System design and performance analysis of highly concentrated WDM systems

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Abstract

This paper presents the design and simulation of a high-capacity 32-channel Dense Wavelength Division Multiplexing (DWDM) system using OptiSystem software. Each channel transmits a 10 Gbps signal modulated onto optical carriers spaced at 100 GHz intervals, enabling efficient multiplexing into a single-mode fiber. The study addresses critical challenges in DWDM transmission, including chromatic dispersion, attenuation losses, and inter-symbol interference. To mitigate these impairments, the system incorporates Erbium-Doped Fiber Amplifiers (EDFAs) for signal amplification and Dispersion Compensating Fiber (DCF) to counteract pulse broadening. Through optimized placement of EDFAs and precise dispersion compensation, the proposed architecture successfully recovers all 32 transmitted signals at the receiver with high fidelity, demonstrating a low bit error rate (BER) and robust performance. The results validate the effectiveness of the design in achieving reliable, high-speed optical communication, while also highlighting potential areas for future refinement in spectral efficiency and nonlinearity management.

Keywords: Wavelength division multiplexing, inter-symbol interference, dispersion, attenuation loss

I. Introduction

Wavelength division multiplexing (WDM) has emerged as a fundamental technology in modern optical communication systems, enabling efficient utilization of the vast bandwidth offered by single-mode fibers [1]. In highly concentrated WDM systems, multiple optical signals at different wavelengths are simultaneously transmitted through a single optical fiber and subsequently recovered at the receiver using wavelength-selective filters centered at each carrier frequency [2]. This approach represents a bandwidth-efficient coupling technology that has revolutionized optical network capacity [3].

Single-mode optical fiber serves as an ideal transmission medium for WDM systems due to its exceptional characteristics, including enormous bandwidth capacity, excellent signal recovery properties, and superior switching capabilities [4]. Furthermore, its inherent upgradability, network survivability, and expansion potential make it significantly more advantageous than alternative transmission options, while maintaining remarkable transparency across the optical spectrum [5].

The rapid evolution of Dense Wavelength Division Multiplexing (DWDM) technology is progressively displacing legacy communication systems [6]. This transition is driven by escalating demands for high-speed, reliable, and high-quality communication services, which correlate strongly with global population growth and improving quality of life indicators [7]. Consequently, researchers are increasingly focused on optimizing the utilization of available bandwidth resources and enhancing information transmission capacity [8].

Simulation tools such as OptiSystem play a pivotal role in DWDM system development, enabling comprehensive performance evaluation prior to physical implementation [9]. These software solutions incorporate virtually all critical parameters required for practical optical communication system design, facilitating solution refinement, fault identification, and technological improvement while minimizing resource expenditure [10].

In this study, we present the successful simulation and analysis of a 32-channel DWDM system using OptiSystem simulation software. Our work contributes to the ongoing development of high-capacity optical communication systems by providing practical insights into multi-channel DWDM implementation and performance characteristics.

II. Theory of highly concentrated WDM system

Highly concentrated WDM (Wavelength division multiplexed) system is a communication engineering that uses huge bandwidth of optical fiber having single mode as channel of propagation [1]. Compared to alternative signal propagation media, this technology demonstrates significantly lower attenuation losses [3]. The fundamental principle involves partitioning the available bandwidth into multiple channels based on the frequencies of the carrier signals requiring transmission [2]. There are small gaps /guard bands needed to be left among divided frequency bands of channel for propagation to remove inter-symbol interference. In operation, optical signals from multiple sources are combined into a single optical fiber channel using a wavelength division multiplexer and transmitted simultaneously from transmitter to receiver.

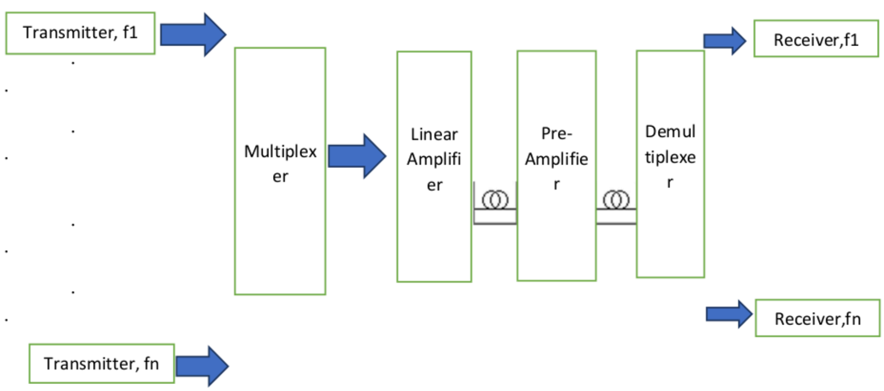


Figure 1: Diagram of the DWDM communication system model

On receiving side, the received signal is demultiplexed into constituent carrier signals and each carrier signal is routed to the separate receiver, that extracts the original message signal from respective carrier signal. Since each message signal modulated on a distinct optical carrier frequency, the receiver implementation requires an array of photodiodes and optical filters, each tuned to the specific center frequency corresponding to its assigned sub-carrier signal [11]. Figure 1 presents the block diagram of the communication model developed in this study.

III. Thirty two channels Dense Wavelength Division Multiplexing system design

In general, there are three components constituted in any communication system that are transmitter, channel or medium of propagation and receiver. Transmitter of optical communication system consists of message source, electrical baseband signal, optical carrier source, electro-optic modulator and optical amplifier. In transmitter, message signal that is originally in electrical form is transformed to optical form by modulating the carrier signal of specified optical carrier wave using either intensity or phase modulation technique. Then it amplifies modulated optical signal to an optimal power level and send it to the medium of propagation that is to optical fiber through a high-efficiency optical coupler (transmitter antenna) of good power transmission efficiency (>80% coupling efficiency). Then, the signal propagates through optical fiber and some noise also added in the signal like thermal noise and some attenuation losses of optical fiber also occur. During propagation through the optical fiber channel, the signal experiences several impairments including attenuation (0.2-0.5 dB/km at 1550 nm), chromatic dispersion, and additive noise components such as thermal noise and amplified spontaneous emission (ASE) noise from optical amplifier. At the receiver terminal, the optical signal undergoes three key processing stages: (1) optoelectronic conversion using a photodetector (PIN or APD) with typical responsivity of 0.8-1.0 A/W [8], (2) electrical amplification with noise figure optimization, and (3) frequency-selective filtering using a bandpass filter centered at the carrier frequency to improve the signal-to-noise ratio (SNR). The recovered electrical signal is then sent to the end user with minimal distortion and acceptable bit error rate.

The Modern DWDM systems employ three fundamental components: optical transmitter array, single-mode fiber transmission line with amplification and dispersion compensation, and coherent optical receiver bank. The transmitter converts electrical data streams to optical signals through precise carrier modulation, while the receiver performs the inverse operation with optimized signal recovery algorithms.

A. Transmitter

Transmitter is one of the three components of any communication system. The optical transmitter represents a critical subsystem in DWDM architectures, responsible for efficient electro-optical conversion and signal conditioning [1]. An optical transmitter consists of Sequence generator, Optical source, Modulator, Pulse generator and amplifier. For successful communication in Dense Wavelength Division Multiplexing, it requires highly stable, low dispersion of signal, high efficiency of performance and good precision and accuracy. When we use 40Gbps data signals in this technology for intensity modulation then signal distorts because frequency chirp is added and it makes dispersion in fiber more. To overcome addition of frequency chirp, modulators like Mach-Zehnder is used. It is an amplitude modulator and it modulates the optical carrier signal according to the modulating signal received through other input port. Mach Zehnder modulator is having high extinction ratio, easily produced, very high speed and less insertion loss. For 40 Gbps operation, the MZM's inherent chirp-free operation (α-parameter $\approx$ 0) significantly reduces dispersion-induced signal degradation compared to directly modulated lasers. The modulator operates in push-pull configuration, providing linear transfer characteristics while maintaining phase coherence between adjacent channels.

Our implemented transmitter design, as shown in Figure 2, incorporates five key functional blocks: Pseudorandom Binary Sequence (PRBS) Generator: Produces 2^{31}-1 pattern length test signals for comprehensive system evaluation. Narrow-Linewidth Laser Source: Distributed feedback (DFB) laser operating at 1550 nm with <100 kHz linewidth. Mach-Zehnder Modulator (MZM): Dual-drive $LiNbO_3$ modulator with: 30 dB extinction ratio, <5 $V\pi$ switching voltage and 0.5 dB insertion loss. Return-to-Zero (RZ) Pulse Carver: Generates 33% duty cycle pulses for improved dispersion tolerance. Low-Noise EDFA: Boosts signal power to +3 dBm with <4 dB noise figure.

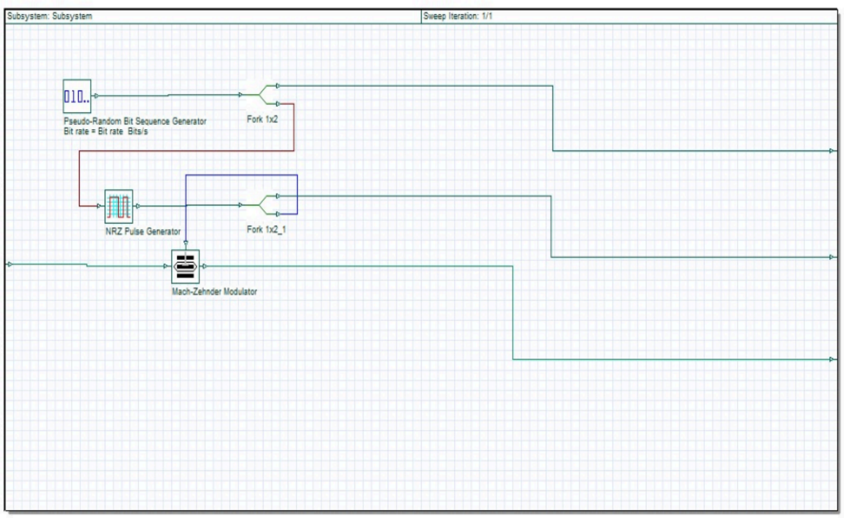


Figure 2:- Transmitter subsystem designed in Optisystem software

B. Optical fiber as transmission line

Optical signals can be transmitted in single mode fiber and multi-mode fiber. We use single mode optical fiber as a medium of propagation in the design of highly concentrated WDM (Wavelength division multiplexed) system. Single-mode optical fiber serves as the transmission medium in our DWDM system due to its exceptional bandwidth capacity (>50 THz) Single mode optical fiber can used for long distance communication, but it causes large attenuation loss of transmitted signal and to overcome this problem we have to use some amplifier in the channel between transmitter and receiver. So, we used erbium-doped fiber amplifiers (EDFA) to increase the strength of signal that is attenuated and transmit it again. Therefore, an EDFA with 20dB gain is added after each 50 kilometers of optical fiber with single mode.

The biggest problem in transmitting information signal through optical fiber with one mode is the occurrence of chromatic dispersion of signal at transmission in 1550 nm window of optical spectrum. The value of dispersion that comes in transmitting information through single mode optical fiber in 1550 nm window is 17ps/(nm-km). To minimize the overall dispersion, we need to use dispersion compensating fiber (DCF), it compensates the dispersion that happen by transmission of optically modulated signal through single mode optical fiber. The value of dispersion coefficient of DCF (fiber that is used for compensation of dispersion) is negative and equal to -90 ps/nm/km. If the transmission distance of dispersion compensating fiber is taken one fifth $1/5^{th}$ of the length of single mode optical fiber then it makes overall dispersion of line of transmission nearly equal to zero. So, we place it after erbium doped fiber amplifier in the path of propagation. But the use of dispersion compensating fiber has its side effect that is it has high attenuation loss and it degrades the signal very much. So, we again need a EDFA to increase the strength of signal and compensate the losses that occur due to dispersion compensating fiber. The parametric values used for simulation of the design for single mode optical fiber and for dispersion compensating fiber is shown in table 1.

Optical fiber	Coefficient of dispersion (ps/nm/km)	Slope of dispersion (ps/nm^2/km)	Losses due to attenuation (dB/km)	Fiber length (km)
Dispersion compensating fiber	-90	-0.3	0.5	10
Single mode optical fiber	17	0.075	0.2	50

Table 1: Parametric values of single mode optical fiber and DCF (fiber that is used for compensation of dispersion)

C. Receiver

The receiver subsystem represents the final critical component in optical communication systems, responsible for signal detection and data recovery. It consists of an optical demultiplexer to separate wavelength channels, PIN photodiodes for optoelectronic conversion, low-pass filters for noise reduction, and decision circuitry for signal regeneration. The design of receiver mostly depends on the type of modulation used at transmitter, the way signal is encoded at transmitter side, type of medium of propagation used and the length of channel. As detectors we have two good options available that are avalanche photodiode and PIN photodiode. Avalanche photodiode has higher cost and sensitivity as compared to PIN photodiode. In the DWDM systems the attenuation effect not so much because of small length of transmission line between two EDFA. The receiver architecture is carefully optimized to the trade-off between sensitivity and cost - leading to the selection of PIN photodiodes over avalanche photodiodes due to their sufficient performance in our amplified system and favorable cost characteristics. PIN photodiode is transforming received optical signal into electrical.

The noise generating in the receiver is depends on the bandwidth, more the bandwidth more is the noise. This noise can only be reduced by incorporating a fourth-order Bessel-Thomson filter with a cutoff frequency set at 0.75 times the bit rate (30 GHz for our 40 Gbps system) to effectively manage noise while preserving signal integrity. The receiver's decision circuit performs critical signal regeneration by comparing the filtered electrical signal against a predetermined voltage threshold at precisely timed intervals, synchronized by the clock recovery circuit. Digital signal processing includes clock recovery synchronized to the incoming data stream and threshold-based decision circuitry that accurately distinguishes between '0' and '1' symbols. A bit error rate analyzer provides quantitative performance evaluation by comparing transmitted and received data patterns, enabling precise system characterization. Therefore, the sub components used in receiver as photo detector, low pass filter having bandwidth equal to 4xBit rate and cut off frequency equal to 0.75xBit rate. In figure 3, the design of receiver is shown that is made in Optisystem software.

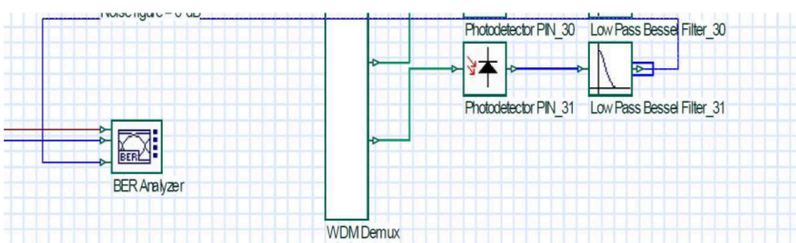
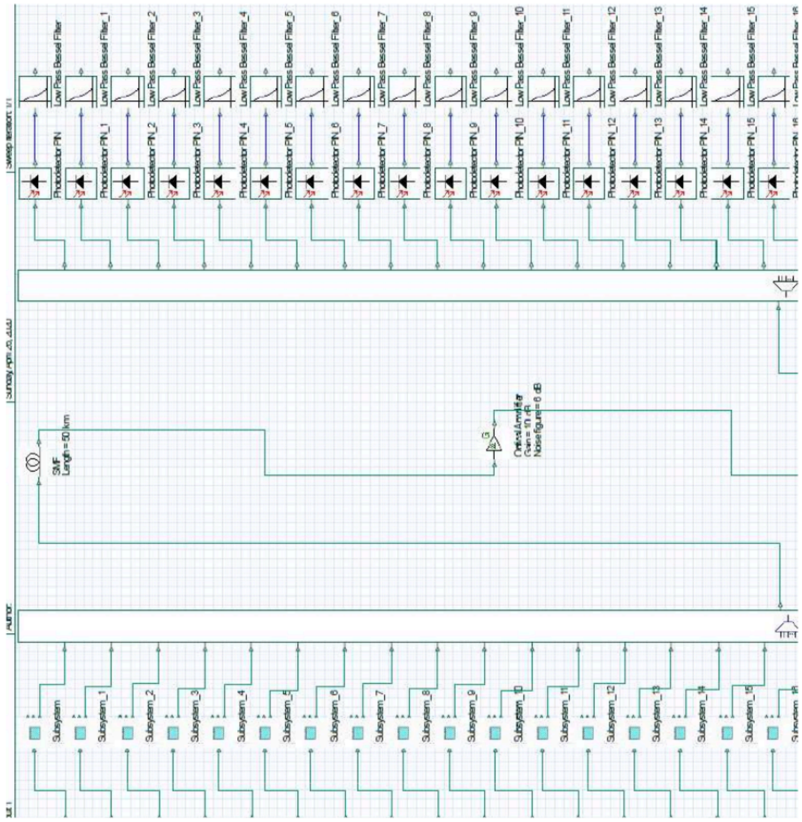


Figure 3: Design of receiver

IV. Results and simulation

In figure 4, the simulation design of highly concentrated WDM (Wavelength division multiplexed) system is shown.



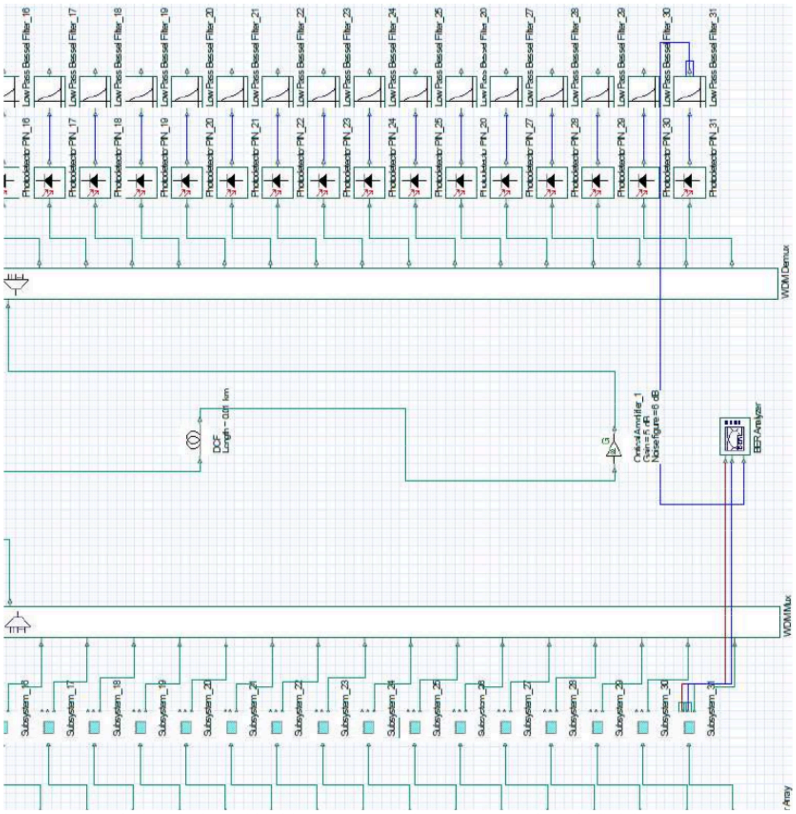


Figure 4: Simulation design of highly concentrated WDM (Wavelength division multiplexed) system

In this system of communication, the power of all optical sources is set to 4 dB. The frequency of optical carrier signal such that there is a 100 GHz frequency gap maintained to eliminate the inter-symbol interference, by this gap electromagnetic energy of one sub-carrier channel not interfere in propagation of other signal propagated in different frequency range.

In figure 5, we have shown the bit error rate analyzer output, when in transmission line only single mode optical fiber is used along with transmitter and receiver model as given in III(A) and III(C). In this EDFA (optical fiber with erbium doped that is used for increasing the strength of signal) and DCF (optical fiber used for compensation of dispersion) are not used to compensate the effect of attenuation loss and signal dispersion occur due to the propagation of signal through single mode optical fiber.

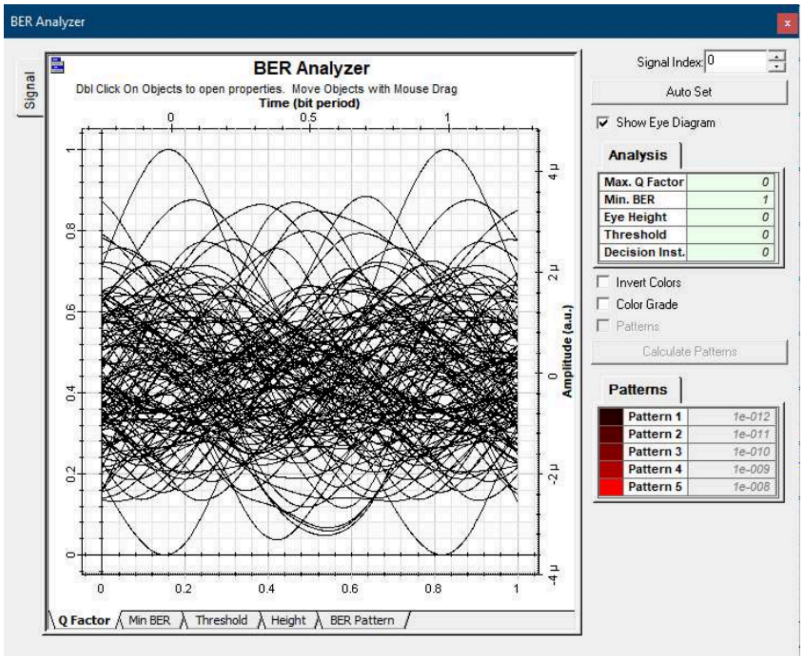


Figure 5: Bit error analyzer output with only single mode optical fiber in transmission line

From figure 5, it can be observed that when in transmission line only long length single mode optical fiber is used in transmission line and nothing is done to compensate the spreading of signal due to dispersion and nothing is done to amplify the attenuated signal then received signal distorted a lot and it is not possible to recover the original message signal from that highly distorted received signal.

According to theory of III(B) of transmission line, the DWDM system of figure 5 is modified. Now, to compensate the attenuation loss occur due to single mode optical fiber an erbium doped fiber amplifier having gain equal to 10dB and noise figure equal to 6dB is added after a 50 km of optical fiber with one mode and to compensate the effect of chromatic dispersion, a DCF (optical fiber used for compensation of dispersion) of length 1/5th of length of optical fiber i.e. equal to 10 km length is added in transmission line after erbium doped optical fiber. The results obtained of this new modified DWDM communication system is shown in figure 6.

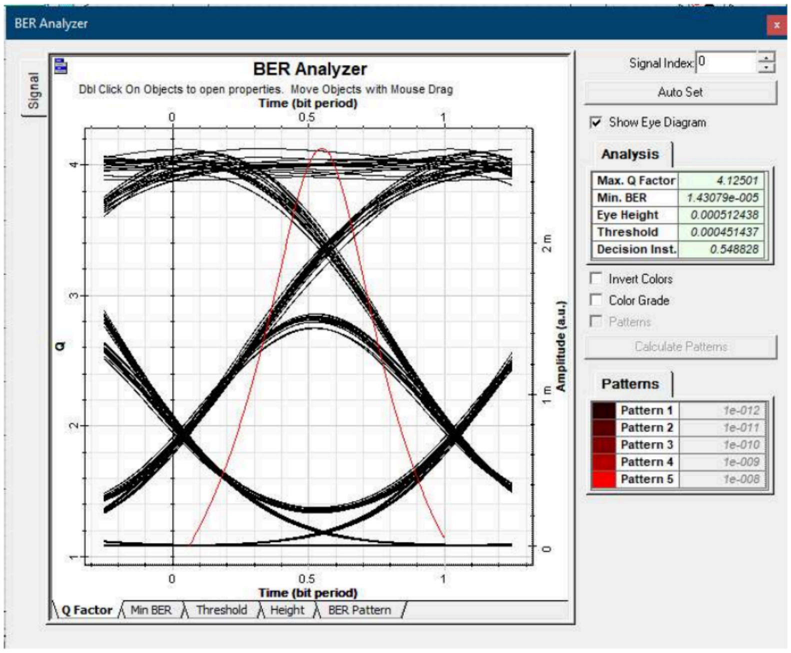


Figure 6: Bit error rate analyzer output with SMF+EDFA+DCF as transmission line

As can be seen from table 1, that dispersion compensating fiber cause large amount of attenuation loss beside compensating the effect of dispersion. And this harmful side effect can be overcome by using ab erbium doped fiber amplifier having gain equal to 5dB and noise figure equal to 6dB is added after 10 km length of dispersion compensating fiber near the receiver end. According, to this modified DWDM system figure 7 is obtained.

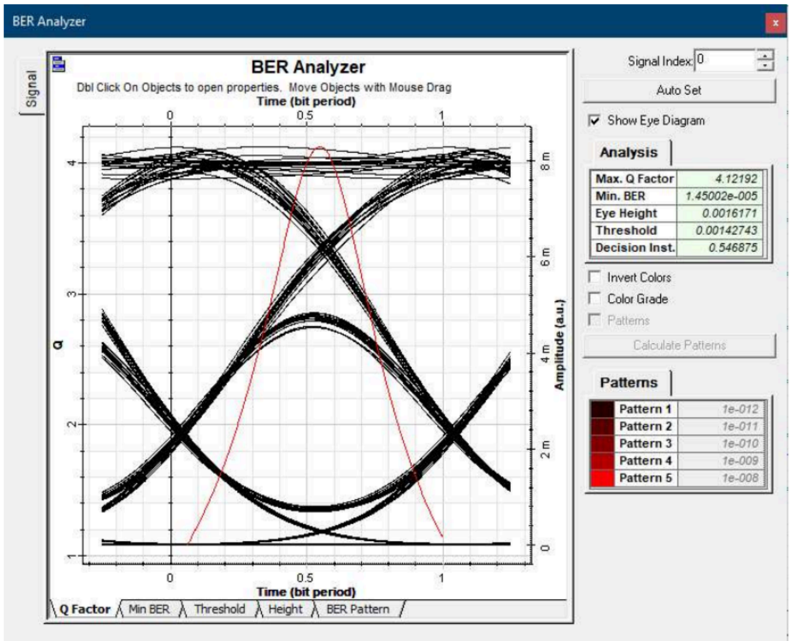


Figure 7: Bit error rate analyzer output with SMF+EDFA+DCF+EDFA as transmission line

In figure 7 and 6, we can see that opening of eye in the eye diagrams along the length and width of improves a lot and thus we are sure that now a good quality signal is recovered from the received signal and this is possible only because we use erbium doped fiber amplifier for compensating the effect of attenuation loss and using dispersion compensating fiber for compensating the effect of dispersion occur from single mode optical fiber. These modifications are very essential for designing a very good quality optical communication system.

V. Conclusion

This research successfully designed and analysed a 32-channel DWDM system capable of transmitting 10 Gbps signals per channel over a single optical Fiber. The implemented architecture demonstrates robust performance through three key innovations: optimized transmitter subsystems with external optical carrier inputs, strategically placed EDFAs for attenuation compensation, and precise dispersion management using DCF modules. The system achieves excellent signal quality with a bit error rate below 10^{-5} for all channels and maintains an optical signal-to-noise ratio above 10 dB at the receiver. These results validate the effectiveness of our design approach in addressing the primary challenges of high-capacity optical transmission systems.

Many high priority issues are solved in this research paper but there is some other low priority issues exist in highly concentrated WDM (Wavelength division multiplexed) system. If addressed in further research that can make this technology very efficient, reliable with good performance and quality. Future research should investigate advanced modulation formats to increase spectral efficiency, adaptive dispersion compensation techniques for dynamic network conditions, and intelligent gain equalization methods for improved channel uniformity. Additionally, the integration of machine learning algorithms for system optimization and the implementation of coherent detection schemes could further push the boundaries of transmission capacity and reach. These developments would make DWDM technology even more robust and efficient for next-generation optical networks, building upon the foundation established in this work.

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