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RESEARCH ARTICLE

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Improving DWDM system performance through EDFA and DCF strategies

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Abstract

In modern optical communication, the DWDM systems allow high-speed data transmission over long distances. The undesired phenomena like dispersion and nonlinearity of optical fiber affect the system performance and reduce the signal quality. This work examines improving DWDM system performance through EDFA and DCF strategies. An eight-channel DWDM system at 10 Gbps per channel is tested under different EDFA designs. The results showed that adding DCF to the system improves signal quality. Additionally, the booster amplifier setup performed better than other positions of EDFA in the optical link. Moreover, using a bidirectional pumping schema has a higher Q-factor average with more stability than a forward pumping configuration. Also, the pump wavelength at 1480 nm always achieved a good performance compared to 980 nm.

Keywords: Wavelength division multiplexing; EDFA; non-linear effects

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1. Introduction

Dense Wavelength Division Multiplexing (DWDM) systems are important for modern optical communication networks. Their ability is to allow high-speed data transmission over long distances. However, some limitations are available such as attenuation, dispersion and nonlinear effects which comes from the nature of the optical fibers [1]. They can lower signal quality and limit the distance of the system. Because of that, Erbium-Doped Fiber Amplifiers (EDFAs) and Dispersion Compensation Fiber (DCF) are essential to overcome these problems.

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In the literature, previous studies have explored the use of the EDFA and DCF in WDM systems. In one study, different methods to reduce nonlinear effects was reviewed by Saaid et al. [2]. Further studies by Singh et al. investigated the effects of Four-Wave Mixing (FWM) and noise on WDM optical star networks, aiming to determine the optimal placement of amplifiers within the system [3-4]. It was also found unequal channel spacing can lower FWM power in long-distance WDM systems [5]. Another study looked at how EDFA configuration affects FWM in high-speed WDM systems with different EDFA design, using only a 980 nm pumping design [6]. Unequal channel spacing investigated in detail with only forward pumping configuration in another work [7]. In one of the previous works, a laser oscillation technique was applied to the WDM system for reducing the FWM power with only one EDFA schema [8]. Han and Lee showed that by adding random time delays between channels could decrease nonlinearity of the system [9]. To reduce the FWM and nonlinear effects in DWDM systems, optical phase conjugation is applied in one of the hybrid WDM system works [10]. The effects of the Self-Phase Modulation (SPM), XPM and FWM were investigated in L-Band EDFAs by using new techniques on the transmission fibers [11]. One recent study demonstrates the optimization of 80-channel DWDM systems using EDFA and DCF strategies, evaluating various fiber types and practical areas achieved through bit error rate analysis and fiber length optimization [12]. Hybrid erbium-doped fiber/Raman amplifiers (HFAs) can improve DWDM system performance by increasing the reach and capacity of optical channels. However, due to their higher cost, recent study [13] suggests using optimization models to place them strategically, reducing their number while improving network efficiency. Another recent work has demonstrated that symmetrical DCF schemes are more effective than pre- and post-compensation methods in mitigating chromatic dispersion and nonlinear impairments in long-haul WDM systems [14]. A recent study proposed a dual-polarization (DP)-128 QAM-based optical back propagation (OBP) system to address nonlinear impairments in WDM networks, demonstrating that a symmetrical OBP configuration with dual-directional pumping achieves superior performance, enabling transmission over 6500 km at a BER of 10^{-3} [15].

Despite these significant contributions to understanding nonlinear effects and amplification in WDM systems, a comprehensive investigation of the combined impact of DCF implementation and EDFA configurations, particularly regarding their positioning and pumping arrangements in DWDM systems, still needs to be explored in the literature. This study presents a detailed analysis of an eight-channel DWDM system operating at 10 Gbps per channel, examining the intricate relationships between DCF implementation, EDFA placement strategies (pre-amplification, inline amplification, and post-amplification), and various pumping configurations (forward and bidirectional) at both 980 nm and 1480 nm wavelengths. Through systematic simulation, we evaluate system performance metrics, including Q-factor analysis, under different architectural configurations to establish optimal design parameters for high-capacity DWDM networks. This comprehensive approach aims to bridge the existing knowledge gap and provide valuable insights for designing and optimizing modern optical communication systems.

2. System model

This study investigates the performance of EDFAs and DCF in a Dense Wavelength Division Multiplexing optical communication system using OptiSystem simulation software. The proposed system architecture (illustrated in Figure 1) comprises three main segments: the transmitter section, the optical link, and the receiver section. The optical link consists of a 50 km Standard Single-Mode Fiber (SMF) compliant with ITU-T G.652.D specifications and a 10 km DCF segment. This configuration is specifically designed for high-capacity, long-haul optical networks with paramount signal integrity. The fiber lengths are optimized to mitigate chromatic dispersion effects, particularly FWM.

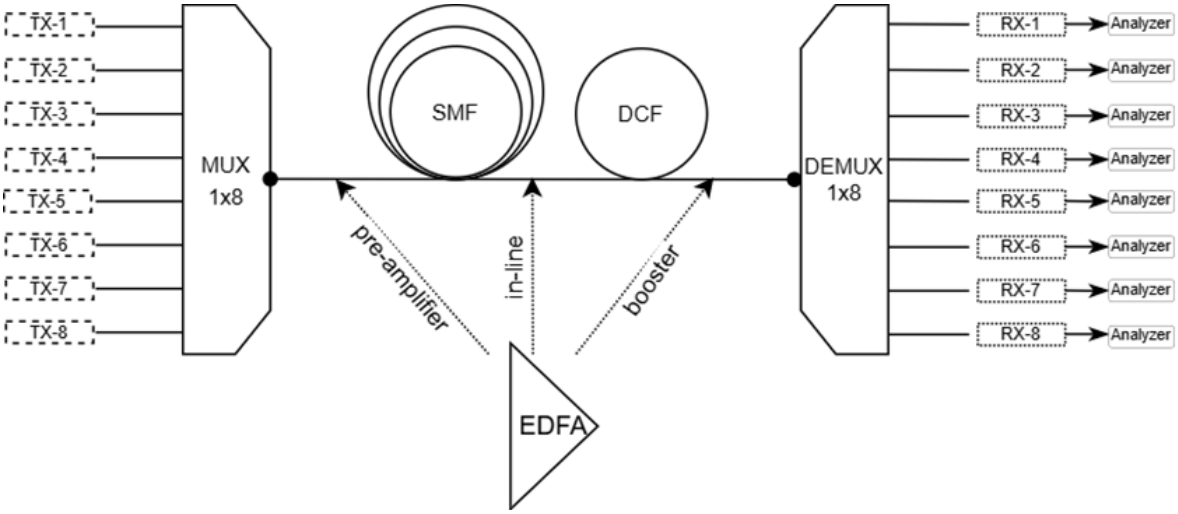


Fig. 1. The system model that used to simulate the optical fiber link.

The DWDM transmission system employs eight channels operating at 10 Gbps per channel, as shown in Figure 2a. Each transmitter implements Non-Return-to-Zero (NRZ) encoding with Intensity Modulation On-Off Keying (IM-OOK). The transmission wavelengths range from 1549.02 nm to 1551.72 nm (corresponding to frequencies from 193.55 THz to 193.20 THz), with a 50 GHz channel spacing by the ITU-T G.694.1 DWDM grid specifications. The input power per channel is maintained at 0 dBm to ensure the presentation of FWM effects. Ideal multiplexer and demultiplexer configurations focus the analysis on amplification effects.

The multiplexed optical signal traverses through the transmission link, where EDFAs are strategically positioned at three locations: pre-amplification, inline amplification, and post-amplification stages. Two distinct pumping configurations are implemented and analyzed: forward pumping with 100 mW power and bidirectional pumping with 60 mW power per pump. Both configurations are tested using pump wavelengths of 980 nm and 1480 nm to assess their impact on system performance under various amplification conditions.

At the receiver end (Figure 2b), the multiplexed signal is demultiplexed into individual channels. Each receiver comprises an Avalanche Photodiode (APD), a low-pass Bessel filter, and a regenerator. System performance metrics, including Bit Error Rate (BER) and Q-factor, are analyzed using eye diagram analysis for each receiver channel under different EDFA configurations.

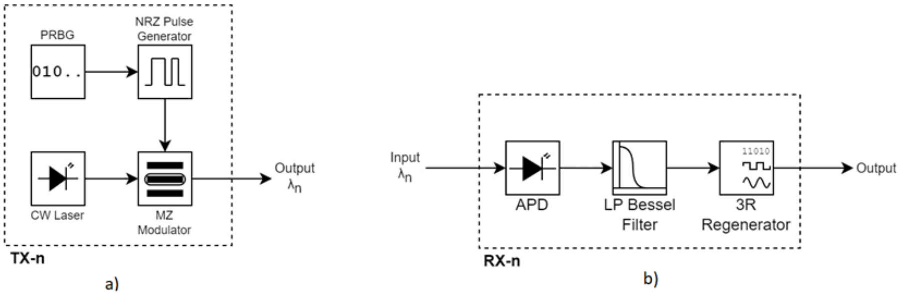


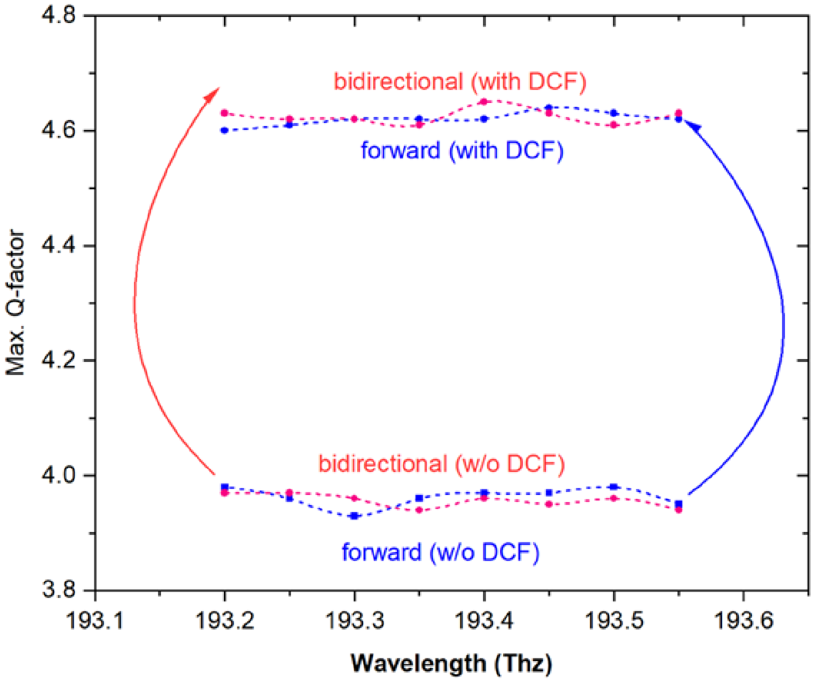
Fig. 2. (a) Transmitter and (b) receiver of the system.

3. Results

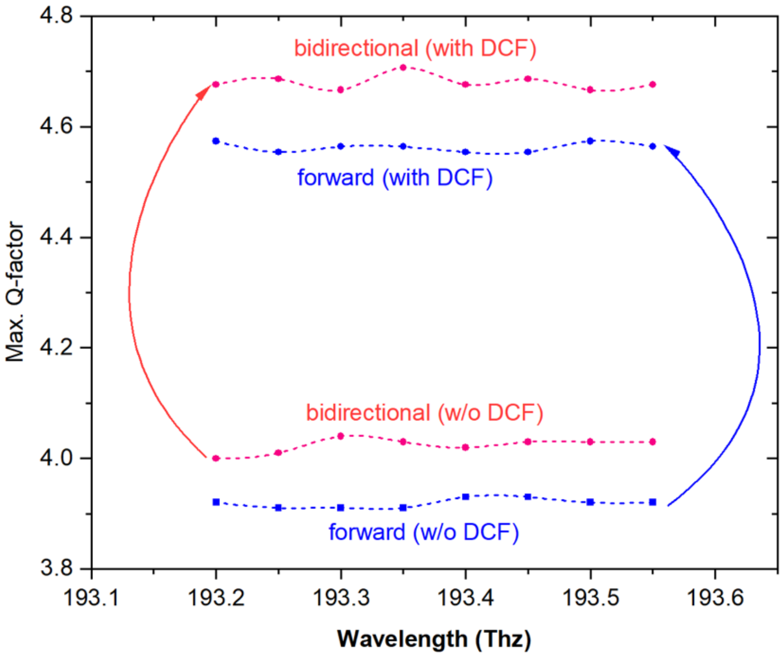
3.1. The impact of the DCF on the system

In this analysis, we investigated the impact of DCF on signal quality. The EDFA was strategically positioned at the output of the transmission link to optimize amplification efficiency. Furthermore, we examined the system performance under varying pumping configurations and wavelengths in Fig. 3. The system performance with 980 nm pumping demonstrates strong Q-factor characteristics across all configurations. With DCF implementation, the bidirectional pumping achieves a maximum Q-factor of approximately 4.7, maintaining stable performance across the wavelength range. The forward pumping configuration with DCF shows a slightly lower Q-factor with a stable average of 4.55. In configurations without DCF, both pumping schemes show reduced performance, with a 0.5 fewer Q-factor. Because of its higher absorption efficiency in the erbium ions, which results in improved population inversion and gain characteristics, the 980 nm pump wavelength is effective.

When we changed the pump wavelength to 1480 nm (in Fig. 2), the system showed similar patterns but had minor differences compared with 980 nm pumping. The bidirectional pumping with DCF achieves higher Q-factor values, which reach up to 4.8. Interestingly, the stability across all eight channels is less strong than in the 980 nm configuration. Forward pumping with DCF maintains around 4.6 of Q-factor, which has improved performance on the 980 nm counterpart. Without DCF, the performance of the forward pumping configuration is worse than the bidirectional one in the 1480 nm pump wavelength. It is not like the 980 nm pumping configuration. In general, the 1480 nm pump wavelength's better performance comes from lower quantum defect and efficient power conversion, resulting in slightly better signal quality, particularly in the bidirectional pumping configuration.



a)



b)

Fig. 3. The impact of the DCF on the system with different pumping configuration and wavelength at (a) 980 nm and (b) 1480 nm.

3.2. The impact of the EDFA position on the system

This section evaluates the influence of EDFA placement on the performance of the DWDM system under bidirectional pumping configurations at 980 nm and 1480 nm pump wavelengths (Fig. 4). The three EDFA positions analyzed include pre-amplifier (before the transmission fiber), in-line amplifier (between fiber spans), and booster amplifier (post-transmission) configurations. The system performance was assessed regarding the Q-factor across the frequency range of 193.2–193.55 THz. For the 980 nm pumping wavelength, the booster amplifier configuration consistently demonstrated the best performance, with an average of 4.64 Q-factor value. The in-line amplifier configuration exhibited intermediate performance, with Q-factors between 4.40 and 4.42. In contrast, the pre-amplifier configuration showed the lowest Q-factor values at the level of 4.15. The lower performance of the pre-amplifier setup is caused by non-linear effects in the optical fiber, which worsen at high power levels. These effects, like self-phase modulation and four-wave mixing, reduce signal quality and limit the Q-factor.

When the pump wavelength was changed to 1480 nm, all setups performed better than the 980 nm case. The booster amplifier setup continued to perform the best, achieving the highest Q-factor around 4.70. The in-line amplifier also increased from 4.40 to 4.55. Moreover, the pre-amplifier setup significantly improved, increasing around 0.2 at Q-factor values. This better performance in the 1480 nm pump wavelength has also been shown in the previous section, which comes from reducing some of the non-linear effects in the optical fiber. These results show how important the position of the EDFA is for the DWDM system performance. The booster amplifier setup performed the best because it could make up for transmission losses while keeping noise low. The in-line amplifier setup gave a balanced performance by spreading the amplification across the link. Although the pre-amplifier setup had the lowest performance, its improvement with 1480 nm pumping shows that carefully managing input power and pump wavelength can help reduce the negative effects of fiber non-linearities.

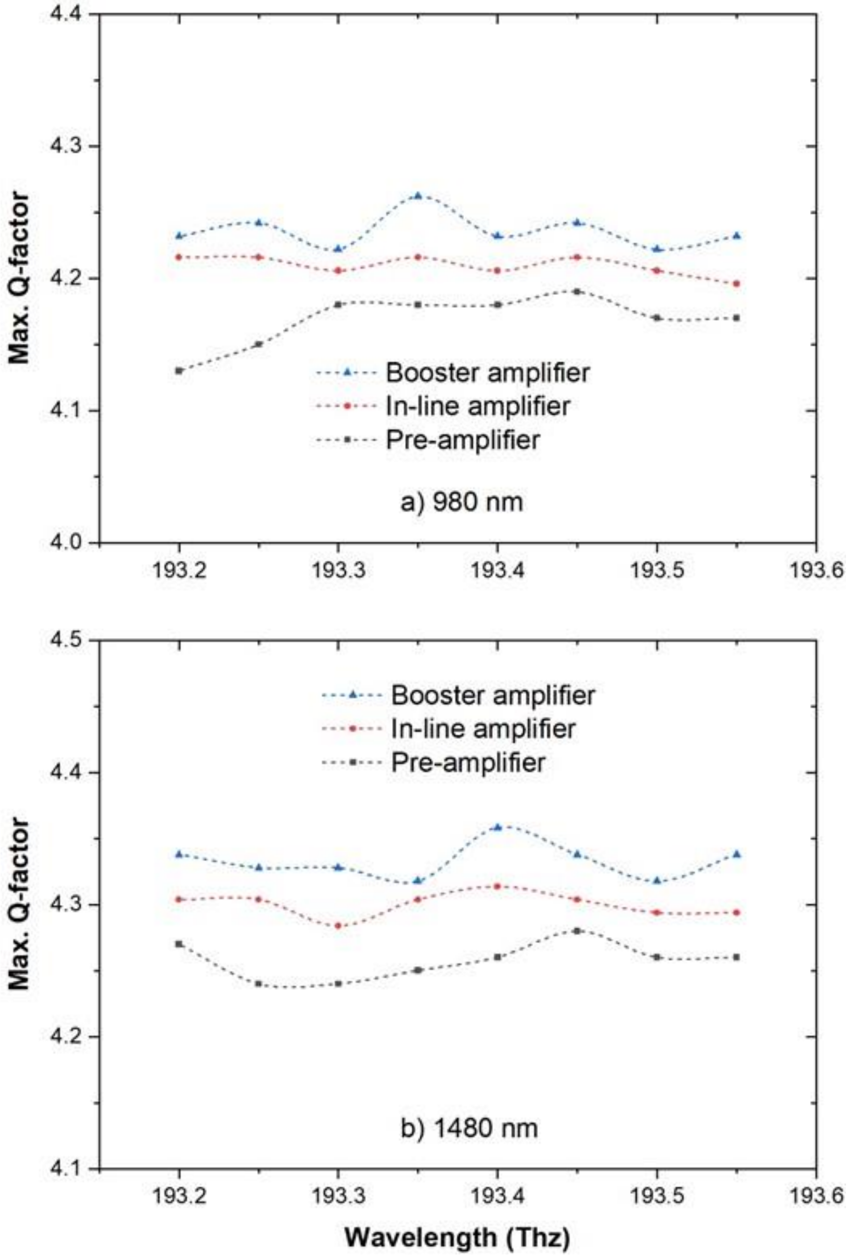


Fig. 4. Q-factor performance of the DWDM system for different EDFA positions under bidirectional pumping at (a) 980 nm and (b) 1480 nm pump wavelengths.

3.3. The effect of pumping configuration on the system

This part explores how the pumping direction, whether forward or bidirectional, affects the Q-factor performance of the DWDM system in the booster amplifier setup (illustrated in Fig. 5). For the 980 nm pump wavelength, the bidirectional pumping configuration consistently outperformed the forward pumping configuration. The Q-factor for bidirectional pumping ranged between 4.1976 and 4.2372, showing a more stable performance than the forward pumping configuration, which exhibited a Q-factor around 4.10, with a slightly higher variability. The superior performance of bidirectional pumping can be attributed to its ability to distribute pump power more evenly along the fiber, reducing the impact of non-linear effects such as self-phase modulation and four-wave mixing. Forward pumping, on the other hand, concentrates pump power at the beginning of the fiber, leading to higher non-linearities and signal degradation.

At 1480 nm, both configurations showed improved performance compared to the 980 nm case. The bidirectional pumping configuration achieved a Q-factor (between 4.36 and 4.38) with highly stable performance, the same as 980 nm pumping. The forward pumping setup showed an average Q-factor of 4.34, slightly less variation than the bidirectional setup. While bidirectional pumping was still better, the difference in performance between the two setups was smaller at 1480 nm than at 980 nm. Also, the variation in Q-factor across all channels was more acceptable with 1480 nm pumping compared to the 980 nm case. These results show how important bidirectional pumping is regarding the best system performance, especially at 1480 nm. It balances gain distribution and reduces non-linear effects.

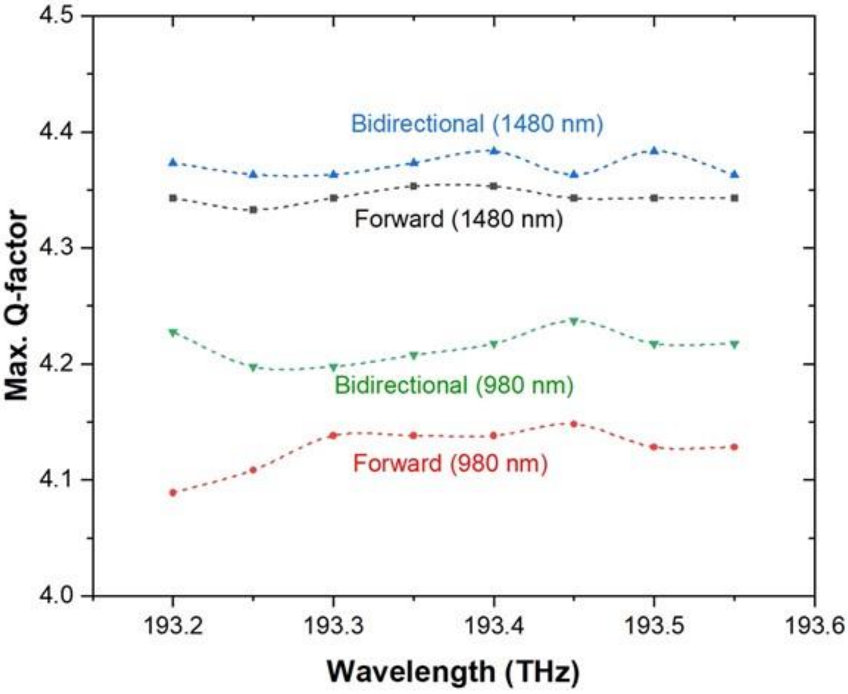


Fig. 5. The performance of the DWDM system for forward and bidirectional pumping configurations at 980 nm and 1480 nm pump wavelengths.

4. Conclusion

In this work, the placement of EDFA and the pumping configuration were investigated using DCF in a DWDM optical communication system. The results showed that the optical link with DCF significantly improves the signal quality in EDFA setup as pumping configuration and wavelength. Also, the position of EDFA in the link directly affects the Q-factor. The booster amplifier always performed better performance with bidirectional pumping at 1480 nm. Moreover, it should be noted that good stability across eight channels was achieved dramatically in the pump wavelength of 1480 nm rather than 980 nm. Finally, the results revealed that the bidirectional pumping schema always performs better than all EDFA designs. We can say that the maximum signal quality could be observed when the EDFA placement with pumping configuration and DCF use should be considered carefully. These findings provide valuable ideas for designing high-speed optical networks. For future work, the investigation will focus on non-symmetrical system configurations, where the placement of DCF and EDFA is not restricted to the middle of the optical link. This study will analyze how varying the positions of these components impacts signal quality, Q-factor, and overall system performance in DWDM networks.

Author Contribution

The writing of the manuscript and all analyses were performed by Firat Ertac DURAK.

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