



Enhancing the optical communication system efficiency by using ideal-DCF and fibre Bragg gratings for remote-distance

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An optimized Fiber Bragg Grating (FBG) setup is used to enhance network efficiency is presented in this work. By testing comparing the proposed setup with a reference network. One with no FBGs, and a second with a FBG network, the configuration employing single-mode optical fibre (SMF) for data transmission demonstrated superior performance due to the narrowing of the spectral width of the optical source. our system previously sustained efficiency levels over 140 km even when with variations in channel length and Ideal Dispersion Compensation Filter (Ideal DCF) types. Simulations suggested a high system reliability, verified by a Q factor and Bit error rate (BER) of $1.47324e-09$. Measurements of performance such as eye height are assessed at distances confirming the system robustness. The entire system is simulated using OptiSystem and MATLAB.

Keywords: Fiber Bragg grating; Ideal dispersion compensation filter; SMF; BER.

1. INTRODUCTION

The fibre Bragg gratings, also known as FBGs, consist of changes, in the refractive index along a specific length of the fibre core. These alterations in index within the core have paved the way for the development of optical tools used in sensing and communication applications [1,2]. While FBGs have found ranging applications their application to enhance optical transmission link performance has brought advancements to the telecommunications industry. Consequently, contemporary researchers are incorporating cascaded FBG configurations into communication setups to boost performance by

narrowing the width of laser sources and mitigating dispersion effects [3]. Thus, investigating the characteristics of cascaded FBG structures and their influence, on optical communication systems holds importance. A uniform set of four Fiber Bragg Gratings (FBGs) is studied in reference [4,5] where they have been cascaded in a series. Such arrangement showed improvement in band width and reduction in well side lobes strength. The amount of reflectivity at each stage of this design is modified in a degenerating fashion [6]. To address this problem, a different solution is derived from follow-up study where an FBG structure using unevenly ranged lengths is proposed to be deployed in a four-stage cascaded configuration with enhanced reflectivity [7,8]. Some other studies focused on the improved performance of a wavelength division multiplexing (WDM) system by using four stages cascaded FBGs of different lengths. This set of structures are essential in obtaining a linewidth of the continuous wave (CW) laser in order to improve the system [9-11]. Furthermore, a range of partial differential equations are also used to create a cascaded apodized FBG structure for dispersion compensation in WDM networks [12]. The purpose of this framework is to mitigate the effects of the source within the system. Its performance has been tested for ranges up to 100 km based on several factors such as bit error rate (BER) and Q factor [13-14]. Moreover, the efficiency of an optical communication system can be improved by the use of a set of Tanh apodized Fiber Bragg Gratings in conjunction with the time division multiplexing transmission method as discussed in [15]. This article describes the development of a four-stage cascaded FBG structure with lengths for an optical communication system for system performance testing. In this case, the output of the wave (CW) laser source is used as the input for the cascaded FBG structure and the optical signal reflected from this structure is then fed into the Mach Zehnder (MZ) modulator [16].

The described narrowing of the width by the cascaded setup helps in reducing dispersion in the system thus improving its performance. In the first step, an exclusive analytical formulation of this structure is developed using Coupled Mode Theory (CMT). Using the transfer matrix method (TMM). In the result, the systems performance is evaluated with regards to Bit Error Rate (BER) and Q factor metrics. Dispersion compensation is one of these techniques in optical communication systems meant to deal with the problems caused by dispersion related issues [17].

The existing compensation framework seeks to explore and replicate the dispersion compensation method by employing a blend of fibre Bragg grating and an emulator over an optical fibre distance of up to 250 km. Factors such as signal to noise ratio (SNR), optical signal to noise ratio (OSNR), gain (G), noise figure (NF), and degree of polarization (DOP) are integral to the simulation process [18,19]. Nanostructured fibre engineering has enhanced the performance of cascaded FBG configurations in optical communication systems. The integration of nanoscale coatings and metallic nanoparticles improves spectral selectivity and linewidth narrowing, supporting efficient dispersion management in WDM links [20,21]. Furthermore, it investigates the amplifier's output power under varying bias currents and length, highlighting its potential for high gain in photonic communication applications [22].

Optical communication components have significantly improved due to the substantial advancements in nanotechnology. In FBG networks and DCF, nanoscale structural engineering has opened promising avenues for controlling dispersion and enhancing signal integrity in long-distance communication systems [22-25].

The phases of the investigation encompass understanding the fundamentals of FBG and DCF, alongside gaining proficiency in the software employed for simulations to assess these systems. The research explores the principles of using FBG and Ideal DCF in communication frameworks and then advances to establish the necessary configurations for conducting simulations. Subsequently, a comparison of these systems is performed based on their efficiency using the collected data,

culminating in a discussion of the findings to demonstrate the effectiveness and performance of the proposed system in this research [26-30].

2. WORKING PRINCIPLE OF FBG

The way Fiber Bragg Grating (FBG), as in figure (1), works is, by reflecting light in fibres. These fibres have a core made of glass surrounded by a cladding layer [23,24].

1. Creating the Grating on the Fiber; A patterned grating is made on the fibre using ultraviolet laser light. This grating contains sections, with indices that vary periodically.

2. Selective Reflection; When light of a wavelength travels through the fibre the wavelength that matches the gratings pattern gets reflected. This particular wavelength is known as the Bragg Wavelength. Can be calculated using an equation 1 [31-35].

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

Where: λ_B is Bragg wavelength, n_{eff} is effective refractive index of the fiber, and Λ is distance between the grating points.

3. Sensing Applications; Fiber Bragg gratings (FBGs) have uses in detecting alterations in pressure, temperature, or strain [23]. These variables prompt variations, in the index or the distance, between the grating points resulting in a modification of the Bragg wavelength. This alteration can be accurately gauged to ascertain the required measurements [36].

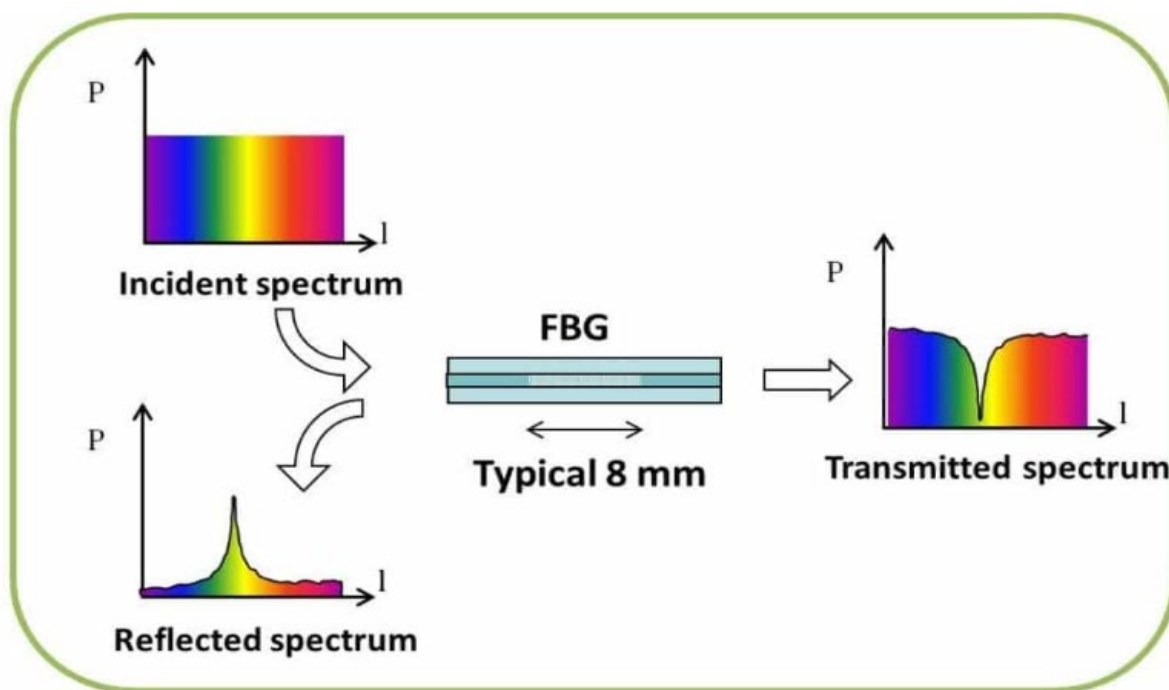


Figure 1 Working principle of FBG.

3. THE OPERATION PRINCIPLE OF THE IDEAL DISPERSION COMPENSATION FILTER (DCF)

In communications involves counteracting dispersion effects, within optical fiber systems. Dispersion, which results in light wavelength speeds and signal distortion over extended distances is effectively managed by the DCF through introducing a dispersion influence [37]. This process restores the signal form ensuring data transmission quality [25].

3.1. How a dispersion compensation filter works

1. Understanding Dispersion; In fibres dispersion can manifest as wavelength dependent or modal (mode dependent). The main concern, in single mode fibres is dispersion, where various light wavelengths disperse over time causing signal distortion. This is caused by the varying speeds of wavelengths within the fibre material.

2. Mitigating Dispersion; The Dispersion Compensation Filter (DCF) is crafted to introduce dispersion to counterbalance the dispersion in the fibre. This involves creating a filter with a dispersion characteristic that opposes that of the transmission fibre. The objective is to realign the spreading of wavelengths to their original positions effectively compressing the signal pulse back, to its initial form.

3. Filter Design and Implementation;

a. Dispersion Compensating Fiber (DCF); This unique optical fibre is designed with negative dispersion properties. These fibres are connected into the transmission path to offset the dispersion that builds up along the transmission fibre.

b. Fiber Bragg Gratings (FBG); These devices aid, in dispersion compensation by reflecting wavelengths at different points along the grating. The reflection causes a delay that helps counteract the dispersion effect.

c. Chirped Fiber Bragg Gratings (CFBG); A variation of FBG where the grating period changes, along the fibres length offering customized dispersion compensation by introducing delay profiles for wavelengths [26].

4. Mathematical Representation; The impact of dispersion is often explained using a dispersion parameter $D(\lambda)$. In a scenario the DCF offsets a dispersion of $D(\lambda)$. When the fibre introduces a phase shift $\phi(\lambda)$ the DCF adds another phase shift of $\phi(\lambda)$ leading to a balance [27], in dispersion;

$$\phi_{total}(\lambda) = \phi(\lambda) - \phi(\lambda) = 0 \quad (2)$$

This guarantees that any signal distortion, from the transmission fibre is cancelled out.

3.2. System architecture and simulation, with optisystem and matlab

In this optical communication setup various essential elements are utilized, such as Fiber Bragg Gratings (FBGs) a Mach Zehnder Modulator (MZM), single mode optical fibers, signal amplifiers, Ideal Dispersion Compensation Filters (Ideal DCFs) a PIN photodiode, a Low Pass Filter (LP filter) and equipment, for analyzing Bit Error Rate (BER) and Eye Diagram. In the diagram depicting the system structure, it is demonstrated that OptiSystem and MATLAB are utilized for implementation and simulation purposes. The Figure (2) Illustrates the System diagram [38-40].

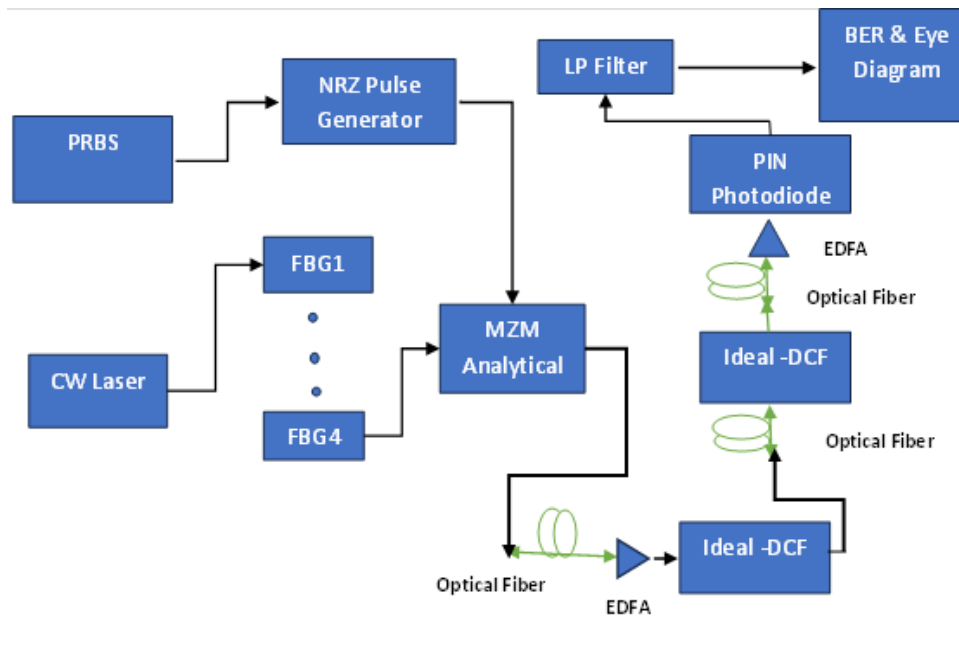


Figure 2 A diagram of the communication system.

4. AN OPTICAL COMMUNICATION SYSTEM USING FBG, AND IDEAL DCF

In today’s communication setups, the harmonious collaboration of parts is vital, for data transmission and reception. Every element, be it transmitters or receivers works together to ensure an exchange of information, within networks. As shown in the following [41-45].

4.1 Transmission segment

The process begins with four Fiber Bragg Gratings (FBGs) in the transmitter section. These FBGs are employed to control light wavelengths by acting as filters that reflect certain wavelengths while allowing others to pass through. This manipulation shapes the spectrum of the transmitted signal. The filtered light then goes into a Mach Zehnder Modulator (MZM) which modulates the signal with the data intended for transmission. Through interference patterns the MZM encodes information onto the carrier, by altering the intensity, phase or frequency of the light.

4.2 Channel

The channel is made up of parts that help transmit the modulated signal across long distances. The modulated signal travels through a mode fiber, which permits only one light mode to move reducing dispersion and maintaining the signals integrity. Signal amplifiers, like Erbium Doped Fiber Amplifiers (EDFAs), are strategically placed along the fiber to enhance the signal strength compensating for any loss that happens during transmission. The initial Ideal Dispersion Compensation Filter (Ideal DCF) is utilized to counteract the dispersion gathered in the fiber segment by introducing negative dispersion that realigns wavelengths and restores pulse shape. Following this as the signal passes through another section of mode fiber there might be additional dispersion which is corrected by a second Ideal DCF.

4.3 Receiver section

Moving on to the section the optical signal undergoes amplification more to ensure it is sufficiently strong for accurate detection. This amplified optical signal then encounters a PIN photodiode that converts it back into a form. The electrical signal goes through a Low Pass Filter (LP filter) to eliminate high-frequency noise and unwanted components ensuring a signal, for analysis.

At the end, we assess the systems effectiveness by analyzing Bit Error Rate (BER) and Eye Diagrams. BER analysis measures errors, in the data received, giving an evaluation of how enable the systems. Eye Diagrams visually display signal integrity revealing timing and amplitude features to detect problems, like timing fluctuations and amplitude changes.

We tested the network we built as shown in Figure 3 and compared its outcomes with those of another system that does not have FBG and Ideal-DCF as depicted in Figure 4. Furthermore, we contrasted the results of the network with a system that includes FBG but does not have Ideal-DCF as illustrated in Figure 5.

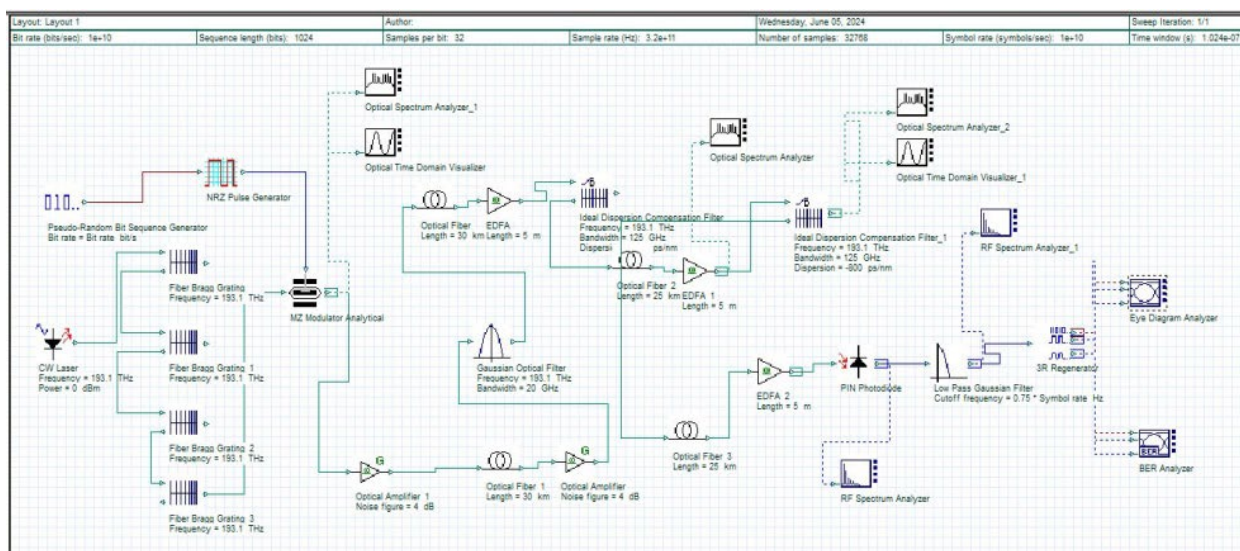


Figure 3 A simulated communication system, with all its parts.

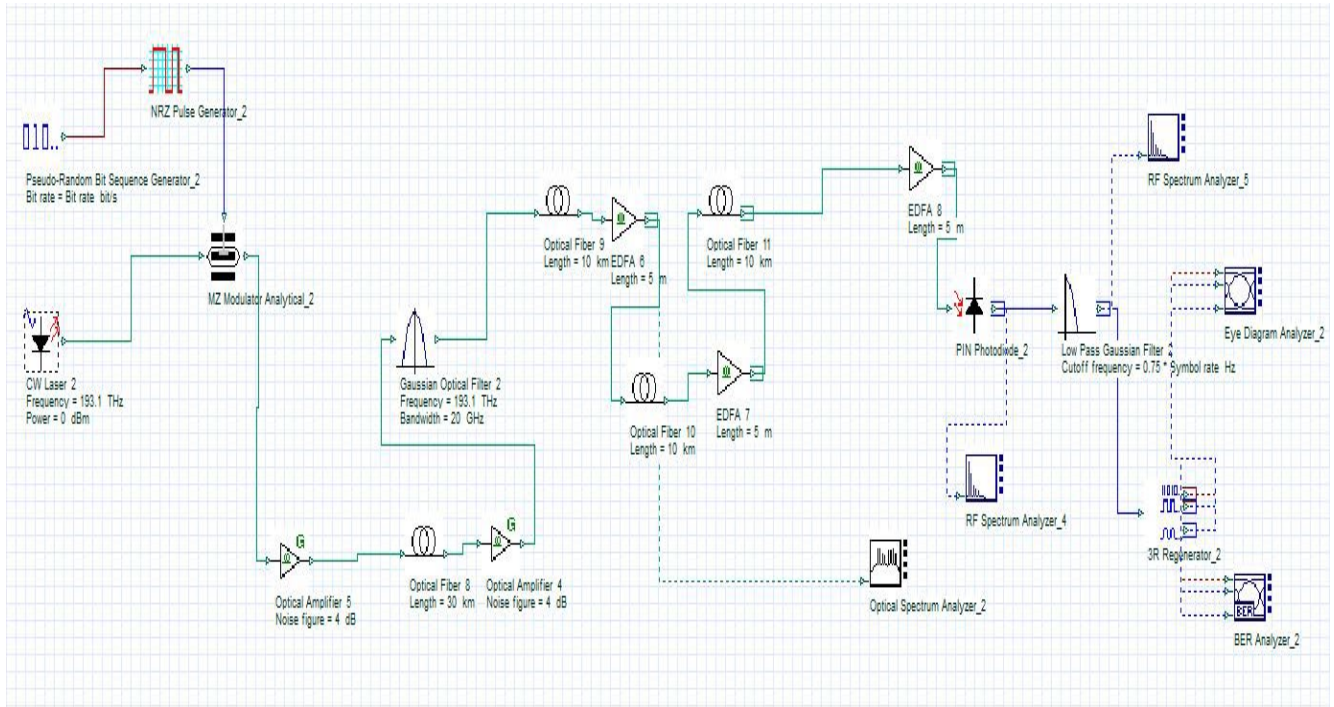


Figure 4 An optical communication system devoid of FBG.

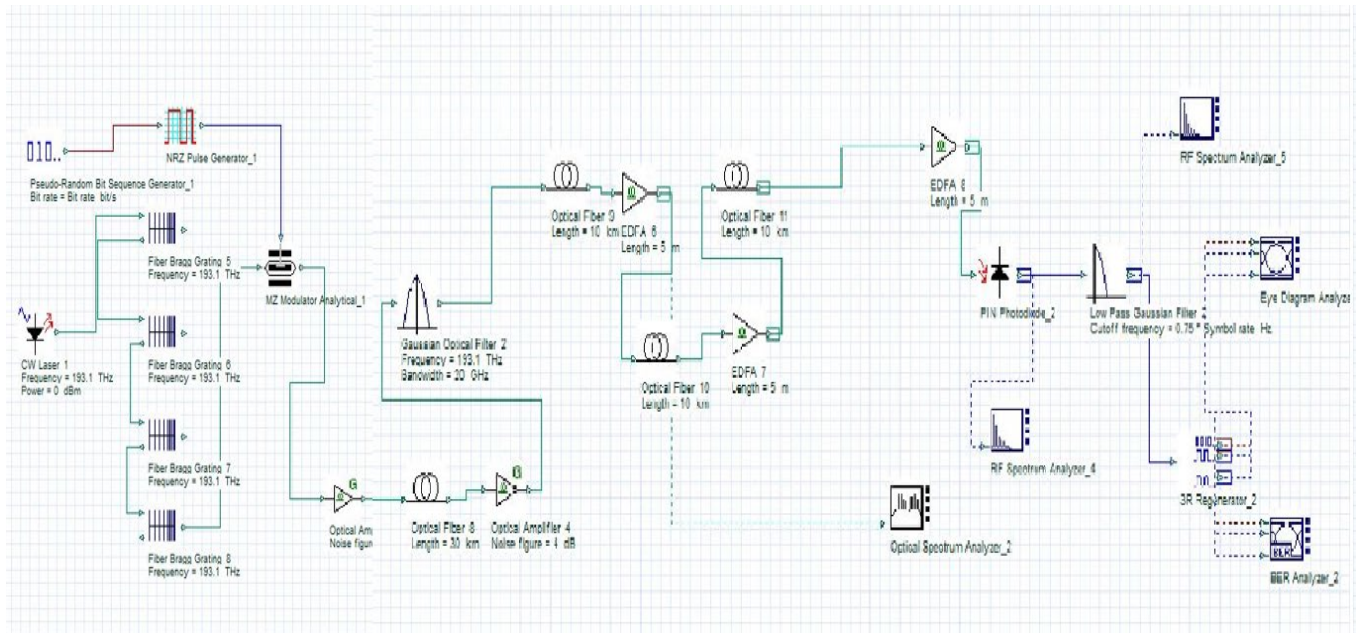


Figure 5 A system utilizing FBGs.

5. RESULTS AND DISCUSSION

In Figures 6 and 7, we have an Optical Spectrum Analyzer (OSA) that is utilized to analyze signals, like power, frequency and spectral width. This device breaks down the signal into its parts according to wavelength. Offers insights, into how optical power is spread across various wavelengths.

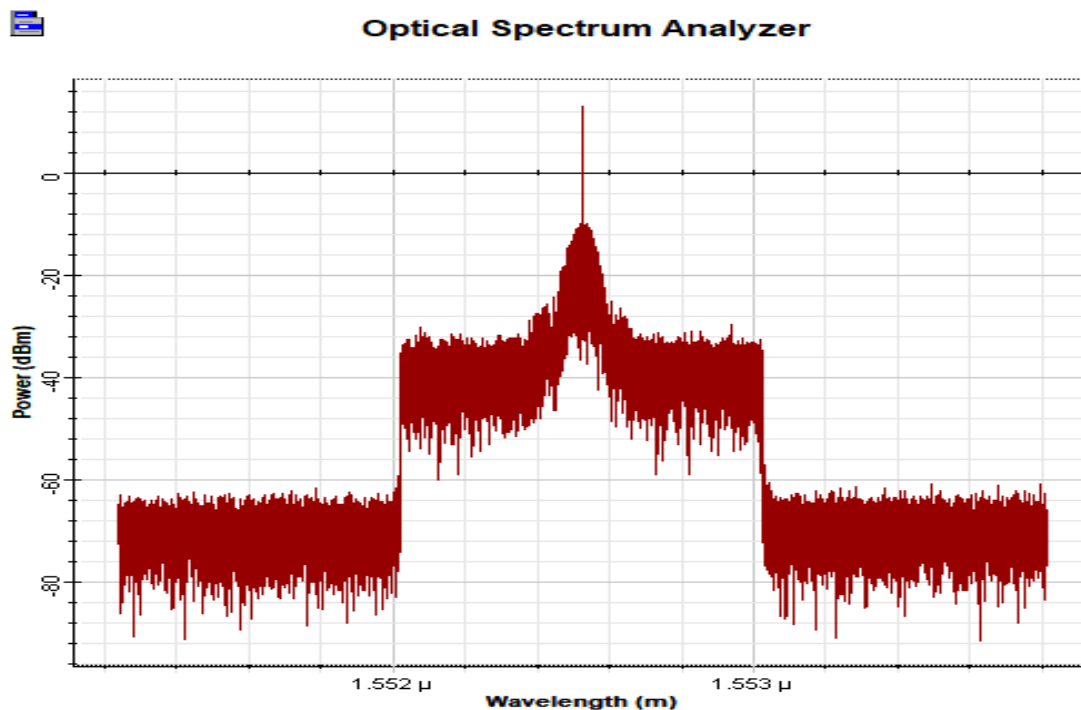


Figure 6 Examining optical signals utilizing.

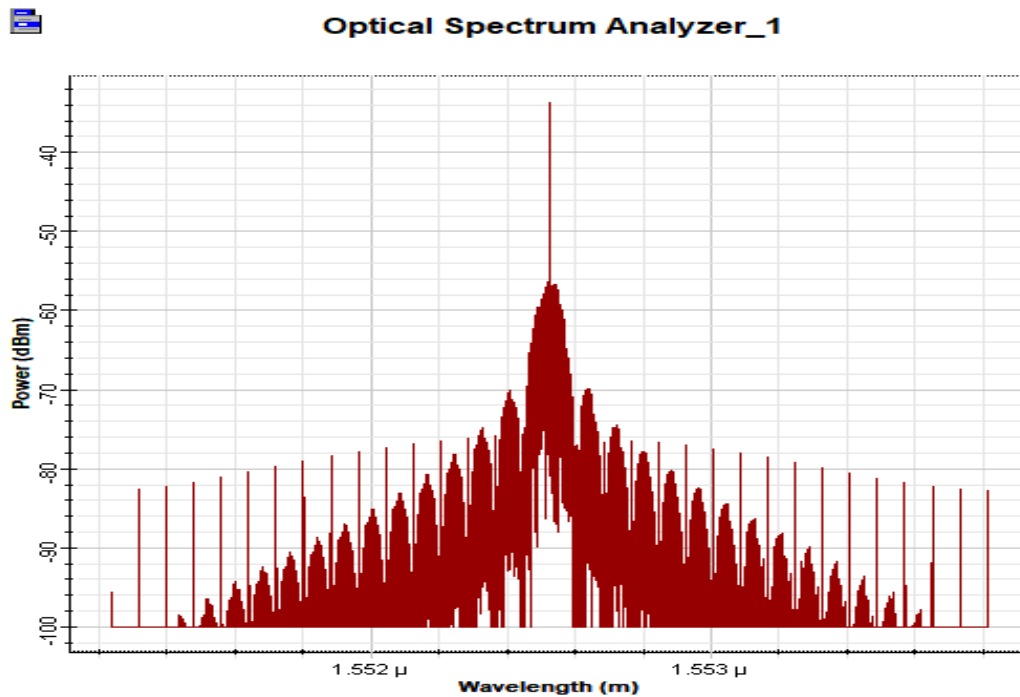


Figure 7 Understanding optical signals utilizing optical spectrum analyzer.

Figure 8 presents an assessment and examination of radio frequency signals spanning frequencies. It breaks down the signal into its components according to frequency. Shows details, on how power is distributed across these frequencies.

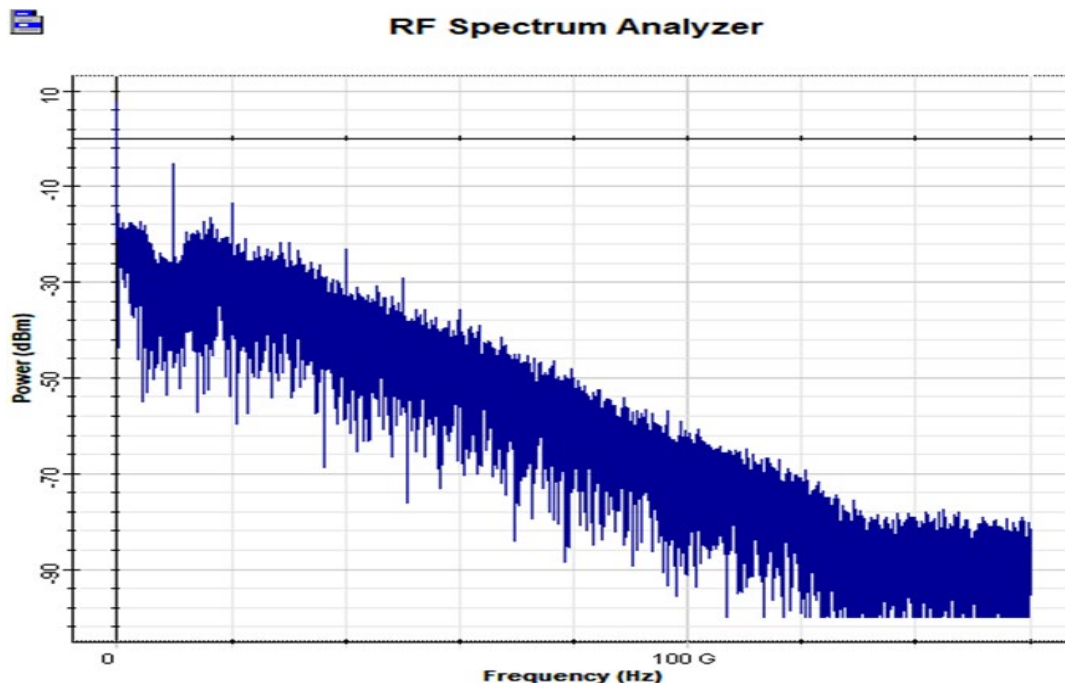


Figure 8 Examining and analyzing radio frequency signals with RF spectrum analyzer

In telecommunications networks the Q Factor plays a role, in evaluating the quality of a signal by showing the signal to noise ratio (SNR), in the system. Looking at this data we can see that the Bit Error Rate (BER) of the signal is tested over a distance of 170 kilometers of fiber giving us a measurement of 1.283×10^{-5} , as shown in figure (9). This value signifies how many bits are received inaccurately compared to the number of bits sent [46-50].

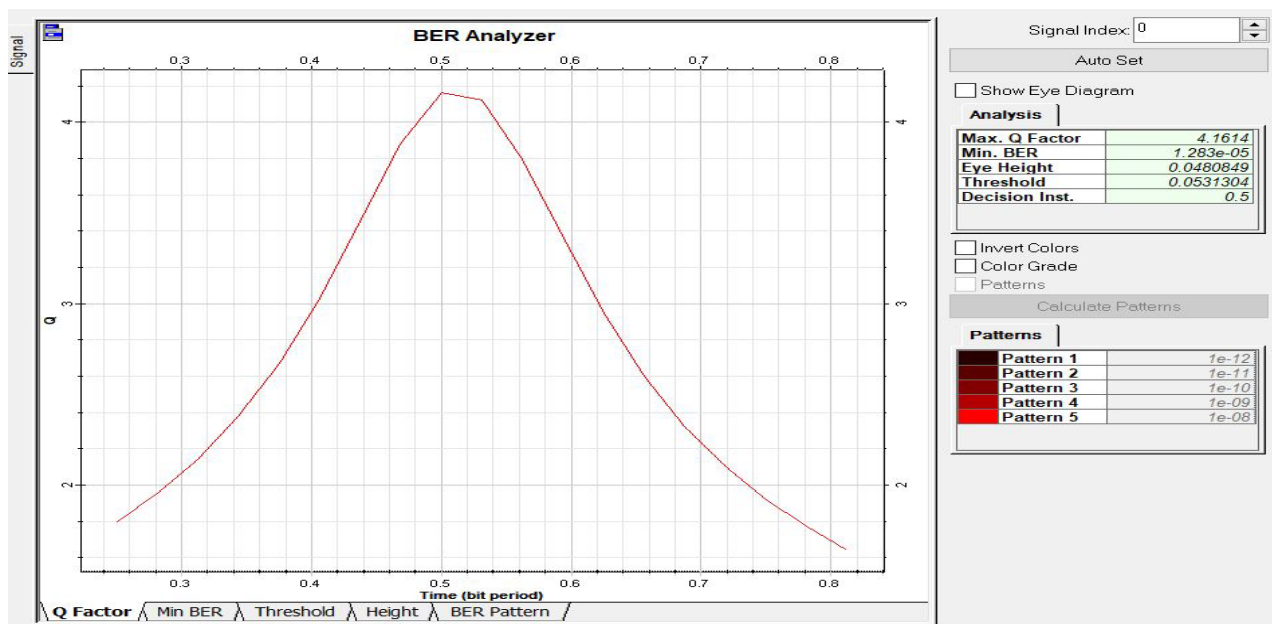


Figure 9 illustrates the Q-Factor value.

In the Eye Diagram analysis shown in Figure (10), it is used to assess the quality of the optical signal and determine the clarity and stability of the transmitted data. The signal is displayed as an eye diagram, which provides details on the extent of signal overlap and the stability of the signal at different time points [51-54]. In this scenario when the BER value is 1.283×10^{-5} , across a 170 km channel the eye diagram shows a level of quality. The visual representation of the signal is sharp and well defined with little, to no blurring or distortion. This indicates that the signal can be read accurately boosting trust in the systems effectiveness.

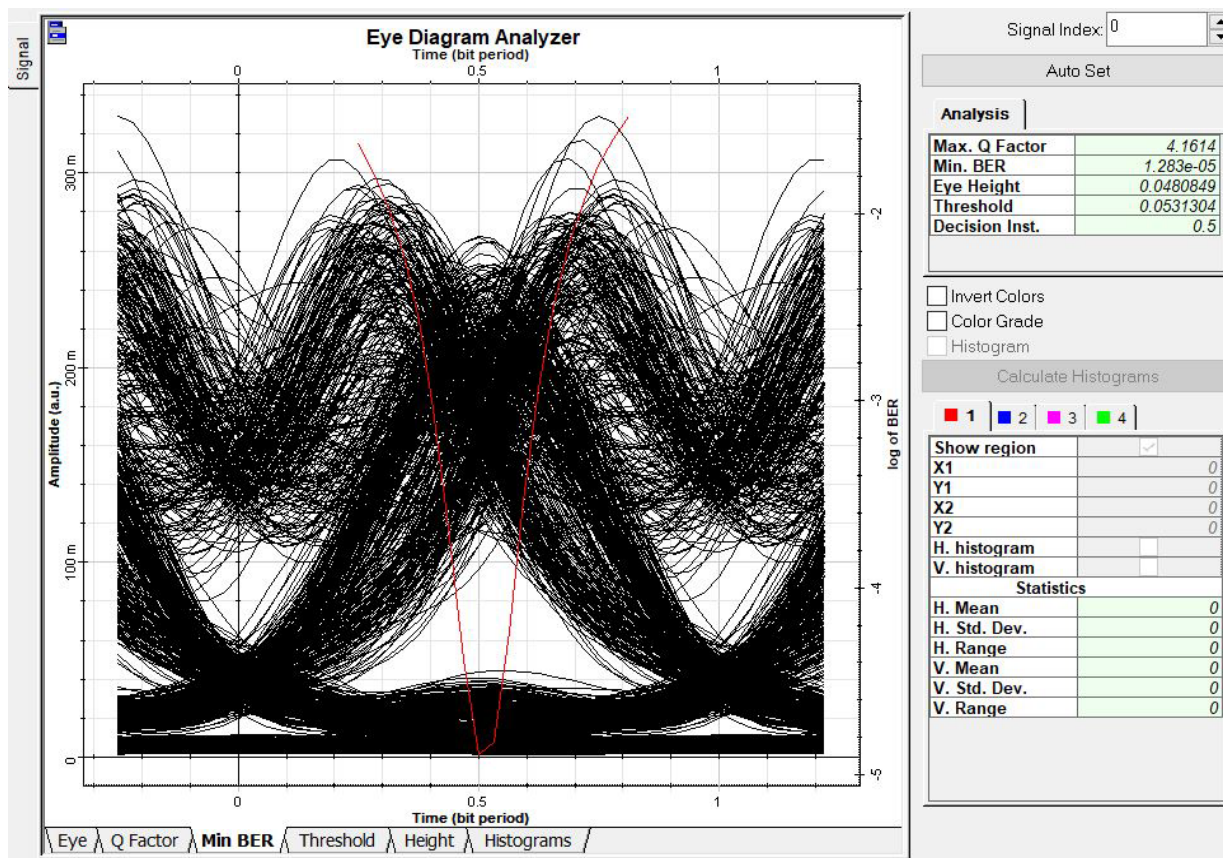


Figure 10 Analysis of eye diagram is demonstrated.

When examining the three systems outlined in Table (1) it is discovered that the main system, which utilized both Fiber Bragg Gratings (FBGs) and Ideal Distributed Compensation Fiber (Ideal_DCF) performed better, than the other two systems. The second system, which did not incorporate FBGs or Ideal_DCF displayed a higher Bit Error Rate (BER) and a lower Q Factor indicating signal quality and a greater occurrence of errors. The third system, which made use of FBGs but not Ideal_DCF exhibited performance compared to the system but still lagged behind the main system. The remarkable capabilities of the system are clear from its BER and elevated Q Factor, preserving performance even over lengthy distances, including transmissions reaching up to 170 km of optical fiber. This highlights the success of integrating FBGs with Ideal-DCF to improve quality and dependability in long-range transmission situations.

Table 1 illustrates the performance comparison of different optical systems utilizing FiberBragg Gratin gs and Perfectly Distributed Compensation Fiber.

Table 1 Comparison of three optical systems according to (BER) values.

Optical fiber length (km)	Free of FBG (BER)	It has FBG (BER)	It has FBG & Ideal-DCF (BER)
70	2.66108e-8	3.76264e-11	3.17028e-36
90	1.04268e-6	2.11423e-7	2.23914e-22
130	0.00053882	0.00004136	4.22628e-15
140	0.000740622	0.00016324	1.47324e-09
170	0.0482131	0.013126	1.283e-05

6. CONCLUSIONS

An optical communication system that utilizes Fiber Bragg Grating (FBG) fiber networks, including a designed FBG type to optimize system performance. A comparative study was carried out between setups, without FBG types and those using FBG fiber networks exclusively. The results emphasize the efficiency of our proposed system over long distances of single-mode optical fiber for data transmission. By narrowing the width of the source effectively our system exhibited improved performance compared to other setups. Throughout the study variations in transmission channel length and different types of optimized FBG fiber networks were thoroughly examined. The simulation results showed the flexibility of the system with the length of the optical fiber up to 170 km, as the BER value when the channel length was 140 km was equal to 1.47324e-09, and the eye diagram shows the high efficiency of the proposed system. In an experimental study, it is possible to verify the operation of the system and obtain practical results, thus comparing them with the simulation results.

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