Loss Mitigation and Digital Fiber Communication System Construction

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Abstract

In this research, we investigate how to increase the maximum Q-factor, minimum bit error rate (BER), and signal optical power (OP) in the event that the fiber cable utilized in the communication network system suffers a fault. In the current network system, we used non-return-to-zero (NRZ) and return-to-zero (RZ) modulation techniques. For both of the modulation types used in the system, we applied an optical amplifier (OA) alone after the fiber optic cable attenuation point in the network to improve the received signal's brittleness. For upgrading the current communication system, we then applied OA + polarization mode dispersion-emulator (PMD-E) techniques in the same serialization as written in the second case, looking for the best improvement results they provide. The study has provided a thorough comparison of the NRZ and RZ modulation strategies when each technique is used for loss enhancement using either OA alone or OA+PMD-E. The greatest performance had a maximum Q-factor of 542.9, a minimum BER of zero, and a received optical power of 12.76 mW when using NRZ modulation with OA+PMD-E. Using OA alone in the system has produced superior loss enhancement with RZ modulation than employing OA+PMD-E method. It recorded a maximum Q-factor of 420.54, a minimum BER of 0, and an optical power reception of 4.59 mW. With each of these improvements, the search is additionally clarified by the eye diagram. According to the study, the best loss enhancement for communication systems is achieved while employing NRZ modulation and applying OA+PMD-E.

Keywords: Loss Mitigation, Digital Optical Communication, Hybrid Amplifiers, Optical Amplifiers, PMD - Emulator, Quality Factor.

Introduction

A key component of the telecommunications infrastructure is fiber optics. Its high transfer speed capabilities and low decreasing characteristics make it ideal for sending large amounts of data. Figure (2) illustrates how an optical fiber communication system works. The transmitting side consists of an optical source and a modulator, which modulates the data from the source before it is transmitted through the transmitting medium (optical fiber). The receiving side is made up of a detector and a demodulator, which is located at the desired location [1]. Unfortunately, signal attenuation and other losses that occur throughout signal transmission through optical fiber lower the operation of the optical communication system. Attenuation in fibers can occur for a variety of reasons, including absorption, dispersion, scattering, bending, splicing, and connections. Temperature fluctuations can also play a role. In order to considerably improve their performance, further study and development of the primary components of Plastic Optical Fibers (POF) are required [2]. Although numerous studies have been conducted to repair these attenuations and losses in various ways, the destination still requires a suitable signal to operate the connection more effectively. The optical amplifier has enabled numerous improvements in optical networks [3]. The goal of current research and development activities is to make conveyed data more visible and to minimize data loss. The modification of the communication system's loss reduction has always been a crucial task for the power supply of the communication system in order to improve their economical operation, as the power loss of the communication network system makes up a sizeable portion of the entire power system. Despite the fact that there are many references on loss reduction strategies at the moment, they primarily concentrate on the theoretical development of various loss reduction strategies. The majority of earlier research has been on computing the power [4]. In this paper, a workable method of loss reduction for the communication system is proposed in order to address the aforementioned issues of unclear received information. NRZ modulation and RZ modulation were proposed, which could optimize multiple crucial goals of the communication system network and effectively reduce the power loss of the communication system network in comparison to other modulation techniques. This method is based on the combined use of optical amplifier first and PMD-E after him in cascade manner, as the results of testing with a vice versa connection did not yield satisfactory results. We measured the maximum Q-factor, minimum BER, and optical received power at various operating wavelengths. We contrasted the outcomes in the current communication system, the results demonstrated that employing NRZ modulation with OA+PMD-E is the preferred method of connection in the communication system, which recorded a maximum Q-factor of 542.9, a minimum BER of nearly zero, and a received optical power of 12760 µW. Which produced better readings in comparison to using OA alone with NRZ Modulation gave 1280 µW, with a maximum Q-factor of 542.9, a minimum BER of zero, OA+PMD-E RZ modulation, 4590 µW with a maximum Q-factor of 1150, a minimum BER of nearly zero, and using OA alone with RZ modulation received optical power of 4590 µW, a maximum Q-factor of 14.55, minimum BER of zero. And the study demonstrates that the best augmentation of the readings is achieved when utilizing NRZ modulation and

OA+PMD-E. The improvement of the communication system was also examined and demonstrated through the eye diagrams.

A digitally controlled multiwavelength variable fiber-optic attenuator employing a two-dimensional digital micromirror device (DMD) was first introduced by Nabeel A. Riza and Sarun in 1999. Results from a proof-of concept-attenuator with four experimental wavelengths 1546.92, 1548.52, 1550.12, and 1551.72 nm showed that it has an 11-bit resolution and a 26-dB dynamic range. The additive noise caused by the nonideal separation of the optical circulator and the attenuator module limited the reported attenuator average coherent optical crosstalk per wavelength channel to 238 dB [5]. When the receiver aperture, d_0, is less than the turbulence coherence diameter, d_0, Shlomi Arnon developed a bit-error probability (BEP) model in 2003 that accounts for both building tilt and tension log amplitude variations (i.e., fading of signal intensity). It is believed that the receiver is aware of the instant signal-fading condition as well as the peripheral statistics of the signal fading [6]. The transmission of 40Gb/s channels across DWDM optically amplified communications systems using RZ, NRZ, CS-RZ amplitude and differential phase shift keying modulation over 320 km standard SMF and 328 km dispersion compensating modules was documented by L. N. Binh and T. L. Huynh in 2007. On these 40G modulation schemes, the effects of optical filtering in a 10 Gb/s DWDM transmission system are described. It has been established that the mutual effects of 10G and 40G co-transmission are minimal [7]. Simranjit Singh and R. S. Kaler looked into post-, pre-, and symmetrical power compensation techniques in 2012 were discovered that using RAMAN-EDFA as a post power adjustment method results in the least bit error rate (10–40) and highest output power (12 dBm) at a signal input power of -15 dBm at the fiber cable [8]. Using the Mobile Telecommunications Network (MTN) Fiber Optic backbone project as a test bed, Alexande. N. Ndife, et. al. conducted experimental characterization in 2015. According to the results, there was essentially no attenuation or dispersion during amplification in an erbium-doped fiber amplifier (EDFA) at 1550 nm. The research work showed a 23% enhancement over earlier works, according to the findings [9]. Yoshiaki Tamura, et al. conducted research in 2018, they used a Ge-free silica-core optical fiber to obtain the lowest transmission losses ever, 0.1419 dB/km at 1560 nm and 0.1424 dB/km at 1550 nm. It was a 4 dB/km increase above the previous record set in 2015 [10]. The optical technique is used in 2020 by Ifeoma Asianuba and Christian Nwabueze to correct for mechanically induced anomalies (micro bends) or external pressure on the optical communication line. A 10% decrease in the micro-bend losses was realized based on the results. The refractive index of the fiber clad was raised in further efforts to minimize losses until it exceeded that of the core. This meant that channel losses caused by micro bends were rising rather than decreasing. Their research has particular relevance since it will help determine the precise marginal refractive index value needed to maximize throughput while ensuring efficiency [11]. In passive optical networks, Aadel M. Alatwi and Ahmed Nabih demonstrated the performance effectiveness of hybrid continuous-phase frequency shift keying (CPFSK)/optical quadrature-phase shift keying (OQPSK) modulation transmission schemes in 2021. Based on hybrid suggested modulation transmission approaches, differences in the maximum Q factor and minimum BER for different bits and symbols were carefully examined in relation to modulation frequency and fiber length. Based on hybrid modulation approaches for CPFSK/OQPSK of 32 bits/symbol and a modulation frequency of 500GHz across a fiber length of 30km, the maximum Q Factor, minimum BER, maximum signal power, and minimum noise power variations were achieved [12]. In a work published in 2021 by Elham Khoobjou et al., a new construction was introduced using metal nanoparticles for photonic crystal fibers (PCF) to reduce dispersion and optical loss. According to simulation studies, at wavelengths between 1.3 and 1.65 m, the loss is 7e4 dB/cm and the dispersion is less than 0.3 PS/nm/km. When compared to other relevant research, the light loss and dispersion are decreased [13]. Demissie Gelmecha, et al. released an article in 2022. Their paper's objective is to use space-division multiplexing (SDM)to increase the capacity of fiber optic communication (FOC) networks. The capacity increased during this procedure is around 14.75 pb/s/fiber, after which it starts to decline, and the transmission distance is 250 km with the usable C + L band wavelength. With single mode fiber (SMF) and multicore fiber (MCF), the signal to noise ratio in FOC is 35 dB [14]. A study on the lowering of optical fiber loss was published in 2022 by Elechi P., et al. To minimize loss and signal scattering caused by bending in optical fiber, they introduced the Marcuse's method and conducted bending studies on both multi-mode and single-mode optical fibers to calculate the loss. It was done to compare the outcomes of the different degrees of bending [15].

Optical Fiber Communication System

The high-performance characteristics of optical fiber communication low-absorption, restricted access, greater data potential, fast response, a longer service life, simple structure, relatively inexpensive, simple repair, small interruption, and good stability over long-distances have led to its widespread use [2]. In the optical spectrum, electromagnetic waves are transmitted by optical fibers, which are physical waveguides. They can be utilized as parts of integrated optical circuits, as a long-distance light wave communication transmission medium, or for biological imaging. Based on how many light rays need to be conveyed concurrently, fiber optics can be built to function in single-mode or multi-mode. Two categories of fiber optics step-index fiber and graded-index fiber can be distinguished based on the refractive index distribution. Fiber optics can be made from a variety of materials, including glass, polymers, and semiconductors [16].

Using a combination of dense wavelength division multiplexing and optical amplification, non-conductive optical fibers provide very high bandwidth. Using connectors or splicing procedures, fibers can be joined to one another [2]. Glass optical fibers are exceedingly expensive, difficult to join, and inappropriate for self-installations due to their readily breakable nature and extremely small core diameter. (POF), in contrast, has proven to be suitable for short-range data transfer, such as digital automobile networks, industrial networks, and home networks. Large core diameter, visible-spectrum operation, simpler and less expensive component requirements, and other benefits are also features of POFs [2]. Compared to glass fibers, installing a network utilizing POF in homes and offices is fairly straightforward, making maintenance easier. Moreover, the easier coupling of light from light sources into the fiber is made possible by POFs' greater numerical aperture (NA) [2]. Materials like polymethyl methacrylate (PMMA), polystyrene (PS), polycarbonates (PC), and others are used to make POFs. Figure 1 illustrates the transmission window that these materials have in the visible spectrum. Because of the extremely high transmission losses caused by light absorption and scattering at these wavelengths, POF can only be employed for short-distance data transfer. Polymethyl methacrylate (PMMA) serves as the primary component of the majority of the commercially available POFs [2].

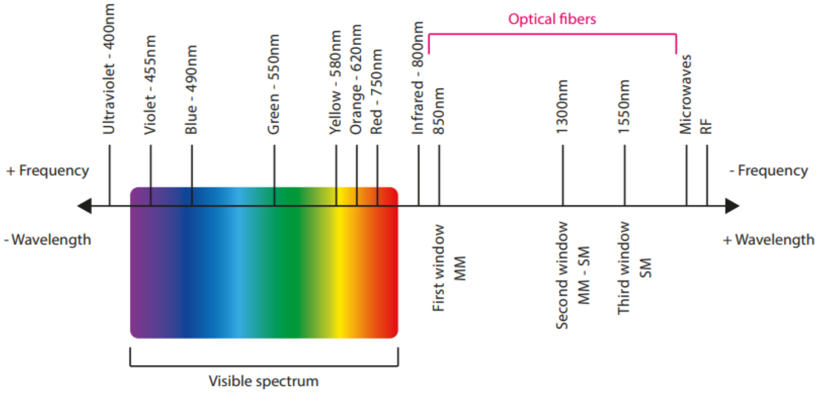


Figure 1. Electromagnetic Spectrum Regions

Figure 2 displays a block diagram of an optical fiber communication system. This system transmits an analog or digital signal across an optical fiber line from the information source to the intended recipient. A transmitter made comprised of a driving circuit, an optical source, and a channel coupler receives an electrical signal from the information source. The electrical-optical conversion is provided by the optical source, it could either be a light-emitting diode or a semiconductor laser (LED). The transmitter's job is to transform the input signal from the input source into an optical signal that can be transmitted. It is made up of an interface circuit and a source drive circuit, two separate components. The electrical signal must be transformed into an optical signal via the driving circuit. By controlling the current that passes through the light source, it was able to accomplish this operation [17]. An optical fiber cable serves as the signal transmission medium. The receiver is made up of a channel coupler, a photodetector, a decision circuit, and electronic circuits for linear channels. Photodiodes can be used to detect optical signals, convert them into electrical signals, and then send the electrical signals to their intended locations. The noise, scattering, dispersion, and absorption processes in the fiber cause the optical signal to gradually weaken and degrade [17]. The optical domain is more effective at signal processing than the electrical domain. Future optical systems should therefore be capable of processing information solely in the optical domain. Amplification, multiplexing, switching, and filtering are all parts of signal processing. Notwithstanding the benefits of using optical fiber for communication systems, more research must be done to enhance these systems and deal with their various problems [16].

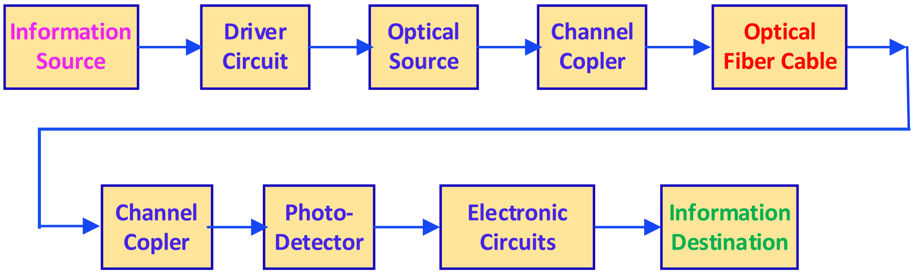


Figure 2. Optical fiber communication system.

Optical Fiber Attenuation

Attenuation or loss is the most significant transmission feature. The overall length of the fiber communication system is constrained by the transmission losses [16]. The optical fiber communication industry's method of data transfer aids in the transmission of extremely high data at the speed of light. Losses are connected to the optical fiber line, though. This problem, also known as attenuations, prohibits the transmission of the complete input signals [15]. When light passes through an optical fiber, attenuation, or loss of optical power, occurs. The ratio of optical output power (Po) to optical input power (Pi), which is the definition of signal attenuation, can be written as in dB [2]:

$$\text{Attenuation, } \alpha = -(10/L)\log 10[power\ out/\ power\ in]\ \text{dB} \qquad (1)$$

L is measured in kilometers, while loss is measured in decibels per kilometer. Extrinsic or intrinsic losses cause attenuation in optical fiber cables. Extrinsic losses are caused by things like mode of splicing, bending, and insertion losses, whereas intrinsic losses are caused by things like absorption, scattering, and dispersion losses [15]. Dispersion is the cause of the distorted digital and analog signals that are sent across optical fibers. Due to internal dispersion mechanisms in the fiber, transmitted light pulses spread as they move along the channel when fiber optic transmission is used, which requires some sort of digital modulation as a key component. Intermodal (modal) dispersion, which only occurs in multimode fibers, and intra modal (chromatic) dispersion, which occurs in all types of fibers (single mode and multimode), can be classified as the two main types of dispersion. These two types can also be divided into two subtypes: waveguide dispersion and material [16]. The intrinsic stress of the waveguide layers, which must be monitored and can be affected by the deposition conditions, is the only remaining source of birefringence. Finite difference BPM techniques were used to determine bending losses. Comparable to low waveguides, the minimum bending radii are as follows: At 1300 nm, a circular bend with a bending radius of 30 mm and an input-output lateral distance of 125 m results in a 0.04 dB loss. A 15 mm radius causes the loss to rise to 0.12 dB. Using tapered waveguides and elliptically linked bends makes it simple to reduce loss [18]. Power loss results from the transmitting light in optical fibers bending and radiating outward away from the core [15]. The material's absorption and Rayleigh scattering are two examples of the intrinsic losses in a POF. The highest allowable transmission loss is caused by absorption and scattering losses, which are dependent on the optical fiber's structure and cannot be reduced. The absorption owing to electronic transitions between various energy levels within molecule bonds and the molecular vibrational absorption of the groups C H, N H, and O H are the two main causes of absorption losses. The scattering resulting from composition, direction, and density changes is what causes the Rayleigh scattering loss [2]. The operational wavelength and the fiber type affect attenuation. Compared to multimode fibers, single mode fibers (SMF) exhibit less attenuation. The attenuation decreases with increasing operating wavelength. There are two absolute minima of attenuation for the PMMA POFs, which are positioned at 522 and 570 nm (green), and a relative minimum at 650 nm (red). Because PMMA POFs fall inside the attenuation window centered at 650 nm, it is customary to employ red lasers or rapid, high-luminosity red LEDs with them. The fiber core diameter also affects attenuation, which rises as core diameter falls. Moreover, it is influenced by the light source's numerical aperture (NA) and spectral bandwidth. Higher attenuation results from an increase in the spectral bandwidth or the source's NA [17]. Extrinsic losses include the scattering aggravated by dust particles, microfractures, bubbles, and other structural flaws in the POF, as well as the absorption brought on by both metallic and organic contaminants. Moreover, there are radiation losses that are caused by changes in the fiber geometry, both microscopic and macroscopic. Radiation losses happen if the POF is bent with a specific curvature radius [2].

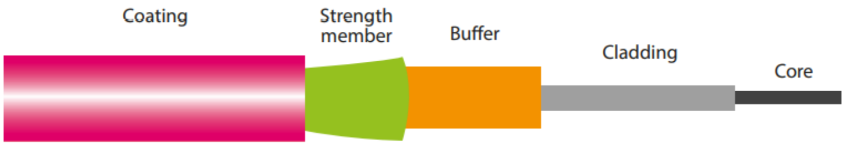


Figure 3. optical fiber cable components

Fiber cabling has losses from absorption and reverse reflection of the light produced by imperfections in the glass. Because attenuation depends on wavelength, it must be provided for the specific wavelength being used [19].

The data rate directly affects modal dispersion, which is only an issue with multi-mode cable. The signal's maximum travel distance before modal dispersion makes it impossible to distinguish between a "1" and a "0" accurately decreases with increasing data rate. Despite the fact that modal dispersion does not affect single-mode fiber, other dispersion effects still limit the distance possible as a function of data rate and induce pulse spreading. One of the most prominent examples of this is chromatic dispersion, where the wider spectrum of some transmitter types can lead to differing travel lengths for various components of a light pulse. Chromatic dispersion rarely becomes a problem before Gigabit speeds [19]. Polarization Mode Dispersion (PMD) is regarded as a significant restriction in long-distance communication transmission systems with the expansion of data rates, greater than 10-Gbits/s/channel, this results from the differential group delay (DGD) between the two primary states of polarization (PSPs), which is caused by random birefringence in fibers and devices [20]. There is no ideal loss-free splice, despite being small and frequently negligible. Refusal to include splices results in several inaccuracies in loss computations. With single mode cable, the typical splice loss is less than 0.01 dB [19]. There isn't a 100% loss-free connector, much like with splices. It is significant to remember that connectors of any quality might become unclean. A fiber light wave can be totally obscured by dirt and dust, resulting in significant losses. Connector loss typically ranges from 0.15 dB (LC) to 0.5 dB. (ST-II). The worst-case situation, presuming a cleaned and polished connector is used, is to employ 0.5 dB loss per connector. It is important to keep in mind that there will always be a minimum of two connectors per fiber segment [19]. A few dB of loss are frequently added as a design margin. Allowing 2 to 3 dB of loss can account for factors like as fiber aging, inadequate splices, temperature and humidity, etc. and guarantee a reliable system. The best way to calculate losses is to take actual measurements after the fiber has been placed. The total of all worst-case parameters inside a fiber section is used to calculate maximum signal loss [19].

Since fibers bend easily, bend losses are a typical issue in waveguides, particularly in optical fiber. Light from core modes (directed modes) is connected to cladding modes when optical fibers are bent, increasing dispersion losses. These losses often rise rapidly once a critical bend radius is reached [15].

The incident angles of light beams at the interface between the core and cladding vary if a fiber is bent. Because the criterion of total reflection, as illustrated in figure 4, is not met, some beams are released from the fiber as a result, and an overflow of attenuation is visible. Bending loss is divided into macro bend loss and micro bend loss based on the bend radius of curvature [2]. The bending effects cause fibers to experience higher losses. Micro bends are frequently overlooked bends in the core cladding interface, while macro bends are massive bends of the cable and fiber. These latter losses are referred to as the cabling loss and spooling loss, correspondingly [21]. Mode field diameter and cutoff wavelength are used to measure macro bending, which is induced by the curve of the whole fiber axis, which created the "MAC number," an experimental parameter that measures the mode field diameter from over cutoff wavelength [22]:

$$MAC = \frac{mode\ field\ diameter}{cutoff\ wavelength} \qquad (3)$$

$$\lambda_c = \frac{\pi d\sqrt{n_1^2 - n_2^2}}{2.405} \qquad (4)$$

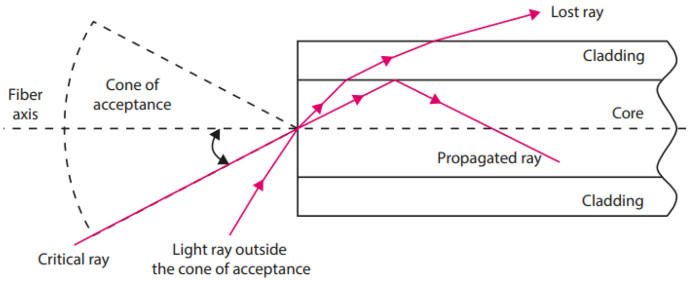


Figure 4. Explanation of bending loss.

Lowering the mode field diameter and raising the core-cladding refractive index difference (relative to the cutoff wavelength) both result in reduced macro bending loss because the smaller the MAC number, the less macro bending loss there will be. Longer wavelengths are less likely to cause loss bends. Figure 5 illustrates the macro bending-induced attenuation at a threshold wavelength, where it is comparatively small at short wavelengths [22]. Micro bending is the term for tiny, microscopic bends in the fiber axis that can occur at any time during production, cable installation, or service. They develop as a result of environmental factors, mainly changes in temperature. Little surface defects brought about by micro bending have the potential to lead to radiation loss by coupling adjacent modes. When a fiber experiences significant bending above a certain level of curvature (the curvature is big compared to the fiber diameter), such as when the fiber is rolled on a wrap, macro bending occurs. Since the enormous bend curvature causes an angle that is too acute for the light to be reflected back into the core, part of it departs from the fiber's core and is attenuated by the cladding. The majority of macro bend production occurs during the installation of POF.

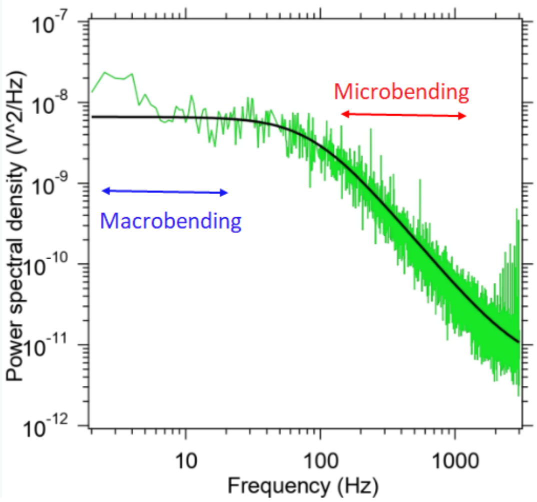


Figure 5. A graph showing pitch Power Spectral Density (PSD) shown in green for a 3 µm birefringent birefringent particle trapped inside the sample chamber [23].

The losses are essentially nonexistent when the curvature is minimal. In a conventional PMMA step index POF, study discovered that radiation power losses grow exponentially for a whole turn like the bend radius reduces [2]. Depending on the fiber requirement and the micro-bend Gaussian shape, Petermann-'s approach provides an approximation of the micro-bending loss; specification and the micro-bend Gaussian geometry is given [22]:

$$\alpha = \frac{q}{m}\left[\frac{A^2B^3}{(B^2+\sigma^2)^{\frac{5}{2}}} + \frac{\sigma^2 B}{2(B^2+\sigma^2)^{\frac{3}{2}}}\right] exp\left[\frac{-A^2}{B^2+\sigma^2}\right] \quad (5)$$

Where:

Q = Constant, K = Wave number, N = Refractive index of the core, α = Standard deviation parameter, A = Average half width at 1/e amplitude.

The variable q is defined as the square of the amplitude of the modest, Gaussian-like oscillations in the radius of the core as indicated by Y2 and the combination of an experimentally determined constant. As a result, we can write q like [22]:

$$Q = 13.644\, Y^2 \qquad (6)$$

The parameter m defines the product of the square of the patch size w and the period (time interval between the Gaussian nodes) between the Gaussian oscillations or micro bends along the fiber line. We possess that

$$m = L\, w^2 \qquad (7)$$

This suggests that a purported decrease in L will result in greater fiber line losses. The following is the result of replacing the variables q and m with their respective expressions in Petermann's equation to simulate the micro bending loss anomaly:

$$\alpha = \frac{13.644\, Y^2}{Lw^2}\left[\frac{A^2B^3 2(B^2+\sigma^2)^{\frac{3}{2}}+\sigma^2 B(B^2+\sigma^2)^{\frac{5}{2}}}{(B^2+\sigma^2)^{\frac{5}{2}}\, 2(B^2+\sigma^2)^{\frac{3}{2}}}\right] exp\left[\frac{-A^2}{B^2+\sigma^2}\right] \qquad (8)$$

A = half-width averaging at 1/e amplitude

σ = The half-width parameter's standard deviation describes fluctuating half-width values.

$$B = \frac{kn\, w^2}{\sqrt{2}} \qquad (9)$$

k = wave number, provided by the expression:

$$k = \frac{2\pi}{\lambda} \qquad (10)$$

n = refractive index of the core.

The method used to simulate the decrease of micro-bending through optimization of the Pertermann model links the anomaly of micro-bending which is known to be caused externally to the internal parameters that reflect the presence of these micro-bends [22]. Moreover, it is quite simple to prevent optical interference between fibers; as a result, crosstalk is not noticeable even when several fibers are connected together, unlike communication utilizing electrical conductors.

Researchers have developed the Marcuse's approach to reduce loss and signal scattering caused by bending in optical fibers. They also conducted bending experiments on both multi-mode and single-mode optical fibers to calculate the loss [15].

Relative refractive indexes can range from greater than one to exactly one. If we switch from material 1 with a refractive index of (n1) to material 2 with a refractive index of (n2), the result will be as shown. Then, you can determine the relative refractive index 1 n2 by dividing the speed of light in material 1 (C1) by the speed of light in material 2, or by dividing the refractive index of material 2 (n2) by the refractive index of material 1, or by dividing the sine of the incident angle (1) by the sine of the refracted angle (2) in Fig. 5 [15].

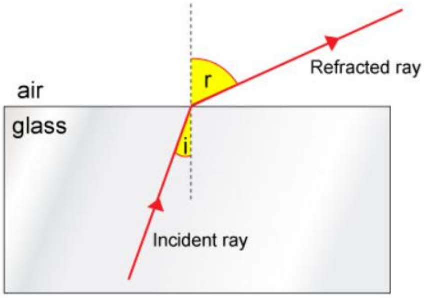


Figure 6. Relative refractive index [15].

Material 1 = glass
Material 2 = air

$$1n_2 = \frac{c1}{c2} = \frac{n2}{n1} = \frac{\sin\theta1}{\sin\theta2} \qquad (11)$$

Critical Angle

when a light ray passes through an optically less dense medium, like air, before arriving at its destination. The light ray travels along the edge between the two materials when the angle of refraction reaches 90 degrees, the angle of incidence is known as the critical angle (ϑ_c). Fig. 6 [15], [16].

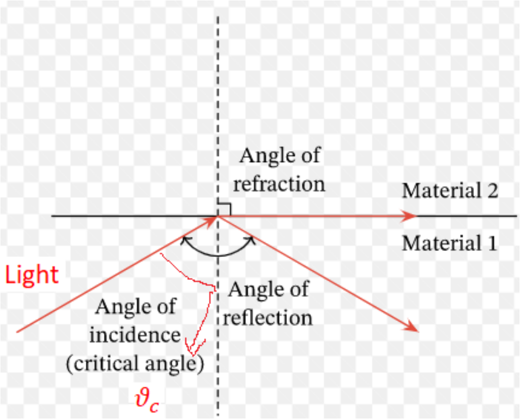


Figure 7. Light at critical angle.

$$S\frac{\sin\theta1}{\sin\theta2} = \frac{n2}{n1} \qquad (12)$$

$$S\frac{\sin\theta c}{\sin 90} = \frac{n2}{n1} \quad (13)$$

$$S\frac{\sin\theta c}{1} = \frac{n2}{n1} \quad (14)$$

$$\sin\theta c = \frac{n2}{n1} \quad (15)$$

If air is the second substance, then m2 = 1 and so on. [15]

$$\sin\theta c = \frac{1}{n1} \quad (16)$$

Total internal reflection, shown in Fig. 7 occurs at the boundary between the two materials if the incidence angle is greater than the critical angle [15].

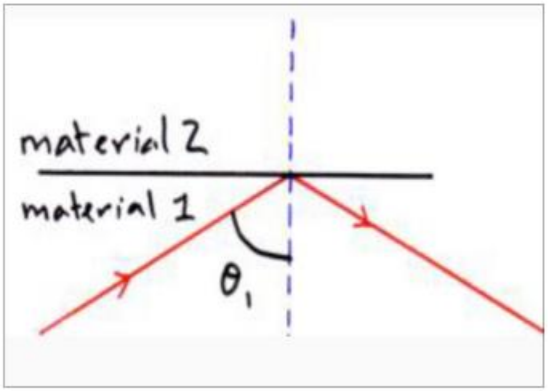


Figure 8. Incident light totally reflected

Step Index Fine glass makes up the core of optical fibers, which is encased in a layer of glass with a lower refractive index than the core. This means that light reflected entirely at the core-cladding interface will be from an angle-shone light entering the core. After passing through several reflections throughout the fiber's length, the light eventually emerges at the opposite end (Fig. 8).

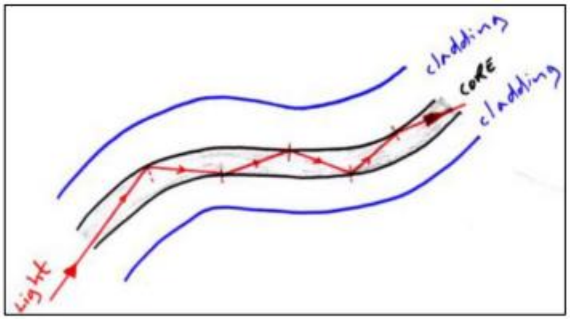


Figure 9. Step index optical fiber or Macro bending schematic in an optical fiber [15].

$$n' = n_{material} . e^{\frac{x}{R}} = n_{material}(1 + \frac{x}{R}) \qquad (17)$$

As comparison to the unstressed condition, the refractive index of a stress bend fiber (n ′) experiences two types of distortion: comprehension along the inner half of the fiber, toward the center of the bend, and tension along the outside half (Fig. 9). It is possible to say this:

$$n_{material} = n\left[1 - \frac{n^2 x}{2R}[P_{12} - v(P_{11} + P_{12})]\right] \qquad (18)$$

where P_{11} *and* P_{12} are components of the photo-elastic tensor and ν is Poisson’s ratio. [15]

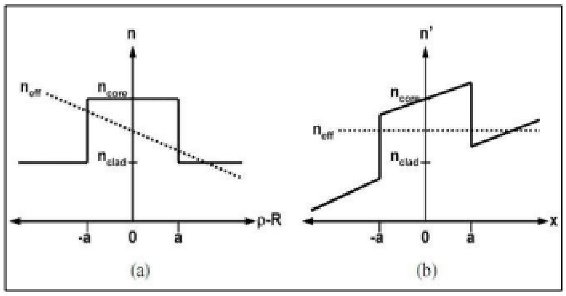


Figure 10. Refractive index distribution of an unstressed bent fiber and its equivalent straight fiber after conformal map [15].

SMF's output optical power is provided by [21].

$$P_o(Z) = P_i \,.\, 10^{\alpha_T . \frac{z}{10} dB} \qquad (19)$$

And provides the attenuation coefficient (α bend) [21].

$$\alpha_{bend} = c_1 e^{-c_2 r_b} \qquad (20)$$

where (c1) and (c2) are constants and (rb) is the fiber bend's radius of curvature. Up until the radius reaches a certain size specified by, the losses are virtually nil [21]:

$$r_{critical} \approx \frac{3 n_2 \lambda}{4\pi (NA)^3} \qquad (21)$$

According to this relationship, the fiber needs to have a high NA and operate at a short wavelength [21].

Air also has a lower refractive index than core glass, therefore the optical fiber would still function without the cladding. Yet, the cladding is advantageous since it safeguards the core and reduces crosstalk and light leakage. The core should be narrowed to reduce multimode dispersions, which occur when light enters the optical fiber at slightly varying angles, travels through the fiber at various rates, and broadens out as a result [15].

The goal of this study is to look into ways to reduce attenuation and signal transmission losses over a fiber optic connection. By using optical amplifiers and the PMD-E connection in series approach, power losses brought on by signal transmission over the 50 km long fiber are reduced in an optical fiber communication system.

Operating Wavelength

The bands designated for intermediate-range and long-distance optical fiber communications are identified by the letters O, E, S, C, L, and U, which are outlined in Table 1 of the International Telecommunication Union's (ITU) regulations. O-band and C-band are the more often used bands since they attenuate the least across the length of the fiber. The lowest attenuation occurs between 1.310 µm and 1.550 µm in wavelength. For these selected bands, where attenuation is less than 0.6 dB per kilometer, the laser source manufacturers have created a variety of laser sources [16].

ITU band regulations

Name	**ITU Band**	**Wavelength λ (µm)**
Original band	O-band	1.260 to 1.360
Extended band	E-band	1.360 to 1.460
Short band	S-band	1.460 to 1.530
Conventional band	C-band	1.530 to 1.565
Long band	L-band	1.565 to 1.625
Ultra Long band	U-band	1.625 to 1.675

Wavelength: 780–850 nm Free Space Optics (FSO) activities are ideally suited for these wavelengths. Reliable, affordable, high-performance transmitter and detector parts are easily accessible at 850 nm. Typically, network and transmission equipment use the wavelength. A 1520–1600 Hz range wavelength can be operated with advanced vertical-cavity surface emitting laser (VCSEL) technology and highly sensitive silicon (Si) avalanche photodiode (APD) detector technology. These wavelengths are appropriate for transmission in free space. Nonetheless, the parts are typically expensive. When compared to Si APD detectors that operate at 850 nm wavelength, the detectors are less sensitive and have a lower receiving surface area. Finally, for the same eye safety classification, 1520-1600 nm may transfer 50–65 times more power than 780–850 nm can [24].

In the wavelength range where optical fibers have a comparatively small transmission loss, fiber-optic communication is primarily carried out [2]. Between 1260 nm to 1650 nm, this low-loss wavelength range is located. Combining numerous optical amplifiers in parallel or series, each of which operates over a different spectral region, is an additional method of realizing wideband optical amplifiers [25]. A hybrid optical amplifier (HOA) is a similar configuration that has been found to improve system capacity and performance [26].

Optical Amplification

For prospective use in optical communication systems, direct optical amplification of signal light is of great interest. For such an application of amplification, nonlinear optical phenomena have received a lot of interest during the past several years. The use of stimulated Raman scattering, stimulated Brillouin scattering, or stimulated four photon mixing can all lead to optical amplification in optical fibers [27].

The two classifications of optical amplifiers are semiconductor optical amplifiers (SOA), and optical fiber amplifiers. Applications for conventional systems that use in-line amplification to make up for optical link losses are dominated by the former. Nonetheless, the SOA is shown excellent promise for application in developing optical communication networks thanks to improvements in optical semiconductor fabrication techniques and device design. It has a variety of functional uses, including as optical switching and wavelength conversion, in addition to its use as a general gain element. Transparent optical networks need these operations, where optical signals are not converted into electrical signals [3].

Fiber attenuation, chromatic dispersion, polarization mode dispersion, and nonlinearity are the significant losses in single mode fiber transmission that have an impact on the efficiency of the system. For transmission systems intended to function over distances more than 100 km, fiber attenuation must be corrected for since its cumulative effects potentially lead the signal to become so weak that data cannot be recovered at the receiver. The loss issue is resolved by optical amplifiers, but the dispersion issue is made worse since dispersive effects can build up over long distances. A dispersion-compensation fiber, fiber bragg grating, and optical phase conjugator can all be used in reality to control the dispersion issue. Chromatic dispersion can be eliminated by using dispersion management [28]. Although SOA are small, they may be integrated with other components on the same chip thanks to the utilization of semiconductor materials. Since SOAs may additionally magnify the signal being processed through electrical pumping, they can be employed for optical signal processing without adding insertion losses [29]. The transmission distance is limited by fiber attenuation. Using either (i) Lumped Amplification or (ii) Distributed Amplification are the two most used methods for loss compensation.

Lumped amplification: The transmission system uses an optical amplifier to account for loss. The Stimulated Raman Effect provides the foundation for distributed amplification [28]. Due to their low effective Noise Figure (NF) performance, distributed Raman amplifiers are finding more uses in long-distance communications and high data rate systems. By rerouting data traffic in the optical domain without first converting it to electrical signals and then back to rerouted optical signals, wavelength converters can significantly increase network accessibility and scalability. Cross-phase modulation (XPM), cross-gain modulation (XGM), and four-wave mixing (FWM) are the typical techniques used to convert wavelengths [29].

Raman amplification is extremely adjustable because stimulated Raman scattering allows a Stokes shift (13 THz) from the pump to the signal, which gives additional freedom for the selection of the pump wavelengths and the Raman gain fiber [30]. Historically, amplification takes place in a closed amplification module that is placed where it is absolutely necessary. Erbium Doped Fiber Amplifiers (EDFA) and Semiconductor Optical Amplifiers are two examples of these lumped amplifiers (SOA). Raman amplification, on the other hand, can happen in any fiber, including the transmission fiber itself. This enables distributed Raman amplification (DRA), a technique that involves pumping the transmitting fiber to amplify the signal traveling through the fiber [29]. Since high PMD fibers are difficult to obtain in the lab, simulators must be used to replicate the characteristics of the fiber used in ancient transmission connections. The temperature can be used by a PMD emulator to create variable birefringence, although installed cables need active PMD compensators [20].

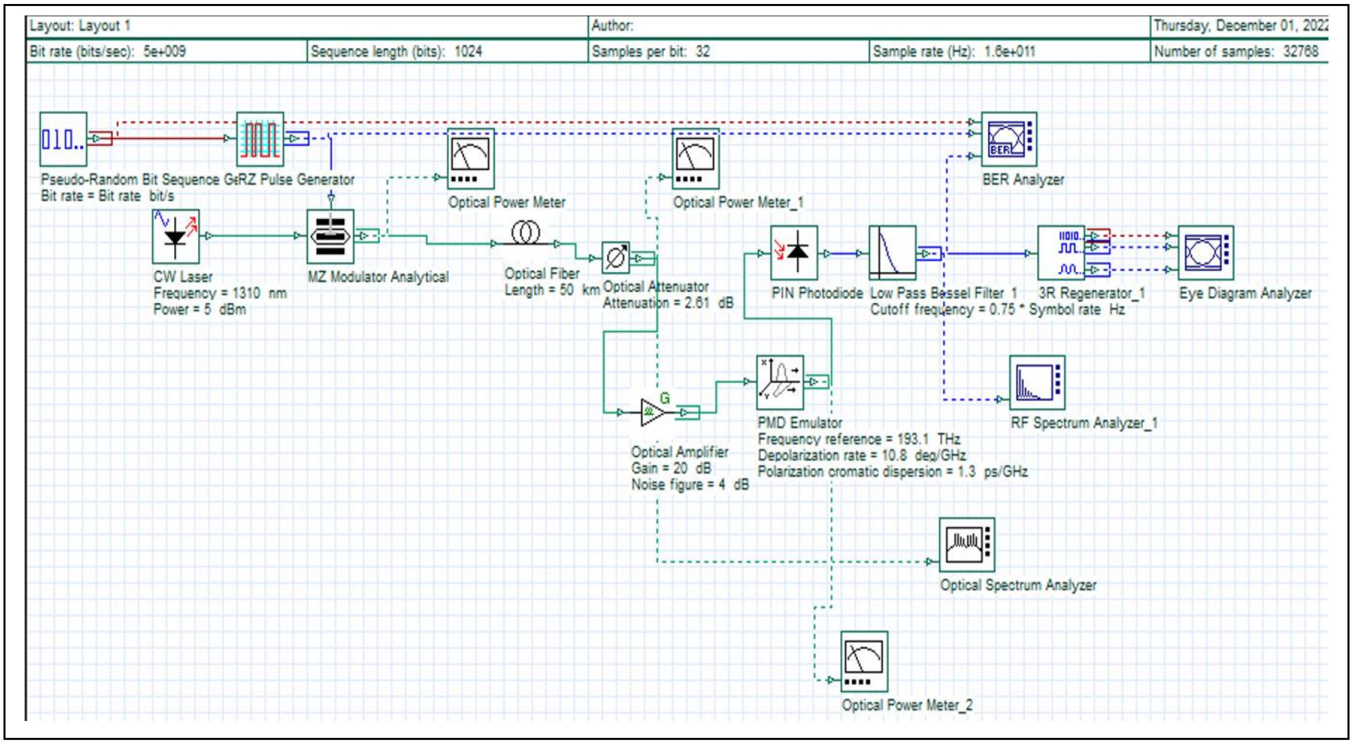
In contrast to single optical amplifiers, hybrid amplifiers amplify differently [31]. PMD-Emulator improves the power in the useable signal to the power in flaws such as to quantify impairments (noise power and distortion power). This demonstrates excellent detection evaluation [32].

Simulation setup

We created the optical fiber communication system depicted in Figures 11 and 12, with their optical communication system block diagrams likewise shown in b branches, in accordance with Table 2's primary simulation parameters. The design of the SMF optical fiber communication system was simulated using the simulation program "OPTISYSTEM 15". The user-defined bit sequence generator is connected to the pulse generators we tested, the RZ and NRZ pulse generators, which are connected to a MZM. The MZM modifies the signal sequence given to it with the laser signal before the prepared signal is sent to the transmission medium, an optical fiber with a length of 50 km. A reliable prediction methodology that can address the many components and assemblies utilized in such a system is now required because to the recent interest in the usage of fiber optic data lines in military/defense, civil, and academic applications. Unfortunately, there were a number of attenuations that occurred during information transmission in optical fiber connection, which decreased system performance and caused communication system degradation and unidentified information signal at the receiver end. A design issue is the core issue with communications. The combination of Communication links is typically referred to as a data link because the Information is restricted to being a series of bits. The input data signal generally refers to the disturbance that the transmitter introduces into the transmission medium. The output data signal is the disturbance that results at the receiver. The main issue with communications in the context of our topic is creating a data link that is suitable for connecting a specific source-user pair. We created the system employing a hybrid connection of an optical amplifier in cascade with a PMD-E in order to improve the communication system and provide a more dependable received information stream.

Table 2. The communication system properties

Parameter	Value
Input Power	5 dBm
Input frequency	193.1 THz
Input Wavelength λ (µm)	1.553 = C band
Bit rate	5 G bit/sec
Optical Fiber Cable Length	50 Km SMF
Attenuation	2.61 dB
Modulation Type	RZ and NRZ
Operating Wavelength λ (nm)	1310 to 1552 = E band and S band



Layout: Layout 1
Author:
Thursday, December 01, 202
Bit rate (bits/sec): 5e+009
Sequence length (bits): 1024
Samples per bit: 32
Sample rate (Hz): 1.6e+011
Number of samples: 32768

Figure 11. Optical Fiber Communication Circuit Design Using RZ-Modulation and Optical Amplifier + PMD-E

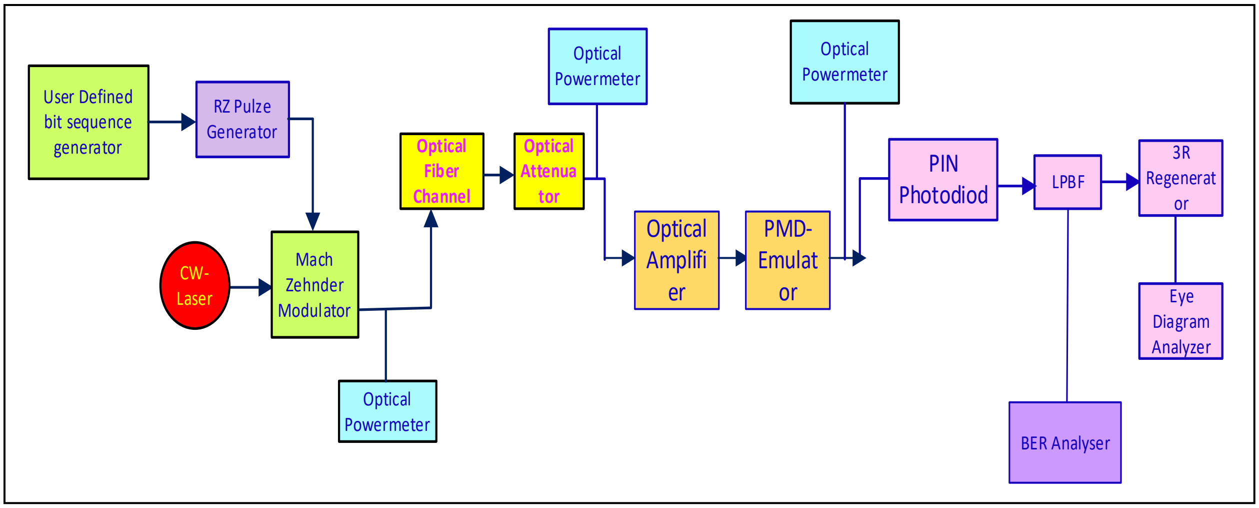
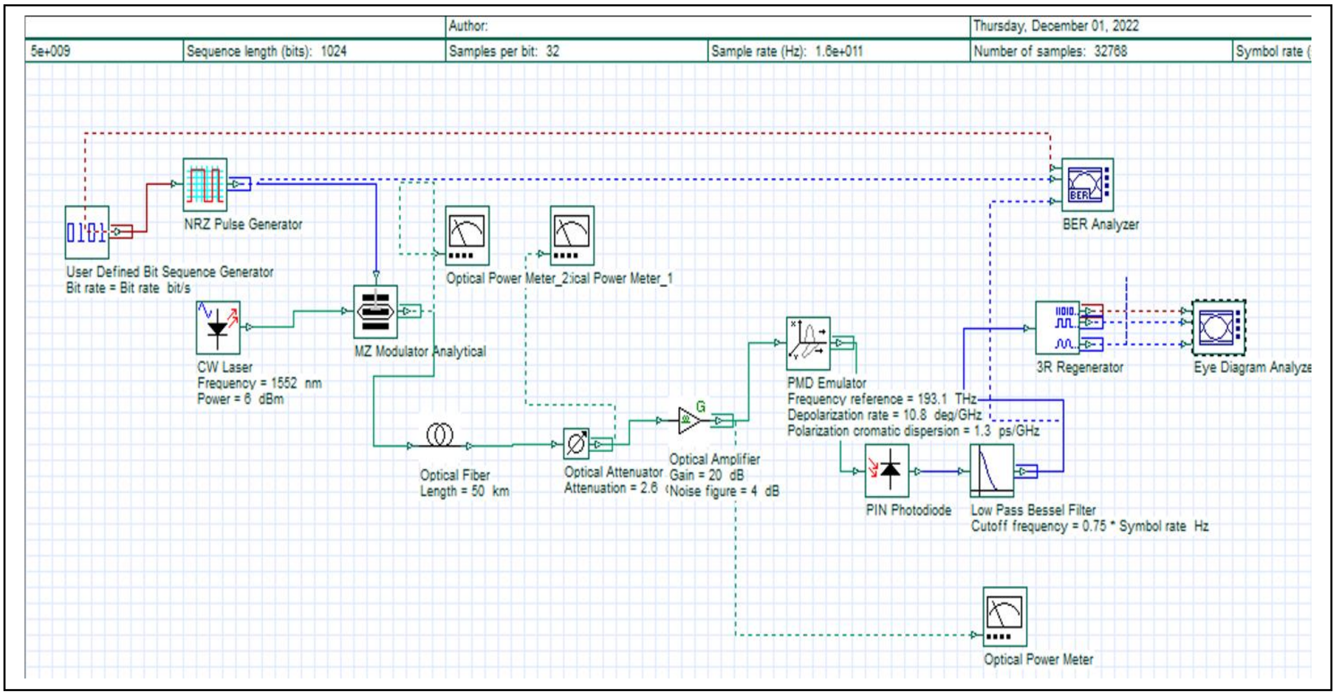


Figure 11. b. Block diagram of RZ-Modulation and Optical Amplifier +PMD-E in the Optical Fiber Communication System Design.


Author:
Thursday, December 01, 2022
5e+009
Sequence length (bits): 1024
Samples per bit: 32
Sample rate (Hz): 1.6e+011
Number of samples: 32768
Symbol rate (

User Defined Bit Sequence Generator
Bit rate = Bit rate bit/s

CW Laser
Frequency = 1552 nm
Power = 6 dBm

Optical Fiber
Length = 50 km

Optical Attenuator
Attenuation = 2.6 (

Optical Amplifier
Gain = 20 dB
Noise figure = 4 dB

PMD Emulator
Frequency reference = 193.1 THz
Depolarization rate = 10.8 deg/GHz
Polarization cromatic dispersion = 1.3 ps/GHz

Low Pass Bessel Filter
Cutoff frequency = 0.75 * Symbol rate Hz

Figure 12. Optical Fiber Communication Circuit Design Using NRZ-Modulation and Optical Amplifier +

PMD-E

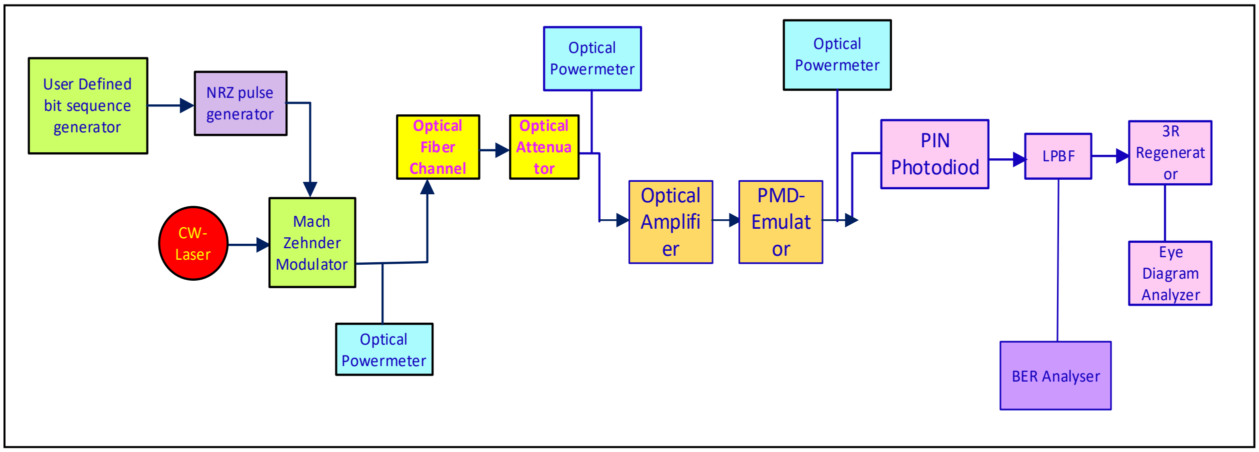


Figure 12. b. Block diagram of NRZ-Modulation and Optical Amplifier +PMD-E in the Optical Fiber

Communication System Design.

Results and Discussion

During transmission distances longer than 50 km, an optical amplifier and PMD-E connection is used to analyze and lessen the impact of attenuation in the optical network. Q factor, received power, and bit error rate (BER) are used to evaluate system performance. In "Optisystem 15," extensive simulation sets are run to research and assess the optimal ways to achieve outcomes in fiber optic communication systems. The attenuation measurement will differ depending on the type of cable and wavelength being utilizedThe objective is to convey the most data across the longest distance with the least degree of signal loss while selecting a transmission wavelength. Absorption is one way that a signal might be attenuated. Little amounts of water vapor or trace metals that are present in the glass can absorb light signals and cause them to be lost. The greatest amounts of absorption occur at particular wavelengths.

A chart showing the attenuation for the full fiber route can also be used to quote attenuation in dB/km. Attenuation is measured in dB. The lowest attenuation occurs between 1.310 µm and 1.550 µm in wavelength. A wave's attenuation rate is directly related to its length. Less attenuation occurs as the wave length grows, but as the signal attenuation rises, the transmission loss rises.

In this study, we looked at the optical fiber communication system we created at working wavelengths of (1310, 1350, 1400, 1450, 1500, and 1552) nm. Our goals included obtaining the most optical power, improving the system's quality factor, and reducing BER. We investigated the use of optical amplifiers in the communication system and contrasted the outcomes with the use of optical amplifier and PMD-E connected in series, exactly as it is written as the order, because, contrary to our expectations, the connection of optical amplifier + PMD-E produced superior outcomes.

Figure 13 displays the optical power readings using RZ-Modulation and an optical amplifier alone. These measurements ranged from (4500 µW to 4590 µW), with the largest optical power of P= 4590 µW at the operating wavelength of 1552 nm. This value was increased from a reading of 40.73 W after attenuations and from the transmitted optical power of 742.84 µW. The optical power readings are enhanced to between values of (4510 to 4590) µW after using optical amplifier + PMD-E figure 14, with the largest optical power reading at 1552 nm operating wavelength being 4590 W that was enhanced to this value with the transmitted optical power of 739.76 µW and from 40.56 W optical power reading after attenuations before enhancement. Which means that by combining an optical amplifier and PMD-E in the optical fiber communication system, we achieved improved optical power results. We compared the results with the use of NRZ-Modulation using an optical amplifier alone (Figure 16) and an optical amplifier plus PMD-E (Figure 17). In the first case, they produced results of 1280 W, where the input power was 2250 W and the power after attenuations was 123.5 W; in the second case, they produced results of 12760 W, where the input optical power was 2250 W and the transmitted power was 123.5 W; and in the third case, they produced results of 12.

Figure 15 displays the Q-Factor results for each amplification technique using RZ-Modulation. As can be seen, using an optical amplifier alone results in a system with a higher Q-Factor at an operating wavelength of 1400 nm, while using an optical amplifier plus PMD-E results in a system with a lower Q-Factor at an operating wavelength of 1552 nm. The Q-Factor results with NRZ-Modulation in the system shown in Figure 18 also employing optical amplifier delivers greater quality factor to the communication system than optical amplifier + PMD-E; they gave 542.9 at 1400 nm operating wavelength and 26.36 at 1350 nm operating wavelength, respectively.

It is obvious that using RZ-Modulation and an optical amplifier alone produced the best system quality and BER performance because it has zero BER at all operating wavelengths, as shown in table 3. However, using NRZ-Modulation in combination with an optical amplifier and PMD-E produced better BER readings because it only has a small amount of BER at 1552 nm wavelength. For each working wavelength, the other methods provided the communication system with low BER measurements. The system's smallest BER reading is 2.78E-50 at 1552 nm operating wavelength when RZ-Modulator and optical amplifier + PMD-E method is used, while it is 6.77E-77 at 1310 nm operating wavelength when NRZ-Modulator and optical amplifier alone are used.

Our investigational findings demonstrate to us that NRZ-Modulation outperforms RZ-Modulation in terms of communication system performance, and that the optical amplifier + PMD-E method combination improves receiver performance.

Table 3. Minimum BER readings according to the wavelengths used

Operating Wavelength	BER			
	RZ		NRZ	
	Optical Amplifier alone	Optical Amplifier + PMD-E	Optical Amplifier alone	Optical Amplifier + PMD-E
1310	0	8.41E-32	0	6.77E-77
1350	0	1.82E-15	0	2.42E-153
1400	0	3.70E-07	0	2.88E-11
1450	0	1.66E-08	0	1.80E-17
1500	0	1.85E-16	0	2.59E-06
1552	0	2.78E-50	1.40E-167	2.14E-34

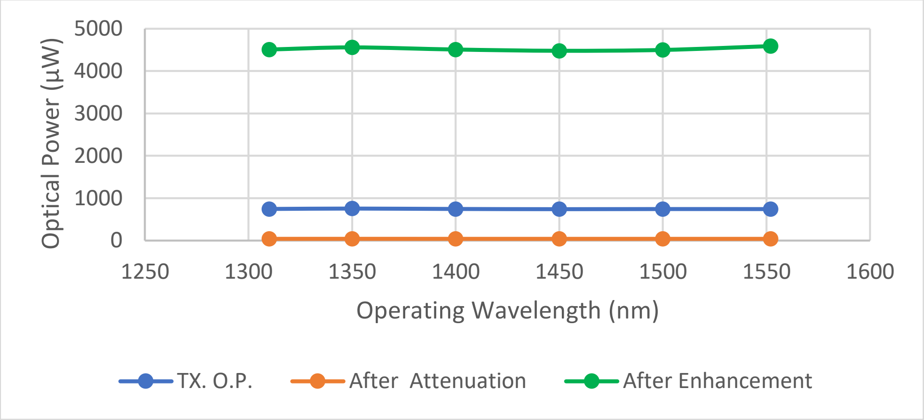


Figure 13. Optical Received Power Versus Operating Wavelength Using RZ-Modulation and Optical Amplifier Alone.

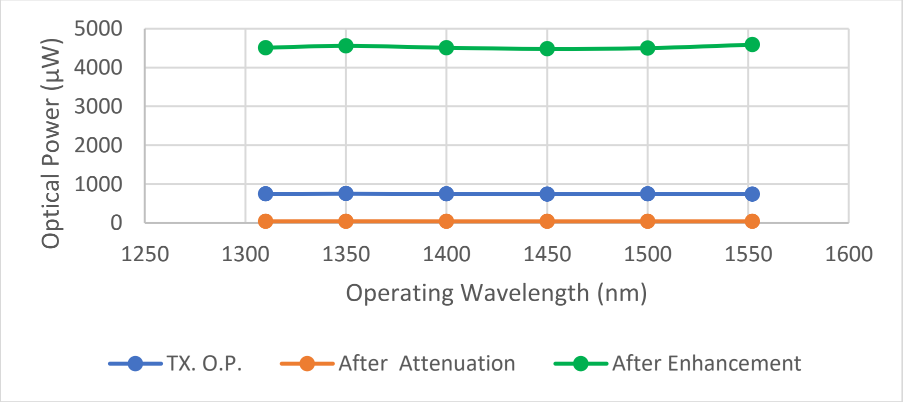


Figure 14. Optical Received Power Versus Operating Wavelength Using RZ-Modulation and Optical Amplifier + PMD-E.

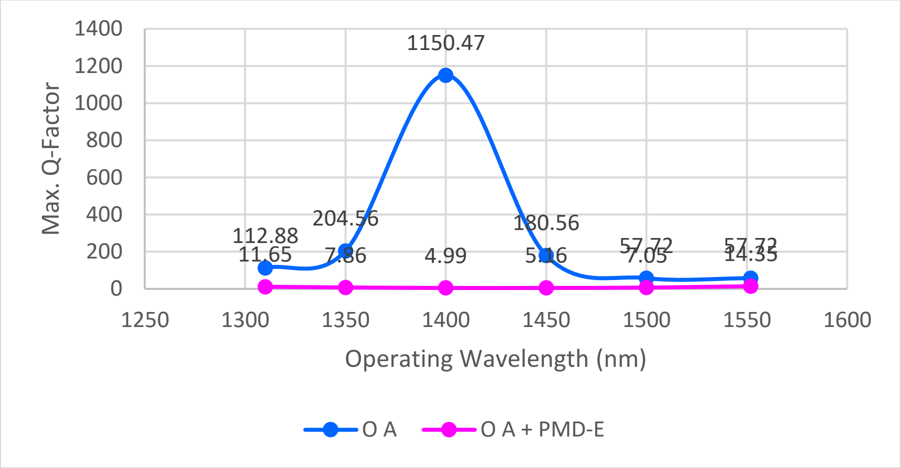


Figure 15. Maximum Q-Factor of Each Amplification Technique Using RZ-Modulation.

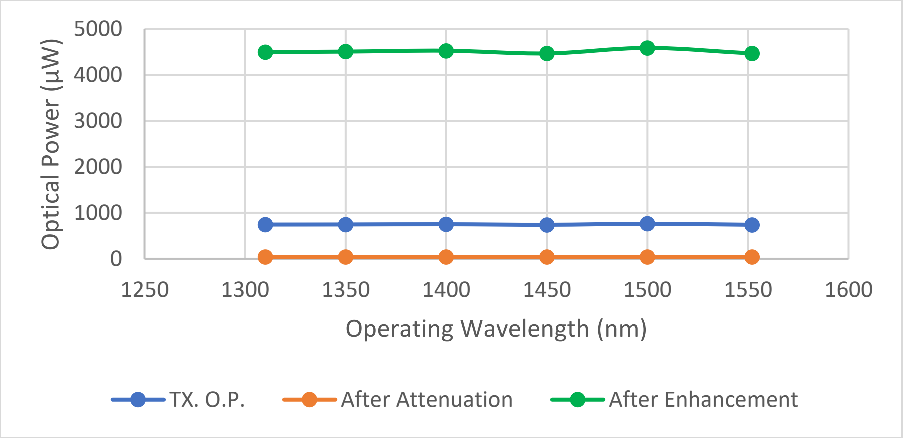


Figure 16. Optical Received Power Versus Operating Wavelength Using NRZ-Modulation and Optical Amplifier Alone.

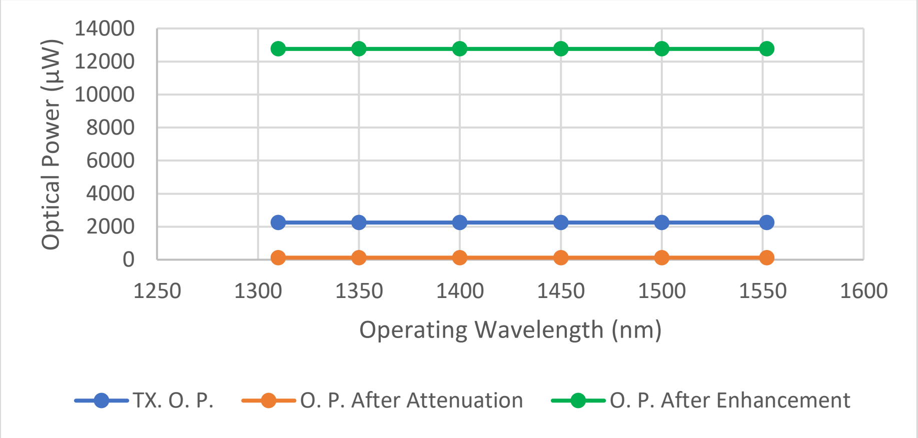


Figure 17. Optical Received Power Versus Operating Wavelength Using

NRZ-Modulation and Optical Amplifier + PMD-E.

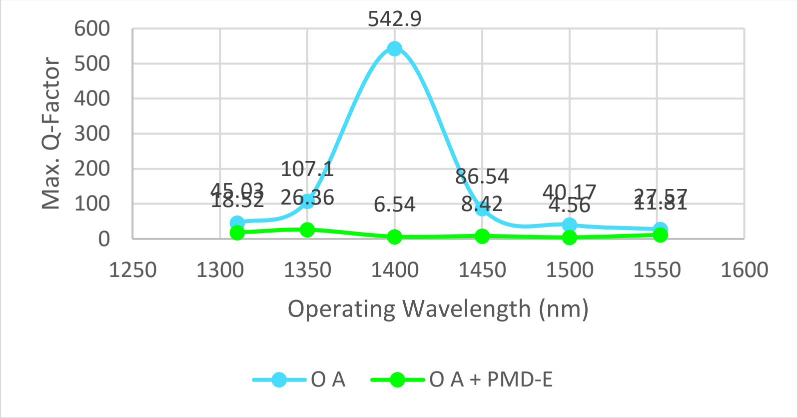


Figure 18. Maximum Q-Factor of Each Amplification Technique Using NRZ-Modulation.

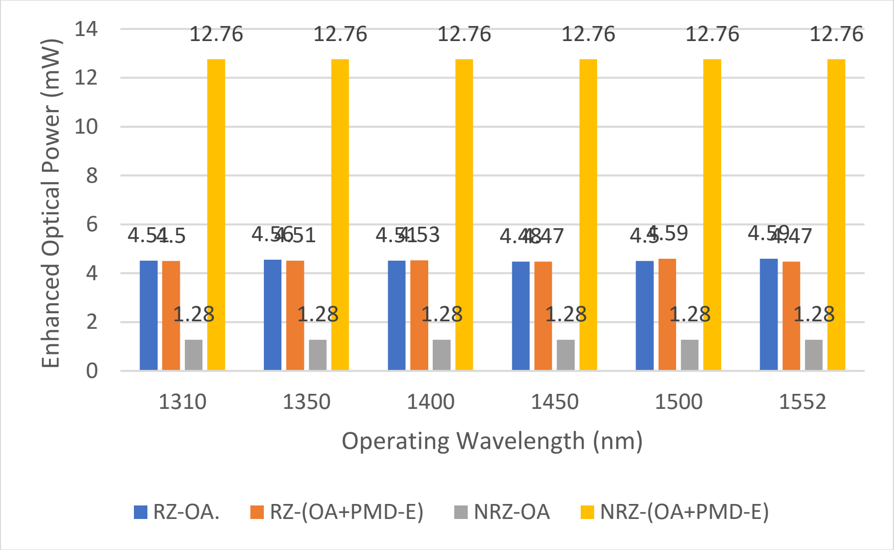
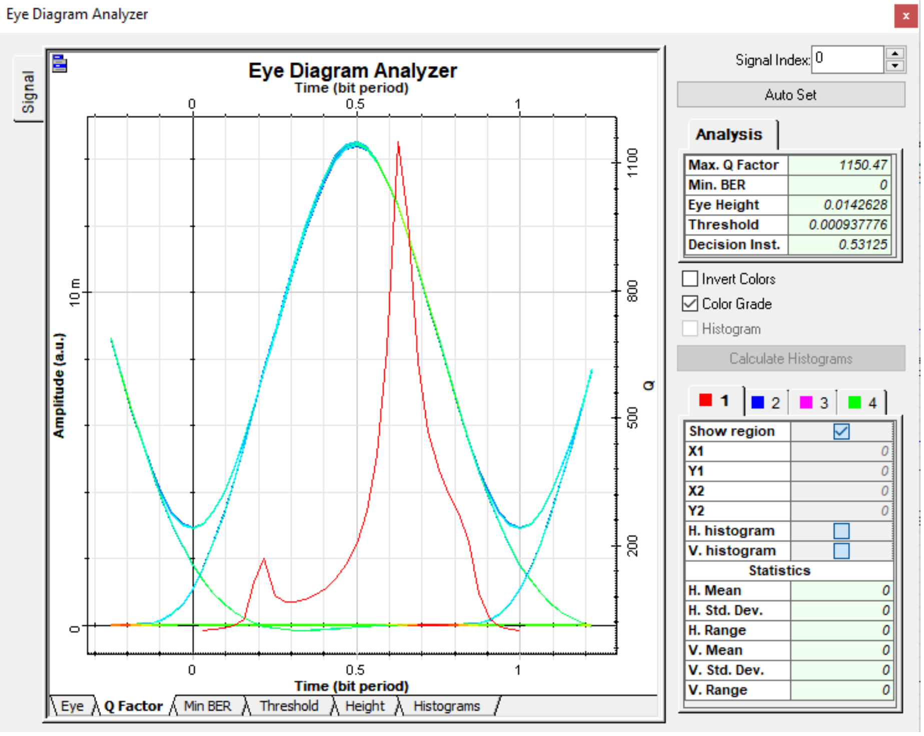


Figure 19. Enhanced Optical Received Power Versus Operating Wavelength Showing All Arrangement Techniques.



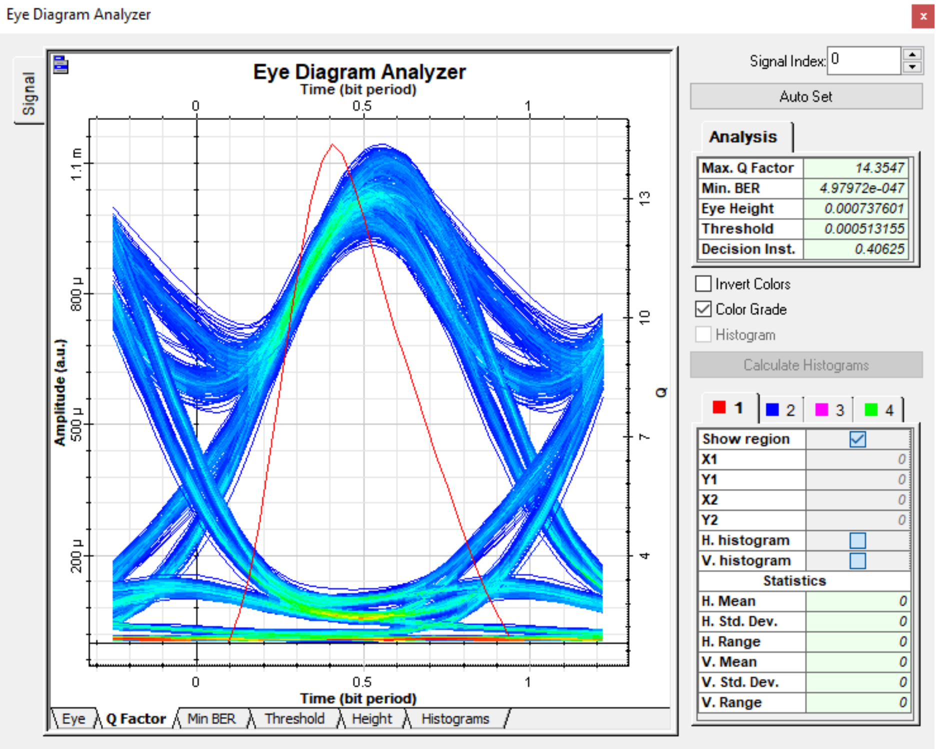
Signal Index: 0

Max. Q Factor	1150.47
Min. BER	0
Eye Height	0.0142628
Threshold	0.000937776
Decision Inst.	0.53125

☐ Invert Colors
☑ Color Grade
☐ Histogram

Show region	☑
X1	0
Y1	0
X2	0
Y2	0
H. histogram	☐
V. histogram	☐
Statistics	
H. Mean	0
H. Std. Dev.	0
H. Range	0
V. Mean	0
V. Std. Dev.	0
V. Range	0

Figure 20. Eye Diagram Case RZ-Modulation and OA Alone



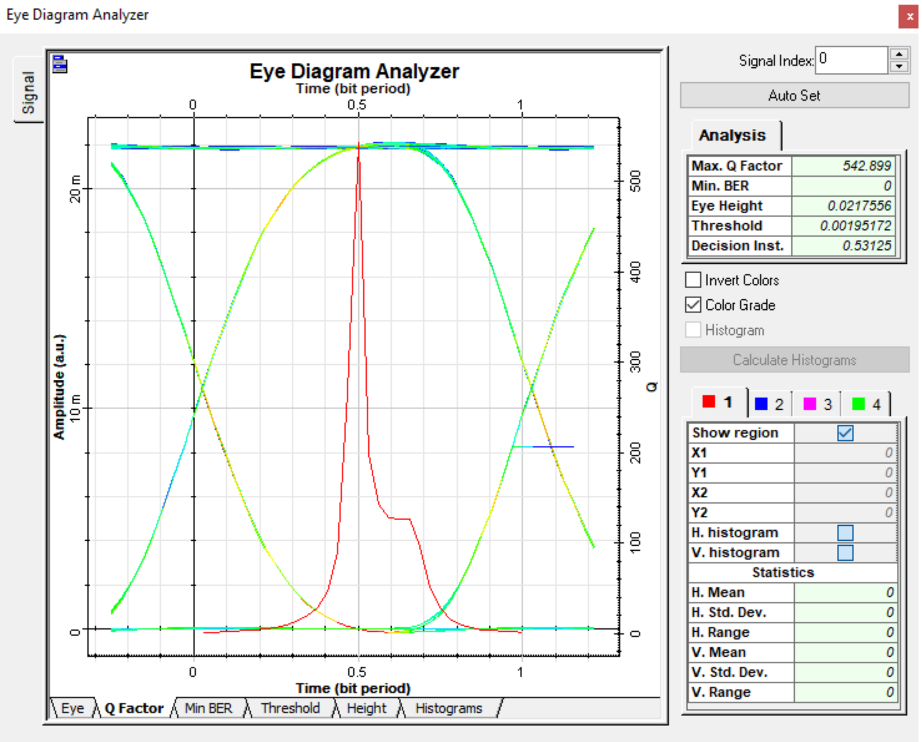
Signal Index: 0

Max. Q Factor	14.3547
Min. BER	4.97972e-047
Eye Height	0.000737601
Threshold	0.000513155
Decision Inst.	0.40625

☐ Invert Colors
☑ Color Grade
☐ Histogram

Show region	☑
X1	0
Y1	0
X2	0
Y2	0
H. histogram	☐
V. histogram	☐
Statistics	
H. Mean	0
H. Std. Dev.	0
H. Range	0
V. Mean	0
V. Std. Dev.	0
V. Range	0

Figure 21. Eye Diagram Case RZ-Modulation and OA+PMD-E



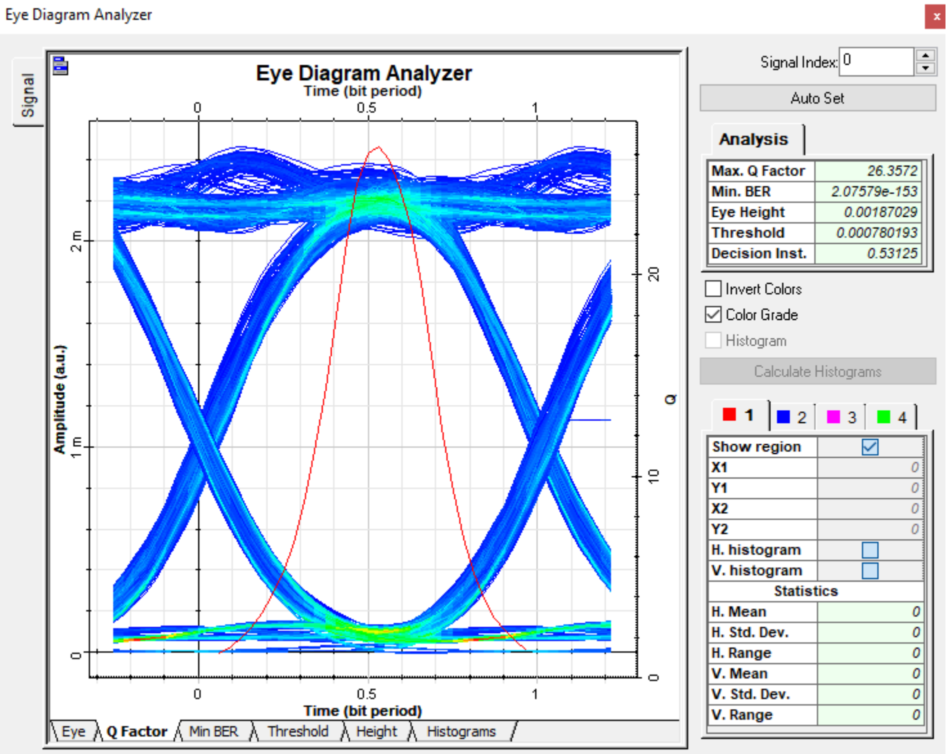
Signal Index: 0

Analysis	
Max. Q Factor	542.899
Min. BER	0
Eye Height	0.0217556
Threshold	0.00195172
Decision Inst.	0.53125

☐ Invert Colors
☑ Color Grade
☐ Histogram

Show region	☑
X1	0
Y1	0
X2	0
Y2	0
H. histogram	☐
V. histogram	☐
Statistics	
H. Mean	0
H. Std. Dev.	0
H. Range	0
V. Mean	0
V. Std. Dev.	0
V. Range	0

Figure 22. Eye Diagram Case NRZ-Modulation and OA Alone



Signal Index: 0

Analysis	
Max. Q Factor	26.3572
Min. BER	2.07579e-153
Eye Height	0.00187029
Threshold	0.000780193
Decision Inst.	0.53125

☐ Invert Colors
☑ Color Grade
☐ Histogram

Show region	☑
X1	0
Y1	0
X2	0
Y2	0
H. histogram	☐
V. histogram	☐
Statistics	
H. Mean	0
H. Std. Dev.	0
H. Range	0
V. Mean	0
V. Std. Dev.	0
V. Range	0

Figure 23. Eye Diagram Case NRZ-Modulation and OA+PMD-E.

Conclusion

In this article, we investigated the power losses brought on the signal transmission through a 50 km single mode fiber SMF. We employed optical amplifier alone and optical amplifier + PMD-E in series connection approaches to analyze RZ-Modulation and NRZ-Modulation kinds because they attenuate the communication system less than other modulation types. We compared how well each of them performed after reading the data. We looked into and studied how the communication system performed when running at (1310, 1350, 1400, 1450, 1500, and 1552) nm wavelengths. According to the experimental results, the communication system produced superior results when NRZ-Modulation, an optical amplifier and PMD-E were used. In comparison to using the NRZ-Modulator and optical amplifier alone (Figure 16), RZ-Modulator with optical amplifier alone (Figure 13), and RZ-Modulator with optical amplifier + PMD-E (Figure 14) techniques, it gave an enhanced received optical power of 12760 µW, enhancing an optical power of 123.5 µW, while they gave the results of 1280 µW, for a transmitted optical power of 2250 µW, and an attenuated optical Following attenuations, the power ratios were 4590 µW for 40.73 µW and 4590 µW for 40.56 µW, respectively (figure 19) for all arrangement techniques.

Also, it is evident that NRZ-Modulation with an optical amplifier and PMD-E boosted a significant amount of attenuated optical power (P(Transmitted) = 2250 µW, the power before enhancement = 123.5 µW, and the attenuated optical power becomes 2126.5 µW). It is possible that after using PMD-E, Q factor decreases. According to the results, the communication system's quality factor was 1150.47 when RZ-Modulation and an optical amplifier alone reduced to 14.35 after OA+ PMD-E were used at operating wavelengths of 1400 nm and 1552 nm, respectively. When NRZ-Modulator and an optical amplifier alone were used, the system's quality factor was 542.9 and it was reduced to 26.36 when PMD-E was used with the OA. at operating wavelengths of 1400 nm and 1350 nm, respectively.

The use of NRZ-Modulation and OA technique to achieve zero-bit error rates improves the communication system's BER readings as well. However, RZ-Modulator and optical amplifier use alone also produced excellent results for the system's bit error rate when compared to other types of techniques used, as shown in figures 22 and 20 respectively.

The output optical power, the quality factor, the signal's quality with a low noise value, and the transmission's length or propagation time were all improved in this study. The end result of the design demonstrated an improvement in the receiver's signal detection.

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