:

$$P_0 = \pi/2\ L_D \qquad (5)$$

To ensure sufficient spacing between solitons, the width of the pulse should be a small fraction of a bit interval.

In Equation (6), the separation between the two solitons is represented by ($2_{q0}\ T_0$).

The β parameter can be defined as:

$$\beta = 1\,/\,(2\ q_0\, T_0) \qquad (6)$$

3. Simulation & design

This section begins by designing and simulating a wavelength division multiplexing (WDM) soliton system using a dispersion compensating method inside the transmission medium. The simulation uses the VPI software, which configures distinct transmission rates at 10, 20, and 40 Gbps. The configuration comprises eight channels, multiplexed via a WDM multiplexer, and each channel is spaced by 100 GHz in terms of frequency. In addition, we combine an RZ pulse transmitter consisting of a user-defined bit sequence generator into each channel's transmitter component. The generation of soliton pulses with the desired wavelengths and powers is the responsibility of the RZ transmitter. In this specific design, a 100-km loop consisting of 15 loops, i.e., a 1500-km link length is used.

The proposed simulation setup design for a 16-channel, high data rate, long-range WDM optical network with a central frequency of 193.1 THz is illustrated in Fig. 1. Table 1 presents further information on the parameters used in the proposed design [20], [21]. The transmitter, channel, and receiver are the three components of the proposed simulation models. 16 optical wavelength division multiplexer (WDM) input modules are introduced into the system, each operating at distinct data rates. The system's design incorporates meticulous control of dispersion using the optical attributes of the dispersion compensation fiber (DCF) and single mode fiber (SMF) within the configuration of the transmission channel. The data rates employed for this purpose include 10, 20, and 40 Gbps. To address fiber losses, the gain of the edfa and fiber-optic amplifier is thoroughly adjusted, considering the distance of the optical fiber. The noise level of the amplifier is consistently maintained at 4 dB throughout the setup.

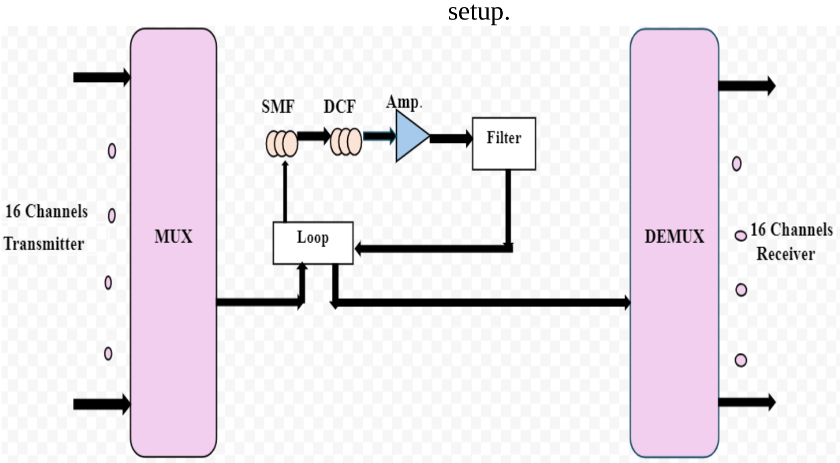


Fig. 1. Block diagram of the designed WDM system (color online)

Table 1. List of the designed soliton-based system parameters used for the long-haul high data rate system

Parameter	Measurement of the parameter
Data rate	10, 20, and 40 Gbps
SMF Span	86 km
DCF Span	14 km
Attenuation	0.2 dB/Km
Dispersion	16 ps/nm/km
Reference wavelength	1550 nm
Noise figure (EDFA)	4 dB

4. Results and discussion

The simulation results of the designed system were determined using the VPI simulation software. Variations in the BER and Q-factor for different transmission distances are shown in Figs. 2 and 3. Transmission distances were varied up to 1500 km, and 8, 16, and 32 channels were multiplexed using WDM with 100 GHz channel spacing. Results are demonstrated for data rates of 10, 20, and 40 Gbps. In optical communication networks with long distances and high data rates, signal quality is degraded with increasing data rates because of nonlinear noise factors such as SRS and FWM. With increasing transmission distance, the effect of dispersion becomes increasingly prominent, resulting in increased values of BER, which can be seen from the results obtained. Thus, the quality factor of the designed system decreases with increasing transmission distance and data rate.

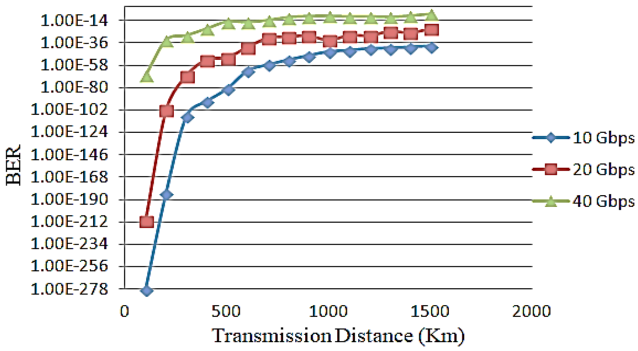


Fig. 2. Graphical representation of the bit error rate with increasing transmission distance for various data rates (color online)

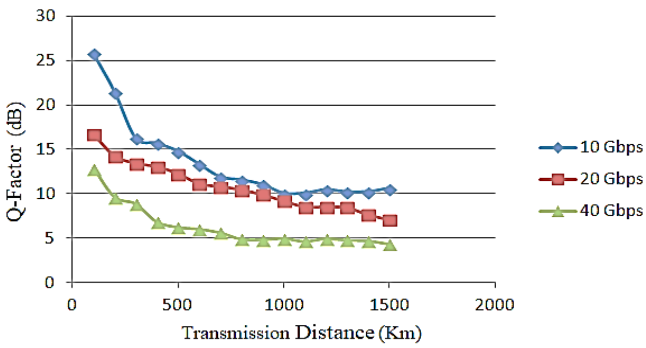


Fig. 3. Graphical analysis of the Q factor for different ranges of data rates with different transmission distances (color online)

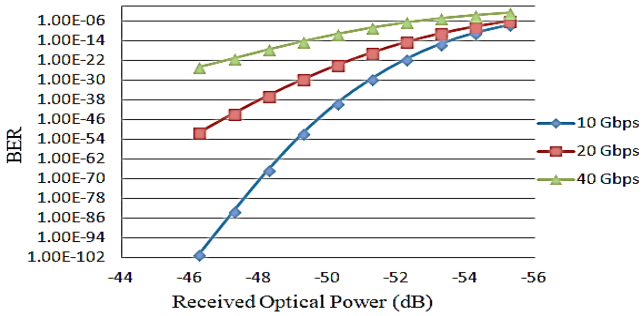


Fig. 4. Graphical analysis of the received optical power (ROP) vs. Bit error rate (BER) for different ranges of data rates with different transmission distances framework (color online)

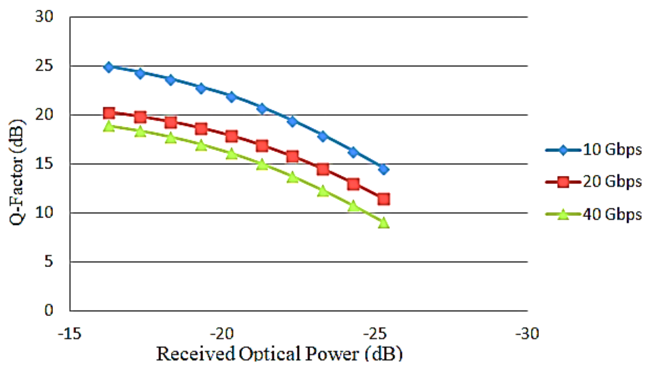


Fig. 5. Graphical analysis of the received optical power (ROP) vs. the Q-factor for different ranges of data rates with different transmission distances (color online)

Figs. 4 and 5 represent the variation in the BER and Q factors for various ROP values. It is evident from the result that with decreasing values of ROP, the BER increases and the Q factor reduces. In addition, based on the different values of the bit rate, it can be concluded that the distortions in signal power increase with increasing bit rate.

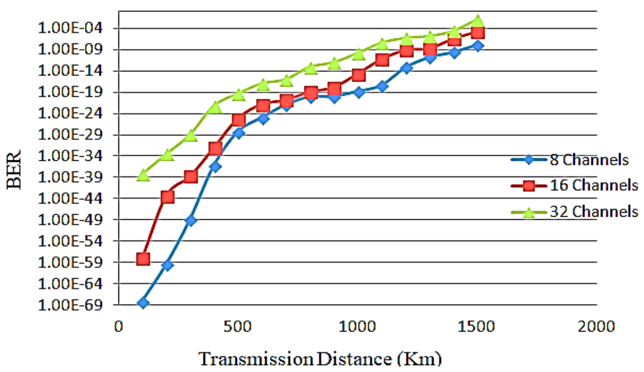
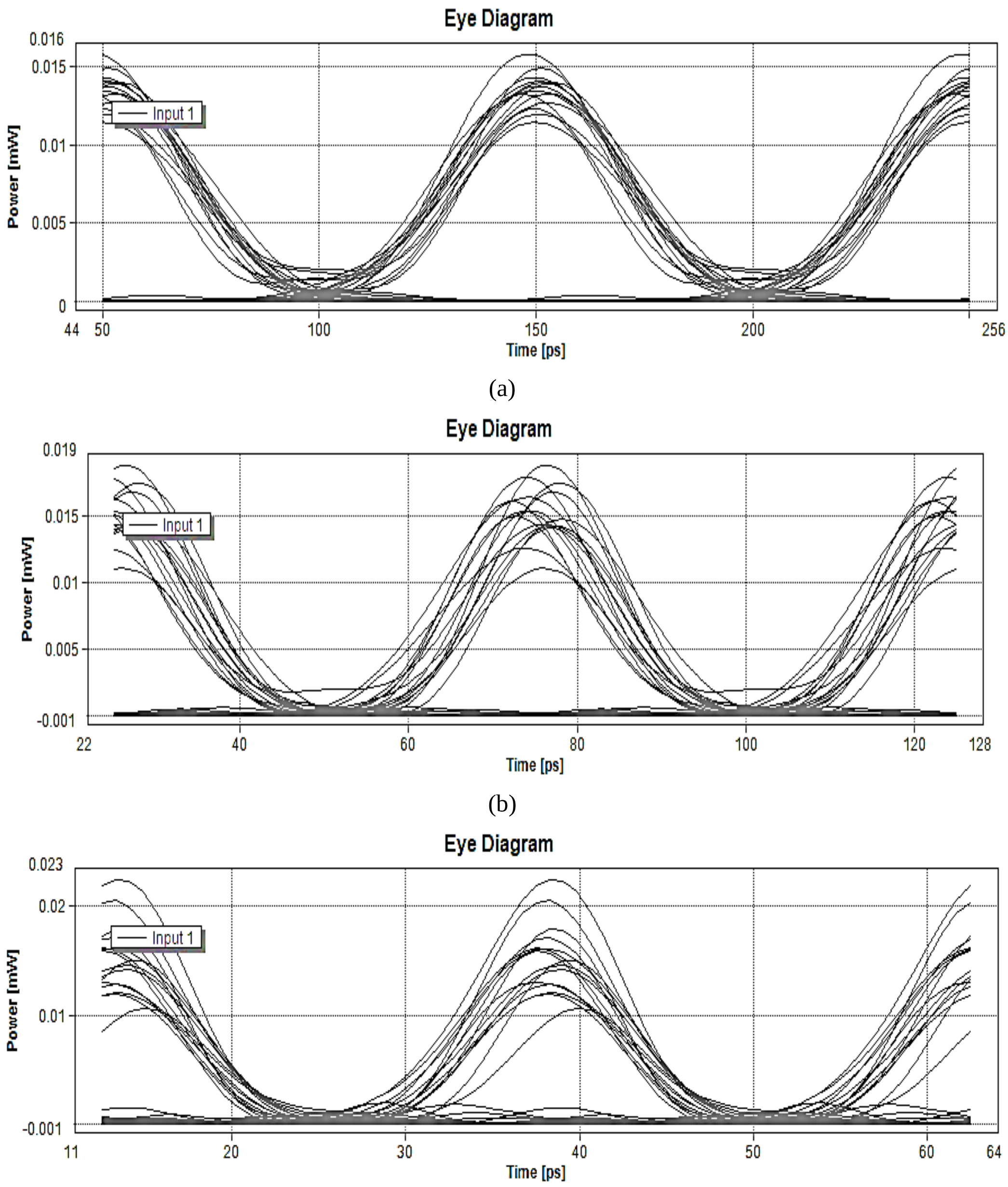


Fig. 6. Graphical representation of the bit error rate with increasing transmission distance for 8, 16, and 32 channels (color online)

Fig. 6 represents the performance of soliton-based WDM communication system with 8, 16, and 32 channels at a data rate of 40 Gbps, focusing on the BER for various transmission distances ranging from 100 km to 1500 km. As the number of channels increases, a general trend of increasing BER can be observed. However, the influence of the transmission distance is evident, BER values tend to increase for longer distances. The findings highlight a balance between the number of channels used and how far data can be transmitted effectively. Over shorter distances, all channel setups show very low BER, but as the distance increases, the BER also increases.



(a)

(b)

(c)

Fig. 7. Eye diagrams at bit rates of (a) 10 (b) 20 Gbps, and (c) 40 Gbps

Fig. 7 shows the eye diagrams at a propagation distance of 1500 km. The eye-opening for 10 Gbps is 0.9192 a. u., for 20 Gbps, the opening is 0.8635 a. u., and finally, for 40 Gbps, an eye-opening of 0.778 a. u. is achieved. It can be seen that eye-opening is maximum at a low bit rate, which corresponds to minimum signal distortion, and with increasing bit rate, eye-opening decreases.

5. Conclusion

The previous conversation revolved around the examination of a high-speed optical fiber communication network with data rates of 10, 20, and 40, Gbps, focusing on extended reach capabilities. Signal deterioration caused by dispersion negatively affects the efficiency of the optical system. To counter dispersion, solitons are an effective choice because of their ability to maintain their shape over long distances. However, when implemented in a WDM context, these narrow optical pulses encounter spreading. This study introduces a new approach that uses a dispersion compensation fiber (DCF) within the transmission system to address dispersion issues in the WDM soliton setup. The outcomes reveal a decline in system quality as data rates per channel and fiber length increase. Nonetheless, by incorporating optical fiber, DCF, and EDFA across the fiber spans individually, the performance of the system is enhanced for data rates of 10, 20, and 40 Gbps, over a distance of 1500 km. The results indicate that nonlinear elements such as FWM and SRS limit the system's efficiency beyond the 1500 km range at high data rates. The performance of the designed system was assessed using several metrics, including the bit error rate (BER) Q factor, received optical power (ROP), eye patterns, and eye-opening. The simulation outcomes show that the system, when employing DCF and EDFA, outperforms the scenario without their utilization, particularly up to a distance of 1500 km. Furthermore, it demonstrates a Q factor of 4.373 dB, accompanied by a remarkably low BER of 1.53×10^-8, obtained for 16 channels with an eye-opening of 0.77 a.u at a distance of 1500 km, while operating at 40 Gbps with a dispersion of 2 ps/nm/km in the optical fiber.

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References

[1] A. Y. Fattah, S. S. Madlool, Int. J. Sci. Technol. Res. **7**(5), 28 (2017).
[2] N. Badraoui, T. Berceli, IEEE Xplore, no. May, 1 (2018).
[3] Y. Song, X. Shi, C. Wu, D. Tang, H. Zhang, Appl. Phys. Rev. **6**, 021313 (2019).
[4] M. M. Abdulwahid, S. Kurnaz, IEEE Xplore no. July, 1 (2023).
[5] Rajeev, C. Kumar, 2023 International Conference on Recent Advances in Electrical, Electronics & Digital Healthcare Technologies 662 (2023).
[6] S. Escobar-Landero, Salma, Xiaohui Zhao, Dylan Le Gac, Abel Lorences-Riesgo, Tugdual Viret-Denaix, Qiang Guo, Lin Gan, J. Light. Technol. **41**(12), 3668 (2023).
[7] B. Gul, F. Ahmad, Opt. Quantum Electron. **55**(6), 1 (2023).
[8] P. Kaur, D. Dhawan, N. Gupta, J. Opt. Commun. (2023) https://doi.org/10.1515/joc-2023-0059).
[9] I. S. Amiri, H. Ahmad, H. M. R. Al-khafaji, American Journal of Networks and Communications, Special Issue: Recent Progresses in Optical Code-Division Multiple-Access (OCDMA) Technology **4**, 6 (2015).
[10] S. P. Chakkravarthy, V. Arthi, S. Karthikumar, A. N. Z. Rashed, P. Yupapin, I. S. Amiri, Results Phys. **12**, 512 (2019).
[11] H. F. Fakhruldeen, A. R. Khekan, I. H. Al-Kharsan, Malaysian J. Fundam. Appl. Sci. **19**(3), 399 (2023).
[12] R. Kaur, R. Randhawa, R. S. Kaler, Optik **124**(8), 693 (2013).
[13] D. Malik, K. Pahwa, A. Wason, Optik **127**(23), 11131 (2016).
[14] A. Hasegawa, Front. Phys. **10**, 1 (2022).
[15] M. Z. Ullah, A. Biswas, S. P. Moshokoa, Q. Zhou, M. Mirzazadeh, M. Belic, Optik **132**, 210 (2017).
[16] S. Singh, R. S. Kaler, Optik **124**(15), 2131 (2013).
[17] S. Singh, Optoelectron. Adv. Mat. **11**(1–2), 51 (2017).
[18] A. Guimarães, J. M. Chavez Boggio, J. D. Marconi, F. A. Callegari, H. L. Fragnito, M. L. Rocha, Opt. InfoBase Conf. Pap., no. Dcm, 989 (2005).
[19] S. Salim, S. Azeem, Optik **252**, 168503 (2022).
[20] P. Kaur, D. Dhawan, N. Gupta, J. Opt. Commun. (2023) https://doi.org/10.1515/joc-2023-0093)
[21] S. Salim, S. Azeem, Optik **252**, 168503 (2022).

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