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**ANALYSIS, INTEGRATION AND OPTIMIZATION
OF OPTICAL COMMUNICATION SYSTEMS
USED ON LAND, UNDER THE SEA AND IN FREE
SPACE**

Shuhad Rabah Awad AWAD

Master's Thesis

Supervisor

Asst. Prof. Dr. Necmiye Özlem ÜNVERDİ

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I hereby declare that all information/data presented in this graduation project has been obtained in full accordance with academic rules and ethical conduct. I also declare all unoriginal materials and conclusions have been cited in the text and all references mentioned in the Reference List have been cited in the text, and vice versa as required by the abovementioned rules and conduct.

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XXXXXXXXXX

DEDICATION

I would like to extend my deepest gratitude to my supervisor Asst. Prof. Dr. N. Özlem ÜNVERDİ, whose support and guidance were valuable during the research period. I also extend my sincere appreciation to my other professors at Altınbas University who fulfil their roles with excellence throughout my academic journey. I dedicate the fruits of my labour to my beloved parent, whose sacrifices paved the way for my success. To my respected great aunt, I have been grateful for you and your support from childhood until now. Finally, to my husband, Rafid, with love and loyalty, I dedicate to you the fruits of my labour and my dream.



ABSTRACT

ANALYSIS, INTEGRATION AND OPTIMIZATION OF OPTICAL COMMUNICATION SYSTEMS USED ON LAND, UNDER THE SEA AND IN FREE SPACE

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The history of optical communication can be traced back to simple signalling techniques like smoke and flame beacons used by ancient cultures to transmit messages over long distances. Significant advancements occurred in the 18th and 19th centuries with the invention and widespread use of semaphore systems and later optical telegraphs, which enhanced visual signalling capabilities. These systems laid the foundation for structured long-range communication. However, practical low-attenuation optical fibers and lasers were developed in the 20th century before optical communication could become an efficient means for high-speed, long-distance data transmission.

Modern telecommunication infrastructures worldwide increasingly rely on extremely long optical fiber cables due to several key advantages. These include the high bandwidth, low signal loss, and overall transmission efficiency of fiber optics. Additionally, fiber optics offer immunity to electromagnetic interference and other forms of crosstalk, such as radiation crosstalk and long-distance crosstalk. Furthermore, they provide high security, data security, and data integrity. These advantages make fiber optics suitable for both urban and remote deployment.

The study employs the OptiSystem 18 simulation platform to comprehensively assess the performance of optical communication systems under three distinct transmission environments: fiber, underwater, and free-space optical channels. An extremely critical system parameter, laser power, operational wavelength, modulation schemes, pulse bit

patterns, and transmission frequency, were systematically varied one at a time to observe their individual effects and the combined effects on system performance. The modelling was conducted with utmost precision. The simulations have offered valuable insights into optimal configurations for maximizing signal integrity, minimizing attenuation, and enhancing overall transmission quality under various environmental conditions.

The results obtained have significantly contributed to a comprehensive understanding of the performance of optical links under various operating conditions. This knowledge has, in turn, led to the generation of valuable recommendations for enhancing systems. The acquired insights will be instrumental in designing robust, user-friendly, and low-power networks in critical sectors and numerous applications and locations.

Keywords: Optical Communications, Modulation Techniques, Quality Factor(Q-Factor), Free Space (FSO), Underwater Wireless Optical Communication (UWOC).

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ABBREVIATIONS

AI	:	Artificial Intelligence
AM	:	Amplitude Modulation
ASK	:	Amplitude Shift Keying
BER	:	Bit Error Rate
CW	:	Continuous Wave
CWDM	:	Coarse Wavelength Division Multiplexing
DCF	:	Dispersion Compensating Fibers
DPLL	:	Digital Phase-Locked Loop
DPSK	:	Differential Phase Shift Keying
EA	:	Electro-Absorption
EDFA	:	Erbium-Doped Fiber Amplifier
FM	:	Frequency Modulation
FSK	:	Frequency Shift Keying
FSO	:	Free Space Optics
FWM	:	Four-Wave Mixing
IoT	:	Internet of Things
ISI	:	Inter-Symbol Interference
LED	:	Light Emitting Diode
Li-Fi	:	Light Fidelity
LOS	:	Line of Sight
MZ	:	Mach-Zehnder
NRZ	:	Non-Return-to-Zero
OFDM	:	Orthogonal Frequency Division Multiplexing

OSNR	:	Optical Signal-to-Noise Ratio
OWC	:	Optical Wireless Communication
PAN	:	Personal Area Network
PM	:	Phase Modulation
PSK	:	Phase Shift Keying
QAM	:	Quadrature Amplitude Modulation
QoS	:	Quality of Service
RZ	:	Return-to-Zero
SNR	:	Signal-to-Noise Ratio
SOA	:	Semiconductor Optical Amplifier
SPM	:	Self-Phase Modulation
TDMA	:	Time Division Multiple Access
TIR	:	Total Internal Reflection
UWOC	:	Underwater Wireless Optical Communication
VLC	:	Visible Light Communication
WDM	:	Wavelength Division Multiplexing
WOBANs	:	Wireless Optical Broadband Access Networks

LIST OF SYMBOLS

θ : Theta

Δ : Delta

n : Refractive index

π : Pi

Δf : Linewidth of Single-frequency Injection Laser

τ : Time period

t : Time

Φ : Angle

$\Delta\phi$: Signal Phase Change

$\Delta\theta$: Phase Difference Between the two Branches

α : Chirp Factor

1. INTRODUCTION

1.1 OPTICAL COMMUNICATION BACKGROUND

Optical communication has been developed since ancient times. All around the globe, people have used smoke signals, fire beacons, or reflective surfaces to convey simple messages regarding, for instance, the result of a battle. This principle was unchanged until the late eighteenth century when semaphore systems used flags and lamps for visual communication. Optical telegraphs with relay stations followed, which made transmission of mechanically coded signals over large distances possible [1].

The first system of this kind was installed between Lille and Paris in 1794; common development followed until, at the latest, 1830, when it was in operation all over Europe. In most such systems, light only rendered coded messages visible for interpretation at the relay stations. Nineteenth-century opto-mechanical communication systems were intrinsically slow and worked at very low data transfer rates, generally well below one bit per second. Although analogy electrical communication technologies soon became the principal force, it would not be until the mid-20th century that a new interest in light as a communication medium would arise [2].

The puzzle was solved with the invention of the laser in 1960. However, with the fiber loss values at critical levels, the practical application seemed extremely difficult, with values well above 1000 dB/km. A milestone paper argued that low-loss fiber could form a proper communication channel. This vision work, honoured with the 2009 Nobel Prize in Physics, started a revolution in the communications industry [3].

Corning's achievement in 1970 in developing the first low-loss fiber (17 dB/km) was a fundamental milestone; subsequent efforts brought fiber losses down progressively to the current value of 0.15 dB/km. Optical communications have grown from mere message conveyance to many other applications, one of the most critical being multimedia transmission at high capacities. The many advantages of this technology—wide bandwidth, security, and low attenuation, accompanied by reduced interference and low impact on the electromagnetic field—make it an efficient candidate for tomorrow's communication

systems. fiber optic cables are extensively deployed in telecommunication networks to enable long-haul communications.

1.2 PURPOSE OF THE THESIS

This paper deals with the performance of optical communication systems under different conditions. The land fiber system, underwater OWC, and space FS system were three independent network models. The special case of the latter was that it gives the effect of weather on the attenuation coefficient — different values given for seawater, river water, and still water.

Key system parameters were set at some given variable values to allow optimal comparative analysis, these included laser power, frequency, and distance. Five modulation schemes (AM, FM, PM, MZ and EA) and two pulse bit patterns (NRZ and RZ) were developed and studied to measure the quality factor under different experimental conditions using Eye Diagram Analyzer. They also help create a graphical representation of the results, which allows for thoroughly assessing parameter interrelationships. Comparison of simulation results obtained using OptiSystem 18 with experimental data done in this study. It leads to insights created to guide network designers in optimizing system performance.

1.3 RESEARCH PROBLEM

1.3.1 Assessment of Modulation Technique

The modulation techniques, namely AM, FM, PM, MZ and EA, were assessed in the study under different environments (air, water, and land) in terms of their bit error rate and spectral efficiency. This investigation evaluated how these modulation techniques performed under a variety of noise and attenuation conditions for the identification of the best techniques for specific scenarios.

1.3.2 Component Quality Impact

The research delved into component quality and, vice-versa, the system's performance. The study answered how pulse bit generators should be rated, ensuring they contribute to higher functions within the system.

1.3.3 System Parameter Analysis

The effect of laser power, wavelength, and modulation frequency on a range of propagation and quality of signals was analysed in each of the environments. The research identified the proper bit pulse generator and modulation technique to be used in each case. It also considered how distance would affect the quality of the signal within each of the environments.

1.4 LITERATURE REVIEW

1.4.1 General Introduction to Optical Communication Systems

1.4.1.1 Introduction

For signals to be transmitted over long distances had been historical media, by carrier waves covering huge frequency ranges from megahertz values to hundreds of Terahertz. The other alternative is optical communication systems, which employ high-frequency carrier waves from the visible or near-infrared spectrum for demodulation.

Having carrier frequencies orders of magnitude greater than microwave systems, the optical systems were often referred to as Lightwave systems. Optical communication was a much narrower subfield in comparison, based on optic fibers to guide light information in large volumes after the first practical devices became widespread in the 1980s. The merge of lightwave technology and microelectronics in the 1990s laid the foundation for the information era, enabling widespread communication across various media and frequency scales.

Following the 1990s invention of low-loss optical fibers, systems utilizing visible, ultraviolet, and infrared spectra gained popularity. This simple technological revolution changed the whole topology of the global communication networks. As seen in Figure 1.1 compares radio waves with light waves.

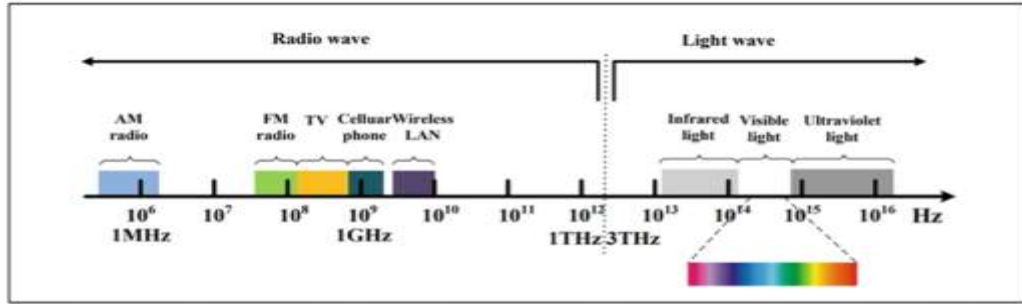


Figure 1.1: Comparison Between Radio Waves and Light Waves [4].

1.4.1.2 Historical perspective of optical communication

Optical communication, the transfer of information by light, dates to ancient China through pyrotechnics. Later developments included semaphores and signal lights. In 1880, the optical telephone advanced the technology, but electrical communication dominated until the 1950s when coherent light sources and transmission media emerged.

The 1960 laser solved the coherent light issue, but high fiber loss (over 1000 dB/km) remained challenging. In 1966, research proposed low-loss fiber for long-distance communication, earning a Nobel Prize in 2009. Another model breakthrough in 1970 produced the first low-loss fiber (17 dB/km), later reduced to 0.15 dB/km.

Another model, as shown in Figure 1.2, The laser/LED signal intensity-modulated and transmitted via fiber, then converted back to electrical at the receiver. Kao predicted 1 Gb/s rates, far exceeding the 1970s' 100 Mbps peak [5].

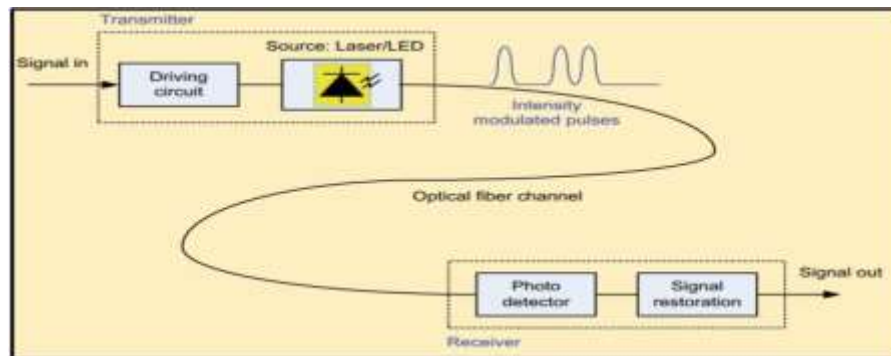


Figure 1.2: Optical Communication System Model.

1.4.2 Literature Review of Research Close to the Thesis Objective

This work presents a performance study for optical communication systems operating at 1550 and 1310 nm ranges. This wavelength has the incoming signals' Q-factor value at this maximum among all the study wavelengths. The value recommended for high-data-rate transmissions over long distances. It was noted that at 1625 nm wavelength, the best BERS is achieved compared to other wavelengths for a considerable cable length of more than 2000 km due to the higher Q values. The modulation techniques were constantly amplitude supplied in OptiSystem 18.1 software. The performance of the whole system is not affected by the desired frequency. Although performance-optimal as the session may be defined, optical fiber is also relatively independent compared with free-space or submarine systems [6].

The present study will also show the influence of four schemes of modulation used in optical links (working at ideal data rate /8.5 Gb/s) and optimal frequency (300 GHz), which were observed at lengths of 500 and 1000 m. Power enhancements have made their performance very high everywhere except fiber optic systems. High erased very Well Performed Very Good till EACs So It Must Be Bering Great Last Deal with EACs Ass Well In general. The work designs a high-capacity fiber optic link using dispersion compensation techniques undergoing a critical evaluation. Varying pre-compensation, post-compensation, and symmetrical compensation for BER and Q-factor at different bit rates and lengths of fiber, this paper implements a simulation for dispersion, one of the most critical limiting factors in fiber optic communication. Generally, symmetrical compensation is better than the other methods, especially at higher bit rates and longer distances [7].

Another paper examines how visibility affects Free Space Optical (FSO) systems in hazy and foggy conditions. It links visibility with beam divergence, bit rate, and optical power, using Q-factor and received power to measure performance. Fog degrades FSO performance more than haze, and minor beam divergence improves results [8]. This work analyses indoor visible light communication (VLC) using white LEDs, testing quality factor and bit error rate at varying distances and data rates via OptiSystem. A 1-Gbps rate was achieved over 3 m, but external light interference remains an issue, mitigated by optical filters. Future work should explore advanced modulation for higher speeds and robustness [9].

A study evaluates optical filters (Bessel, Butterworth, Chebyshev, Gaussian) for free-space optical communication systems. Using OptiSystem 16.1, researchers simulated various atmospheric conditions (clear, hazy, rainy) and link distances (800 m, 1000 m, 1500 m). Results consistently favoured Bessel filters due to superior BER, Q-factor, and eye height. The Butterworth filter showed better resistance to increasing link distances regarding the Q-factor. The findings highlight the [10].

A free-space optics (FSO) system uses longer wavelengths for greater distances. Machine learning helps predict the best wavelength for OFDM-FSO systems. While Linear Regression performs poorly, the Random Forest Algorithm proves more accurate in selecting the optimal wavelength across different weather conditions [11]. Another study analyses how the Quality Factor in optical communication changes with varying cutoff frequencies of Bessel and Gaussian filters over distances from 10 to 80 km. Bessel and Gaussian filters performed best among the eight filter types, offering more precise eye diagrams and higher quality factors. The quality factor declines with distance, but Bessel filters maintain stable performance, even with cutoff frequency variations, outperforming Gaussian filters. Real-time adjustments to cutoff frequencies can further optimize results [12].

A study was conducted on a free-space optical (FSO) communication system under various atmospheric conditions. We applied hybrid modulation techniques (NRZ, MSK, and PSK) to mitigate turbulence effects and improve reliability. Using OptiSystem 13.0, we simulated system performance in clear, foggy, and hazy weather, analysing BER and Q-factor. Results confirm that the proposed hybrid modulation works effectively in clear weather, enhancing FSO communication performance [13].

A suggestion by a paper examines how atmospheric conditions at 850 nm and 1550 nm affect FSO communication systems. A steepest-descent algorithm optimized performance under typical weather conditions. At 1550 nm, performance was better in low-attenuation environments, while 850 nm performed better under higher attenuation due to its larger Q-factor and eye height. Wavelength choice significantly impacts FSO system performance, and the proposed optimization reduces atmospheric effects [14]. Another study optimized a long-haul WDM system using DCF and EDFAs to counter dispersion and attenuation. An

eight-channel WDM system was achieved, potentially scaling to 16, 32, or 64 channels in future work [15].

A research paper suggested designing a submarine network connecting Timor Leste to Indonesia via the East Palapa Ring Project. Two cost-effective routes were evaluated based on transmission performance. Power link and rise time budgets were analysed for each route, supported by OptiSystem simulations. Results confirmed that both routes met the required standards for attenuation, dispersion, and maximum link loss, proving the feasibility of the submarine connection. The findings suggest potential technological partnerships between the two countries. Key performance limits for propagation loss and dispersion were also outlined, with fiber comparisons based on simulation results [16].

A study analysed key parameters affecting the quality factor in a four-channel FSO communication system between a ground station and a UAV, including multiplexing, amplification, filtering, time delay, and phase shift. Using OptiSystem 7.0, researchers showed the system with a delay line structure to reduce dispersion and attenuation. Results showed that time delay consistently improved the quality factor more than phase shift, though measurement sensitivity was limited to femtosecond-scale delays [17]. Another study developed and simulated an FMCW LiDAR system, evaluating its performance at different target distances. The system showed high sensitivity and signal power at short ranges but performed poorly beyond 500 meters. Future simulations should include real-world conditions to assess their impact on performance [18].

Another research presents a secure optical communication system using the RC4 encryption algorithm, simulated in OptiSystem for 80 Gbps transmission over 100 km. Encryption-induced dispersion reduced the range to 63 km, but dispersion compensation fiber restored it to 100 km. The study confirms that encryption can be integrated with optical communication, with potential improvements using WDM for higher data rates and testing stronger encryption algorithms [19]. Additionally, the performance of an FSO system was analysed at 1 Gbps and 10 Gbps. Optimizing system parameters (link range, beam divergence, receiver aperture) ensured acceptable Q-factors. The 1 Gbps signal outperformed 10 Gbps, offering longer link availability and lower sensitivity to parameter changes, highlighting the trade-offs between data rate, distance, and system design [20].

This paper investigated the performance enhancement of inter-satellite OWC using multiple OWC channels and optical amplifiers. That was based on single-channel Is-OWC systems and usually resulted in a suboptimal system. The performance of the proposed system is analysed for Q-factor versus different data rates and wavelengths using the OptiSystem. The results obtained show that the multichannel system with an amplifier outperforms the traditional single-channel system due to the higher Q-factors for higher data rates, improving the system's performance [21].



2. OPTICAL COMMUNICATION SYSTEM

Like all communication systems, the elements that underline the functioning of an optical fiber communication system simply serve as channels via which messages travel from a source of information to a destination. As given in Figure 2.1, (a) and (b) the general communication system involves three basic components: a transmitter or modulator connected to the information source, a transmission medium, and a receiver or demodulator situated at the destination. In traditional electrical communication systems, the source of information creates an electrical signal, usually derived from a non-electrical message signal like sound. The transmitter then processed this output, and various electrical and electronic components converted the input into a form suitable for propagation through the medium. Typically, this process involves the modulation of an appropriate carrier, an electromagnetic wave.

The wire pair, the coaxial cable, and the free space can also be a transmission medium where the signal guides itself to the receiver. At the receiver, it is demodulated (transformed back to the original electrical form) and then delivered to the destination. In the transmission process, the signal is inevitably attenuated—reduced somehow—and degrades because of noise and other distortions within the transmission medium. These properties limit the maximum distance between the transmitter and receiver, over which effective communication cannot be guaranteed. Long-distance applications, therefore, require repeaters or line amplifiers to retain signal integrity [22].

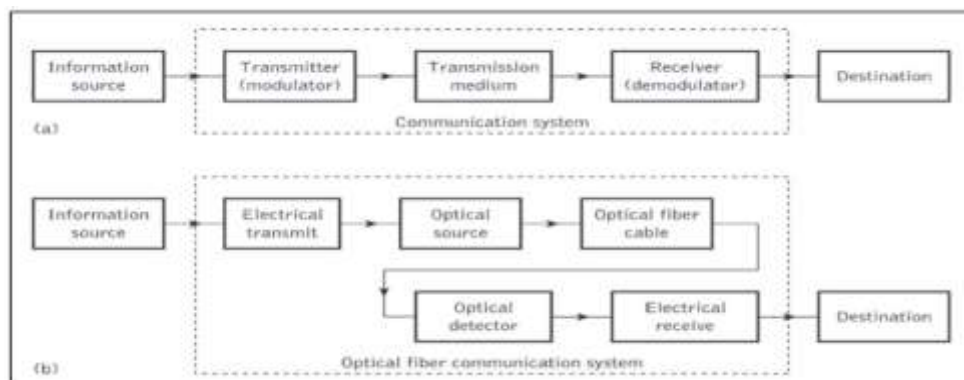


Figure 2.1: (a) The Overall System of Communication. (B) The System for Communication Via Optical Fiber.

2.1 COMPONENTS AND OPERATION OF OPTICAL COMMUNICATION SYSTEMS

The communication systems shown in Figure 2.2, encode information into electromagnetic carrier waves and transmit it across a broad frequency band through various media. Optical communication systems operated at high frequencies and used light as the carrier. Initially, optical communication technologies provided transmission via fiber optic cables on land and underwater; however, they were eventually used wirelessly in free space and underwater. A basic communication system consists of a transmitter, a receiver, and a transmission line. Similarly, optical communication systems comprise a receiver, a transmitter, and a transmission line. The transmitter section converts the incoming information into an optical signal and sends it into the transmission medium. The transmitter included a laser or LED source, an encoder, and an electrical signal in its simplest form. The receiver section consisted of a photodetector, a filter, and a demodulator [23].

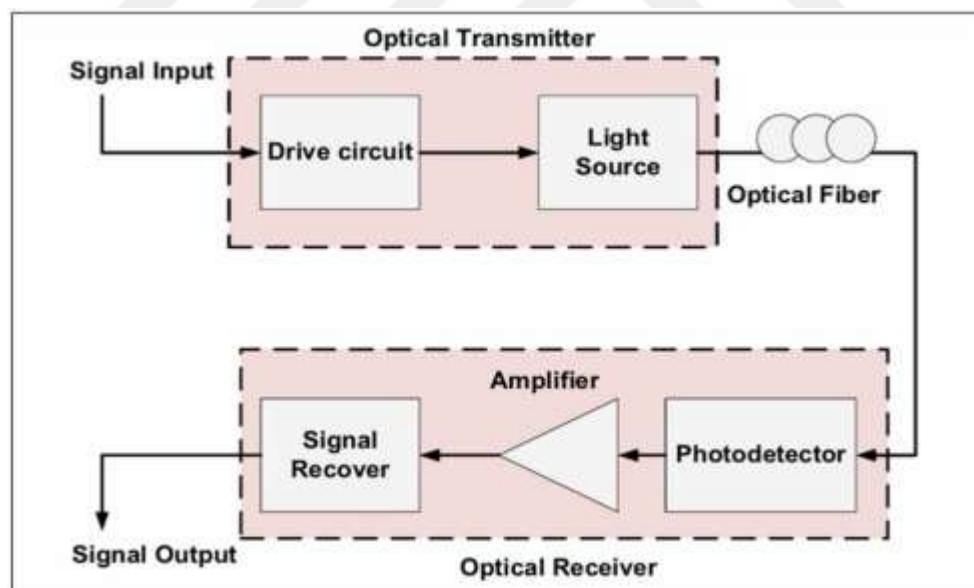


Figure 2.2: Direct Detection Optical Communication System Block Diagram.

2.2 STRUCTURE OF FIBER OPTIC NETWORKS

Optical fibers, one of the most essential innovations in communications and optics is the optical fiber, defined as a transparent and flexible dielectric channel that guides light from an emitting source to a receiver.

2.2.1 Single-Mode Fibers

These were used to transmit light along fragile fibers. They were characterized by the ability to transmit data over very long distances with minimal signal loss. They were used mainly in long-distance networks. International telecommunications networks, for example. One recent paper expounded on an in-series single-mode-(deformed multimode)-single-mode fiber structure for simultaneous measurements of curvature and temperature [24].

2.2.2 Multi-Mode Fibers

Multimode Fibers propagated light through fibers that were relatively larger in diameter. These fibers permitted multiple modes of light to pass through them, which increased the loss and signal dispersion as the distance travelled increased. They were used mainly in local area networks, such as in-building networks. An investigation into the performance of multimode fibers in a space-division multiplexing system is also given in the reference [25].

2.2.3 Plastic Optical Fibers

Plastic optical fibers were used in applications requiring more flexibility and easy installation, like Homer networks and specific industrial applications. An example is a recently published paper that discusses the development of optical chemical sensors using modified plastic optical fibers.

2.3 PRINCIPLE OF OPTICAL FIBER

For TIR fibers to work, they should operate through light refraction and total internal reflection, enabling efficient transmission of light signals over long distances. A typical optical fiber was composed of high-purity silica glass, with the core having a higher refractive index than the surrounding cladding. The core-cladding refractive index

difference created conditions required for total internal reflection. Light introduced into the core was to strike the core-cladding interface at an angle more significant than the critical angle, resulting in total internal reflection rather than refraction into the cladding. Furthermore, it was the mechanism by which the light signal was confined to the core, allowing its propagation along the length of the fiber without escaping [26].

2.3.1 Light and Mode Propagation in Optical Fiber

By propagating an electromagnetic field in a dielectric waveguide, electromagnetic energy was transferred over long distances, i.e., between distant locations in space, in the optical frequency (light) spectrum. The sum of internal contemplation (TIR) established the primary characteristics of this light's passage through an optical waveguide. TIR happened at every angle below which light couldn't move from a specific medium into another medium because it was all totally internally reflected. As illustrated, a glass prism has two sides at an angle of 85.0°. Determine the critical angle for the light traveling from the side glass into the air.

$$\sin(\Theta_{TIR}) = n_1/n_2 \quad (2.1)$$

Therefore,

$$\Theta_{TIR} = \arcsin(n_1/n_2) \quad (2.2)$$

Conversely, "modes of the fiber" refers to the permitted distribution of electromagnetic fields. It is possible to determine the fiber mode derivation of a cylindrical waveguide by solving the Maxwell equation. In the core refractive index of common silica-core, silica-clad fibers were like the siding. An example of a "weakly guiding approximation" is this condition:

$$\Delta = \left(\frac{n_{core}}{n_{core}} - \frac{n_{core}}{n_{core}} \right) \quad (2.3)$$

Where $\Delta n = n_{core} - n_{clad}$ the difference in refractive index, and Δ was the mode's relative (or fractional) refractive index difference [27].

2.3.2 Parameters Affecting Transmission Quality in Optical Fiber

fiber optic communications have transformed the field of telecommunications, resulting in the carriage of high-speed data over long distances with minimal loss of signals. The transmission quality in fiber optics is severely dependent on parameters like the length of the fiber itself, frequency, and laser power. The efficiency and reliability of fiber optic systems were found to be directly interrelated with these parameters.

2.4 EFFECT OF FIBERS OPTICAL DISTANCES

In [26], the influence of fiber length on the performance of fiber optic networks is discussed. They showed that with longer lengths of fiber, there is higher attenuation, mainly caused by absorption and scattering, which directly impinges on the signal strength as it travels along the fiber. This signal loss can decrease transmission quality and may require amplifiers or repeaters to maintain the signal's integrity at long distances.

2.4.1 Effect of Frequency of the Optical Fiber

One crucial parameter affecting transmission through a fiber is its frequency. A recent publication explained how different frequencies could cause various levels of dispersion that would lead to pulse spreading and inter-symbol interference (ISI). Their findings regarding managing frequency can be done with dispersion compensation fibers (DCF) and advanced modulation formats to optimize transmission performance is shown in Figure 2.3 [28].

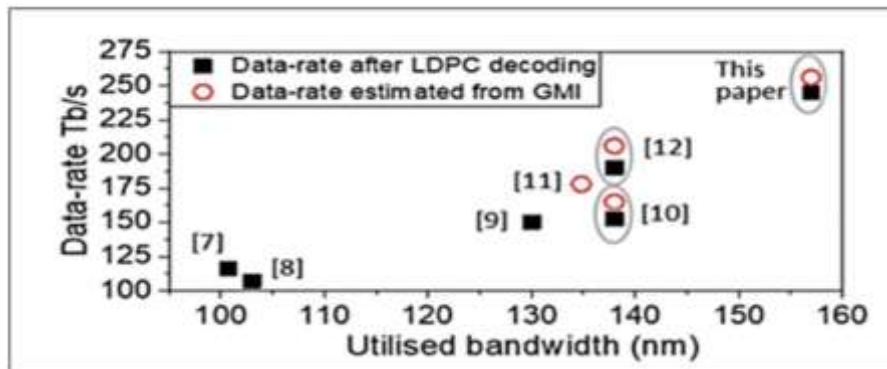


Figure 2.3: Transmission Demonstrations Of >100 Tb/S Using > 100nm Optical Bandwidth Per SMF Or Fiber Core.

2.4.2 Effect of the Power of Laser Source

Fiber optic communication is, therefore, influenced by another critical factor, investigated the underlying effects of laser power in high-speed optical networks. In [29], their findings showed that increasing the laser power improves signal strength but at the same time = results in SPM and FWM. Their study recommended how to achieve optimum power to counteract these non-linear effects.

2.5 WIRELESS OPTICAL NETWORKS AND THEIR WORKIN PRINCIPLES

Free Space Optics (FSO) and Optical Wireless Communication (OWC) transmit data through light beams in the air instead of cables. By using lasers, these networks enable high-speed, low-latency line-of-sight and point-to-multipoint connections. A key advantage is avoiding the high costs and physical constraints of laying fiber optic cables, especially in urban areas [30]. FSO relies on precise alignment between transceivers—even minor misalignment can disrupt the link. Environmental factors like fog, rain, and turbulence also affect reliability. Researchers use adaptive optics and error correction algorithms to counter this and maintain signal integrity [31].

OWC leverages visible light, infrared, or ultraviolet spectra, offering flexibility and high bandwidth for indoor, underwater, and satellite communications. Combining FSO and OWC creates a resilient hybrid network—FSO for long-range outdoor use and OWC (e.g., VLC) for short-range indoor applications [32]. Ongoing research focuses on weather-resistant techniques (e.g., multi-beam paths) and advanced photonic materials to improve transceiver efficiency, making FSO/OWC a promising solution for future networks [33].

2.5.1 Systems of Wireless Optical Communication Classification

Wireless Optical Communication systems are an evolving field classified into several types based on their applications and technology: Free Space Optics, Visible Light Communication, Light Fidelity, and Underwater Wireless Optical Communication. Each type has different characteristics and is suitable for different environments and use cases.

2.5.1.1 Free space optics (FSO) systems

A Free Space Optics system transmits data through free space light beams. It leverages lasers to establish high-speed communication links between two points without using physical cables. These, therefore, work best in environments where optical fibers cannot be installed practically. The extremely high costs and physical limitations make it impractical in urban areas. Thus, there is a good opportunity here. The high bandwidth and low latency of FSO systems come with a flipside, though, as the system performance may be deteriorated by weather conditions (including fog, rain, and atmospheric turbulence) [34].

2.5.1.2 Visible light communication (VLC)

Using the visible light spectrum for data transmission is commonly realized by LED lights, providing both illumination and data transmission, which had been referred to as light-fidelity communication systems. VLC systems were mainly used indoors for high-speed data communications, an alternative to legacy Wi-Fi. The basic advantage of VLC is its surprising way of providing secure communication since light waves do not penetrate walls, reducing the risk of data being intercepted. Researchers have concentrated on improving the modulation techniques and increasing the data rates to make VLC a feasible solution for all applications.

2.5.1.3 Light fidelity (Li-Fi)

It was a particular type of VLC striving to realize high-speed wireless communications by using light. Li-Fi systems have many advantages over communication with radio frequencies: higher data rates, less electromagnetic interference, and better security. Li-Fi has been investigated for application in environments where the use of radio frequencies was inapplicable and contraindicated, such as hospitals, aircraft, and hazardous industrial areas. The development in Li-Fi technology concentrated on better integration with current lighting infrastructure and handover optimization between light sources to maintain uninterrupted connectivity [35].

2.5.1.4 Underwater wireless optical communication (UWOC)

These optical systems were light wave-based and enabled very high data rates through seawater. Applications include everything from underwater exploration and environmental studies to military applications under the sea. Data rates are so much higher than acoustic communications, while latency is so much lower than them. Yet, their performances were significantly affected by the presence of turbidity in water, water absorption, and media scattering. Researchers have tried to improve UWOC systems by developing advanced modulation schemes and error correction coding techniques to be more reliable and efficient [36].

2.6 FREE SPACE OPTICAL FIBER NETWORKS

2.6.1 Their Working Principles

Free Space Optical Fiber Networks implied a significant leapfrog in communication technologies using light to transmit data through free space, such as air or vacuum, rather than traditional optical fiber cables. Technologies of this nature offer flexible, high-speed solutions for all communication needs [37]. FSO networks convert digital data into optical signals using lasers and transmit them through the air to a receiver, where they are converted back into digital data. The major components of an FSO system are the transmitter, receiver, and optical channel (a laser beam, in most cases) [38].

2.6.1.1 Transmission

The laser diode of the transmitter converts electrical signals into optical signals. Modulating the light is the process of encoding the data [39].

2.6.1.2 Propagation

The modulated light beam makes it through free space to where the receiver is. This propagation needs line-of-sight visibility, and the quality of the beam can be disturbed by fog, rain, turbulence, etc.

2.6.1.3 Reception

The photodetector was the device used as a receiver to convert the incoming optical signals into electrical signals again and complete the data transmission process.

2.6.2 Advantages, Challenges and Application

On the positive side, FSO networks had several advantages, notably high data rates, low latency, and easy deployment. On the other hand, they were challenged by atmospheric interference, alignment difficulties, and short transmission distances.

2.6.2.1 Advantages

- a. **High Data Rates:** FSO systems could attain data rates in gigabits per second (Gbps), thus being appropriate for bandwidth-intensive applications.
- b. **Low Latency:** It was realized that communication was minimal, as seen in applications in real time [36].
- c. **Ease Of Deployment:** Free space optics systems require no such infrastructure, so they can quickly be deployed in urban and rural areas.

2.6.2.2 Challenges

- a. **Atmospheric Interference:** Signal quality could be significantly reduced by weather conditions such as fog or rain.
- b. **Alignment:** The need for optimum performance translated to having accurate alignment between the transmitter and the receiver.
- c. **Transmission Distance:** The limited effective range of FSO systems compared to fiber optics meant they could work over long distances only using repeaters.

2.6.2.3 Applications

FSO networks have applications in many fields, including metropolitan area networks, military communications, and satellite communications.

- a. **Metropolitan Area Networks:** FSO offers a wireless connectivity method between buildings in urban areas with high speed, without the requirement of physical cables.

- b. Military Communications: Because FSO systems can be secured quickly and are suitable for rapid deployment, they are ideal for tactical communications on the battlefield.
- c. Satellite Communications: FSO was used for transmitting data between satellites and ground stations because it could work in the vacuum of space.

2.7 MODULATION TECHNIQUES

In communication systems, information had to be carried to the transmission medium through modulation, wherein a sine wave, or signal, was superimposed on a higher-frequency carrier signal. Digital signalling was achieved using analogy signals because analogy signals continuously varied over time, while digital signals assumed only discrete values [40]. The modulation could be achieved by changing the carrier's amplitude, phase, or frequency. While the modulation of amplitude, phase, and frequency worked well for analogy signals, so did amplitude modulation (AM), phase modulation (PM), and frequency modulation (FM). Digital signals use Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK) [41].

In an optical communication system, modulation converts data into light. Amplitude modulation is realized in its simplest form by On-Off Keying. It will be shown that later developments replaced these basic forms with much more sophisticated modulation techniques to work at higher bit rates over longer transmission distances [42]. NRZ, RZ, CSRZ, and Duobinary are some of the methods that were commonly used. Both amplitude modulation and phase modulation are incorporated in current WDM systems to achieve high performance in data transmission. Coding could be external or internal; OOK and Mach-Zehnder (MZ) are other modulators available.

2.7.1 Techniques of Network Modification

In recent years, networking systems have become more efficient and secure, thanks to advanced modulation techniques.

Amplitude Modulation (AM) encodes data by varying signal amplitude, enabling dynamic network adjustments for better traffic flow and adaptability. Frequency Modulation (FM) changes the carrier signal's frequency, improving scalability, cost-effectiveness, and

resource efficiency while reducing hardware dependency. Phase Modulation (PM) adjusts the signal phase to reduce latency, save bandwidth, and enhance quality of service (QoS), making it ideal for real-time applications like IoT and autonomous vehicles [43, 44].

Machine learning (ML) further optimizes networks by predicting traffic patterns, failures, and threats, reducing human intervention and errors [45]. Phase Modulation has come up as a major technique in increasing network performance through variations in carrier signal phase for information encoding. This method brings down latency, saves bandwidth, and improves QoS. PM is presumably extremely useful for cases with demand real-time processing: IoT devices and self-navigating cars. Energy-aware (EA) networking ensures efficient energy distribution, improving performance for low-latency communications and large-scale IoT deployments [46].

2.7.2 Analysis of NRZ And RZ Modulation Techniques in Optical Communication Systems

Optical communication systems primarily use two modulation methods: Non-Return-to-Zero (NRZ) and Return-to-Zero (RZ). NRZ, the most common method, modulates data using On-Off Keying (OOK), where the signal stays on for '1' bits and off for '0' bits without returning to zero between bits. While NRZ is simple and bandwidth-efficient, it suffers from inter-symbol interference (ISI) at high bit rates, degrading long-distance performance—even with Dispersion Compensating fibers (DCF). RZ modulation improves signal integrity by returning to zero between bits, reducing ISI. However, it requires more bandwidth, making it less cost-effective. To balance spectral efficiency and performance, advanced RZ variants like CSRZ and DPSK were developed [47, 48].

Alongside coherent detection, complex schemes like QAM for higher efficiency and better SNR [49]. The limitations of NRZ in high-speed, long-distance applications have driven research into better modulation techniques. Energy Allocation (EA) also optimizes resource distribution in networks, supporting ultra-reliable low-latency communications (URLLC), IoT, and enhanced mobile broadband.

2.7.3 Modulator

Modulators were key in network communications, where they changed the properties of the carrier signal to encode information. The key to optimizing bandwidth utilization and minimizing signal degradation over long distances was to ensure the effective transmission of data. These devices modulate amplitude, frequency, or phase efficiency to ensure effective data transmission. Modulators have been studied considerably recently to enhance network performance and reliability by their effectiveness in modulation-related issues. [50, 51].

2.7.3.1 AM modulator

AM modulators have been key components of communication systems that facilitate transmitting information by varying carrier wave amplitude BM modulators according to input message signal amplitude. They were plentifully applied since they are simple and efficient in broadcasting audio signals over long distances. More recent works have been devoted to emending AM modulator performance and reliability. For example, in a work dated 2022, the authors investigate the prospects of using AM modulators in conjunction with optical communication systems for higher data rates and better signal quality.

Technical background AM, the electrical modulation signal externally modulates the optical carrier. The following equations describe the model's behaviour by assuming that the optical signal E_{in} :

$$E_{out}(t) = E_{in}(t) \cdot \sqrt{mod(t)} \quad (2.4)$$

Where $E_{out}(t)$ is the output optical signal and $Mod(t)$ is defined as

$$Mod(t) = (1 - M1) + M1 \cdot modulation(t) \quad (2.5)$$

MI is the modulation index, and $modulation(t)$ is the electrical input signal. The electrical signal is normalized between 0 and 1.

For parameterized and noise bin signals, the average power is calculated according to the above [52].

2.7.3.2 FM modulator

In communicating systems, the information is encoded by varying the carrier wave frequency using Frequency Modulators (FM). Generally, FM modulators provide better noise immunity and sound quality than AM modulators. Present efforts have, however, been occupied with enhancing the quality and performance of FM modulators. For example, [53] proposed a broadband digital phase-locked loop (DPLL)-based phase modulator, which allowed wide frequency modulation bandwidth, significantly increasing modulation accuracy and system stability. A study [54] applied FM modulation techniques in resonant converters but did not find proper details on the system given control and regulation of the output voltage. These advances keep FM modulators at the forefront of reliable, high-quality communication.

Technical Background:

An optical carrier is subjected to a frequency modulation imposed by the electrical modulation signal; the modulator's behavior can be described by the following Equation assuming that E_{in} is the optical input signal:

$$E_{out}(t) = E_{in}(t) \cdot \exp(j2\pi \int_0^t \Delta f \cdot (\text{modulation}(\tau) - 0.5) d\tau) \quad (2.6)$$

E_{out} is the output optical signal, Δf is the frequency deviation, and is the electrical input signal. Normalization of the electrical signal is done between 0 and 1.

The parameterized and noise bin signals are not affected by this modulator.

2.7.3.3 PM modulator

One of the PM modulator functions is essential in enhancing network communication systems. It was achieved by varying its phase by encoding information onto a carrier wave. This technique proved very useful because it was robust against degrading the signal and against interference. Researchers have confirmed that PM modulation improved network systems' spectral efficiency and resilience, making it a better choice in modern communication infrastructures investigating the performance of PM modulators in diverse network environments [54]. They found out that these modulators realized better

performance in terms of noise immunity and bandwidth efficiency. Adopting PM modulators into network technology marked a significant development in ensuring more reliable and efficient communication systems. Therefore, these modulators allowed the implementation of higher data rates and quality of service, which was necessary for satisfying the needs of modern applications, like streaming services or online gaming, based on cloud computing [55, 56].

Technical Background:

In a phase modulator, an optical carrier is subjected to phase modulation by the electrical modulation signal; the modulator's behavior is described by the following Equation, assuming that the optical input signal is $E_{in}(t)$.

$$E_{out}(t) = E_{in}(t) \cdot \exp(j \cdot \Delta\phi \cdot \text{modulation}(t)) \quad (2.7)$$

where $E_{out}(t)$ is the output optical signal, $\Delta\phi$ is the phase deviation, and $\text{modulation}(t)$ is the electrical input signal. The electrical input signal is normalized between 0 and 1. Parameterized and noise bin signals are not affected by this modulator.

2.7.3.4 MZ modulator

The MZ modulator has driven the development of network communication technology. Most commonly, it modulates optical signals by splitting light into two paths and then recombining them to produce interference, enabling high-speed data transmission and low signal distortion, which are essential for modern optical communication systems. The development of MZ modulators can be considered a real breakthrough in the evolution of optical networks. It made much stronger and more scalable communication infrastructures to support the increased demand for data-intensive applications, including video streaming, online gaming, and services in the cloud [57].

Technical Background:

Mach-Zehnder modulator based on an interferometric principle is shown in Figure 2.4, It consists of two 3 dB couplers connected by two waveguides of equal length utilizing an electro-optic effect; externally applied voltage can be used to vary the refractive indices in

waveguide branches. The paths can lead to constructive and destructive output interference. That can only happen if an appropriate voltage is applied. Then, the voltage modulation of output intensity is possible.

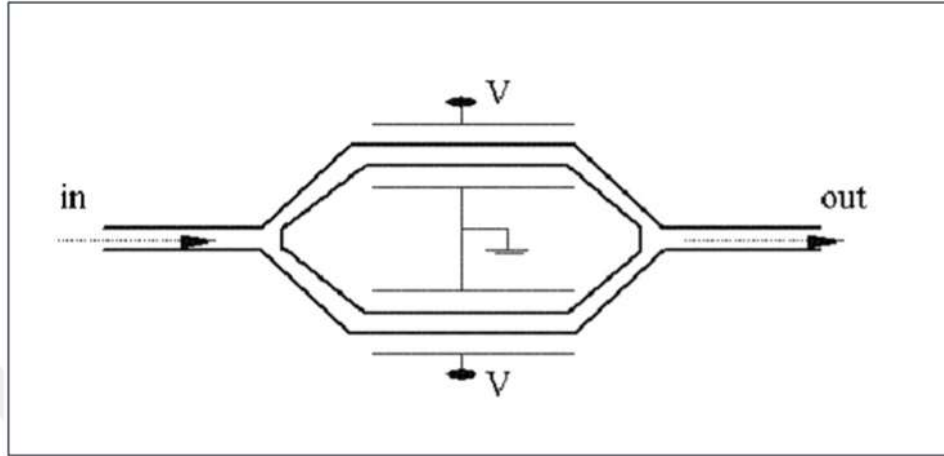


Figure 2.4: Mach-Zehnder Modulator.

The equations that describe the behavior of the MZ modulator are:

$$E_{out}(t) = E_{in}(t) \cdot \cos(\Delta\theta(t)) \cdot \exp(j \cdot \Delta\phi(t)) \quad (2.8)$$

Where $\Delta\theta$ is the phase difference between the two branches and is defined as:

$$\Delta\theta(t) = \frac{\pi}{2} \cdot (0.5 - \text{ER} \cdot (\text{Modulation}(t) - 0.5)) \quad (2.9)$$

with

$$\text{ER} = 1 - \frac{4}{\pi} \cdot \arctan \frac{1}{\sqrt{\text{extrat}}} \quad (2.10)$$

And $\Delta\phi$ Is the signal phase change defined as:

$$\Delta\phi(t) = \text{SC} \cdot \Delta\theta(t) \cdot \frac{(1+SF)}{(1-SF)} \quad (2.11)$$

The parameter SC is -1 if the negative signal chirp is proper or 1 if the negative signal chirp is false. Extract is the extinction ratio, SF is the symmetry factor, and modulation(t) is the

electrical input signal. The electrical input signal is normalized between 0 and 1. For parameterized and noise bin signals, the average power is calculated according to the above.

2.7.3.5 EA modulator

Electro-Absorption (EA) modulators are key in modern photonic communication systems, modulating optical signals by varying light absorption in semiconductors under an electric field. They enable high-speed data transmission, low power consumption, and improved signal integrity, meeting demands like HD video streaming and cloud computing [57]. In [58] research shows EA modulators enhance performance by reducing latency and enabling compact, low-chirp transmitters for high-bit-rate optical links. Their integration into photonic circuits boosts efficiency and reliability [59]. Advances in EA technology have driven more efficient optical communication systems, paving the way for future innovations in photonic networking [58, 59].

Technical Background:

The electrical modulation signal externally modulates the optical carrier, as shown in Figure 2.5.

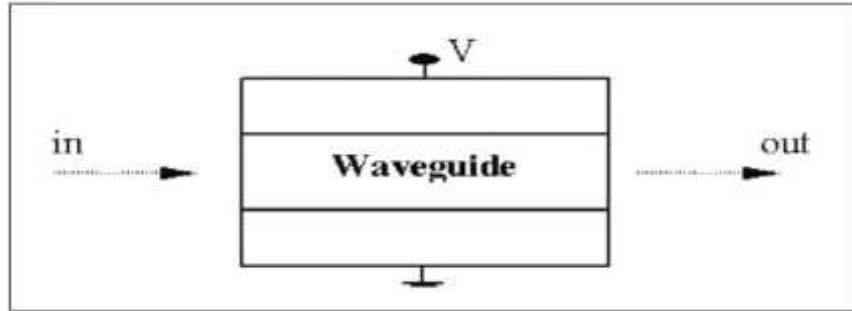


Figure 2.5: EA Modulator.

Assuming that the optical input signal is E_{in} then the behavior of the modulator is described by Equation:

$$E_{out}(t) = E_{in}(t) \cdot \sqrt{Mod(t)} \cdot \exp(j \frac{\alpha}{2} \cdot \ln(mod(t))) \quad (2.12)$$

where $E_{out}(t)$ is the output optical signal, α is the chirp factor, and $Mod(t)$ is defined as

$$\text{Mod}(t) = (1-\text{MI}) + \text{MI} \cdot \text{Modulation}(t) \quad (2.13)$$

For parameterized and noise bin signals, the average power is calculated according to the above.

2.7.4 CW Laser

The CW Laser was integrated into an OptiSystem simulation program. Researchers tried to ascertain how much the CW Laser was added to improve the network's overall efficiency and the signal's stability. Research has shown that continuous lasers offer constant and stable light, which is imperative in achieving high data speeds for transmission in networks. Simulations prove it; continuous lasers lower attenuation and signal noise, resulting in high-quality service in the network. As such, this result indicates the potential applicability of continuous laser technology in advanced communication systems and applications. It was thoroughly confirmed through considerable testing and against known laser technologies [60, 61].

2.7.5 Optical Amplifier

An optical amplifier is an active component in enhancing signal strength from an incoming optical network. It was done by boosting the power levels of optical signals, thus limiting the capacity and distance of a fiber optic communication system. The research was based on EDFAs and Raman fiber amplifiers to prove their effectiveness under varied network conditions. Raman amplifiers also raised the signal quality and reach of optical signals. The other kind was hybrid optical amplifiers, which also enhanced signal quality for applications at low data rates in combination with CWDM systems. Further SOAs were researched for integration into photonic circuits more precisely because they were becoming wider bandwidth and improved functionalities in terms of digital signal processing [62, 63].

2.7.6 Photodiode

The reception of photodiodes has proved critical in realizing advanced communication network designs. These have been widely used in converting optical and electrical signals, significantly improving data transmission. These were very important in enhancing the

sensitivity and speed of optical receivers. It has been reported that advanced material photodiodes in literature work under reduced signal loss for enhanced system performance. Further, their incorporation into dense wavelength division multiplexing systems improved the data rates while minimizing the latencies within networks [64-66].

2.7.7 Advanced Detection Components in Optical Networks

2.7.7.1 PIN photodiode

PIN photodiodes are widely used in optical communication networks because of the efficient conversion of optical signals into electrical ones. These devices were known for high-speed response and low noise characteristics, making them ideal for high-data-rate applications [67]. Recent developments in PIN photodiode technology have further enhanced their performance, especially regarding sensitivity and bandwidth. Moreover, deploying modern optical communication systems has increased network operation's overall reliability and efficiency.

2.7.7.2 Optical chirp detector

Optical Chirp Detectors significantly advance optical communication network performance by precisely detecting and compensating frequency chirps in transmitted optical signals. These detectors are critical in maintaining the very high integrity of signals and reducing phase noise for transmission at very high speeds [68]. Before long, there were further developments in the technology for the detection of optical chirps, resulting in improved sensitivity and accurate measurements; this has highly increased the dependability and effectiveness of the network compared to them. PIN photodiodes are mainly applied due to their high-speed response to light and low noise when converting optical signals into electrical usable form. While flip-chip bonded optical devices are crucial for PIN photodiode-based optical communication systems, their importance is inconsequential when utilizing optical chirp detectors. Also, while both devices are essential for optical communication, the optimization pursuits reversed the application of the conversion of signals in PIN photodiodes [69].

2.7.7.3 Optical phase detectors

They are key components in modern optical communication systems, wherein they measure the phase difference between optical signals with great accuracy. They find applications demanding high precision and stability through coherent optical communication and laser interferometry are based on them. Their sensitivity and accuracy have been boosted by recent developments, making a significant contribution to enhancing the performance of optical systems. Moreover, optical phase detectors play an important role in research on new technologies: quantum communication, and high-resolution spectroscopy [70, 71].

2.7.7.4 Low pass gaussian filter

The low-pass Gaussian filter is applied in diverse signal processing applications for high-frequency noise elimination and data smoothing. The proper execution of the Gaussian function results in a bell curve that properly decays high-frequency components and does not affect the low-frequency information. Researchers have proven that a Gaussian filter must dramatically increase the signal-to-noise ratio in noisy environments by concentrating most of the primary energy on the lower frequency range. Moreover, the Gaussian filter possesses characteristics that grant it much strength in image processing applications, in which it is utilized to cut down the Gaussian noise and, at the same time, generate smoother images. Its effectiveness as a low-pass filter results from linear smoothing: the required property for this case is to have a technique free of unwanted high-frequency signals that spoil the integrity of the original signal [72, 73].

2.8 VISUAL PERFORMANCE ANALYSIS

Typical performance analysis in optical communication systems was viewed with key parameters: quality factor, eye diagram, and bit error rate. Quality Factor is a measurement indicator of SNR over transmission media. The Q-factor is an indicator of signal quality measured by the ratio of the average optical power to BER. Utilization Eye Diagrams are used to visually represent the effect of ISI and noise on the performance of the signal in its set constellation points [74]. Bit Error Rate is a critical measurement that quantifies the number of erroneously received bits concerning the total sent over the communication

channel. These metrics give a general view of system performance and are essential for ensuring the factual transmission of data.

2.8.1 Quality Factor

Network engineering uses the quality factor (Q-factor) to assess performance and reliability. The Q-factor measures signal transmission efficiency by comparing stored energy to energy lost per cycle. Higher Q-factors reduce energy loss, maintaining signal integrity over long distances.

Calculating Q-factors is complex, so researchers use vector network analysers for precise measurements, aiding network optimization. The Q-factor is also crucial in designing resonant circuits and filters for optical and wireless systems. Optical networks help minimize bit error rates and ensure high-quality data transmission, especially in active optical networks where filter choice significantly impacts the Q-factor [75].

2.8.2 Eye Diagrams

In network engineering, eye diagrams as shown in Figure 2.6 and Figure 2.7, assess the performance of various transmission lines. These diagrams visually display signal integrity, showing effects such as ISI, noise, and distortions at different distances and data rates. Researchers analysed them to evaluate QoS and identify potential errors. To create eye diagrams, engineers measured signals at the receiver and overlapped waveforms over one period. An open eye indicated high signal quality with low BER, while a closed eye indicated degradation. For example, a 2022 study used eye diagrams to compare transmission quality across different modulation formats and fiber lengths [76].

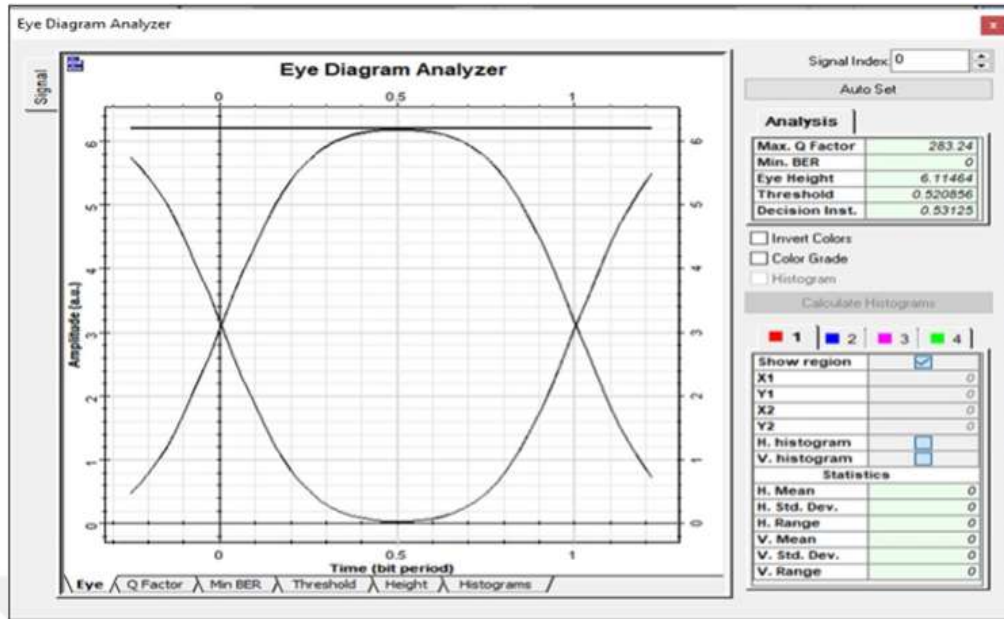


Figure 2.6: Random Result of Analyzing the Eye Diagram in A Very Good Way Using the Optisystem Program.

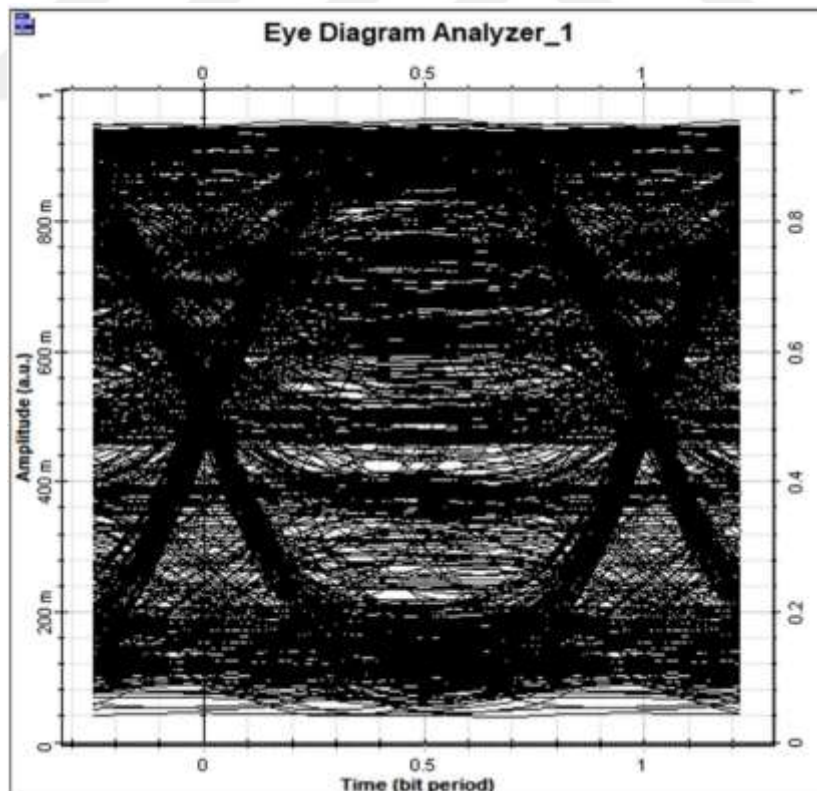


Figure 2.7: Random Result of Analyzing the Eye Diagram in The Worst Result Using the Optisystem Program.

2.8.3 Bit Error Rate (BER)

In network engineering, the Bit Error Rate (BER) was a fundamental metric used to assess the quality of data transmission. BER is the number of erroneous bits received compared to the number sent over a communication channel. BER is a key metric in assessing how well or poorly different network technologies perform and their reliability [77].

2.8.4 RF Spectrum Analyzer

A piece of RF Spectrum Analyzer equipment contributes very excellent performance to networks. That is because it plays a vital role in analyzing the characteristics of frequency signals that point to potential interferences and technical issues likely to happen come 2022. The spectrum analyzer is widely employed in the research to develop 5G. Researchers have conducted many experiments with this device to obtain optimal frequencies and decrease interference. Furthermore, it was used in complex environments, like smart cities, to find network vulnerabilities. The results were that the speed and efficiency of the network improved significantly because of the fine analysis of the frequency spectrum. Hence, it also contributed to more stable networks and less signal loss [78].

2.8.5 Electrical Power Meter

It was realized as an essential device for watching energy consumption in homes and industries. It gives the user a detailed visual of how power is being used at that time so the users can track and optimize their energy expenditure. Scientists came up with more sophisticated visualizers that are interconnected with smart grids to improve energy efficiency. Such visualizers identified peak consumption periods and possible inefficiencies, leading to appropriate energy management practices. Besides, they were endowed with user-friendly interfaces that allowed easy understanding of complicated data [79].

2.8.6 WDM Analyzer

A key enabler of the further development of optical communication systems is found in the Wavelength Division Multiplexing (WDM) Analyzer. This device was applied to analyze and optimize WDM network performance by monitoring different wavelength channels

simultaneously. Other researchers have conducted extensive studies using WDM analyzers to enhance data transmission efficiency over optical fibers. It helped detect signal degradation and channel interference, which increased the system's reliability. Hence, new modulation techniques also could be adopted to increase the bandwidth capacity further. Since the WDM Analyzer also facilitated installing advanced error correction methods, it reduces signal loss and eventually improves the general network performance. Such were the results from the study that the implementation of such analyzers is crucial for the scalability of optical networks in future [80].

2.8.7 Optical Spectrum Analyzer

The optical spectrum analyzer was one of the key elements in delivering high-performance networks through high-accuracy measurements of lightwave signals. Scientists used OSAs to monitor and optimize network parameters to guarantee data transmission is dependable. It enabled signal distortion and wavelength variation, crucial to high-quality communication channels. OSAs made it possible to implement such modulation methods that could significantly improve bandwidth utilization efficiency [81].

2.8.8 Optical Time Domain Visualizer

The Optical Time Domain visualizer contributed greatly to monitoring and optimizing network performances by the company. Its main application lay in signal visualization to identify any possible anomaly within optical networks. It also played an essential role in improving such applications by providing advanced diagnostic tools, consequently increasing general network resilience. That is why the authors stress that an Optical Time Domain Visualizer is, without any exaggeration, “a vitally essential part of a high-performance communication system to be compliant with the scalability of the modern optical network.” [82].

2.9 OPTICAL FIBERS AND WIRELESS OPTICAL FIBER NETWORKS, THEIR RELATIONSHIP AND APPLICATIONS IN SMART SYSTEMS AND IOT (INTERNET OF THINGS)

Smart systems and IoT rely heavily on optical fibers and wireless optical networks for fast, reliable data transmission. Researchers have shown how fiber sensors enable real-time,

accurate temperature and pressure monitoring in smart systems. Wireless optical networks, like Free Space Optics (FSO), offer high-capacity communication without cables, making them ideal for urban areas where laying fiber is difficult. These networks support seamless connectivity, from smart homes to autonomous vehicles [83, 84].

Hybrid networks combining fiber and wireless technologies enhance performance, enabling advanced IoT applications like remote health monitoring and industrial automation. These networks leverage fiber's high bandwidth and wireless flexibility, improving efficiency and reducing latency. Additionally, optical fibers enhance security as they resist electromagnetic interference. Advanced encryption further ensures data integrity and confidentiality in IoT communications [85, 86].



3. IMPLEMENTATION OF DESIGN OF DIFFERENT ENVIRONMENTS

This section discusses the simulation of land, underwater, and space networks using the OptiSystem 18 program, using optical fiber and wireless optical communication technologies. The simulations were carried out, and the quality factors were obtained by sequentially varying the parameters of distances, frequencies, and source laser power. Plots showed the change in the quality factor with a variation of a specific parameter during operation using Excel analysis software. The modulators (MZ Modulator Analytical, EA Modulator Analytical, Amplitude Modulator, Phase Modulator, Frequency Modulator) were interchanged successively. They so also were the bit rate generators in (NRZ Pulse Generator and RZ Pulse Generator) Attenuations in the three environments were accounted for.

3.1 FIBER OPTIC NETWORK ON THE LAND

The network uses this fiber, which changes the information sequentially with an attenuation rate of 0.2 dB/km as shown in Figure 3.1. Readings were obtained from the visualizer library (Optical Spectrum Analyzer, Optical Time Domain Visualizer, Optical Power Meter, WDM Analyzer, BER Analyzer, Eye Diagram Analyzer, RF Spectrum Analyzer, Electrical Power Meter Visualizer, Oscilloscope Visualizer). The quality factor values were also extracted while sequentially changing the modulator (MZ, AM, FM, PM, EA). Excel was used to extract charts, and the bit pulse generator was changed (RZ, NRZ).

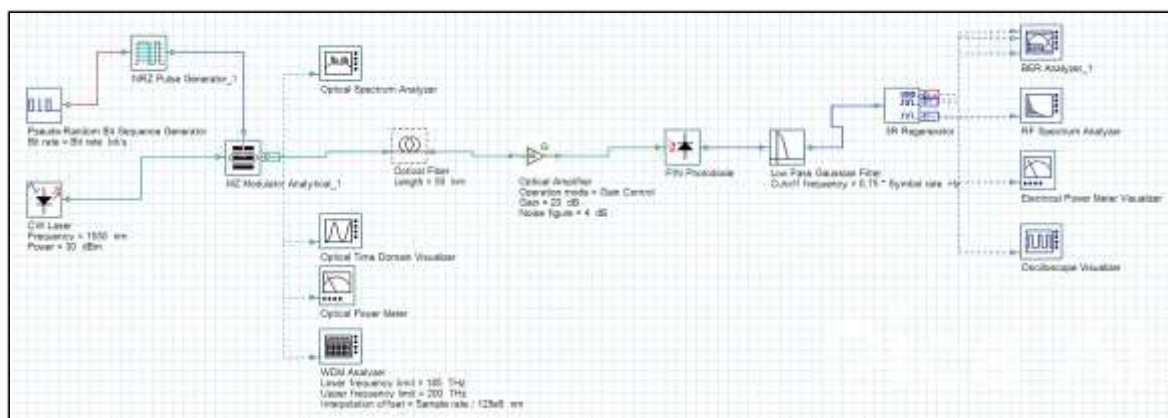
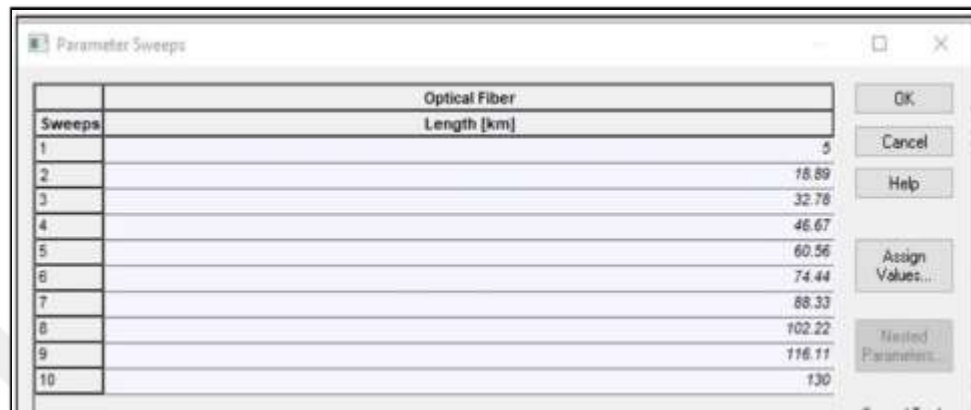


Figure 3.1: Optical Fiber Network Design on Land.

3.1.1 Fiber Optic Distances

These numbers were used as distances are given in Figure 3.2, the frequency was fixed to 1550 nm, a value, and the laser source power was fixed at 20 dBm [87].

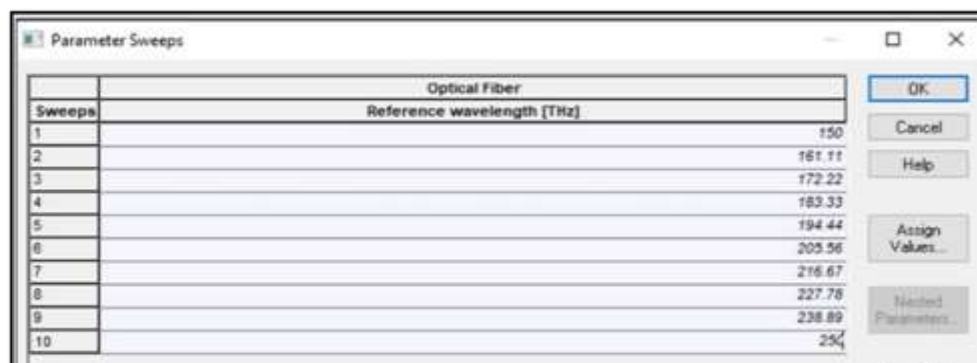


Sweeps	Optical Fiber Length [km]
1	5
2	18.89
3	32.78
4	46.67
5	60.56
6	74.44
7	88.33
8	102.22
9	116.11
10	130

Figure 3.2: Optical Fibers Set in The Network Using Optisystem 18.

3.1.2 Fiber Optic Frequencies

These numbers were used as frequencies are in Figure 3.3, and the distance was fixed to 5 km a value, and the laser source power was fixed to 20 dBm.



Sweeps	Optical Fiber Reference wavelength [THz]
1	150
2	161.11
3	172.22
4	183.33
5	194.44
6	205.56
7	216.67
8	227.78
9	238.89
10	250

Figure 3.3: Frequencies of Optical Fibers Setting in The Network Using Optisystem18.

3.1.3 Laser Source Power

These numbers were used as laser powers are in Figure 3.4. The distance was fixed to a value of 5 km, and the optical fiber frequency was 1550 nm.

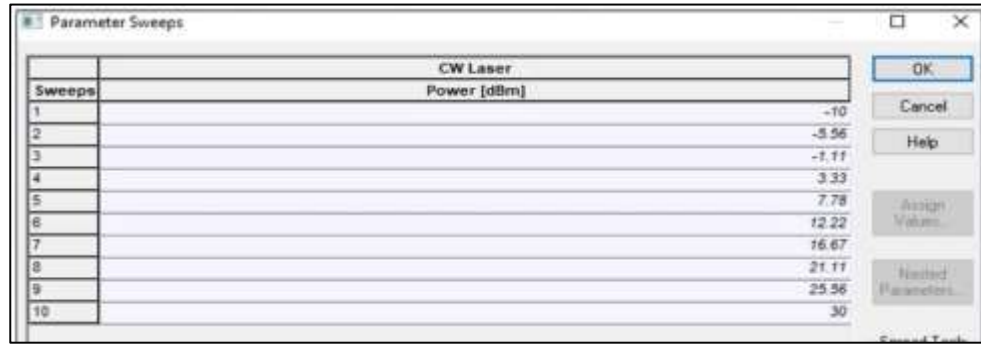


Figure 3.4: Laser Power Setting in The Network Using Optisystem18.

3.2 FSO FREE SPACE OPTIC

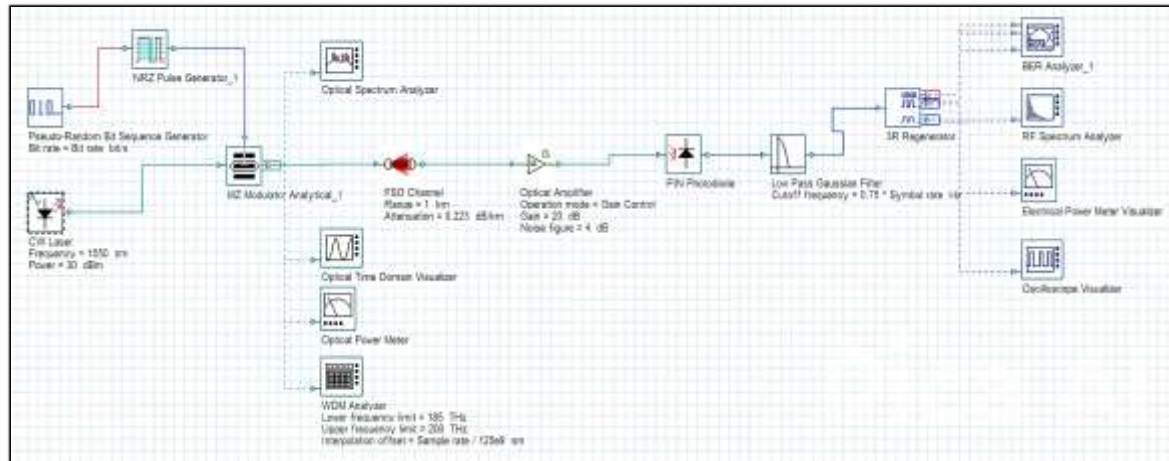


Figure 3.5: FSO Network Using Optisystem18.

As shown in Figure 3.5, the design consisted of a transmitter, receiver, and essential measurements. The quality factor was calculated, and the clarification of the effect of the differences in the results according to the five modulators (AM, FM, MZ, EA and PM) and the two pulse generators (RZ pulse bit generator and NRZ pulse bit generator) were performed. The analysis of the quality factor was conducted using the Excel program. This network was implemented with distances, frequencies, and laser source power changes. All of this was done according to weather conditions, or in other words, the attenuation that occurs in the air at different times, the parameters are in Table 3.1 below.

Table 3.1: Attenuation Coefficients for Various Meteorological Conditions.

Meteorological conditions	Attenuation Coefficient (dB/km)
Clear	0.233
Hazy	2.3706
Light rain	6.27
Moderate rain	9.64
Heavy rain	19.28

3.2.1 FSO Network Distance

These numbers were used as distances are in Figure 3.6, and the frequency was fixed to 1550 nm, a value, and the laser source power was fixed at 20 dBm.

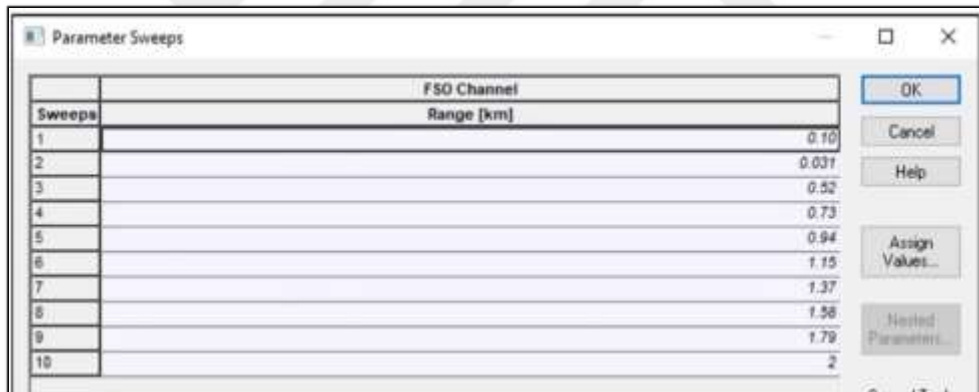


Figure 3.6: FSO Setting in The Network Using Optisystem18.

3.2.2 FSO Frequencies

These numbers were used as frequencies are in Figure 3.7, and the distance was fixed to 0.10 km a value, and the laser source power was fixed at 20 dBm.

Parameter Sweeps	
FSO Channel	
Sweeps	Frequency [nm]
1	150
2	161.11
3	172.22
4	183.33
5	194.44
6	205.57
7	216.67
8	227.78
9	238.89
10	250

Figure 3.7: Frequencies Setting of FSO Network.

3.3 OPTICAL WIRELESS COMMUNICATION (OWC)

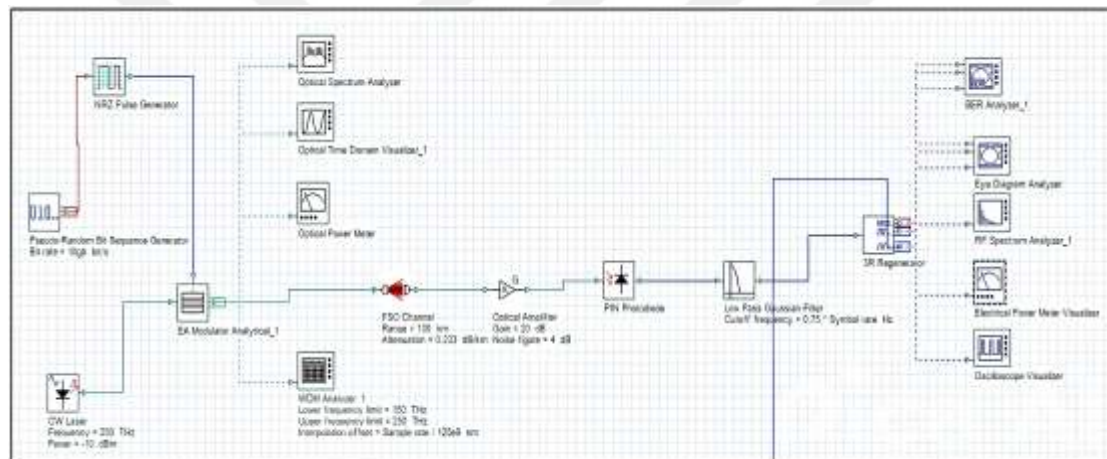


Figure 3.8: FSO Network Using Optisystem18.

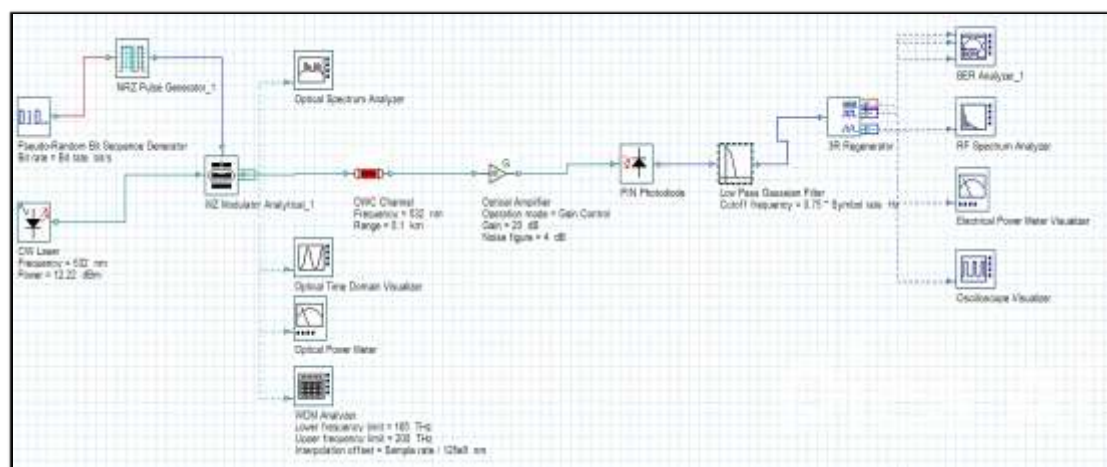


Figure 3.9: OWC Network Using Optisystem18.

As shown in Figure 3.8 and 3.9 above, a 200 km link is achieved from the satellite to the ship using free space optics with an attenuation of 0.225. The network from the ship to the submarine is now set up as the third parameter. Three parameters were set at first varying: length, frequency, and source power. AM, FM, PM, MZ, EA; RZ pulse generator, and NRZ pulse generator were implemented in succession. Using Excel, the quality factor was extracted and analysed based on varying attenuation in water as in the Table 3.2.

Table 3.2: Attenuation Coefficients for Various Weather Conditions.

Water condition	Attenuation	The appropriate frequency used
Sea Water	500 dB/km	490 nm [86]
Still Water	87 dB/km	532 nm [87]
River water	200 dB/km	490 nm

3.3.1 OWC Network Distances

These values shown in the Figure 3.10, were used as distances in km for the grating, and the attenuations were utilized with the frequencies shown in the table. The source laser power was set at 20 dBm.

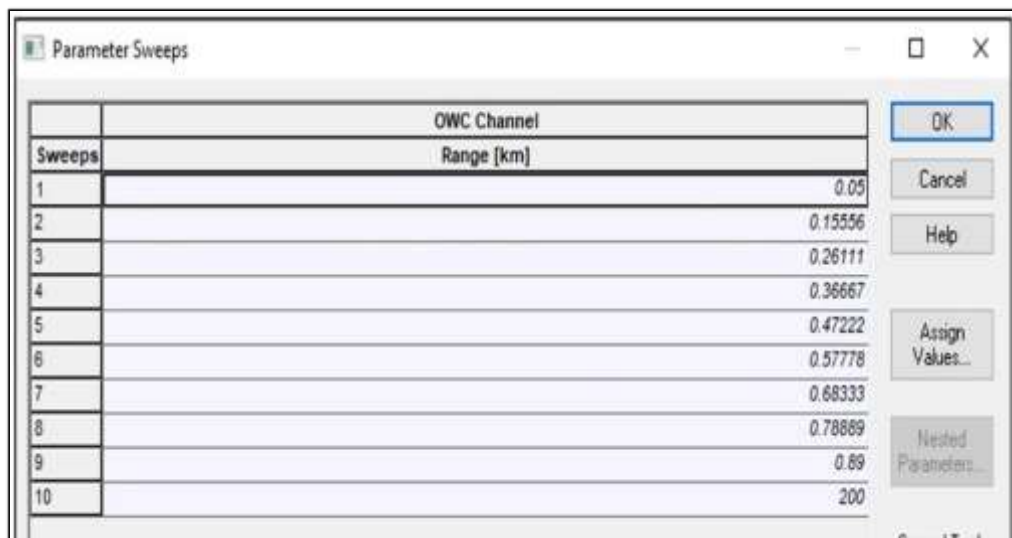
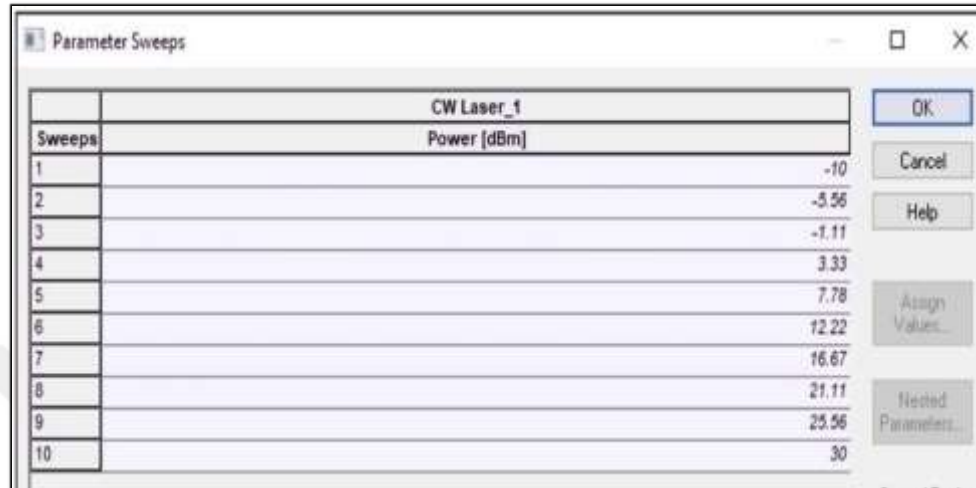


Figure 3.10: OWC Setting in Network Using Optisystem18.

3.3.2 Laser Source Power

These powers values were used in the laser source, as shown in Figure 3.11, The attenuations and frequencies in the Table 3.2 were used, with the length fixed at 0.5 km.



Sweeps	CW Laser_1 Power [dBm]
1	-10
2	-3.56
3	-1.11
4	3.33
5	7.78
6	12.22
7	16.67
8	21.11
9	25.56
10	30

Figure 3.11: Laser Power Setting in The Network Using Optisystem18.

3.4 LOS CHANNEL NETWORK

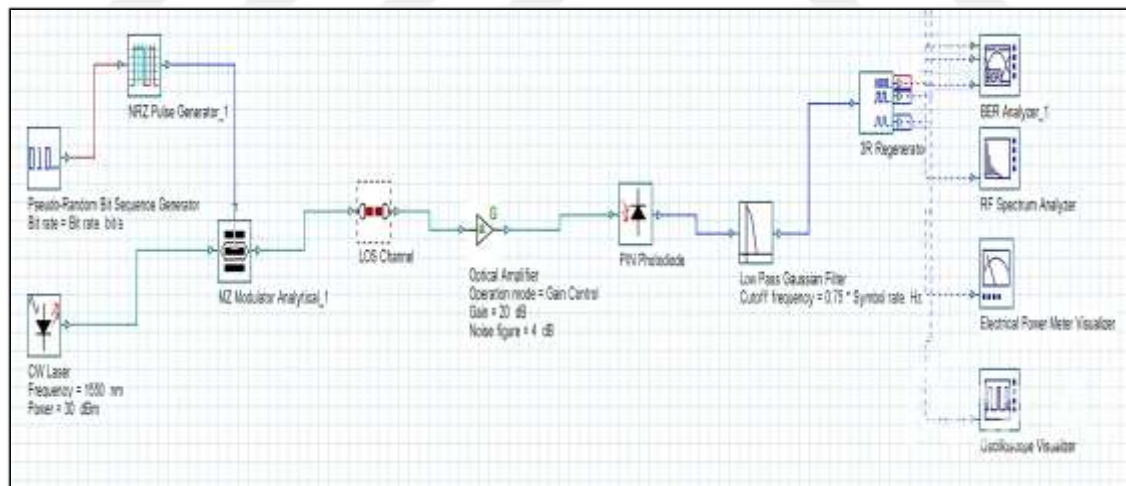


Figure 3.12: Network Using LOS Using Optisystem18.

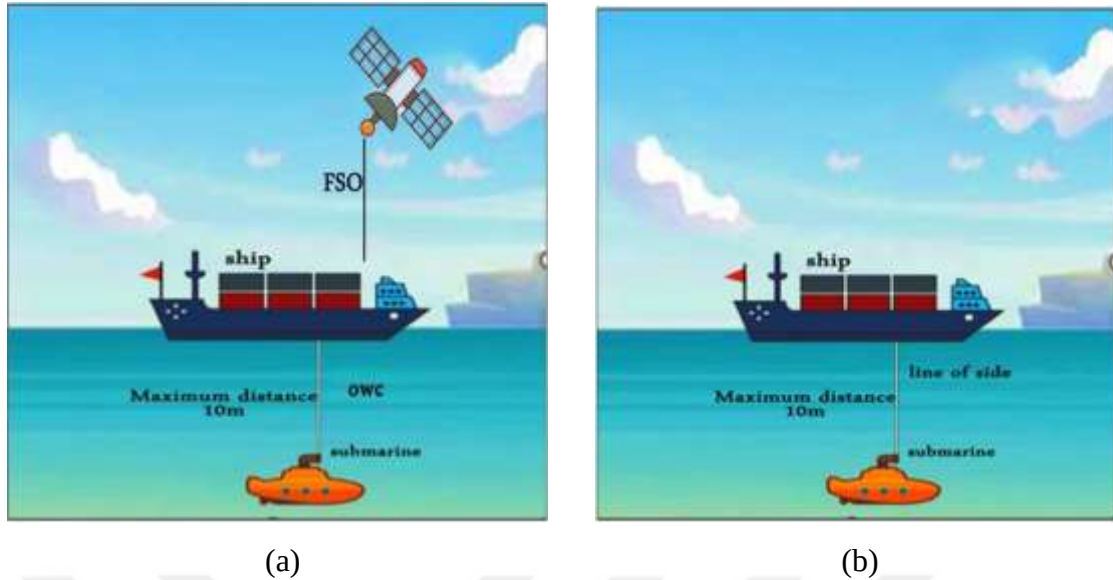


Figure 3.13: An Illustrative Example Of The Network Between Satellite And Ship Using (OWC) And Submarine Using (Los) (B) - An Illustrative Example Of The Network Between Ship And Submarine Using (Los).

As shown in Figure 3.12 and 3.13 above, Line of Sight (LOS) Fiber Optic Transmitter, a simulation was made between a ship and submarines using an LOS channel with approximately 8-10 meters at a frequency of 550 nm.

3.5 THE INTERIOR NETWORK ON THE SHIP

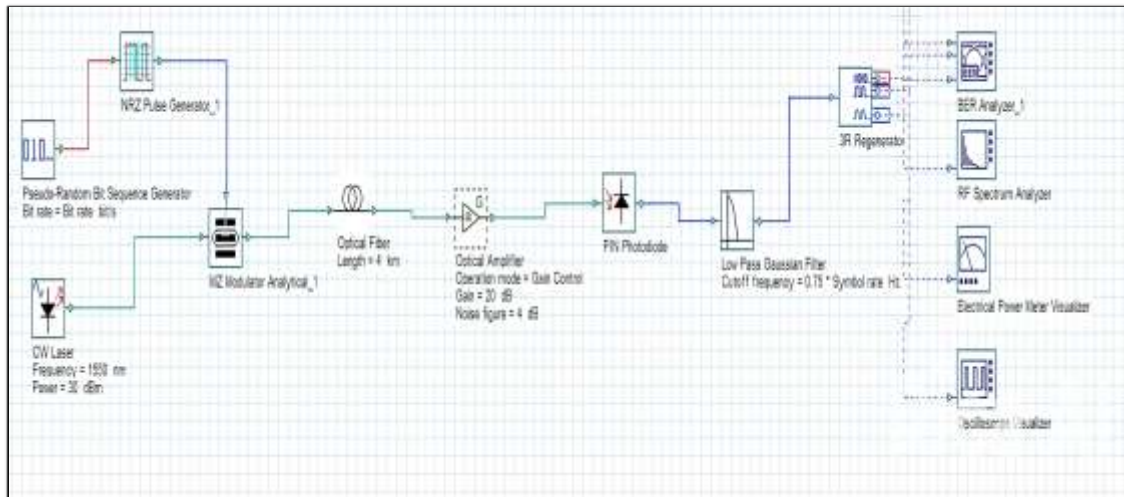


Figure 3.14: Network Interior Network on The Ship.

LOS Channel Properties

Label: LOS Channel

Main | Simulation | Random numbers | Custom order

Disp	Name	Value	Units	Mode
☐	Distance	2	m	Normal
☐	Transmitter half-angle	60	deg	Normal
☐	Irradiance half-angle	20	deg	Normal
☐	Incidence half-angle	20	deg	Normal
☐	Detection surface area	1	cm ²	Normal
☐	Optical concentration facto	90	deg	Normal
☐	Index concentration factor	1.5		Normal
☐	Propagation delay	0	ps/m	Normal

OK Cancel Evaluate Script

Figure 3.15: Network Interior Network on The Ship Using Optisystem18.

Using the interior network on the ship as in the Figure 3.14, and using the characteristics given in the Figure 3.15, were adopted, and the distance of 10 meters was used incrementally from 1 meter to 10 meters.



Figure 3.16: Image as An Illustrative Example of The Network.

As shown in the Figure 3.16 above, the simulation was conducted for a network with an area of 400 m, operating at a frequency of 1550 nm at a laser power of 20 dBm.

3.6 IMPORTANT TABLES WERE USED IN IMPLEMENTING THE NETWORKS IN DIFFERENT ENVIRONMENTS

Table 3.3: System Parameters with Multiple Distances in Km for The Network on The Land.

Parameter	Values
Data rate	10 Gbps
Distance in km	[5,18.89, 32.78,46.67,60.56,74.44, 88.33, 102.22, 116.11, 130] km
Power of CW Laser	20 dBm
Attenuation	0.233 dB/km

Table 3.4: System Parameters with Multiple Frequencies for The Network on The Land.

Parameter	value
Data rate	10 Gbps
Distance	5 km
Power of CW laser	20 dBm
Attenuation	0.2 dB/km

Table 3.5: System Parameters with Multiple Laser Power in dBm For the Network on The Land.

Parameter	Values
Data rate	10 Gbps
Distance in km	0.1, 0.031, 0.25, 0.73, 0.94, 1.15, 1.37, 1.58, 1.79, 2
Power of CW Laser	20 dBm
Attenuation	0.233 dB/km

Table 3.6: System Parameters with Multiple Distances in Km For (FSO).

Parameter	Values
Data rate	10 Gbps
Distance in km	5 km
Power of CW Laser	[-10, -5.56, -1.11, 3.33, 7.78, 12.22, 16.67, 21.11, 25.56, 30] dBm
Attenuation	0.02 dB/km [86]

Table 3.7: System Parameters with Multiple Frequencies in THz for (FSO).

Parameter	Values
Data rate	10 Gbps
Distance in km	1 km
Power of CW Laser	20 dBm
Attenuation	0.233 km /dBm

Table 3.8: System Parameters with Multiple Power of The Laser in dBm for (FSO).

parameter	Values
Data rate	10 Gbps
Distance in km	1 km
Power of CW Laser	-10, -5.56, -1.11, 3.33, 7.78,12.22,16.67,21.11, 25.56, 30 dBm
Attenuation	0.233 dB/km [8]

Table 3.9: System Parameters with Multiple Distances in Km for (OWC).

Parameter	Values
Data rate	10 Gbps
Distance in m	0.05
Power of CW Laser	-10, -5.56, -1.11, 3.33, 7.78,12.22,16.67,21.11, 25.56, 30 dBm
Attenuation	500 dB/km

4. RESULTS

In this chapter, the quality factor was relied upon in all networks, as it was obtained with multiple parameters, multiple modulators, and multiple pulse bit generators, considering attenuation or atmospheric conditions. Some critical readings were also recorded, which will be mentioned successively in this chapter.

4.1 FIBER OPTIC NETWORK ON THE LAND

Optical fiber was used in the network, and the parameter information was changed sequentially at an attenuation rate of 0.2 dB/km [86]. Tables Table 3.3, Table 3.4 and Table 3.5 were used sequentially with varying distances, frequencies, and power of the source laser.

4.1.1 Responding to Changes in Distances

A. NRZ Pulse Bit Generator

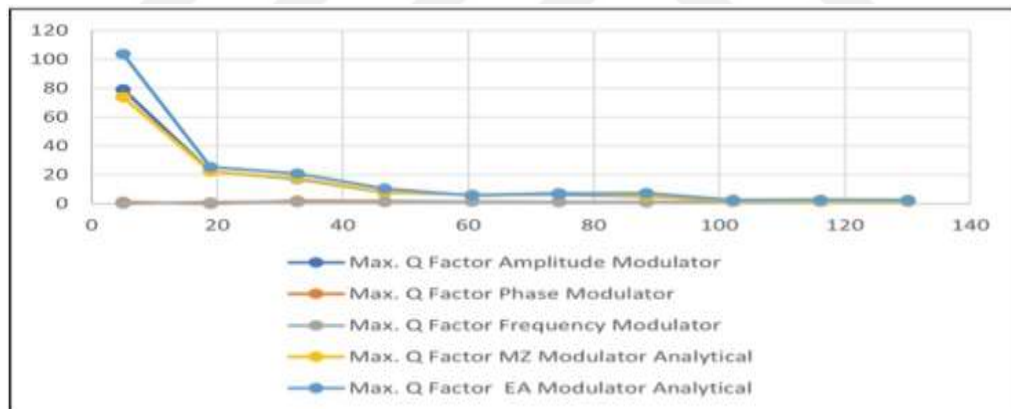


Figure 4.1: The Relationship Between the Quality Factor and Distances.

As shown in Figure 4.1, the graph shows the Q-Factor graph for different modulation techniques over increasing distances. The X-axis represents distance ranges from 0 to 140 km; for this measurement, it is assumed that the unit of distance is a kilometer. The vertical or Y-axis shows maximum values of the Q-Factor, which varies from 0 to 130, and the Q-Factor shows how well the system is transmitting the signal with some level of noise or

distortion. The best reading was 103.492 about the EA modulator Analytical reading at 5 km. The quality factor was at its worst with the Phase and Frequency Modulators.



(A)



(B)

Figure 4.2: (A) Optical Power Meter After Modulator (B) Electrical Power Meter Visualizer at Destination.

As shown in Figure 4.2 (a) the values at the beginning of the Network (after modulator): 49.901 E-3W, and 16.901dBm, while Figure (b) the values at the end of the network (at destination), The values due to degradation and distortion of a signal along a network is 297.247 E-6 W.

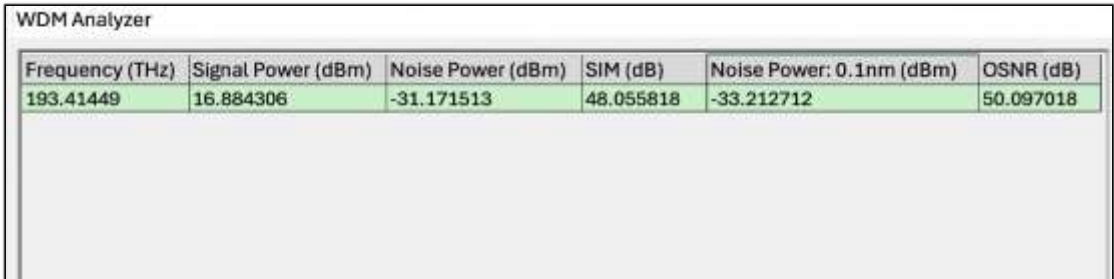


Figure 4.3: Reading of WDM Analyzer Before Optical Fiber.

The power is higher than expected when the signal is strong at the beginning. The reading "-5.269 dBm" indicates a reasonable power level. On the contrary, any reading in Figure (b)

will be on the low side due to interference and losses in the signal across the network. For this reason, first-image reading is preferred since it represents a stronger and less distorted signal.

as shown in Figure 4.3, the obtained results give an overview of the performance of the optical system used in this simulation. Now, let's evaluate each value one by one:

- a. Frequency (THz): - 193.41449 THz. This is the central frequency of the optical signal used. This is all Depends on how the system is designed and on the technical requirements of the signal.
- b. Signal Power (dBm): - 16.884306 decibels milliwatt. A high value means the signal at the beginning of the network was strong; in this case, the system was designed to avail very high transmission power that could cover possible losses across the network.
- c. Noise Power (dBm): - 31.171513 decibels milliwatt. This negative value signifies that the noise level is very low; hence, the system was effective in the reduction and control of noise.
- d. SNR (dB): 48.055818 decibels. A high signal-to-noise ratio simply means a signal is very pure compared to the level of noise. This value is kept very high to ensure that the quality of data transmission and reception is high.
- e. Noise Power: 0.1nm dBm: -33.212712 decibels milliwatt. This is the noise in the spectral bandwidth specified, 0.1 nanometres. The negative value reflects that the noise is very low, enhancing the signal quality.
- f. OSNR (dB): 50.097018 decibels. Optical signal-to-noise ratio. This is a very high value, and as such, it shows that there is good transmission of the signal without much interference.

These results signify an effective optical system with low noise and a strong signal reflecting good design and effective management of various network factors. Frequency, Power, and Signal-to-noise Ratio issues reveal the performance of the system and how it triumphed over the challenges of interference and distortion.

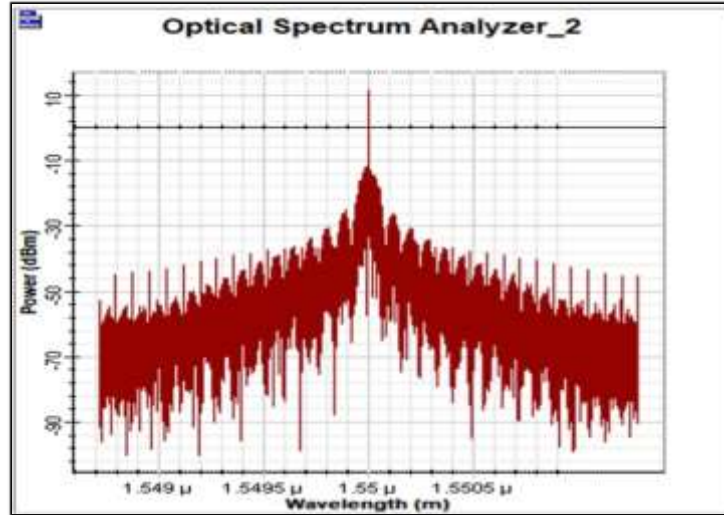


Figure 4.4: Optical Spectrum Analyzer After EA Modulator Analytical.

The results from the "Optical Spectrum Analyzer" as shown in Figure 4.4, after EA Modulator Analytical within the network using simulation software. The horizontal axis represents the wavelength in micrometers (μm), approximately ranging from 1.549 μm to 1.5505 μm . The vertical axis represents the power in (dBm), ranging from -90 dBm to 10 dBm. The graph shows a peak in the spectrum around 1.55 μm , where the power reaches approximately 10 dBm at the peak, then gradually decreases on both sides. The results mean that the optical signal has the highest concentration of power around a specified wavelength ($\sim 1.55 \mu\text{m}$), showing how the power is distributed across different wavelengths.

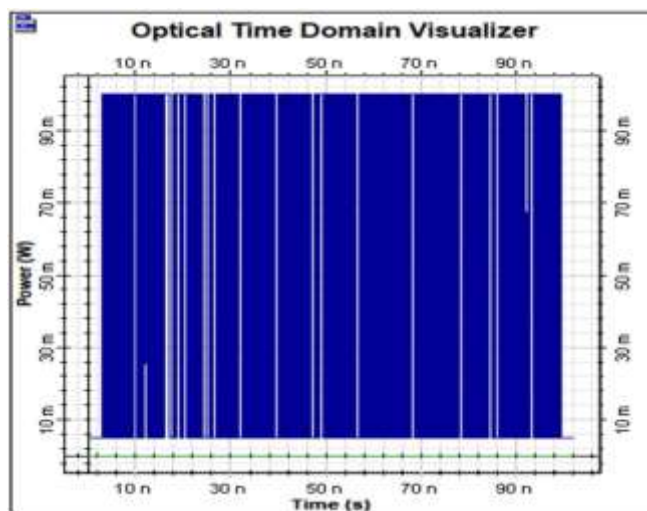


Figure 4.5: Optical Time Domain Visualizer After EA Modulator Analytical.

As in the graph 4.5, which represented the output from an "Optical Time Domain Reflectometer". The horizontal scale was in nanoseconds (ns) and extended from 0 to 100 nanoseconds. The vertical scale was in milliwatts (mW) and extended from 0 to 100 milliwatts. The blue vertical lines indicated power at a given time. This graph is usually used for the analysis of performance by optical signals in the network, more precisely after filtering, to observe the strength and quality of signals concerning time.

Power: The scale from 0 to 100 milliwatts gave the variation in power over nanoseconds (ns). These high values showed that the modulator was doing a pretty good job of amplifying or changing the optical signal without much loss of power. Variation in time: If the power was stable over time, then performance was stable by the modulator and there was little to no major distortion or interference.

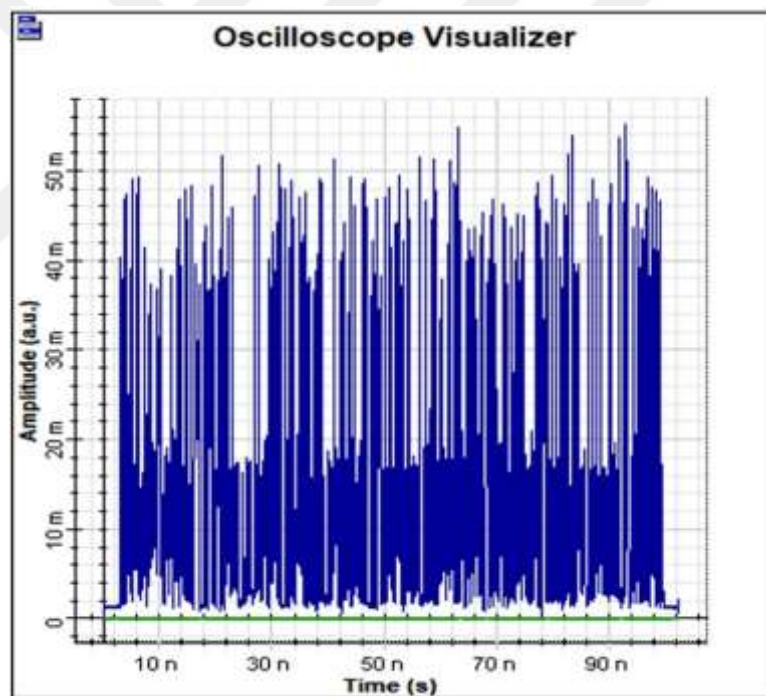


Figure 4.6: Oscilloscope Visualizer at Destination.

As shown in graph 4.6, the results for the "Optical Time Domain Analyzer" at the receiver in the network, as taken from simulation software. Horizontal Axis represents time in nanoseconds (ns), extended between 0 and circa 100 nanoseconds. Vertical Axis represents amplitude in arbitrary units (au), extended between 0 and circa 50 milliwatts or another unit. Blue Lines represent the optical signal at the receiver.

In the case of the latter, it has a very big variation of amplitude within time - namely, it fluctuates fast and many times in amplitude. These fluctuations might then mean that the signal at the tail of the network might have been subjected to noise or interference when it traversed the network.

Results Interpretation:

- a. The High Signal at The Start: The implication was that the signal started strong, then fluctuated rapidly. Several fluctuations: Suggested that the signal may have been interfered with or distorted because of interference with other signals.
- b. Average Stability: If the fluctuations were not too great, this could indicate reasonable stability in the signal; however, there were some distortions.

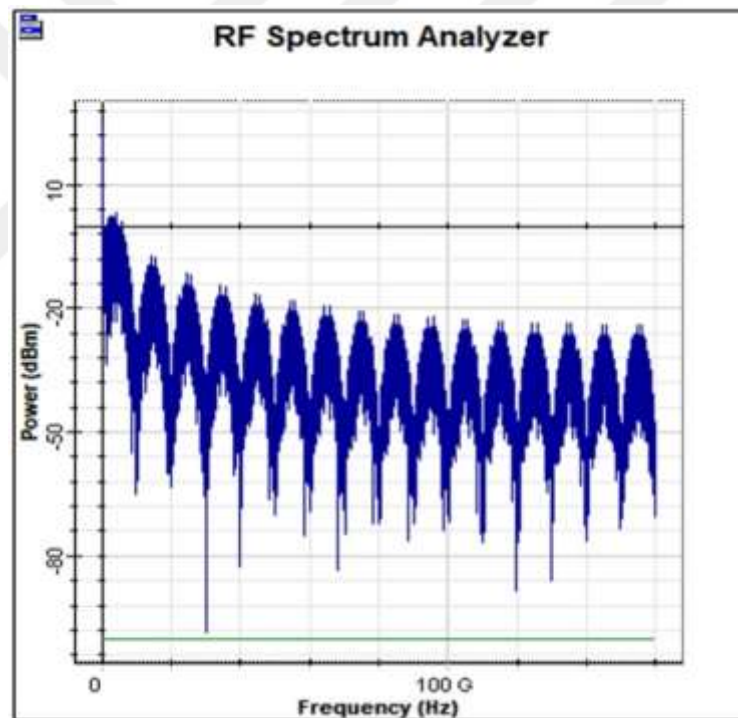


Figure 4.7: RF Spectrum Analyzer at Destination.

As shown in Figure 4.7, the result of the "Spectrum Analyzer" at the destination in the network. The X-axis, which is in frequency (Hz), goes up to 100 GHz showing the different frequencies of the signal. The Y-axis gives the power level of the signals in (dBm), ranging from -80 dBm to 10 dBm. This graph plotted, in blue, is a spiky up-and-down trend that

represents the level of power that could see at any given frequency. These peaks and troughs thus indicated multiple frequency components or signals within the analysed spectrum.

Interpretation:

- a. Peaks: These showed the frequencies of the strong signal; these might indicate channels or bands of frequency applied in the network.
- b. Valleys: Represented frequencies in which the signal was weak or when noise existed.

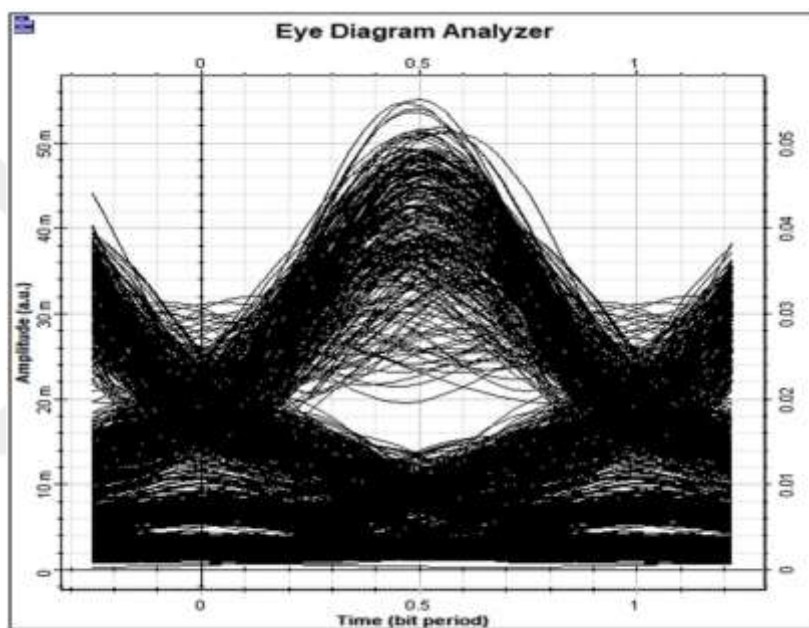


Figure 4.8: Eye Diagram Analyzer at Destination.

As shown in Figure 4.8, an eye diagram from an Eye Diagram Analyzer. Time, in a (bit period) was along the horizontal axis while the amplitude, along the vertical axis, was in arbitrary units (au). The diagram was a superposition of several signal bits in a pattern such that it looked like an eye. The eye diagram visualizes the quality of the signal at the receiver. It showed the clarity and the timing of the received signal.

A large, well-opened eye showed good quality, while a closed or distorted eye showed that something was amiss, such as noise or distortion. In this case, there was an opening of the eye large and clear, which means that at the receiver, the quality of the signal is pretty good.

The opening, being small or completely closed, would indicate system problems that need further improvement. The worst readings were at the FM Modulator.

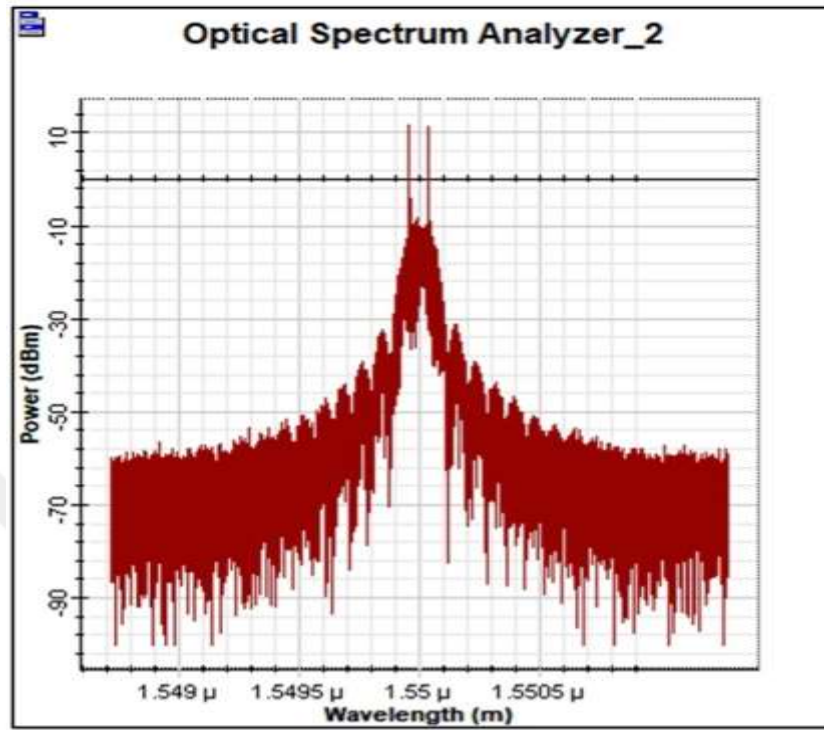


Figure 4.9: Optical Spectrum Analyzer Before Optical Fiber.

As shown in Figure 4.9 shows results given by the OSA, which is the optical spectrum analyser, after the modulator within the network using simulation software. The horizontal axis of this OSA represents the wavelength in micrometres (μm) and covers approximately from 1.549 μm to 1.5505 μm , while the vertical one represents the power in decibel-milliwatts (dBm), and it covers from -90 dBm to 10 dBm. This graph peaks around 1.55 μm , where the power reaches about 10 dBm at the peak and gradually decreases on either side.

Result Interpretation

The peak at 1.55 μm showed that there was a strong optical signal at this wavelength, meaning that the system had properly modulated the signal and was injecting adequate power. This was a typical decline on either side, as observed with the optical spectrum, where the power is lower and farther from the central wavelength. These results illustrated the efficiency of the modulator in generating a strong stable optical signal at the desired wavelength for good network performance.

WDM Analyzer					
Frequency (THz)	Signal Power (dBm)	Noise Power (dBm)	SIM (dB)	Noise Power: 0.1nm (dBm)	OSNR (dB)
193.41449	19.936679	-33.414096	53.350775	-35.455296	55.391975

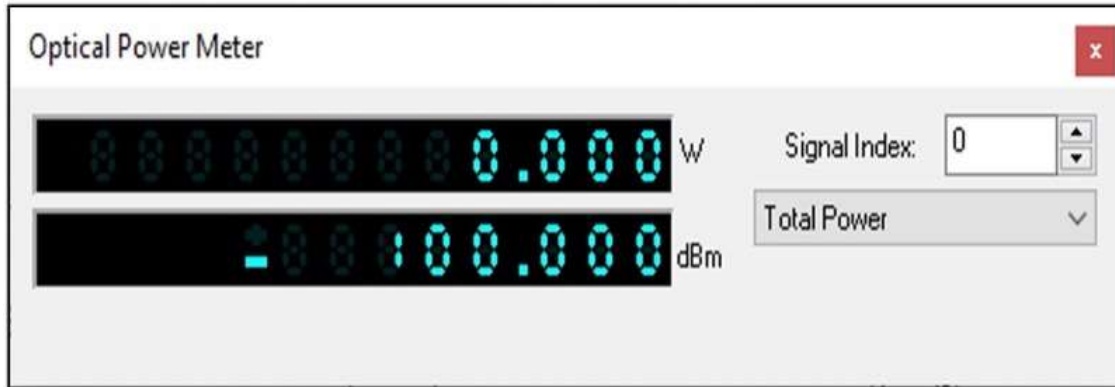
Figure 4.10: Reading of WDM Analyzer Before Optical Fiber.

The results obtained from the WDMA which are in Figure 4.10, after the FM Modulator in the network, based on the conducted simulations software, were shown by the image.

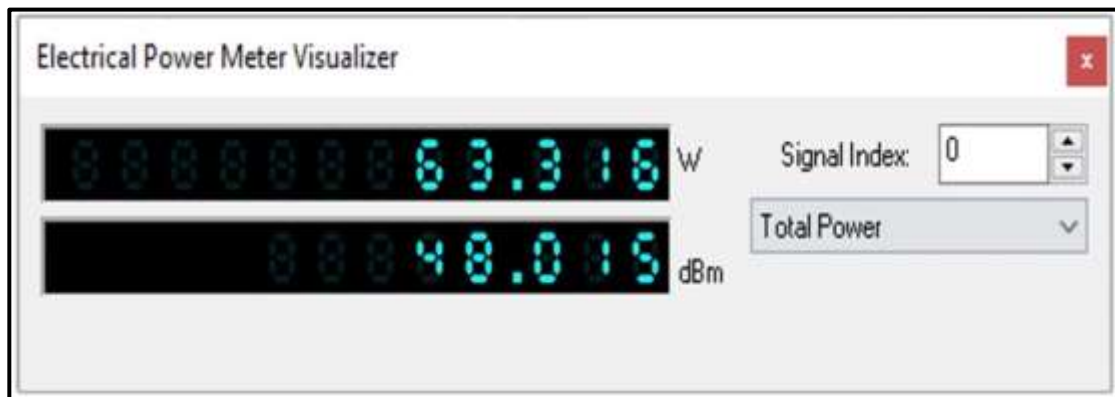
Results Analysis:

- Frequency-THz: - This shows the central frequency of the optical signal transmitted in the network.
- Signal Power-dBm: - This was the power of the transmitted signal that seemed very strong at a value of 19.936679 dBm.
- Noise Power dBm: - The noise power has a negative value of -33.414096 dBm, which reflects low intensities within the band.
- SNR dB: - The SNR provided a high value at 53.350775 dB, representative of a very clear signal with high quality.
- Noise Power 0.1 nm dBm: - Noise power at 0.1 nm, once again showed a negative value of -35.455296 dBm, low noise in the given bandwidth.
- OSNR (dB): - In this case, the optical signal-to-noise ratio was 55.391975 dB, used to check the quality of the signal at the output of the optical channels.

The above results proved that the modulator would work properly and provide a bright, stable optical signal with low noise and a good quality factor. These values showed that after the modulator, the system is also performing very well.



(A)



(B)

Figure 4.11: (A) Optical Power Meter After Modulator (B) Power Meter at Destination.

Result Interpretation:

Reason for the result: (a) in Figure 4.11 the reading at the source point. (b) Electrical Power Meter Visualizer. The screen above reading at (b) was 63.316 W, while that below gave the same reading but in decibel-milliwatts as 48.015 dBm.

Explanation Of Results

- Power in Watt: The reading 63.316 W showed that the system was producing or consuming 63.316 watts of power, and by this, it means that it has a high power.
- Power in dBm: The reading of 18.015 dBm means this output is high compared to one milliwatt and reflects strong network performance in power transmission.

These measurements showed that the system was functioning well, with a few high-power levels at the receiver showing a good indication of the general performance of the system.

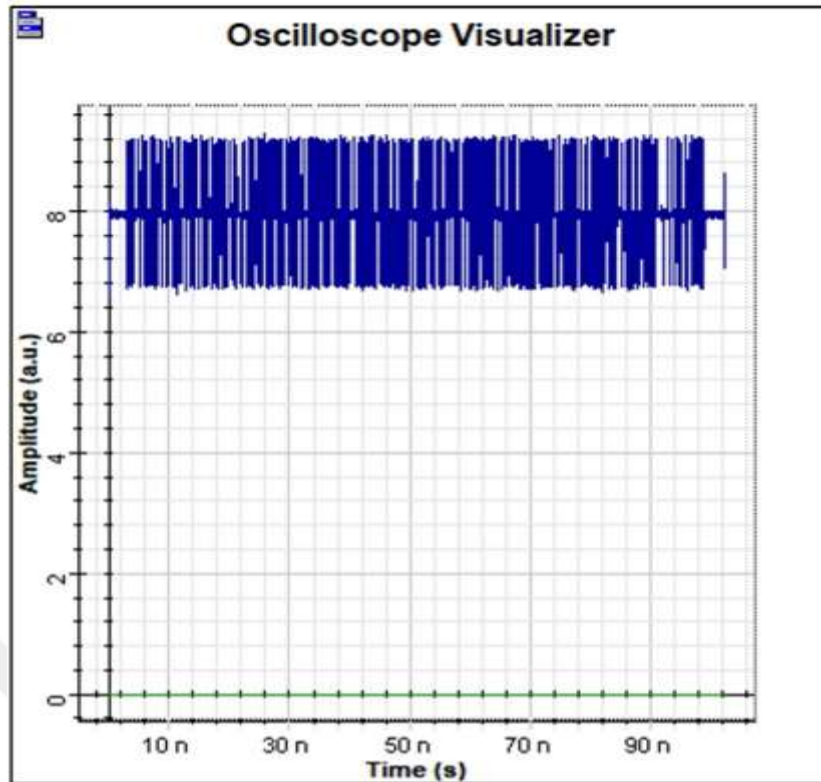


Figure 4.12: Oscilloscope Visualizer at Destination.

As shown in figure 4.12 The graph depicted, in results, quantitative outputs from the tool or device called "Electrical Power Meter Visualizer," at an endpoint, using OptiSystem software. The graph depicted the signal over time, where horizontal axis with time framings in seconds (s): ranged from 0 to 100 nanoseconds (ns). Vertical axis with amplitude reading in arbitrary units (au.) ranged from 0 to 10 arbitrary units.

The signal was blue, and the cross-section was around an amplitude of approximately 8 arbitrary units throughout the displayed time range. Here, results showed a quite high amplitude with small amplitude oscillations. These resembled good-quality signal performances at the endpoint of the network.

Interpretation of the results

- a. High Amplitude: The amplitude being around 8 arbitrary units indicated considerable strength of the signal at the endpoint, which shows a good system quality.
- b. Minor Fluctuations: They seem to denote minute interferences and distortions, which yet appear not strong enough to manifest perceptibly on signal quality.

Overall, the results have indicated that the signal maintained quite good quality even at the network's endpoint, with slight fluctuations blamed on environmental effects or signal interferences during transmission.

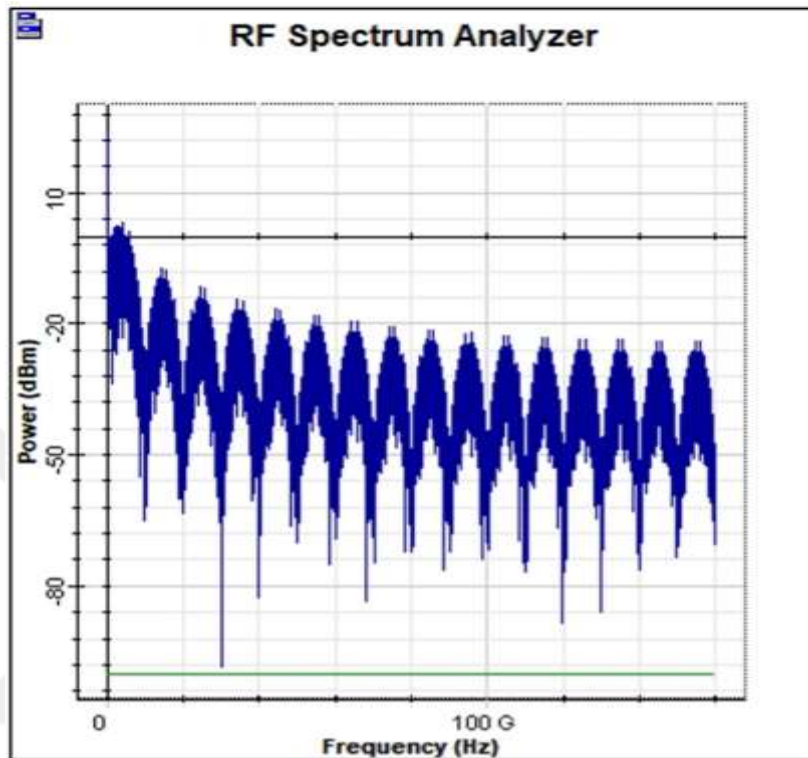


Figure 4.13: RF Spectrum Analyzer at Destination.

As in the graph 4.13, the frequency spectrum plot was taken from an "RF Spectrum Analyzer" using OptiSystem simulation software. The horizontal axis was in frequency unit (Hz), and the vertical axis was power in units of (dBm). The horizontal and vertical limits were chosen to range between 0 to 100 GHz and -80 dBm to 10 dBm, respectively. This graph plotted a discretional series of peaks and troughs, which meant that there would be several frequency components with different power levels.

Interpretation of the results

- Peaks in the Spectrum: These were representative of high-power level frequencies, purporting that at those
- Troughs in the Spectrum: These were frequencies at which there was a lot of noise or lower power levels.
- Why was it that way?
- Interference: The signal at this network endpoint could interfere with other signals within the spectrum.
- Overall network losses: A loss of power levels manifested as troughs within the spectrum probably occurred due to distance and dispersion.
- System correction: With so many parts involved, it would not have been surprising that the power was divided unevenly between the frequencies.

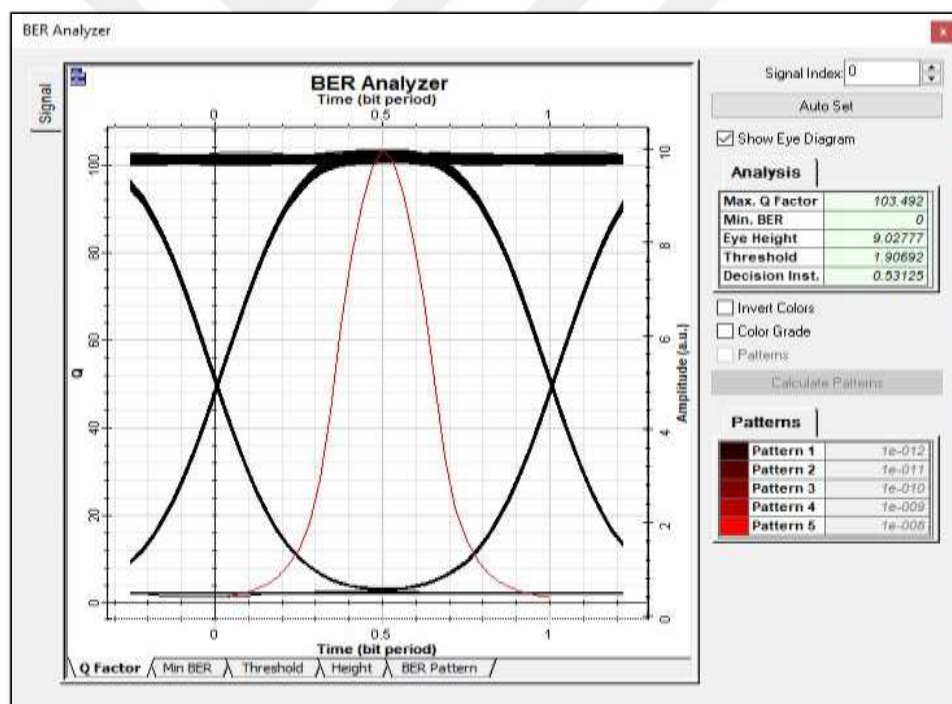


Figure 4.14: Eye Diagram Analyzer at Destination of EA Modulator.

As given in Figure 4.14, an eye diagram generated from an eye diagram analyser and BER bit error rate. The BER for the EA modulator shows the best reading of Q-factor 103.492 over all other modulators. The diagram plotted the electrical signal with time in the horizontal axis in (bit periods) and amplitude in the vertical axis in arbitrary units (au). The

resultant eye diagram serves as a general tool in the study of digital networks, using which an approximation of the quality of a digital signal can be made. Therefore, this uniquely shaped diagram will reflect any signal problem, such as noise or interference, making it very handy in network design and testing.

B. RZ Pulse Bit Generator

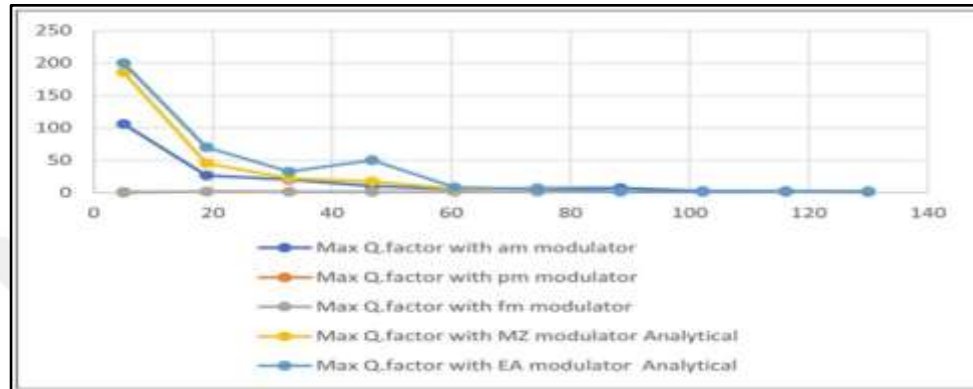


Figure 4.15: The Relationship Between the Quality Factor and Distances with The RZ Pulse Bit Generator.

As shown in graph 4.15, that shows the Q-factor for each type of modulator, with a maximum Q-factor in the specified range of values given on the x-axis, starting from 0 to 140. The y-axis defines the Q-factor with its values ranging from 0 to 250. The graph identified five different lines of different modulator types, which are in turn the AM Modulator, the PM Modulator, the FM Modulator, the MZ Modulator, and the EA Modulator in colours blue, orange, gray, yellow, and light blue analytical lines, respectively. This graph showed that the Q-factor for all types of modulators started very high and then suddenly plummeted. After the drop, the Q-factor was very stable in the lowered values with the increased value on the x-axis. The best reading was with the EA Modulator Analytical at 5 km with Q-Factor 199.225.

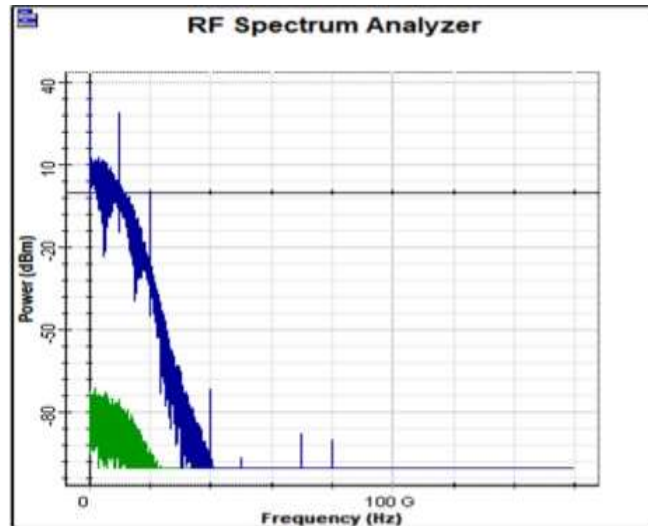


Figure 4.16: RF Spectrum Analyzer.

As shown in graph 4.16, the output from the spectrum analyser of the radio frequency plot. The horizontal axis gives a frequency in Hertz (Hz), while the vertical axis gives the power in decibel milliwatts (dBm). In this plot, the power over the spread of frequency was given by the blue and green curves. Such plots were used to analyse radio signals and to determine the frequency bands at which the energy was concentrated.

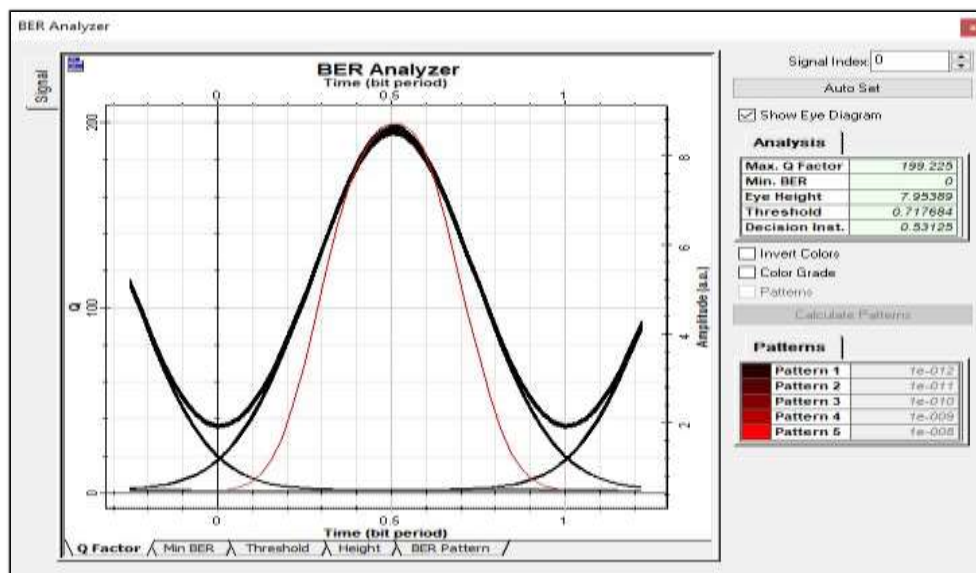


Figure 4.17: BER Analyzer and EYE Diagram of EA Modulator.

As shown in graph Figure 4.17, the BER analysis and the EYE diagram. The BER reading shows the Q-factor of 199.225 with EA modulator at 5 km. Furthermore, the EYE diagram which here it indicates a bad digital signal performance throughout the system.

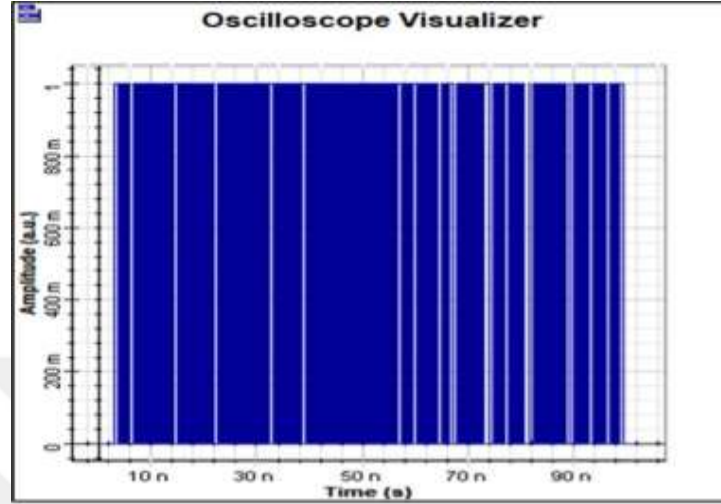


Figure 4.18: Oscilloscope Visualizer.

An oscilloscope graph as shown in Figure 4.18, of an electrical signal over time. The horizontal axis is the time scale in nanoseconds (ns), and the vertical axis is the amplitude in arbitrary units (au). On this graph, there were reproduced electrical signals that were in between very short times with high amplitudes.

4.1.2 Responding to Changes in Frequency

A. NRZ Pulse Bit Generator

As shown in the graph 4.19, the relationship between frequencies x-axis in (THz), and the quality factor in the beginning on y-axis, (NRZ) pulse bit generator was used with five modulators (AM, FM, PM, EA and MZ) consecutively, and system parameters, The reference wavelength for the MZ Modulator reading is roughly 150 THz.

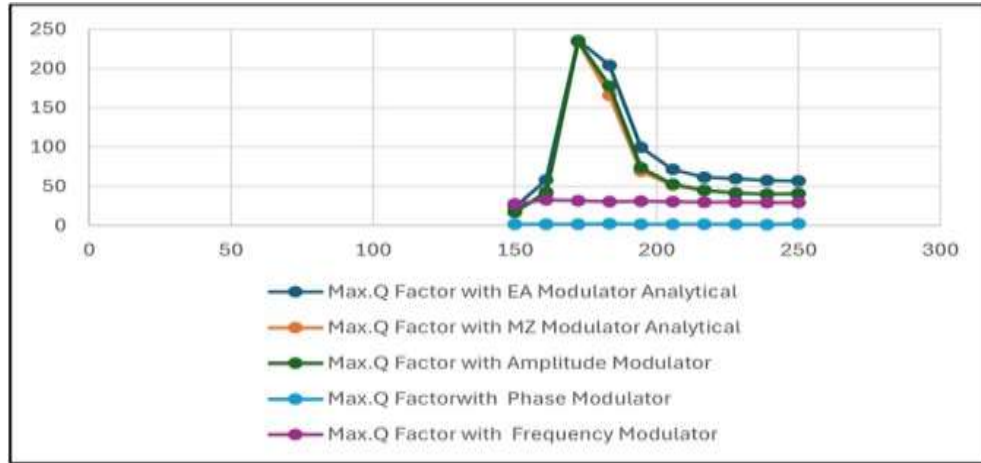


Figure 4.19: The Diagram Shows The Relationship Between The Quality Factor (Q-Factor) (Y-Axis) And The Reference Frequencies Wavelength (X-Axis) Using (NRZ) Pulse Bit Generator With Five Types Of Modulators.

As shown in Figure 4.19, shows the Q-factor y-axis and reference wavelength x-axis in (THz) for the MZ Modulator reading is roughly 150 THz. Modulator EA at a reference wavelength of approximately 100 THz, the EA modulator achieves its ideal quality factor reading. With an increase in reference frequency wavelength, the quality factor progressively falls. Transformer with Amplitude At a reference Frequency wavelength of about 50 THz, the Amplitude Modulator's optimal quality factor reading is achieved with an increase in the reference wavelength, and the quality factor progressively falls. Best readings using AM Modulator with 172.22 THz Analytical at destination, with a Q-factor of 229.773.

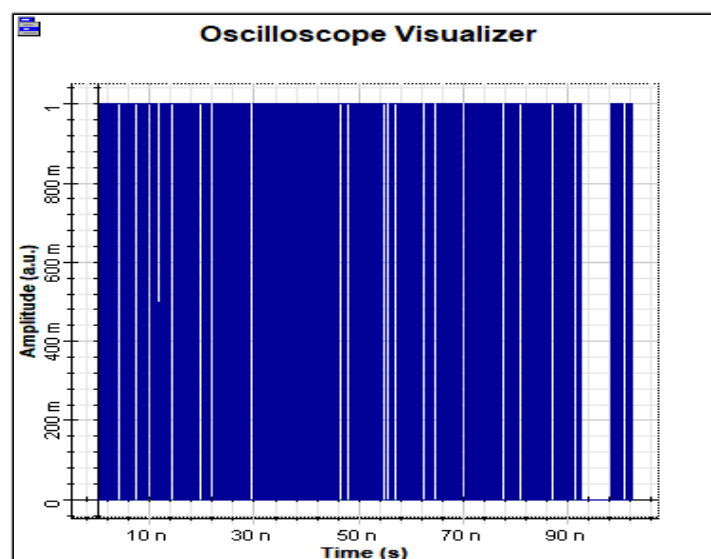


Figure 4.20: Oscilloscope Visualizer.

As shown in Figure 4.20 the x-axis is time in nanoseconds (ns), while the y-axis is amplitude in arbitrary units (au). It can be observed from this graph that there are some intermittent high-amplitude signals. That would mean there are pulses or repetitive signals at the shortest possible time intervals. That reading was not good because it gave a profile for uneven and intermittent transmission signals, which could indicate noises or possible interference with a signal.

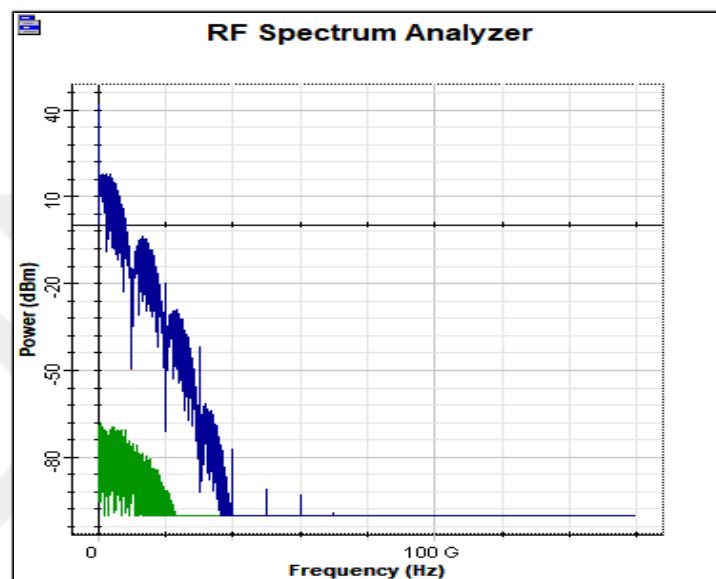


Figure 4.21: RF Spectrum Analyzer.

As shown in graph 4.21, an RF Spectrum Analyzer; the X-axis was the frequency in Hertz (Hz), and the Y-axis was power in decibels relative to one milliwatt(dBm). The graph presented two major curves: one blue from lower frequencies, extending up to about 100 gigahertz while showing a trend with a decay of power as the frequency increases; and another one, a green one in the region of lower frequencies also presenting a decay in power. Interpretation obviously showing acceptable reading.

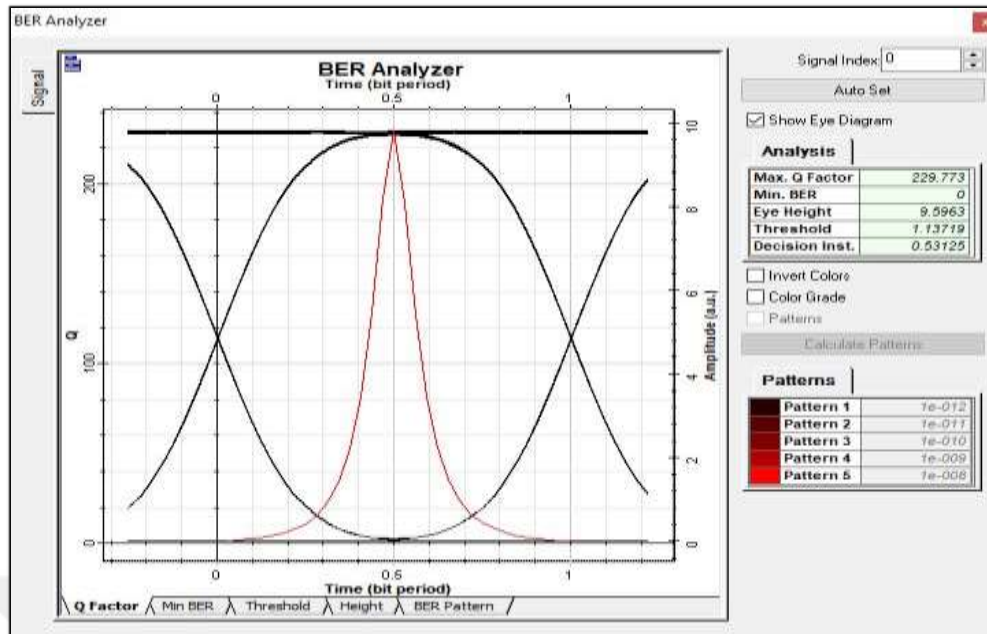


Figure 4.22: BER Analyzer and EYE Diagram of AM Modulator.

As shown in Figure 4.22 which represents BER and EYE diagram. The BRE analyser indicates the best reading of 229.773 Q-Factor by using AM modulator at 172.22 THz the modulator shows best result over other modulators. Furthermore, EYE diagram indicates a good digital signal performance throughout the system.

B. RZ Pulse Bit Generator

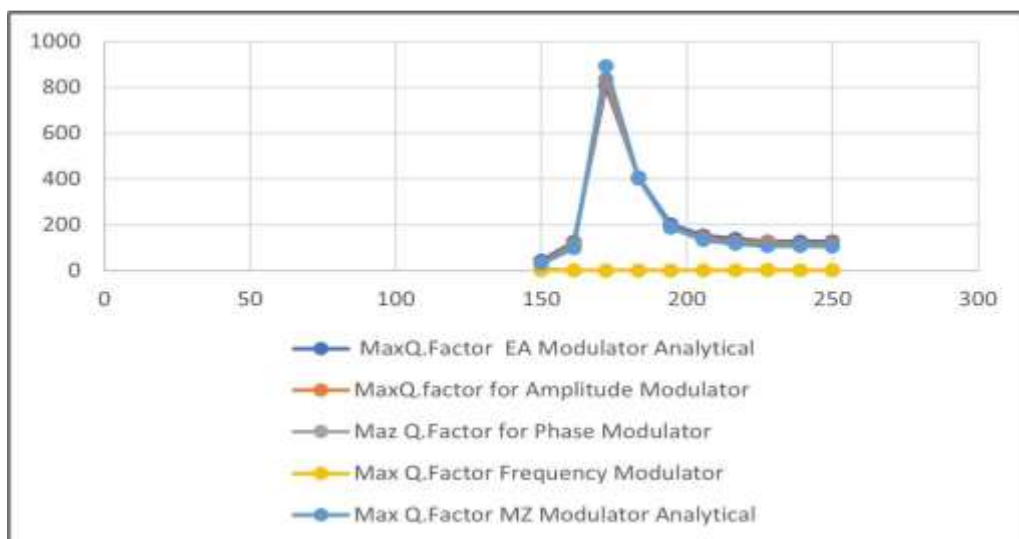


Figure 4.23: The Relationship Between the Quality Factor (Q-Factor) (Y-Axis) and The Reference Frequencies Wavelength (X-Axis) Using The (RZ) Pulse Bit Generator.

As shown in graph 4.23, at the x-axis that represent the frequencies, a frequency of 150THz, the maximum quality factor represented on the y-axis throughout equals the MZ analytical maximum quality factor, attaining a value of 892 At a frequency of 172.22THz, Best readings using MZ Modulator with 172.22 THz Analytical at destination

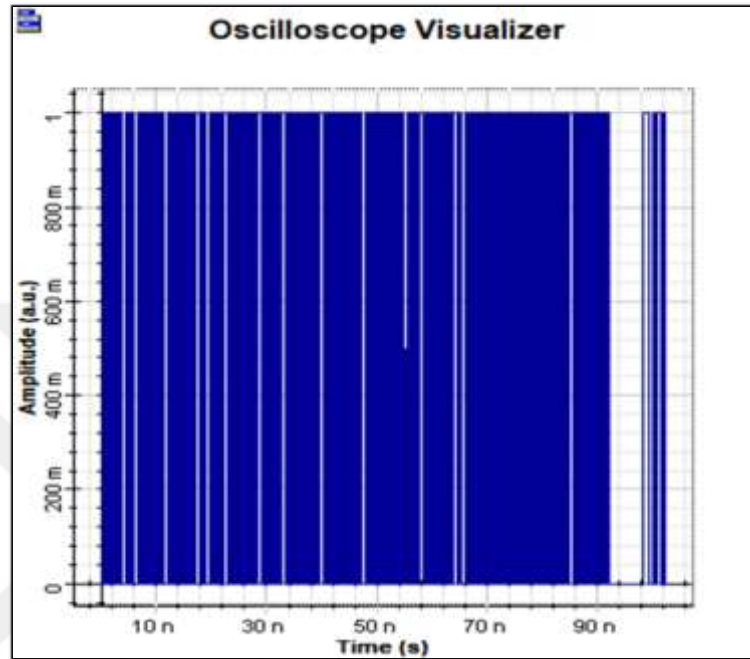


Figure 4.24: Oscilloscope Visualizer at Destination.

As shown in Figure 4.24, the period during which the intensity of the optical signal changed was plotted on the horizontal axis. It is measured in nanoseconds (ns). The vertical axis amplitude denoted the intensity of the optical signal at a given moment in time. The unit of measurement here was arbitrary (au). The actual amplitude at a given instant was therefore described using varying units. In general shape, the peaks of the signal in the pulse correspond to the maximum amplitude of the signal within that pulse, and the distance between the peaks of two consecutive pulses represents the pulse period.

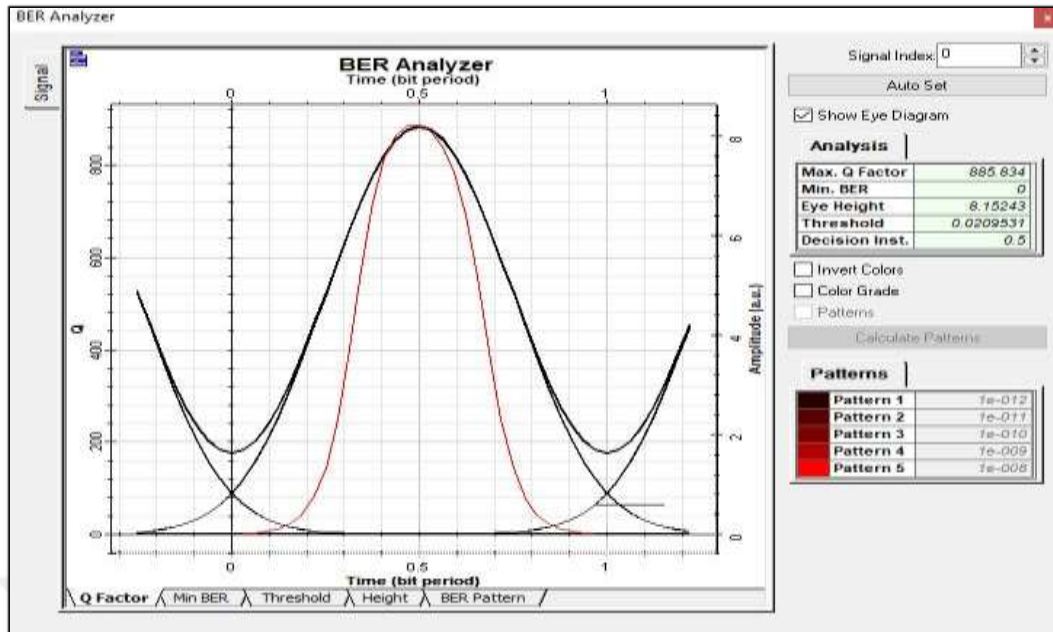


Figure 4.25: BER and Eye Diagram Analyzer of AM Modulator.

As shown in Figure 4.25, that represents BER and EYE diagram. The BRE analyser indicates the best reading of 885.834 Q-Factor by using AM modulator over other modulators at 172.22 THz. Furthermore, EYE diagram indicates a bad digital signal quality.

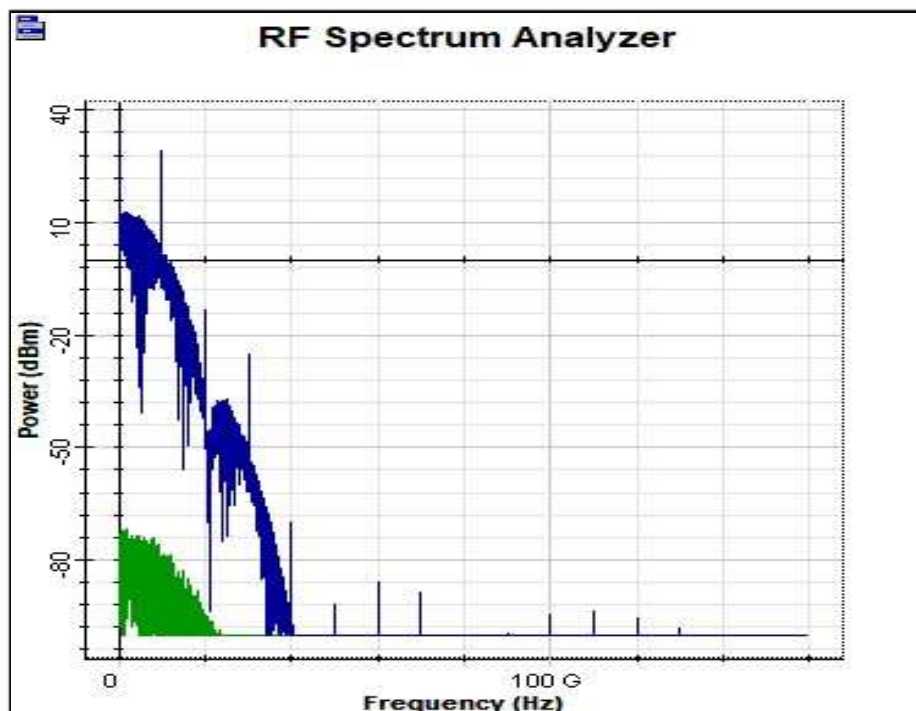


Figure 4.26: RF Spectrum Analyzer.

As shown in Figure 4.26, the plot of an RF spectrum analyzer: frequency in (Hz) on the x-axis, power in decibels milliwatts (dBm) on the y-axis. On this plot, there were two major curves, one colored blue, showing the signal power across frequency the other colored green, reflecting the other signal powers or noise across frequency. For a good reading, the signal power had to fall within the expected magnitudes of the desired signal normally higher power at wanted/required frequencies and low elsewhere.

4.1.3 Responding to Changes in Laser Power in dBm

A. NRZ Pulse Bit Generator

The power values as shown in the chart 4.27, the relationship between the power of CW Laser at x-axis and the quality factor on y-axis in the beginning, (NRZ) pulse bit generator was used with five modulators (AM, FM, PM, EA and MZ) consecutively, and system parameters shown in the table below:

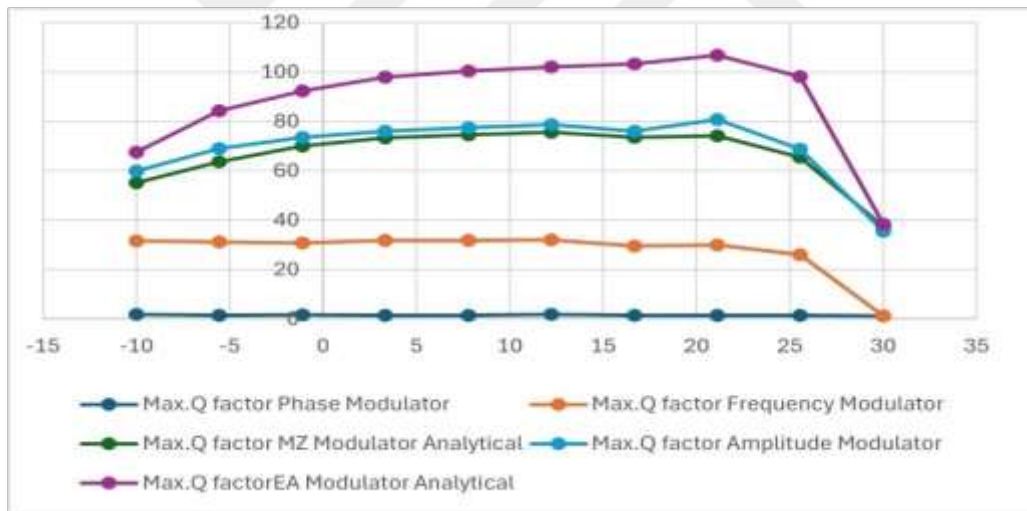


Figure 4.27: The Diagram Shows The Relationship Between The Quality Factor (Q-Factor) (Y-Axis) And Power Of Laser Source With (dBm) (X-Axis) Source Using (NRZ) Pulse Bit Generator.

The maximum Q-factor is plotted as shown in Figure 4.27 against the power of the CW laser source in dBm. The observation of increasing Q-factor with increasing power of CW Laser can be attributed to improved SNR values with higher laser source power levels.

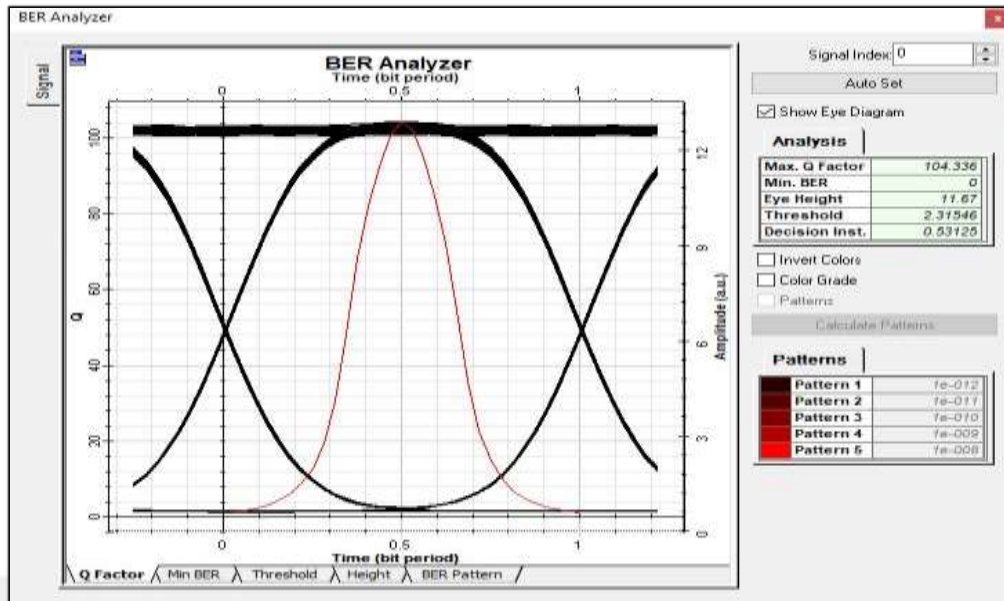


Figure 4.28: The BER and EYE Diagram of EA Modulator.

The best Q-factor obtained for the given EA modulator is in figure 4.28 was with a power level of 21.11 dBm, giving a value of 104.336 db. The same operating principle is employed by the PM modulator and the AM and MZ modulators. No significant change in Q-factor occurred for PM or FM modulators. Furthermore, EYE diagram indicates a somewhat bad digital signal quality due to distortions, with good BER reading.

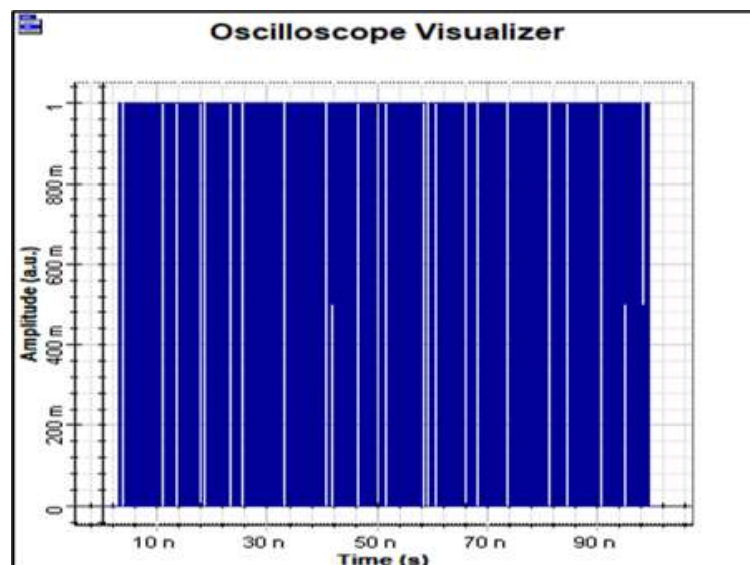


Figure 4.29: Oscilloscope Visualizer.

As shown in Figure 4.29, the oscilloscope visualizer plot, with time in nanoseconds on the horizontal axis and amplitude in arbitrary units on the vertical. It indicates poor quality due to noise or interference. A good-quality signal would have had a much more consistent and well-defined waveform.

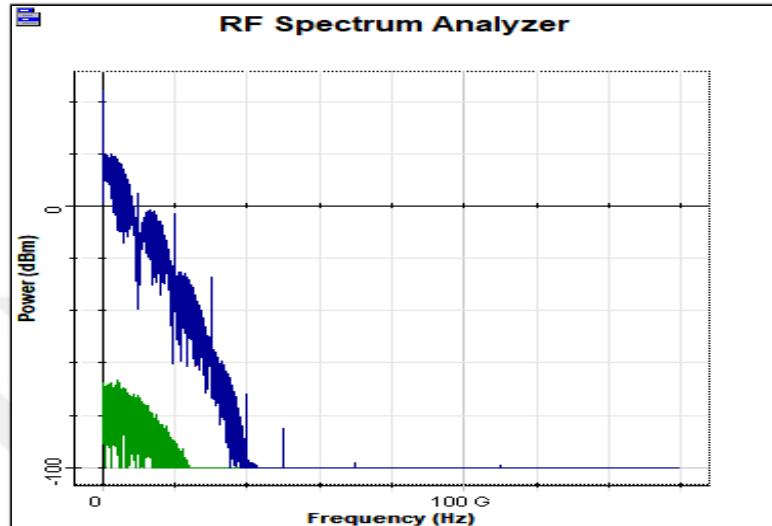


Figure 4.30: RF Spectrum Analyzer.

As shown in Figure 4.30 that plot indicates the power level decreased with an increase in frequency.

B. RZ Pulse Bit Generator

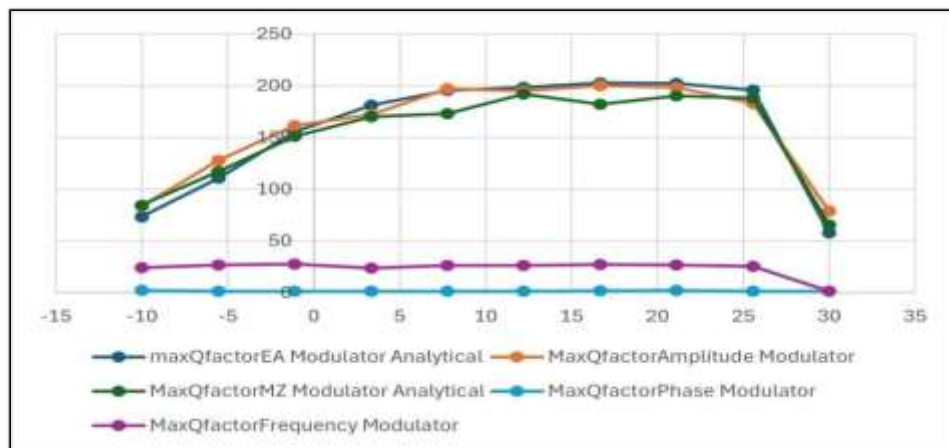


Figure 4.31: The Diagram Shows The Relationship Between The Quality Factor (Q-Factor) (Y-Axis) And Power Of CW Laser With (dBm) (X-Axis) Source Using (RZ) Pulse Bit Generator.

The Max Q-factor is plotted on y-axis against the power of the CW laser source in (dBm) as given in Figure 4.31. The observation of increasing Q-factor with increasing power of CW Laser can be attributed to improved SNR values with higher laser source power levels.

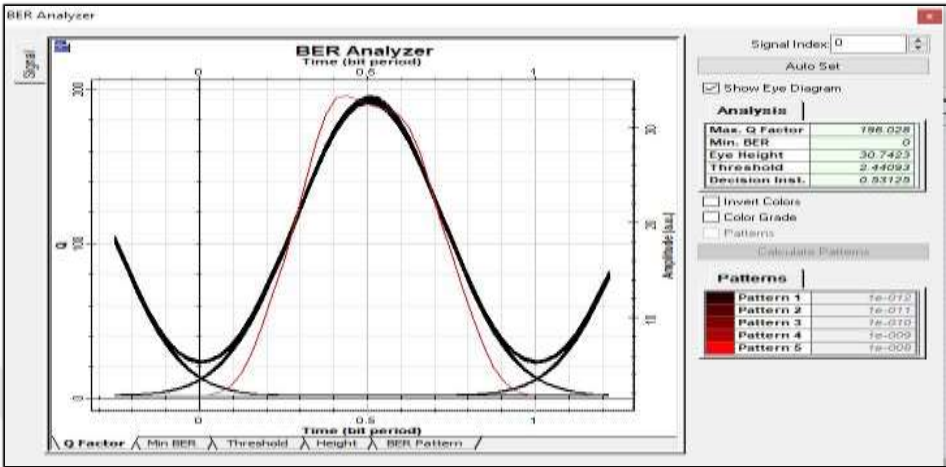


Figure 4.32: The BER and EYE Diagram with EA Modulator.

As shown in Figure 4.32, The best Q-factor obtained for the given EA modulator was with a power level of 21.11 dBm, giving a Q-factor value of 196.026. The same operating principle is employed by the EA modulator and the AM and MZ modulators. The modulator outperforms other modulators used in the system.

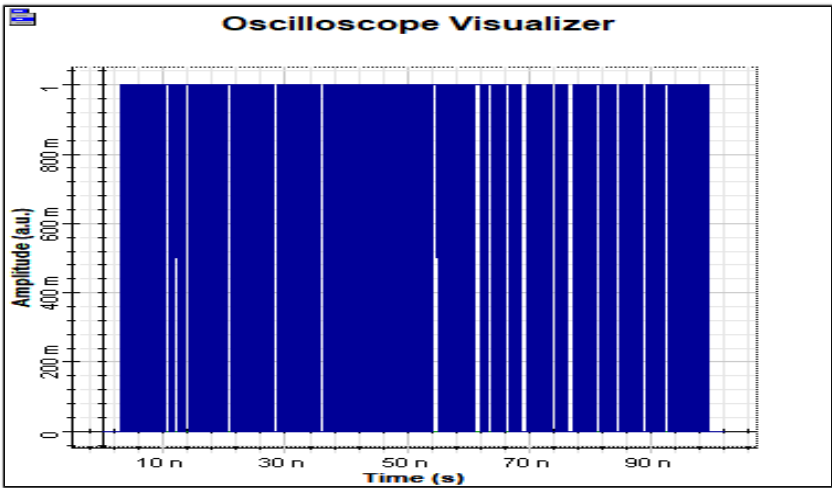


Figure 4.33: Oscilloscope Visualizer.

As shown in Figure 4.33 time in nanoseconds (ns) and Amplitude in arbitrary unit (au.) The reading was not so good as it displayed irregular and intermittent signals.

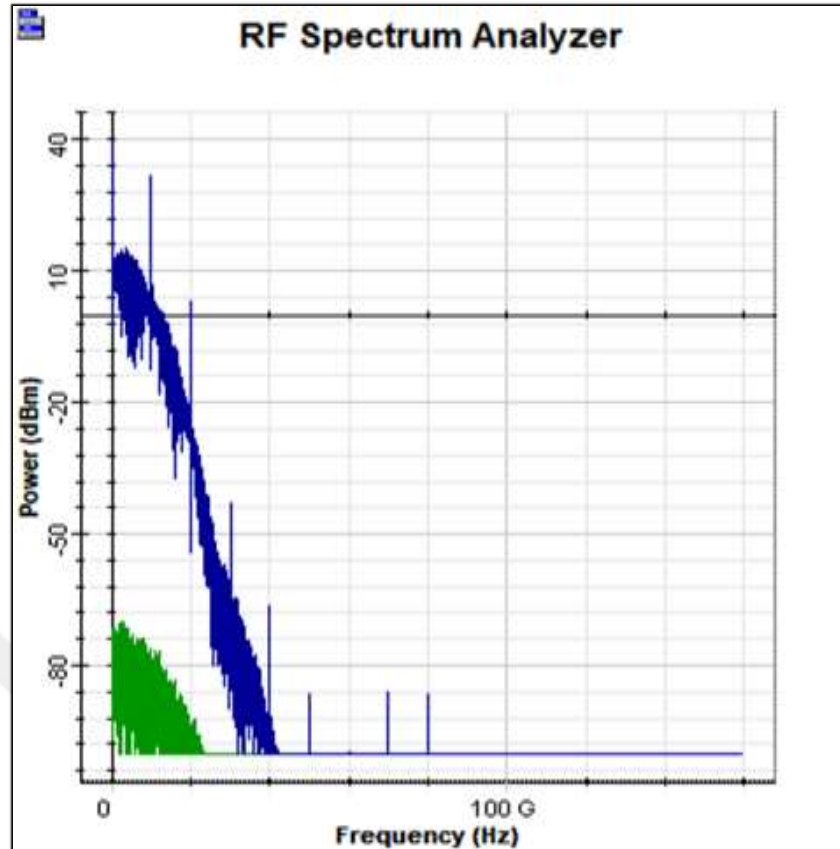


Figure 4.34: RF Spectrum Analyzer.

As shown in Figure 4.34, it represented an RF spectrum analyser reading. frequency was along the x-axis in hertz (Hz), and power was in (dBm) along the y-axis. it showed a spectrum that ranged from 0 to about 100 GHz. there were two collared regions: a blue region and a green region. the blue region contains higher power signals at lower frequencies, and the green area shows lower power signals in the same frequency range. reading was good if the wanted signals were easily discernible and without interference by unwanted signals.

4.2 FREE SPACE OPTICAL (FSO)

FSO network was used, and the parameter information was changed sequentially at an attenuation in Table 3.2, Table 3.6, Table 3.7 and Table 3.8 were used sequentially with changing lengths, frequencies, and energies.

4.2.1 Clear Weather 0.233

4.2.1.1 Responding to changes in distances

A. NRZ Pulse Bit Generator

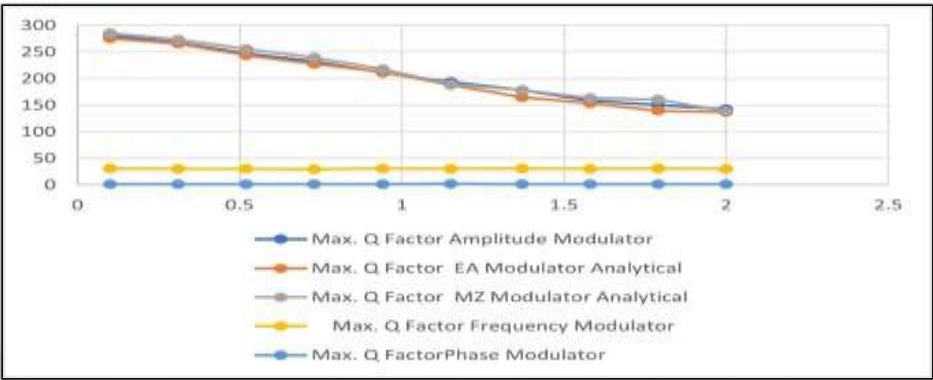
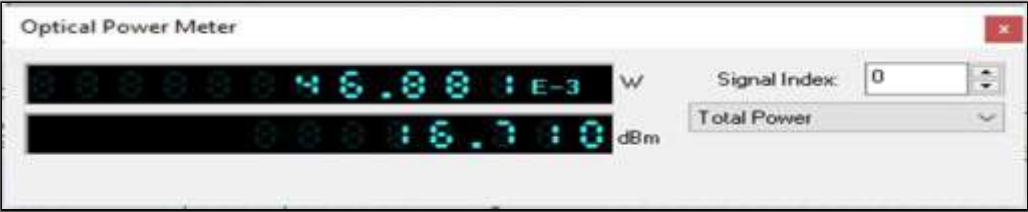
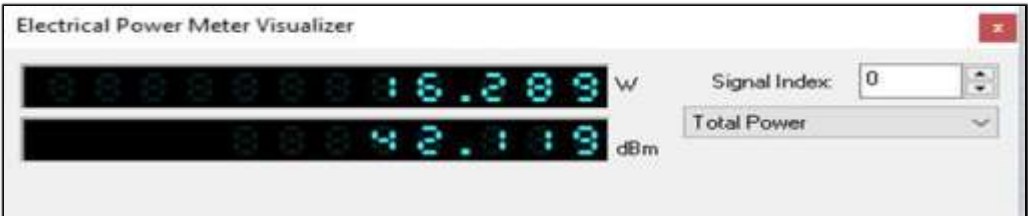


Figure 4.35: The Relationship Between the Quality Factor and Distances with The NRZ Pulse Bit Generator.

As shown in Figure 4.35, the maximum Q-Factor in various modulators. The horizontal axis had numbers from 0 to 2.5 represent distances and the vertical one ran from 0 to 300 represent the Q-factor. There were five different curves shown in the graph. The best reading of Q-Factor with MZ Modulator Analytical of Q-factor 288.064.



(A)



(B)

Figure 4.36: (A) Optical Power Meter After MZ Modulator (B) Electrical Power Meter Visualizer at Destination

As shown in Figure 4.36 (a) the optical power meter displayed two readings: 46.881 E-3 W (watts) representing actual power and 16.710 dBm indicating power relative to 1 mw. The 46.881 W and 16.710 dBm reading reflected the power at the source point. (b) The Electrical Power Meter Visualizer displayed two readings: 16.289 W representing actual power and 42.119 dBm indicating power relative to 1 mw. The 16.289 W reading reflected the power at the destination point, while 42.119 dBm helped assess signal strength.

The first one was taken around the middle, while the second one was taken close to the end. Any position difference could move actual measurement values by varying direct and indirect involvement interaction lengths with other components along the way. Power losses are most likely due to diminishing power quality as the signal propagated through the network a part of its power probably was lost due to absorption as well as scattering of natural phenomena.

Measurement at the end in terms of losses must have been more accurate than that in the middle due to interference noise and other disturbances. Interference and noise of other network components could have contributed to their interference and noise signals going through the network. Interference measurement at the far end would show more cumulative interferences along that path. Interference measurement accuracy.

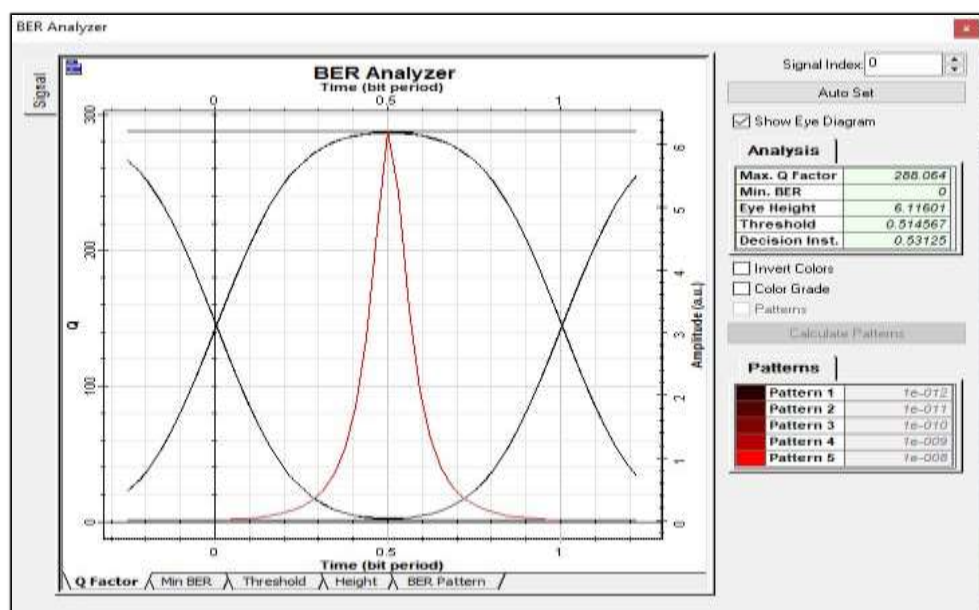


Figure 4.37: BER Analyzer at Destination of MZ Modulator.

As shown in Figure 4.37, which represents the BER and EYE diagram. best Q-factor obtained for the given MZ modulator giving a Q-factor value of 288.064. Furthermore, EYE diagram indicates a good digital signal quality over time, and BER indicates good reading.

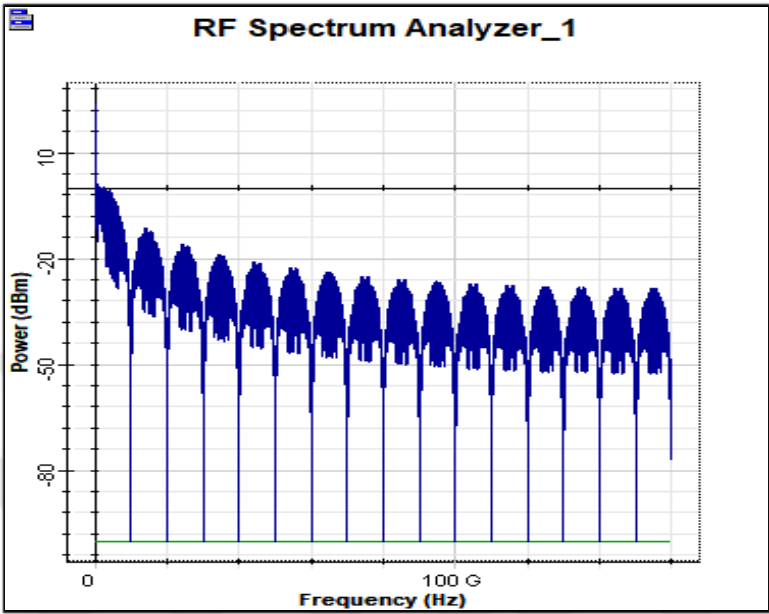


Figure 4.38: RF Spectrum Analyzer.

As given in graph 4.38, shows an analysis of the frequency spectrum using an RF Spectrum Analyzer. The horizontal axis represents the frequency (Hz) while the vertical axis represent power in (dBm). The graph showed a series of recurrent peaks whose power gradually decayed with increased frequency. Reading was not as good since the power provision quite significantly decreased with the presiding frequency, hence implying that the signal might have been weak or noisy.

WDM Analyzer					
Frequency (THz)	Signal Power (dBm)	Noise Power (dBm)	SIM (dB)	Noise Power: 0.1nm (dBm)	OSNR (dB)
193.41449	15.5416	-27.815426	44.357026	-29.856625	45.398226

Figure 4.39: WDM Analyzer.

As shown in Figure 4.39, the results of a Wavelength Division Multiplexing (WDM) analysis for an optical wave at a specific frequency. It contains the following columns. The reading was good as the Signal-to-Noise Ratio SNR and Optical Signal-to-Noise Ratio OSNR were high indicating good signal quality.

B. RZ Pulse Bit Generator

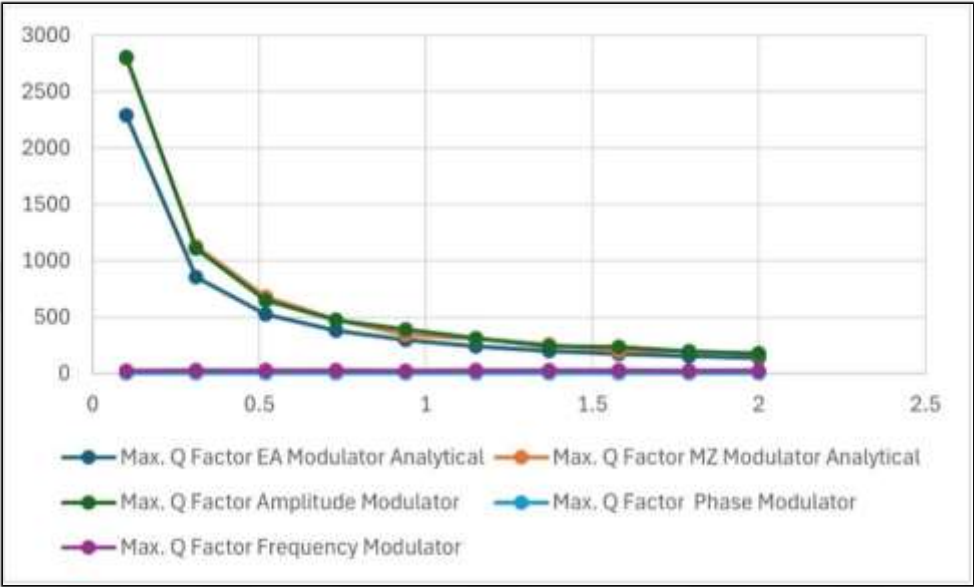


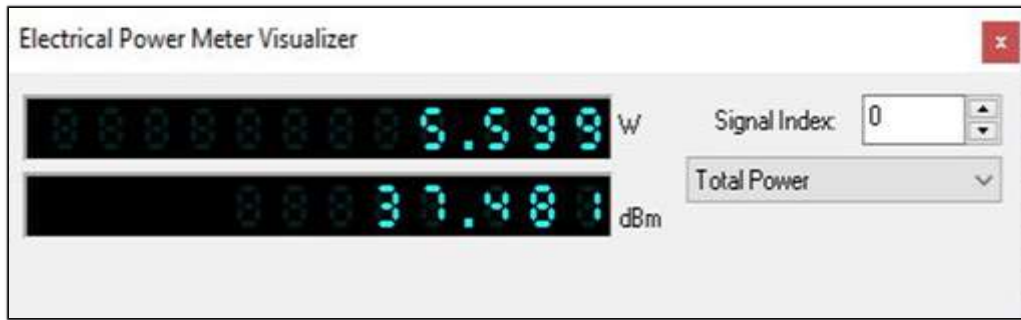
Figure 4.40: The Relationship Between the Quality Factor and Distances with The RZ Pulse Bit Generator.

As shown in Figure 4.40, the relationship between Q-factor y-axis and distances x-axis, the Table 3.4 is used as references parameter. The best reading with max Q-factor value 2844.15 using Amplitude Modulator. The best reading is using an AM modulator at 0.1 km.



Figure 4.41: (A) Optical Power Meter After AM Modulator (B) Electrical Power Meter Visualizer at Destination.

(A)



(B)

Figure 4.42: (A) Optical Power Meter After AM Modulator (B) Electrical Power Meter Visualizer at Destination.

As given in Figure 4.41 (a) the Optical Power Meter with two digital readings. The first reading was 23.672 milliwatts E-3 W and the second reading was 13.735 dBm the device also had a signal index set to 0 and a dropdown menu displaying Total Power reading was good if it was within the expected or required range.

(b) An Electrical Power Meter Visualizer The interface contained two digital readings the first displayed the electrical power value 5.599 W and the second displayed the power showing the value 37.48 dBm. There was also an index for selecting the signal Index set to the value 0 and a dropdown menu displaying Total Power The reading was good if it was within the expected or required range the difference between the two testing readings given in the text from the middle.

From the end, these same readings were measured for the second time. Probe Position: The measured values may also be different if the probe's location is the beginning or end of the network; in comparison, the measured values at the middle of the network may have fewer ambiguities.

Transmission Losses: The cumulative effect of this loss in a network otherwise might sum up as noise could scatter each signal further from its correct reading. This would mean that the values at the end might be somewhat lower than those at the midpoint. Interference and Noise: Signals at terminal devices are prone to weaker noise interference coming from other components within the network compared to those at the center device. This would affect signal quality and hence the reading done at the end of the network. Accuracy of Measurement: The measuring instruments might not have been set equally or else there was

some element of inaccuracy in any one set of measurements, making a difference between the first and second readings.

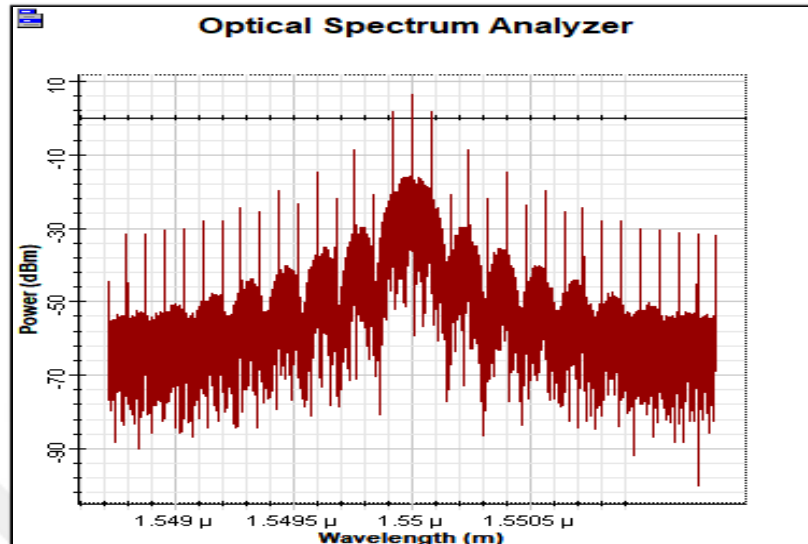


Figure 4.43: Optical Spectrum Analyzer After Modulator.

As shown in Figure 4.42, the wavelength in (m) on x-axis, and power in (dBm) on y-axis. The spectrum showed a main peak around 155 micrometres with oscillations around this peak. The reading appeared to be good as it showed a clear and stable peak indicating a strong and focused signal in this wavelength range.

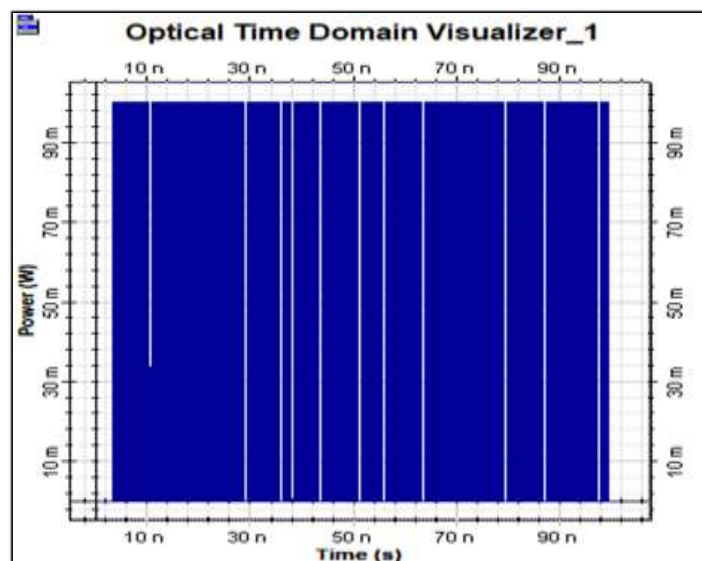


Figure 4.44: Optical Time Domain Visualizer After Modulator.

As shown in graph 4.43, it represents multiple narrow vertical lines on a blue background, showing many optical signals. The signals are ‘noisy.’

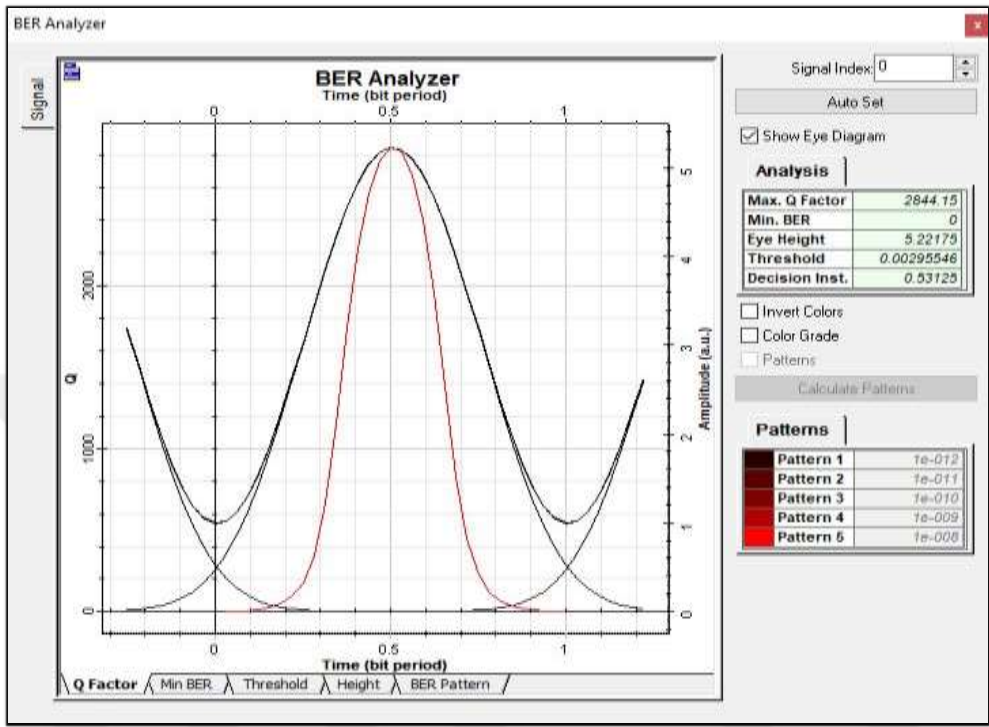


Figure 4.45: BER Analyzer at Destination of AM Modulator.

As shown in Figure 4.44, the horizontal axis represents the time bit period, and the vertical axis represents the Q value. The graph showed a bell-shaped curve with a red line peaking at around 0.5 on the horizontal axis and a Q value of approximately 3000 This graph showed Q-factor of 2844.15.the eye diagram showed bad signal quality and the BER is somewhat bad also. The horizontal axis shows time (bit period), and the vertical axis shows amplitude in arbitrary units (au).

4.2.1.2 Responding to changes in frequencies in THZ

A. NRZ Pulse Bit Generator

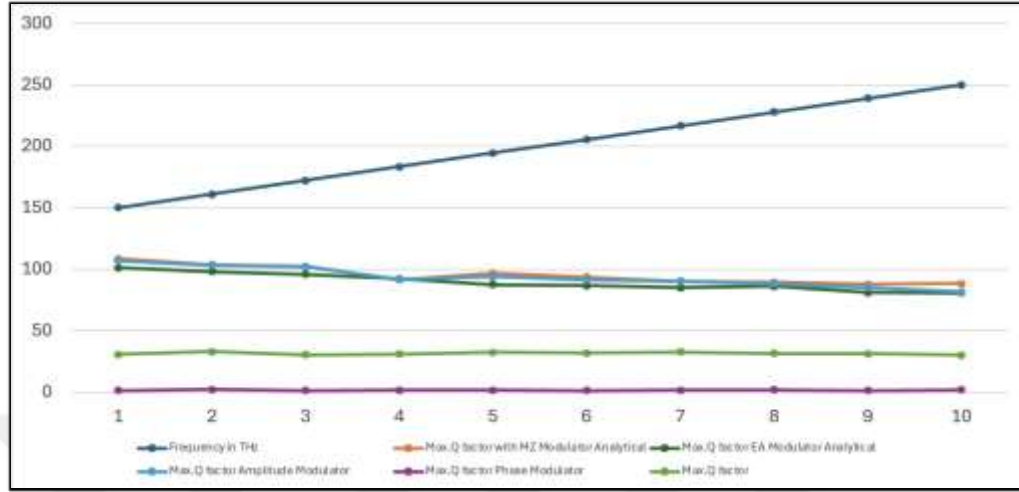


Figure 4.46: The Relationship Between the Quality Factor and Frequencies with The NRZ Pulse.

As shown in graph 4.45, The graph demonstrated a significant decrease in the maximum Q-Factors on y-axis at the 150 THz frequency on x-axis for all modulators except for the phase and frequency modulators.



(A)



(B)

Figure 4.47: (A) Optical Power Meter After MZ Modulator (B) Electrical Power Meter Visualizer at Destination.

As shown in Figure 4.46 (a) the reading on the device displayed 46.784 E-3 watts and -16.701 dBm at the source point. (b) contained two digital readings The first reading was 3.265 E-3 watts, and the second reading was 5.139 dBm, at the destination.

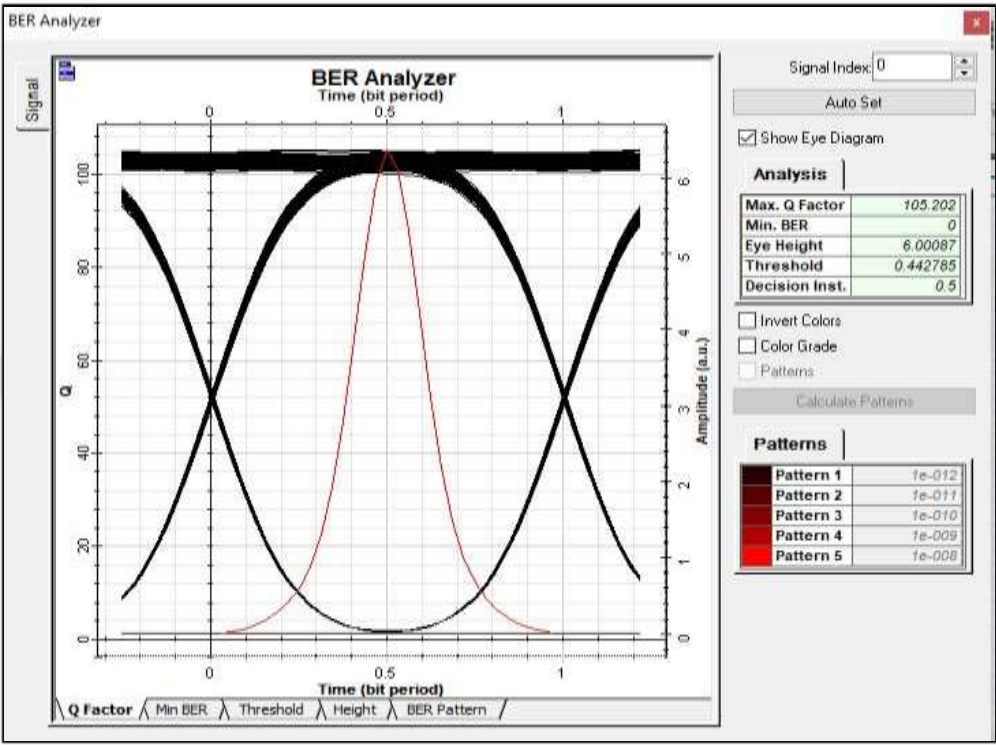


Figure 4.48: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.47, a bell-shaped red curve BER peaking at 0.5 in x-axis in the (bit period) the reading was suboptimal because the BER which indicates the Q-factor not peaked sharply and then dropped indicating that the system was operating efficiently at that point in time. The eye diagram demonstrated the shape of the digital signal over multiple bit periods, the reading of the diagram showed open eye with distortion or noise. The best reading was with MZ Modulator Analytical at 150 THz with Max Q-Factor 105.202.

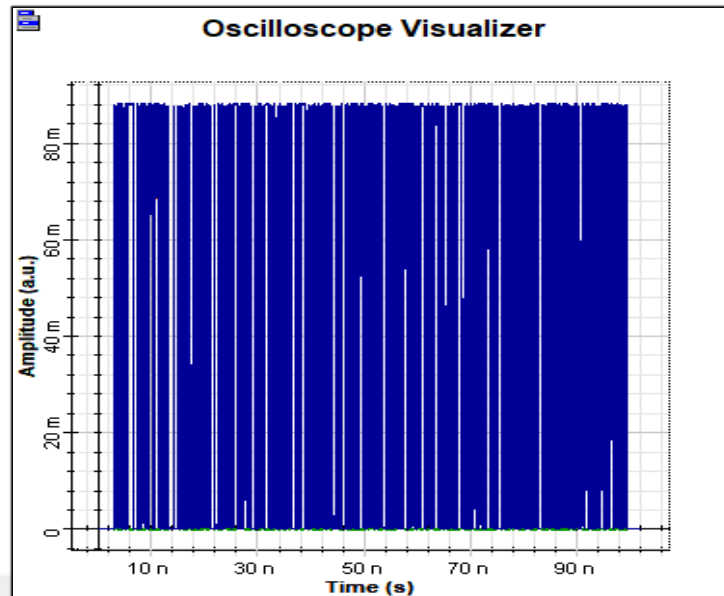


Figure 4.49: Oscilloscope Visualizer at Destination.

As shown in Figure 4.48, the x-axis represents time in nanoseconds (ns) and the y-axis represents amplitude in (au), the signal displayed in the graph appeared to oscillate significantly between high and low values indicating rapid fluctuations in the electrical signal. The reading was not stable and showed sharp oscillations which might suggest noise or interference in the signal.

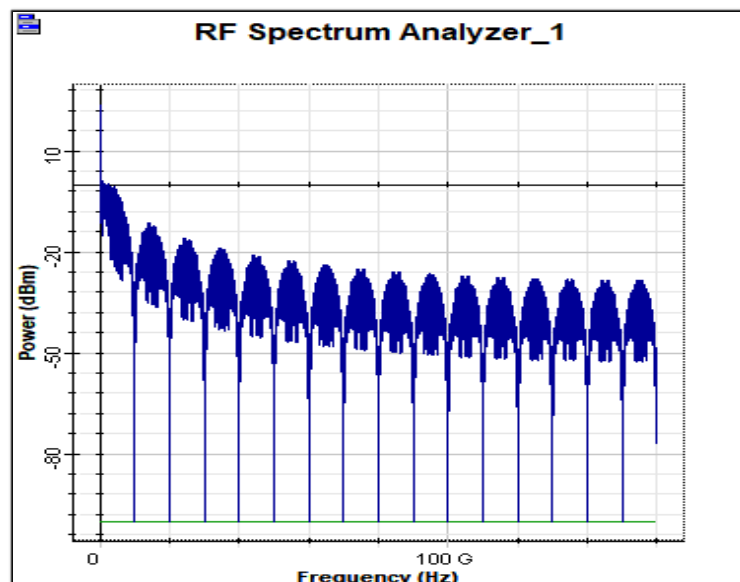


Figure 4.50: RF Spectrum Analyzer.

As shown in Figure 4.49, the horizontal axis represented the frequency in hertz (Hz), and the vertical axis represented the power in decibels (dBm). The graph demonstrated a progression of higher-intensity peaks that decreased in volume as the frequency increased. The reading was less successful than expected, there were significant changes in power that indicated noise or interference in the signal. Overall, the signal appeared to have a random and flaky nature.

B. RZ pulse bit generator

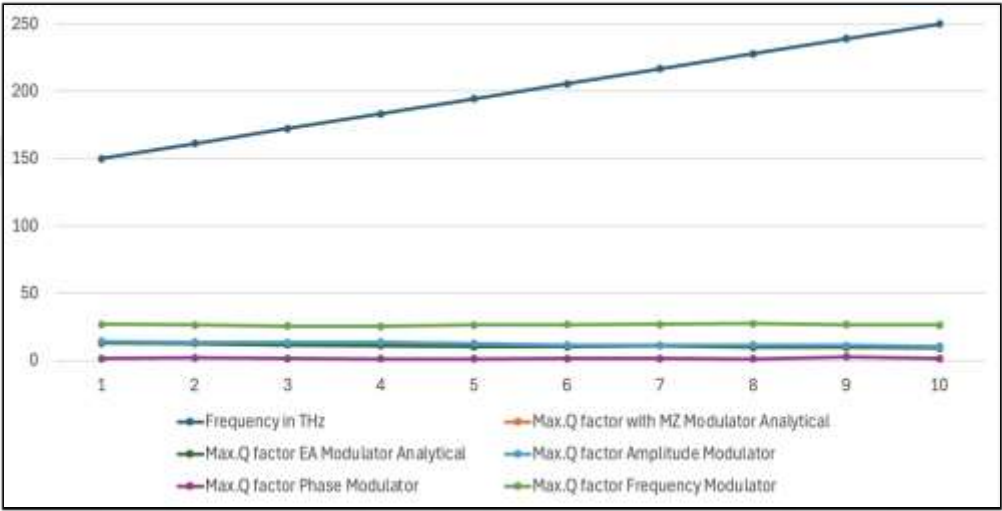
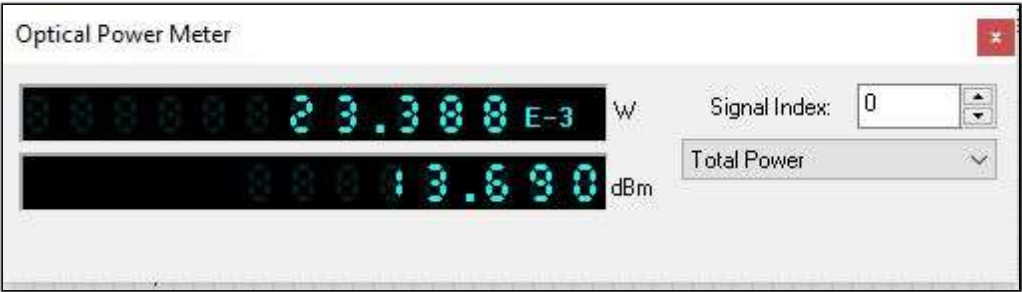


Figure 4.50: The Relationship Between the Quality Factor and Frequencies with The RZ Pulse Bit Generator.

As given in graph 4.50, which demonstrated a stability state in the maximum Q-factors on y-axis with the increase in frequency for all modulators on x-axis except for the phase and frequency modulators.



(A)

Figure 4.51: (A) Optical Power Meter After AM Modulator (B) Electrical Power Meter Visualizer at Destination.



(B)

Figure 4.51: (A) Optical Power Meter After AM Modulator (B) Electrical Power Meter Visualizer at Destination. "Figure Continue"

As shown in figure 4.51 (a) an Optical Power Meter displayed two readings The first reading was 23.388 E-3 watts W, and the second reading was 13.690 decibel-milliwatts dBm at the source point. (b) Power reading is 1.112 E-3 W, and 0.463 dBm at the destination.

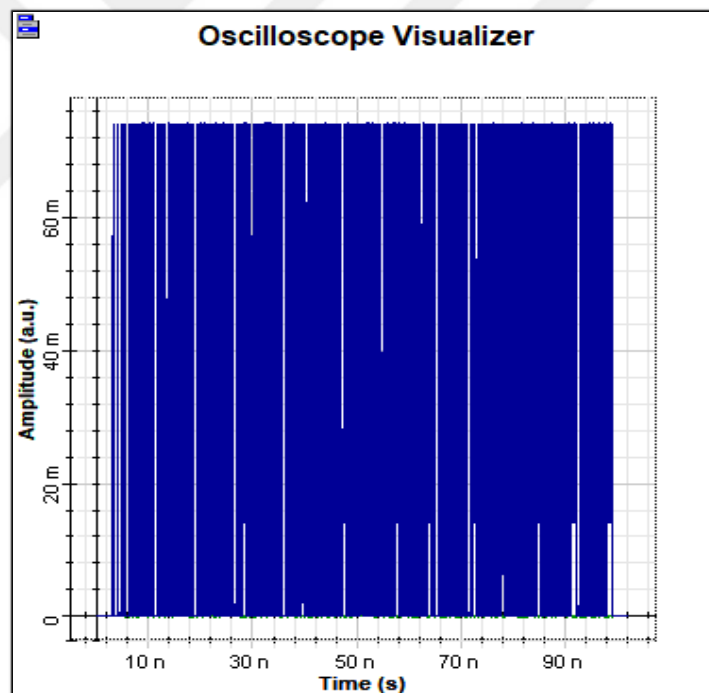


Figure 4.52: Oscilloscope Visualizer at Destination.

As shown in Figure 4.52, the x-axis represents the time in nanoseconds (ns) and the y-axis represents amplitude in (au). The signal displayed in the graph appeared to oscillate significantly between high and low values indicating rapid less fluctuations in the electrical

signal The reading was not stable and showed fewer sharp oscillations which might suggest noise or interference in the signal.

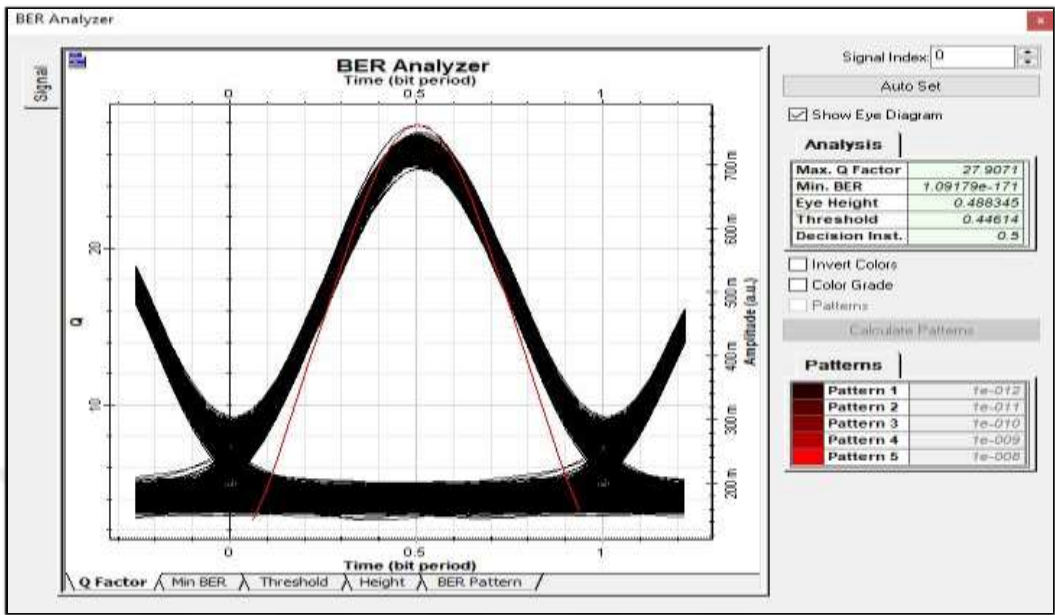


Figure 4.55: BER and EYE Diagram of FM Modulator.

As shown in Figure 4.53, the best reading of Q-Factor with FM Modulator With 27.9071 at 227.78 THz and the eye diagram shows a distortion in the signal and bad signal quality. furthermore, the red curve line BER shows bad result also, the signal measured in amplitude (au) on y-axis and time in (bit period) on x-axis.

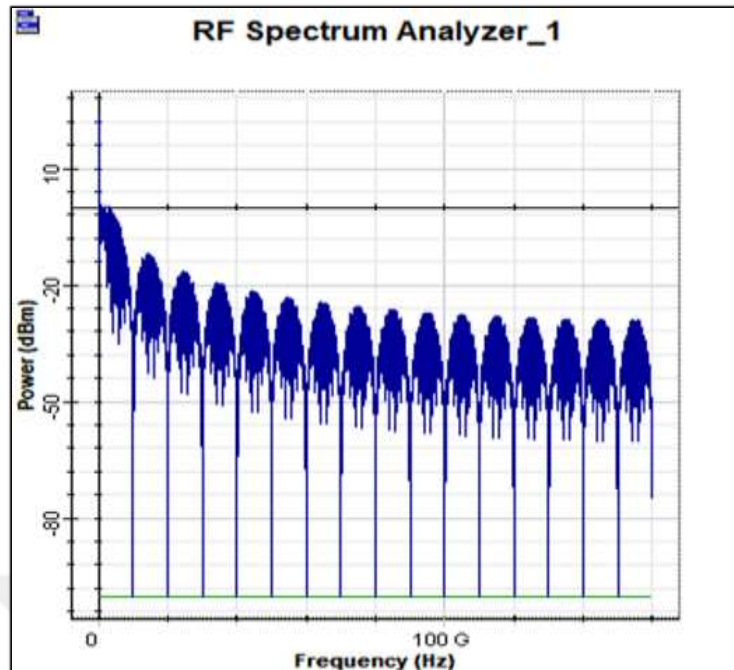


Figure 4.56: RF Spectrum Analyzer.

As given in Figure 4.54, decreases in power on y-axis as the frequency increases on x-axis. The reading is not good, because there is intense oscillation of power other than the different interference or noise present throughout the frequency range, which is a major negative point affecting the signal these could be interference with signals or situations within the system.

4.2.1.3 Responding to changes in power of laser source

A. NRZ pulse bit generator

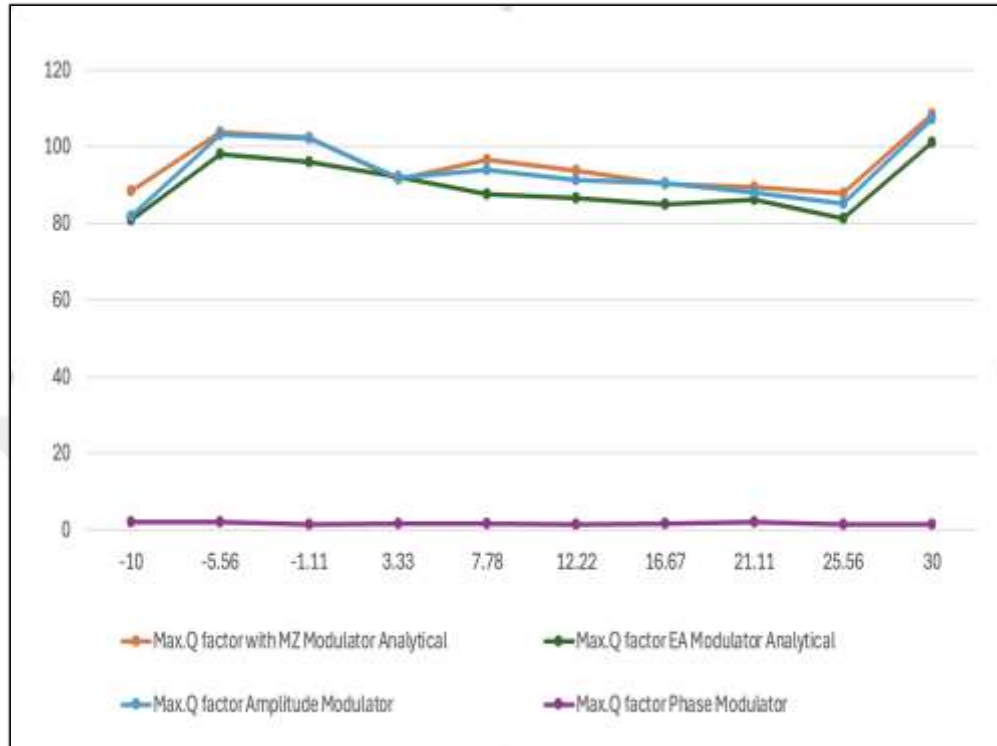


Figure 4.57: The Relationship Between the Quality Factor and Power of The Laser with The NRZ Pulse Bit Generator.

As shown in graph 4.55, it displayed a plot showing the correlation between power in dBm on x-axis and maximum Q-Factors for different modulators on y-axis. From the graph we see that maximum Q-Factor values for most modulators lie in the range of 80-120 showing fair to good performance except PM. The best reading was 285.393 Q-factor with MZ modulator analytical at 30 dBm as in the figure below. Furthermore, the eye diagram and the red curved line showed a good reading. The result is in Figure 4.56, the BER and EYE diagram of the MZ modulator.

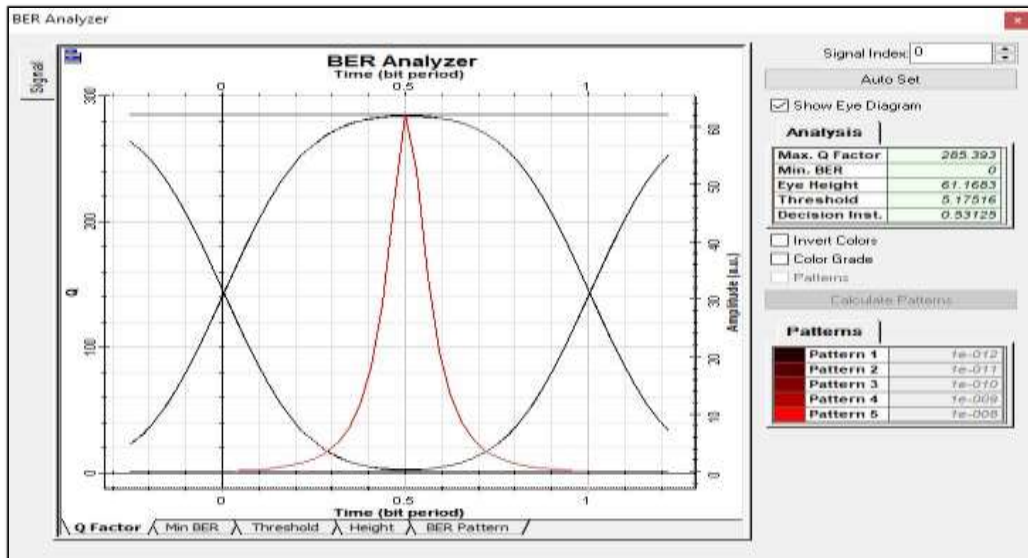
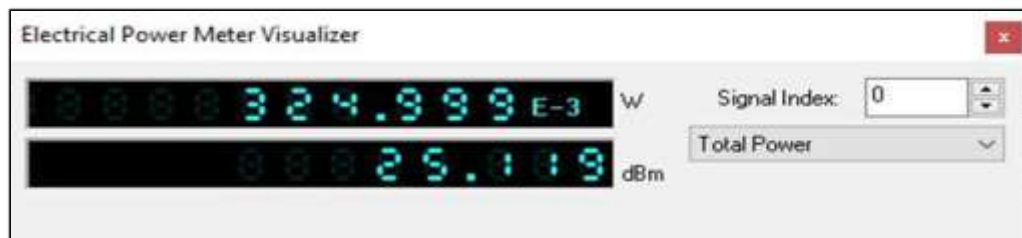


Figure 4.58: The BER and EYE Diagram of MZ Modulator.



(A)



(B)

Figure 4.59: (A) Optical Power Meter After MZ Modulator (B) Electrical Power Meter Visualizer at Destination.

As shown in Figure 4.57 (a) The reading on the picture indicated the optical power to be 465.889 E-3 watts and 26.682 dBm at the source point. (b) the reading at the destination was 324.999 E-3 W and the lower screen's power reading in dBm was 25.119 dBm. there was a dropdown for Signal Index with current value set at 0 and another dropdown to select the type of reading.

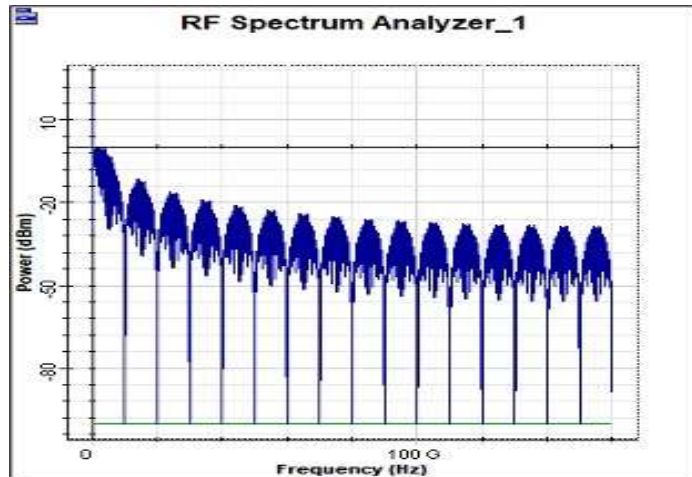


Figure 4.60: RF Spectrum Analyzer.

As shown in Figure 4.58, the horizontal axis represented frequency in hertz (Hz) and the vertical axis represented power in decibel milliwatts (dBm), the graph displayed a series of repetitive peaks that gradually decreased in power as the frequency increased the reading was not good as it showed significant oscillations and sharp drops in power indicating interference or noise in the signal. The result of environmental interference or flaws in the device used.

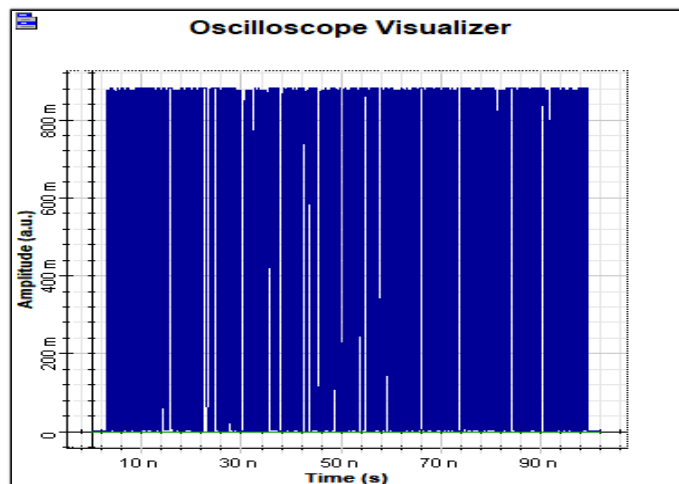


Figure 4.61: Oscilloscope Visualizer.

As shown in Figure 4.59, which corresponds to the electrical signal as a function of time the horizontal axis was in nanoseconds (ns) for time while the vertical axis was in arbitrary units

(au) for amplitude the provided signal represents a high-frequency digital one, with high and quick fluctuations of amplitude concerning time.

B. RZ Pulse Bit Generator

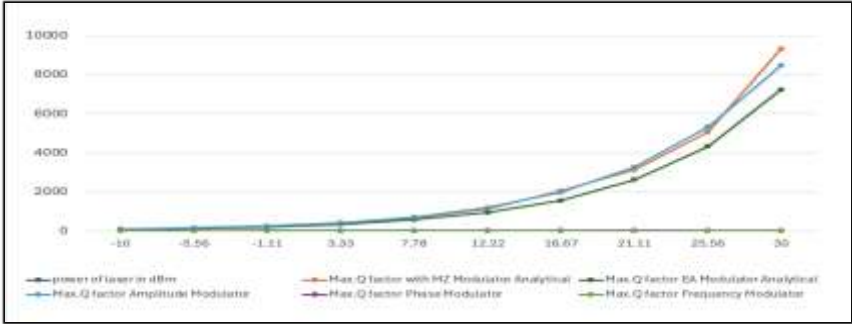


Figure 4.62: The Relationship Between the Quality Factor and Power of The Laser with The RZ Pulse Bit Generator.

Different types of modulators are in graph 4.60, which display the power on x-axis and Q-factor on y-axis and the relationship between the power and Q-factor. The best modulator was the MZ. From -15 to 35 as displayed on the horizontal axis. The modulators show gradually increase in in Q-factor value as the laser power increases except for FM.

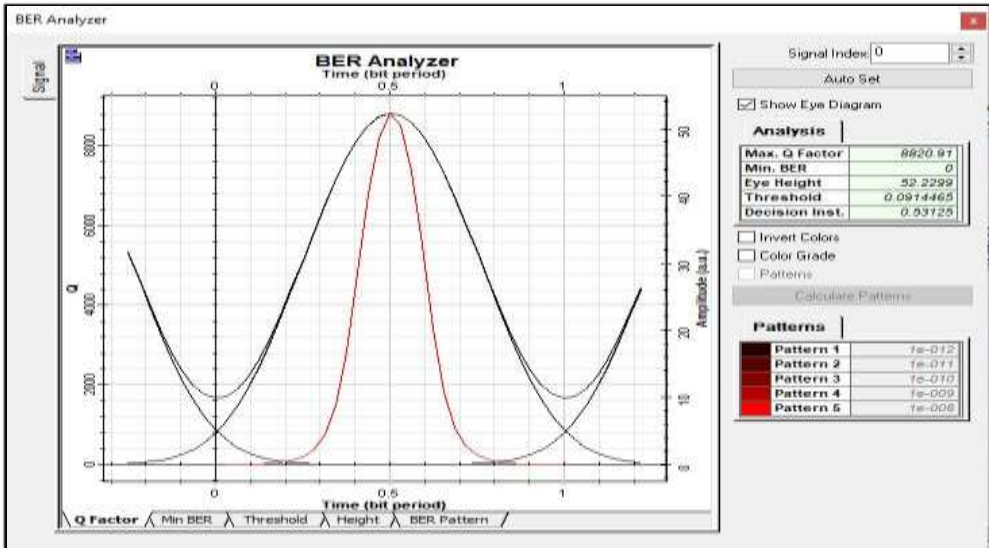


Figure 4.63: The BER and EYE Diagram of MZ Modulator.

The MZ Modulator analytical Q-factor was 8820.91 at 30 dBm. The eye diagram indicates bad signal quality, and red curved line BER showed good reading.

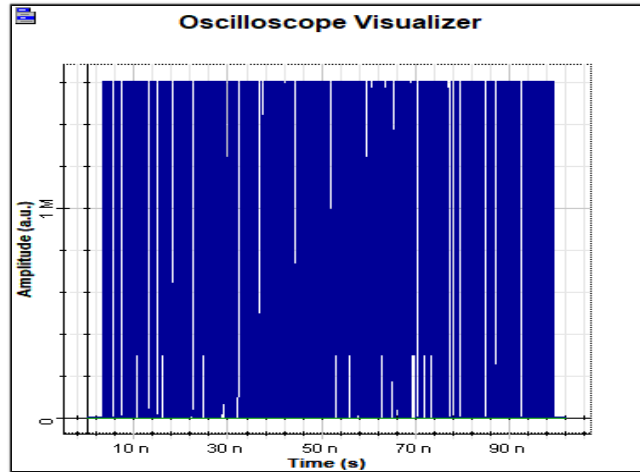


Figure 4.64: Oscilloscope Visualizer at Destination.

As shown in the graph 4.62 above, the x-axis in nanoseconds (ns) and y-axis in (au) the reading appeared to be stable and good with regular oscillations reflecting good performance of the system.

4.2.2 Hazy Weather 2.3706

4.2.2.1 Responding to changes in distances in Km

All properties in Table 3.4 except attenuation.

A. NRZ Pulse Bit Generator

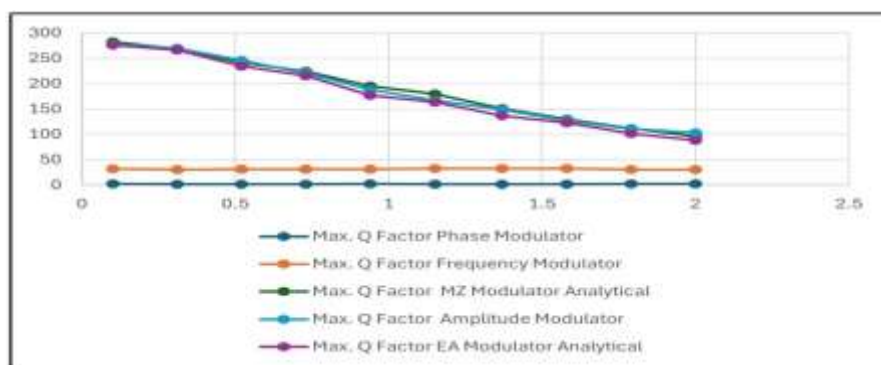


Figure 4.65: The Relationship Between the Quality Factor and Distances with The NRZ Pulse Bit Generator.

As shown in Figure 4.63, the maximum Q-Factors for five different types of modulators the horizontal axis represented values from 0 to 2.5 while the vertical axis represented values

from 0 to 300. it was observed that the maximum Q-Factor values for the analytical modulators green and purple started at around 285.982 and gradually decreased as the values on the horizontal axis increased, in contrast, the maximum Q-Factor values for the other modulators dark blue orange and light blue remained relatively constant at low values ranging between 0 and 50 the best reading with MZ Modulator Analytical with Q-Factor value 284.982 at 0.1km as in figure 4.64 shows the BER and EYE diagram of the MZ modulator.

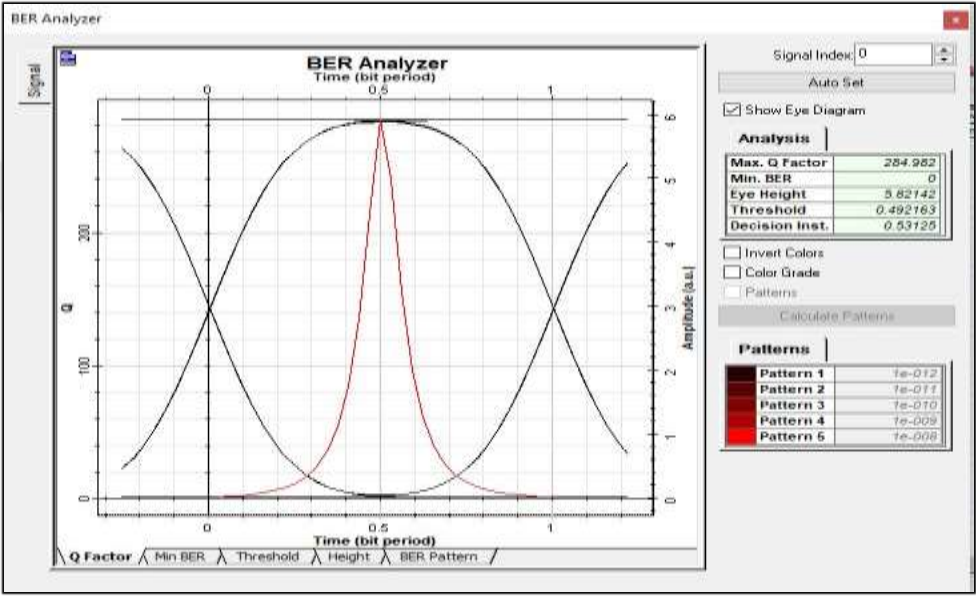


Figure 4.66: The BER and EYE Diagram of MZ Modulator.

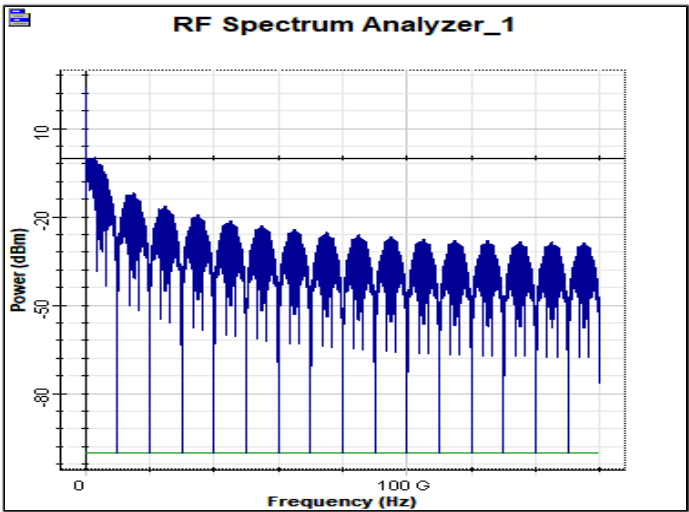


Figure 4.67: RF Spectrum Analyzer.

As shown in Figure 4.65 the horizontal axis represented frequency in Hertz Hz and the vertical axis represented power in decibels milliwatts dBm. The plot revealed a series of repeated peaks that gradually decreased in power as the frequency increased, the reading was not good as it showed unwanted interferences and oscillations in the spectrum which indicated noise or interferences that affect the signal quality.

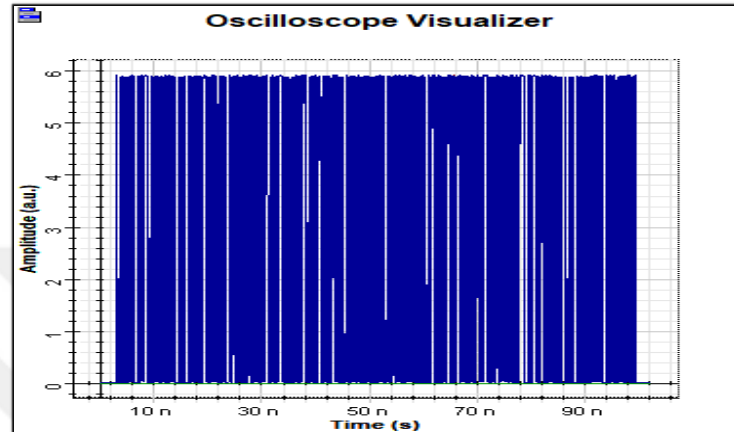


Figure 4.68: Oscilloscope Visualizer.

As shown in Figure 4.66, the horizontal axis represented time in nanoseconds (ns) and the vertical axis represented amplitude in arbitrary units (au). The signal appeared as repeated and irregular pulses indicating rapid oscillations in the signal. The reading was not good because it showed many irregular and frequent oscillations which indicate noise or interference in the signal.

B. RZ Pulse Bit Generator

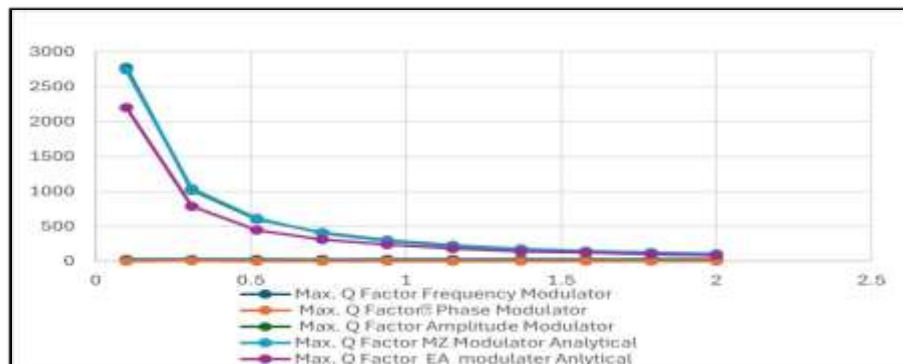


Figure 4.69: The Relationship Between the Quality Factor and Distances with The RZ Pulse Bit Generator.

As given in graph 4.67, the maximum Q-Factor on vertical axis decreased sharply as the values on the horizontal axis increased and stabilized at low values after the point 1 the best Max Factor was 2845.37 Amplitude Modulator at 0.1 km the best reading with amplitude modulator at 0.1 km at destination.

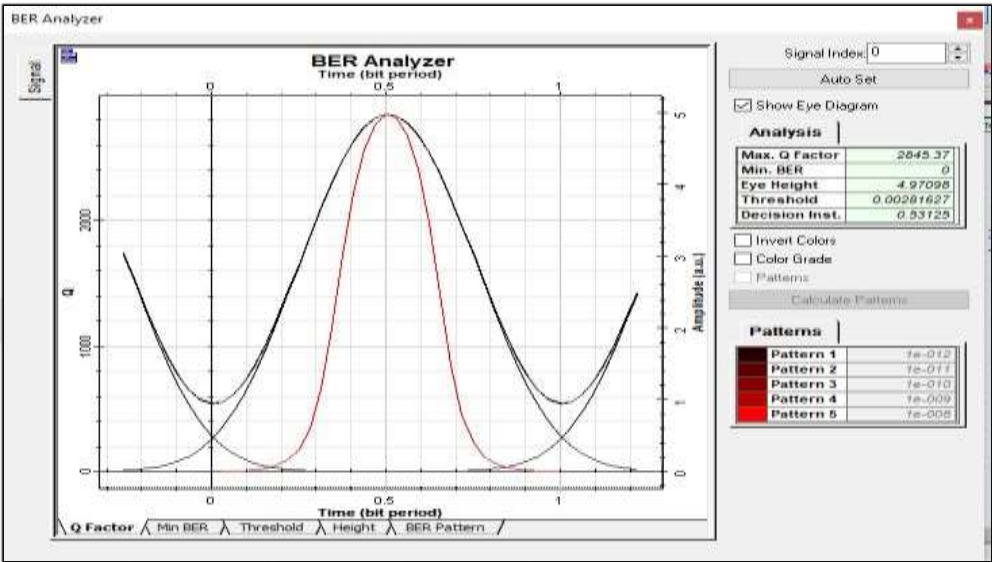


Figure 4.70: BER and EYE Diagram of AM Modulator.

The Q-factor and eye diagram is in Figure 4.68, The eye diagram showed bad signal quality and the BER indicates bad reading also.

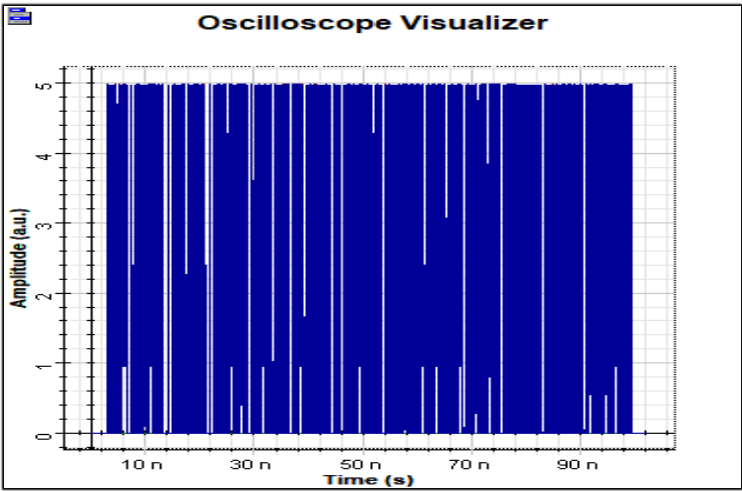


Figure 4.71: Oscilloscope Visualizer.

As shown in Figure 4.69, shows time in nanoseconds (ns) on horizontal axis and Amplitude in (au) on vertical axis. The graph showed a reading at different time intervals. The readings were very fluctuating with the amplitude varying between 0 and 5. This indicate that the measured signal was changing very rapidly with time

4.2.2.2 Responding to changes in frequencies in THz

A. NRZ Pulse Bit Generator

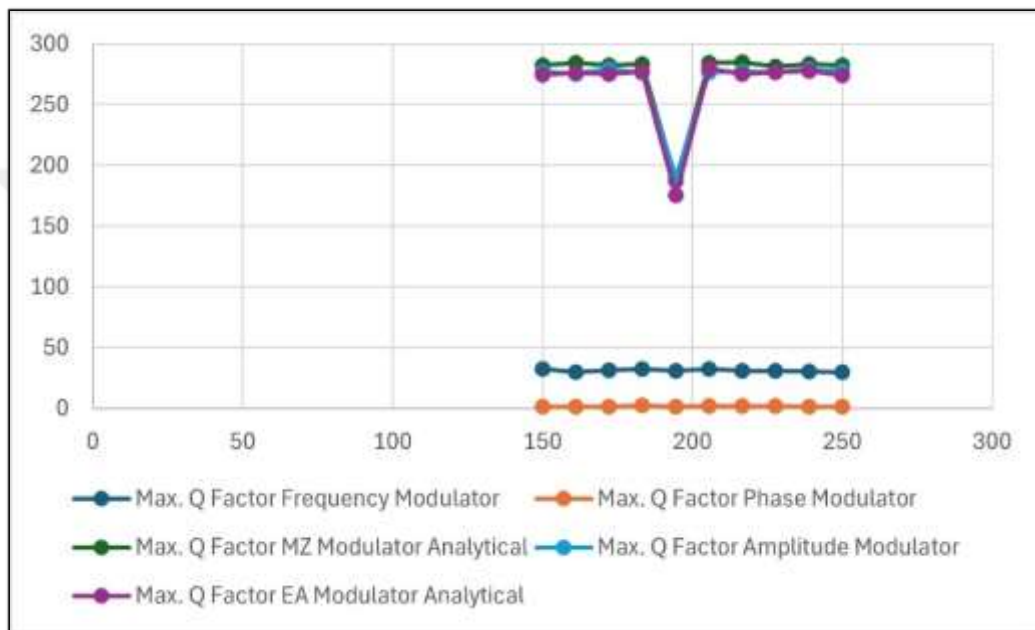


Figure 4.72: The Relationship Between the Quality Factor and Frequencies with The NRZ Pulse Bit Generator.

As shown in Figure 4.70, the graph showed that the maximum Q-Factors on vertical axis and frequencies on the horizontal axis for the MZ and EA analytical modulators were constant at around 260 with a sharp dip in the middle of the graph while the maximum Q-Factors for the frequency phase and amplitude modulators were constant at much lower values. The best reading is with MZ Modulator Analytical with 267.43 Q-factor at 216.67 THz.

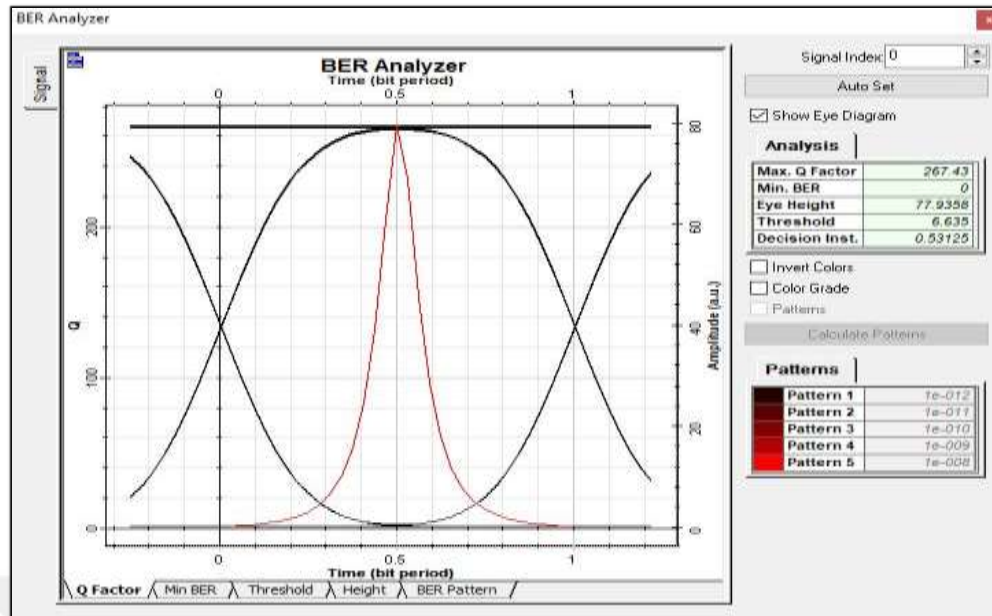


Figure 4.73: BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.71, the horizontal axis represents time in nanoseconds (ns) and vertical axis amplitude in arbitrary units (au), the eye diagram and the red curved line which indicate good reading and good signal quality.

B. RZ Pulse Bit Generator

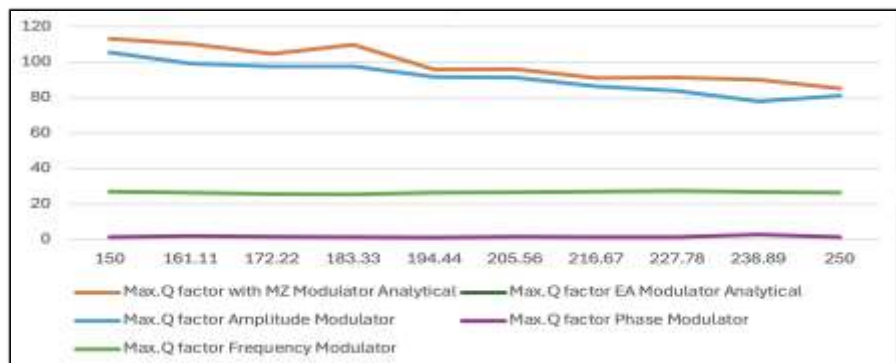


Figure 4.74: The Relationship Between the Quality Factor and Frequencies with The RZ Pulse Bit Generator.

As shown in Figure 4.72, which represent the frequencies on x-axis and Q-factor on y-axis, it was observed that most lines decrease at high values except for the purple line which has the lowest value. The best reading with MZ modulator which was 118.689 Q-factor at 150 THz.

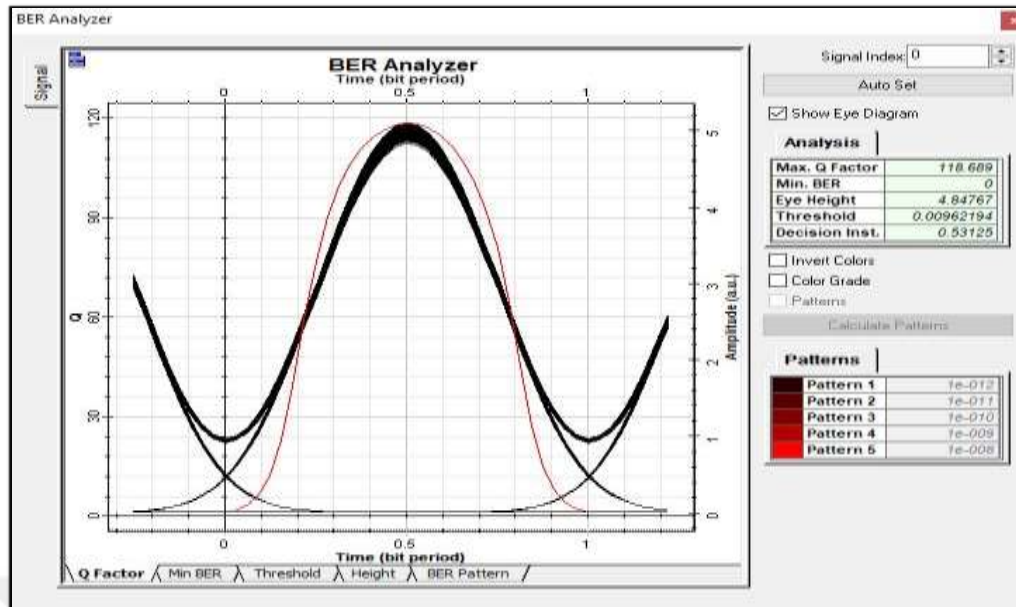


Figure 4.75: BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.73, the EYE diagram and BER of low-quality signal and reading for the signal.

4.2.2.3 Responding to changes in the power of the laser source

A. NRZ Pulse Bit Generator

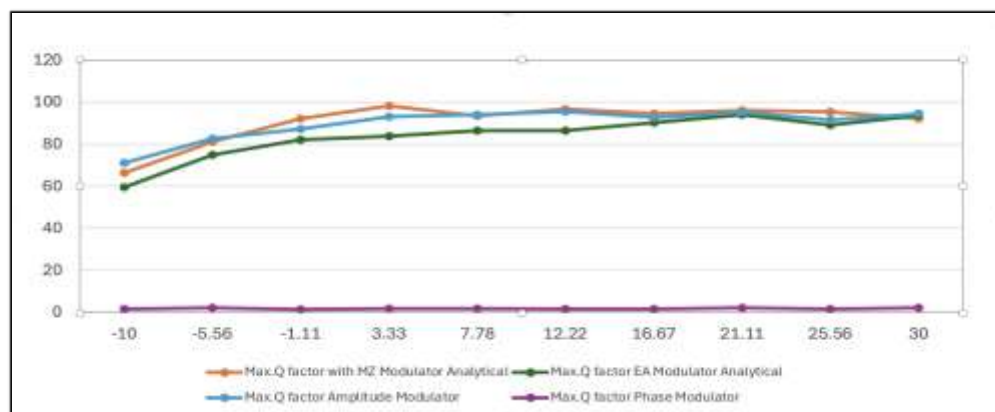


Figure 4.76: The Relationship Between the Quality Factor and Power Laser with The NRZ Pulse Bit Generator.

As shown in Figure 4.74, the graph shows the result of increasing the laser power on x-axis and the decrease in the Q-factor on y-axis. The maximum Q-factor was obtained with MZ modulator which was 98.4796 at 3.33 dBm as in the figure below.

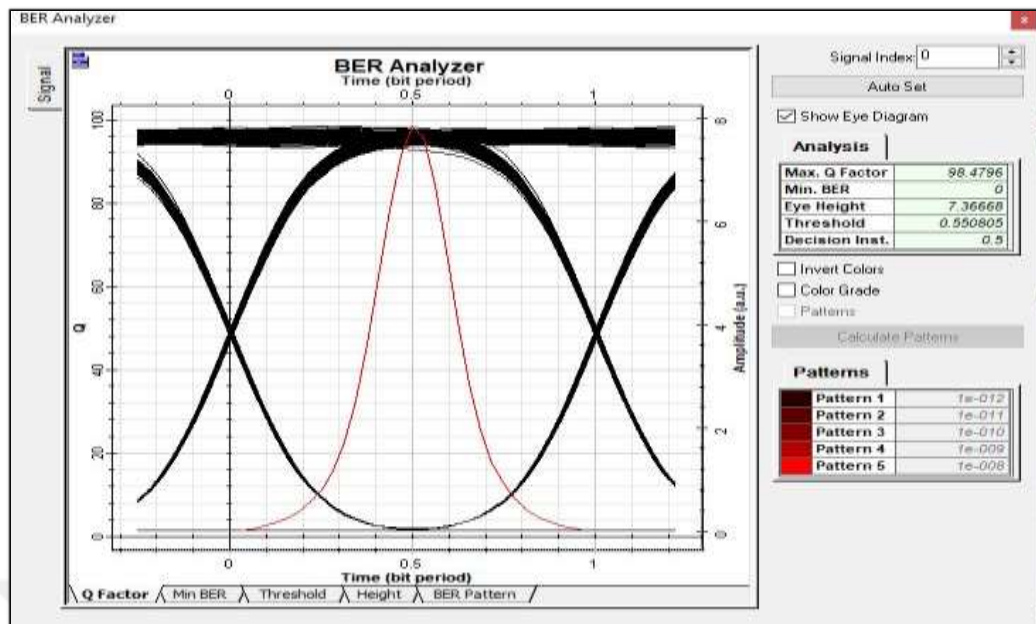


Figure 4.77: BER and EYE Diagram of MZ Modulator.

As given in Figure 4.75, shows the eye diagram which indicates that there is distortion in the signal quality, and the curved red line is showing good reading.

B. RZ Pulse Bit Generator

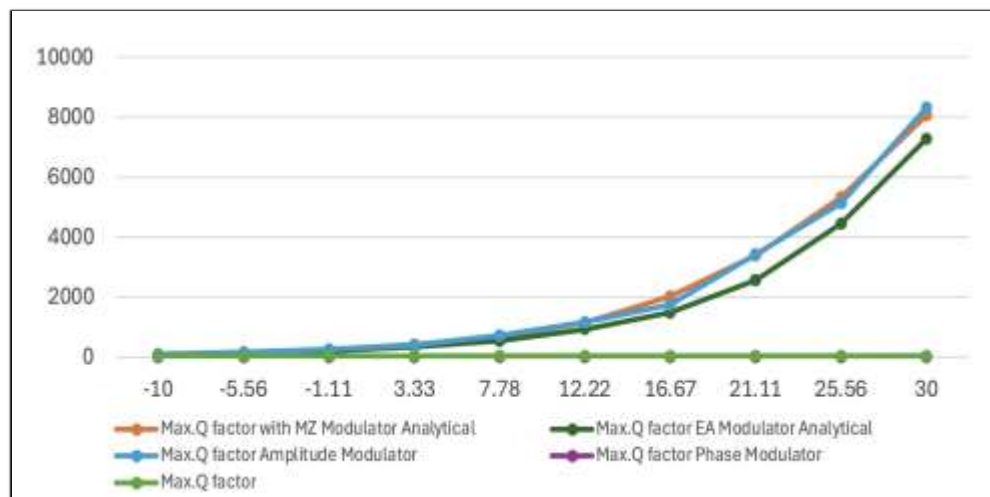


Figure 4.78: The Relationship Between the Quality Factor and Power Laser with The RZ Pulse Bit Generator.

As shown in Figure 4.76, it was noted that the purple line remained constant at zero while the other lines showed varying increases in maximum Q values on vertical axis as the values

on the horizontal axis increased the best reading with MZ Modulator Analytical with Q-Factor 8316.59 at 30 dBm.

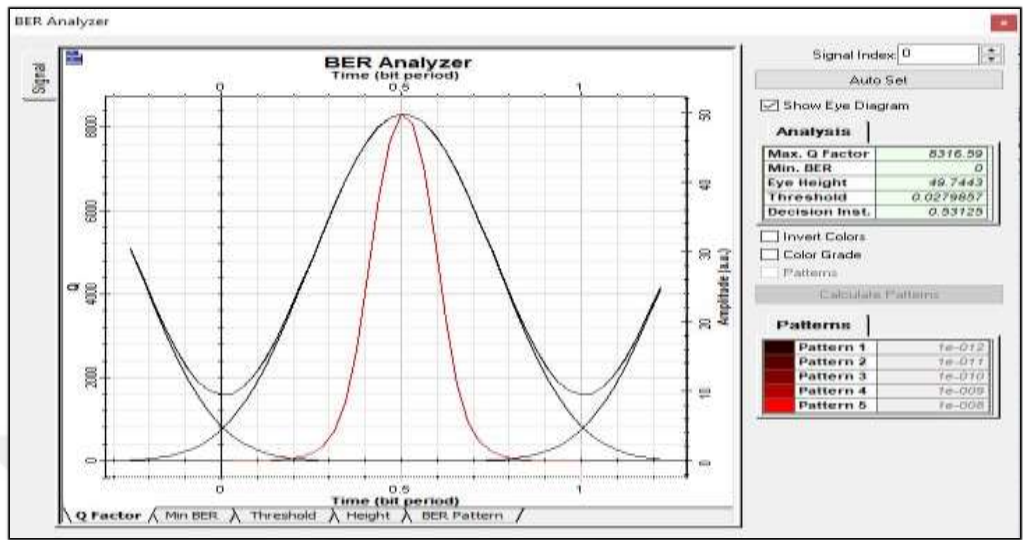


Figure 4.79: BER and EYE Diagram of MZ Modulator.

As given in Figure 4.77, shows that the eye diagram has somewhat good reading of signal quality and the red curved line showed a good reading.

4.2.3 Light rain 6.27 responding to changes in distances in Km

The properties of Table 3.4 were used.

A. NRZ Pulse Bit Generator

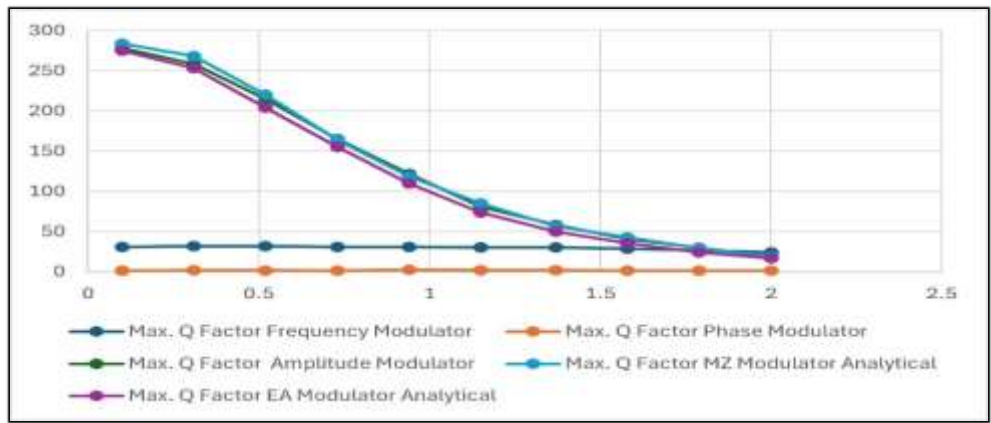


Figure 4.80: The Relationship Between the Quality Factor and Distances in Km with The NRZ Pulse Bit Generator.

As shown in Figure 4.78, very line graphed in different data varied along with max Q-Factors for various modulators against the horizontal axis ranging from 0 to 2.5 and against the vertical axis ranging from 0 to 300. There was an observation of decrease in reading in maximum 'Q' values on all the lines with an increase in values along the horizontal axis. The best reading using MZ Modulator Analytical with 0.1km with Q-Factor 282.713.

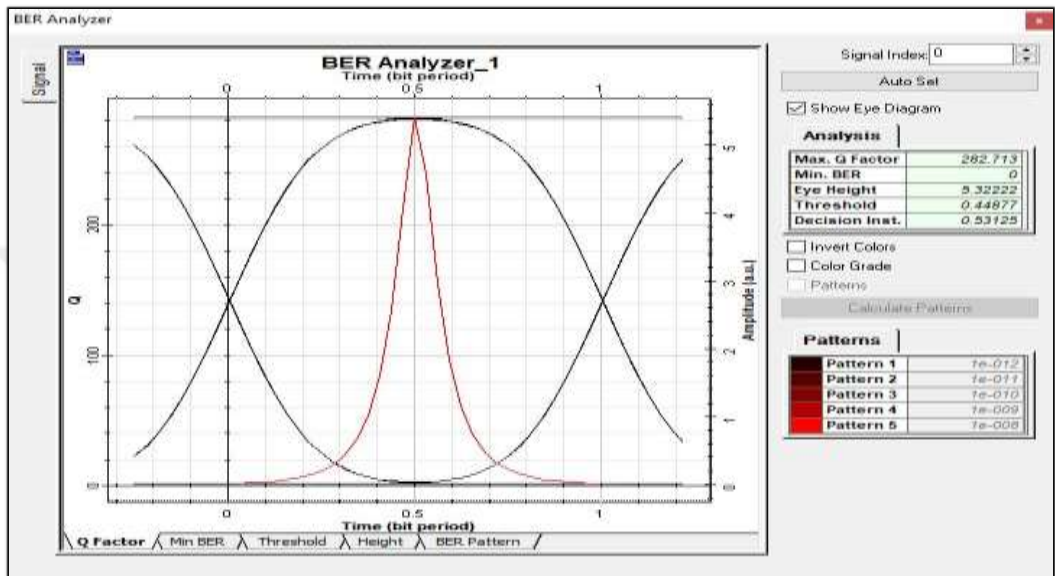


Figure 4.81: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.79, the eye diagram shows good signal quality, and the red curved line shows good reading.

B. RZ Pulse Bit Generator

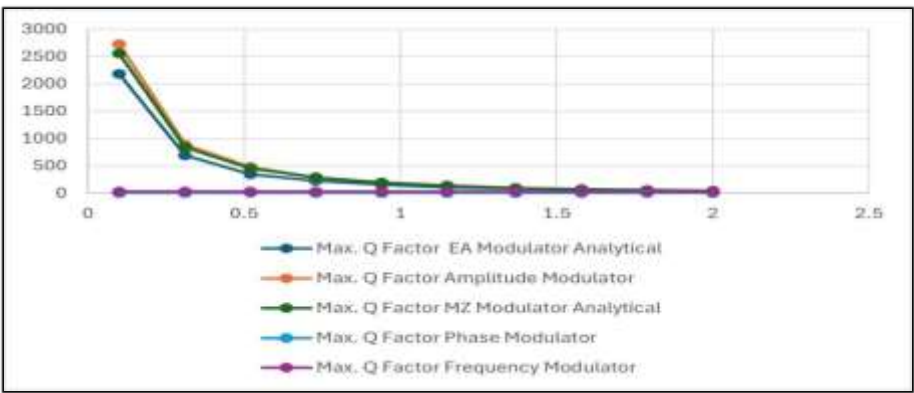


Figure 4.82: The Relationship Between the Quality Factor and Distances in Km with The RZ Pulse Bit Generator.

As shown in Figure 4.80, the maximum Q-Factor and different types of modulators the horizontal axis represented values from 0 to 2.5 while the vertical axis represented values from 0 to 3000 there were five types of modulators represented by different coloured lines. The graph showed that the values started high at point 0 then quickly dropped and stabilized at lower values after point 0.5 The best reading using Q-Factor Amplitude Modulator with 0.1km with MZ modulator with a Q-Factor 2670.82.

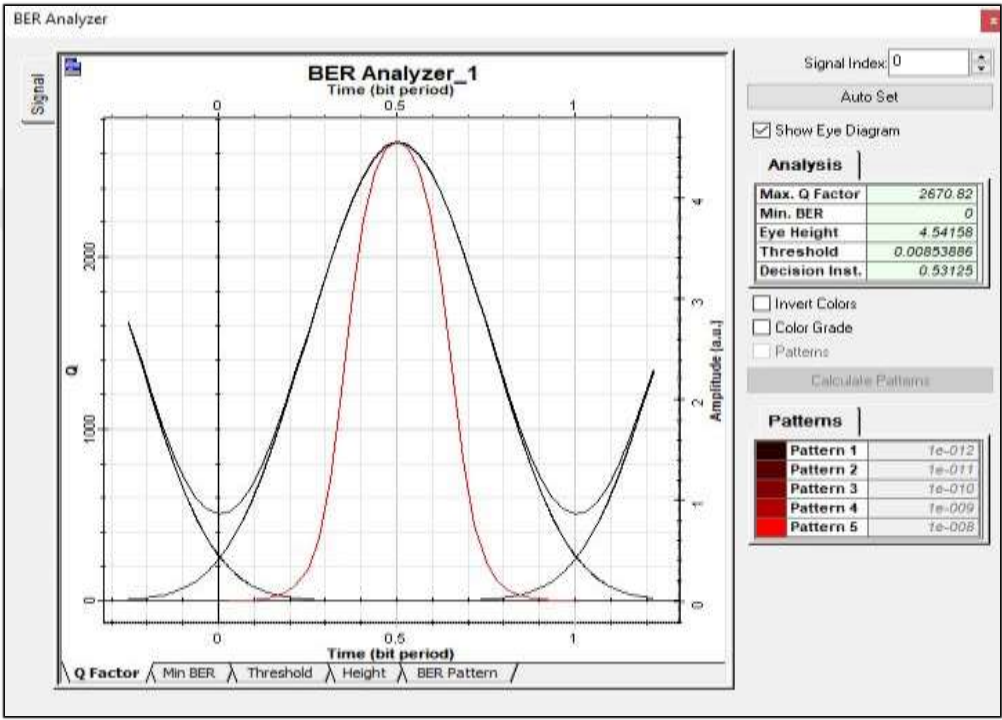


Figure 4.83: The BER and EYE Diagram of AM Modulator.

As shown in Figure 4.81, shows the eye diagram which indicates somewhat good signal quality along with the distortion while the red curved line indicates also somewhat good reading.

4.2.3.1 Responding to changes in frequencies in THz

A. NRZ Pulse Bit Generator

The properties of Table 4.4 were used.

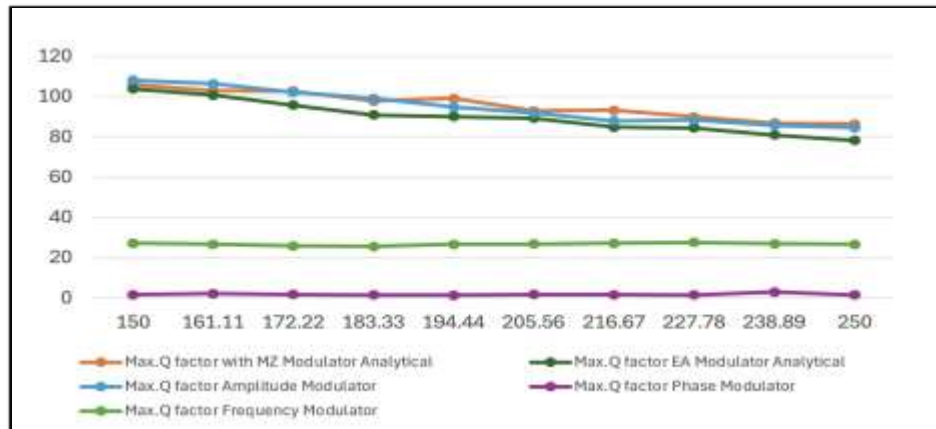


Figure 4.84: The Relationship Between the Quality Factor and Frequencies In THz with The NRZ Pulse Bit Generator.

As shown in Figure 4.82, the plot of the maximum Q-factors on vertical axis with different types of modulators on horizontal axis. These were plotted on the abscissa and ordinates from 0 to 300, five types of modulators represented by different colours. The graph indicates that the maximum Q-Factors for AM was the best reading, then starts to decrease as the frequency increased.

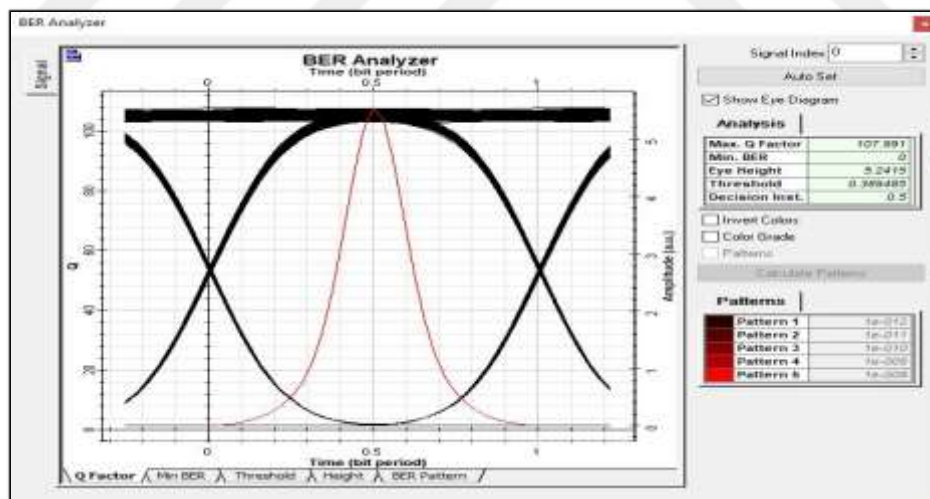


Figure 4.85: The BER and EYE Diagram of AM Modulator.

The best reading using AM Modulator Analytical with 150THz with Q-Factor 107.991. the figure above shows the eye diagram which is open and there is some distortion in signal quality while, the red curved line indicates good reading.

B. RZ Pulse Bit Generator

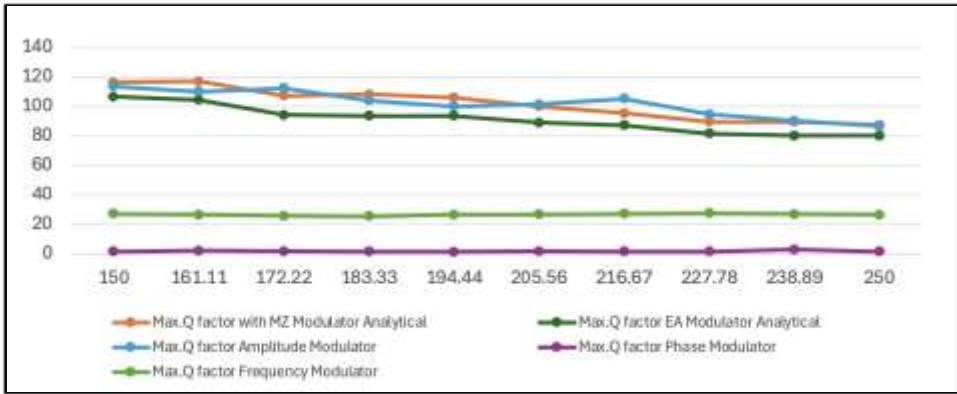


Figure 4.86: The Relationship Between the Quality Factor and Frequencies with The RZ Pulse Bit Generator.

As shown in Figure 4.84, the graph indicates the Q-factor on y-axis of five modulators represented by different colours and frequencies on x-axis. Apart from frequency and phase modulators, all other Q-factors face a gradual decrease from all modulators at 161.11THz.the graph shows that the reading is decrease as the frequency increases. The best reading using MZ Modulator Analytical with 150 THz with Q-Factor 117.177.

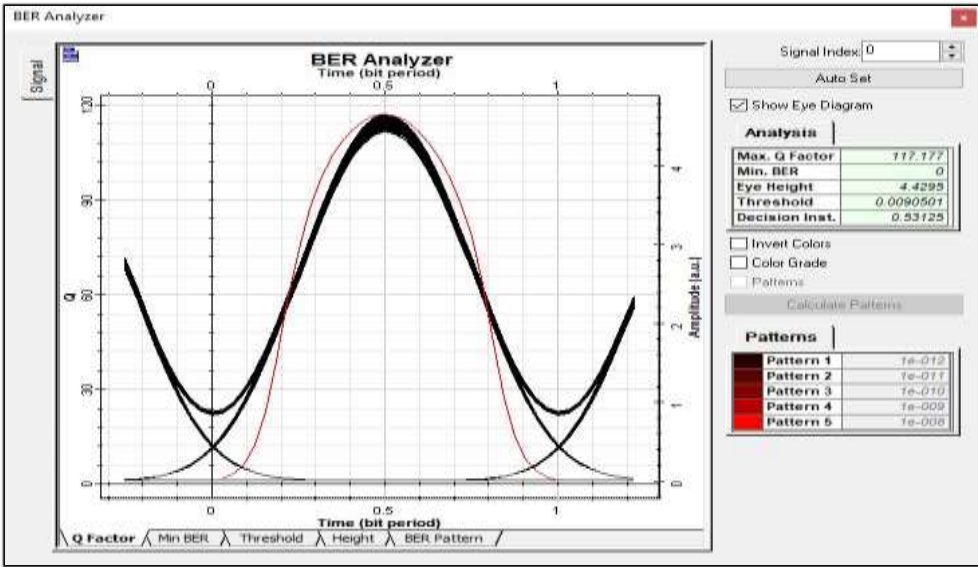


Figure 4.87: The BER and EYE Diagram of MZ Modulator.

As given in Figure 4.85, shows a distortion and bad eye diagram and signal quality, the red curved line BER indicates bad reading for the signal.

4.2.3.2 Responding to changes in the power of the laser source

A. NRZ Pulse Bit Generator

The properties of Table 4.5 were used.

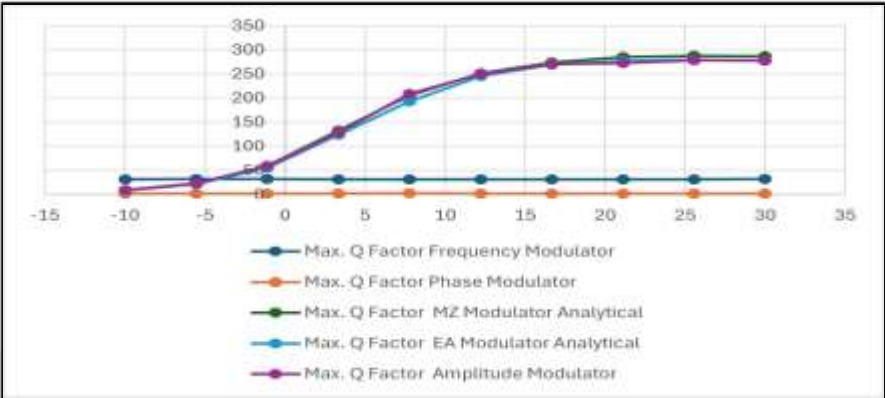


Figure 4.88: The Relationship Between the Quality Factor and Power Laser with The NRZ Pulse Bit Generator.

As shown in Figure 4.86, the maximum Q-Factors for different types of modulators the horizontal axis represented values from -15 to 35 while the vertical axis represented values from 0 to 350 there were five types of modulators represented by different coloured lines. The best reading using MZ Modulator Analytical with 256.453 Q-factor with 30 dBm.

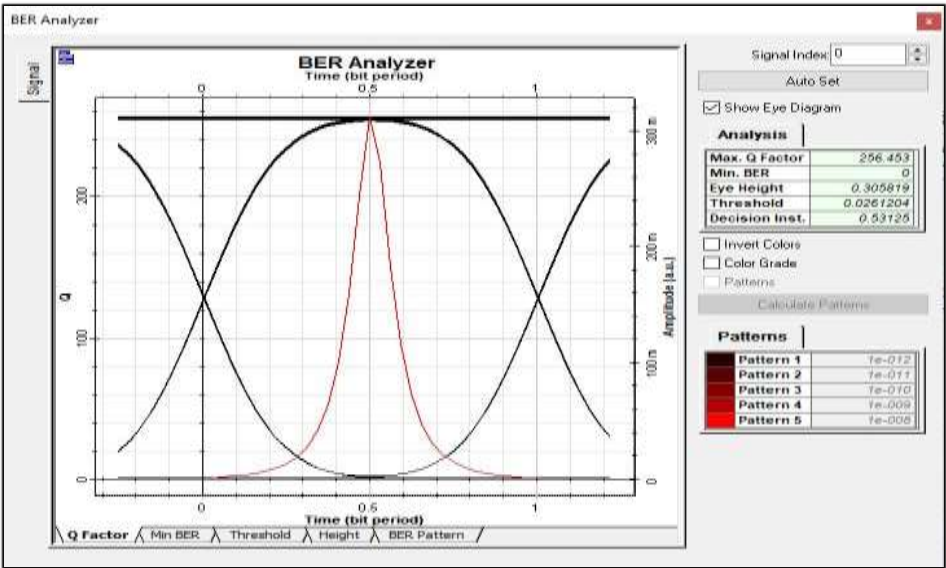


Figure 4.89: The BER and EYE Diagram of MZ Modulator.

As given in Figure 4.87, shows the eye diagram which indicates few distortions and good open eye and that mean good signal quality while the red curved line indicates good reading of the signal.

B. RZ Pulse Bit Generator

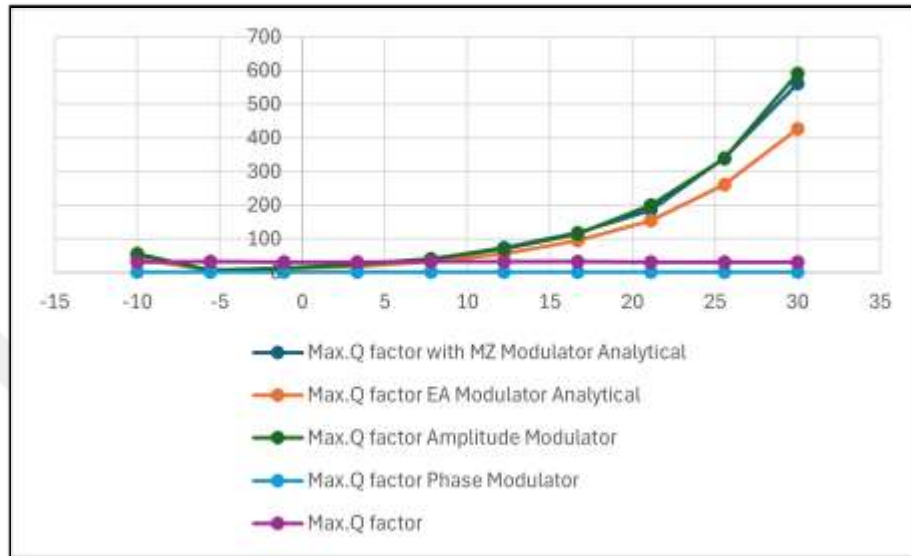


Figure 4.90: The Relationship Between the Quality Factor and Power Laser with The RZ Pulse Bit Generator.

As shown in Figure 4.88 the maximum Q-Factors for five different types of modulators the horizontal axis represented values from -15 to 35 while the vertical axis represented values from 0 to 700 the different coloured lines represented the different types of modulators. It was observed that the AM modulator has the best reading. While the maximum Q-Factors for the frequency modulator remained almost constant at a low value. The best reading using AM Modulator Analytical with 30 dBm with Max Q-Factor 590.96.

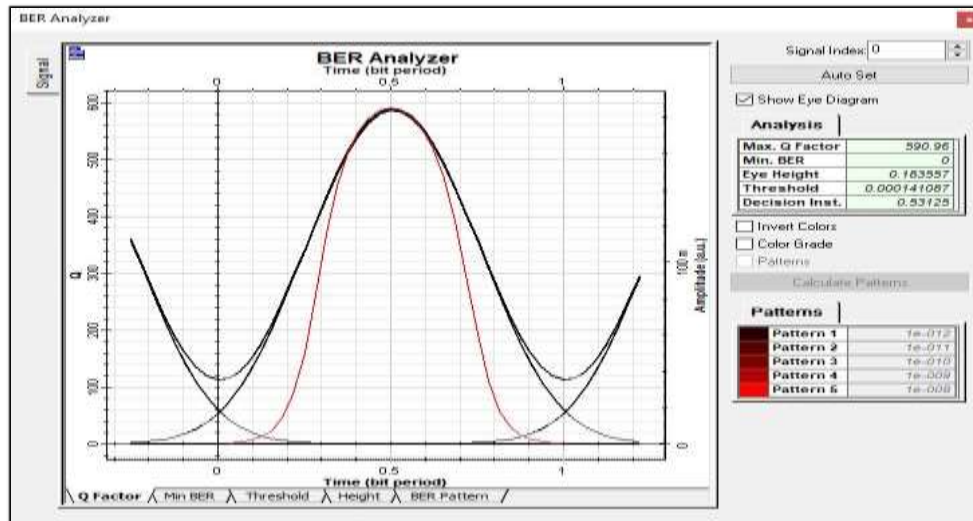


Figure 4.91: The BER and EYE Diagram of AM Modulator.

As given in Figure 4.89, shows the eye diagram which indicates bad signal quality with distortion and the red curved line indicate bad reading also.

4.2.4 Moderate Rain 9.64 Responding to Changes in Distances in Km

A. NRZ Pulse Bit Generator

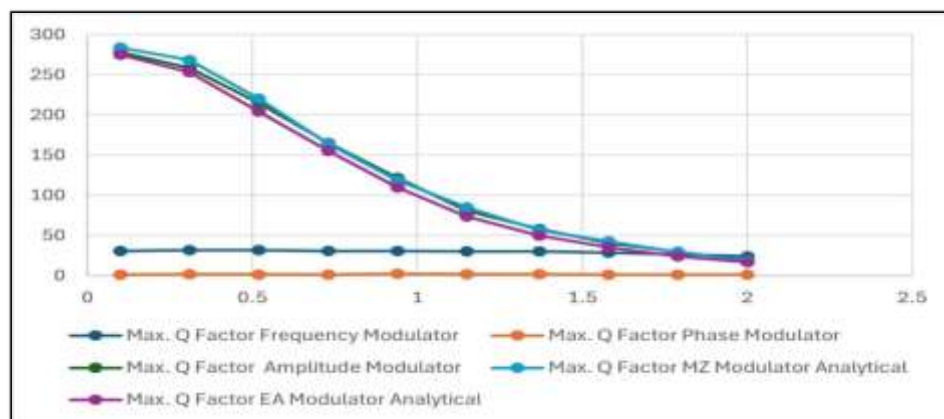


Figure 4.92: The Relationship Between the Quality Factor and Distances with The NRZ Pulse Bit Generator.

As shown in Figure 4.90, the horizontal axis represented values from 0 to 2.5 while the vertical axis represented values from 0 to 300 there were five sets of data represented by different coloured lines. It observed that the values started high at point 0.1 and then gradually decreased as the values on the horizontal axis increased except for the PM

modulator. The best reading using MZ Modulator Analytical with 0.1km with Max Q-Factor 282.915.

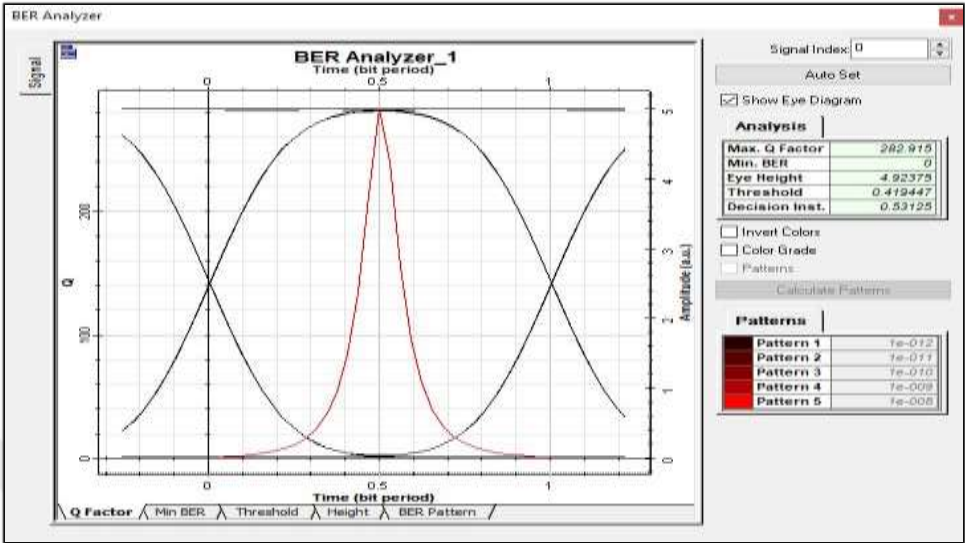


Figure 4.93: The BER and EYE Diagram of MZ Modulator.

As given in Figure 4.91, shows the eye diagram which indicates good signal quality, and the red curved line indicates also good reading for the signal.

B. RZ Pulse Bit Generator

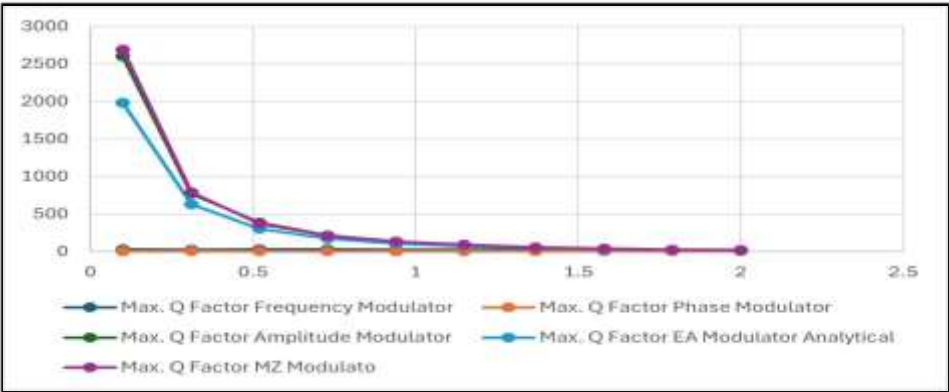


Figure 4.94: The Relationship Between the Quality Factor and Distances with The RZ Pulse Bit Generator.

As shown in Figure 4.92, the maximum Q-Factors for different types of modulators the horizontal axis represented values from 0 to 2.5 while the vertical axis represented values from 0 to 3000 there were five types of modulators represented by different coloured lines.

The graph showed that the maximum Q-Factor values quickly decreased as the values on the horizontal axis increased and stabilized at low values after the point 1.5 The best reading using MZ Modulator Analytical with 0.1km with Max Q-Factor 2461.08.

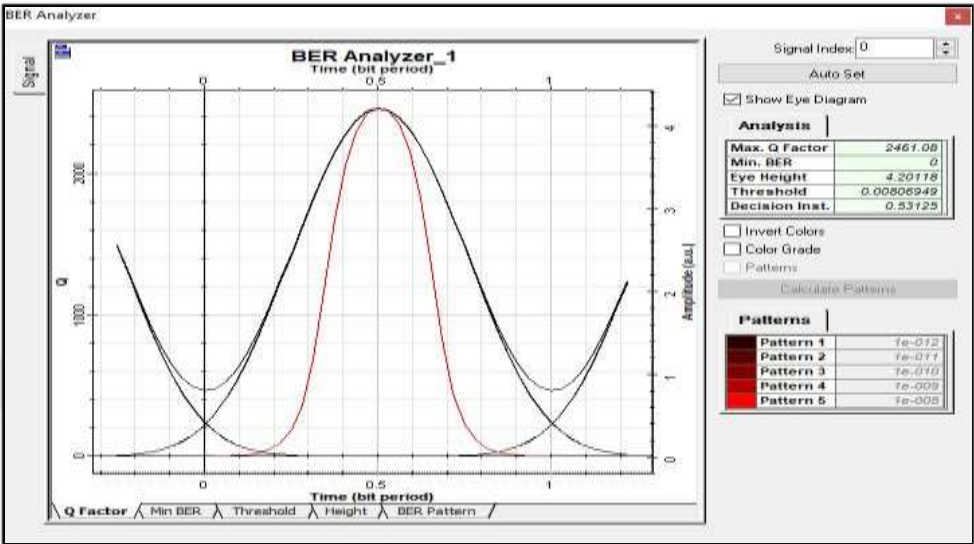


Figure 4.95:The BER and EYE Diagram of MZ Modulator.

As given in Figure 4.93, shows the eye diagram which indicates distortion in the signal quality and the red curved line indicates not very good reading.

4.2.4.1 Responding to changes in frequencies in THz

A. NRZ Pulse Bit Generator

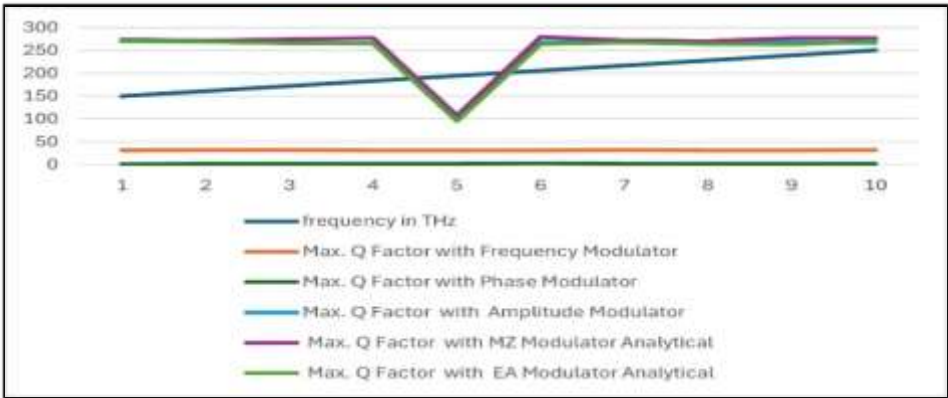


Figure 4.96: The Relationship Between the Quality Factor and Frequencies with The NRZ Pulse Bit Generator.

As shown in Figure 4.94, the relationship between frequency in THz and the maximum Q-Factor using different types of modulators the horizontal axis represented the frequency in THz from 1 to 10 while the vertical axis represented the value of the maximum Q-Factor there were six different coloured lines in the graph each representing a different type of modulator. It was noted that the best reading using MZ Modulator Analytical with 194.44 THz with Q-Factor 262.103.

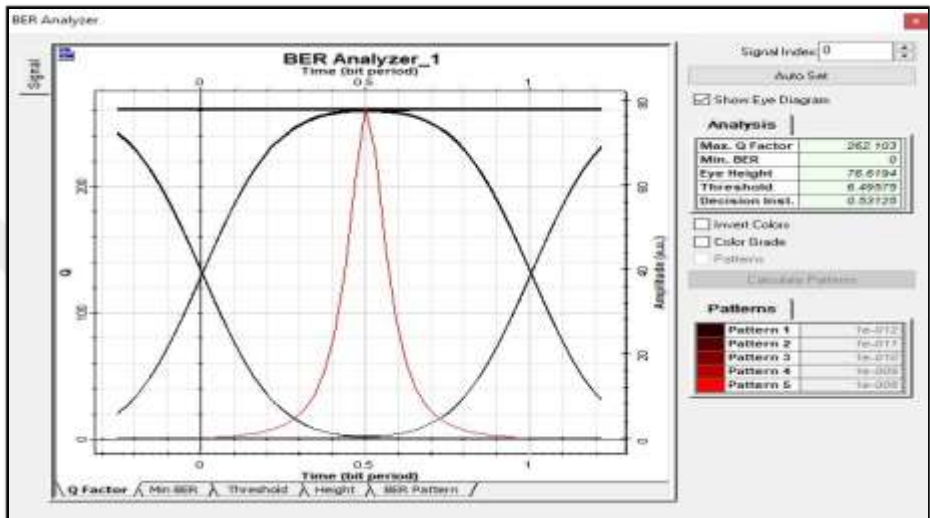


Figure 4.97: The BER and EYE Diagram of MZ Modulator.

As given in Figure 4.95, shows the eye diagram which indicates a good signal quality, and the red curved line indicates a good reading for the signal.

B. RZ Pulse Bit Generator

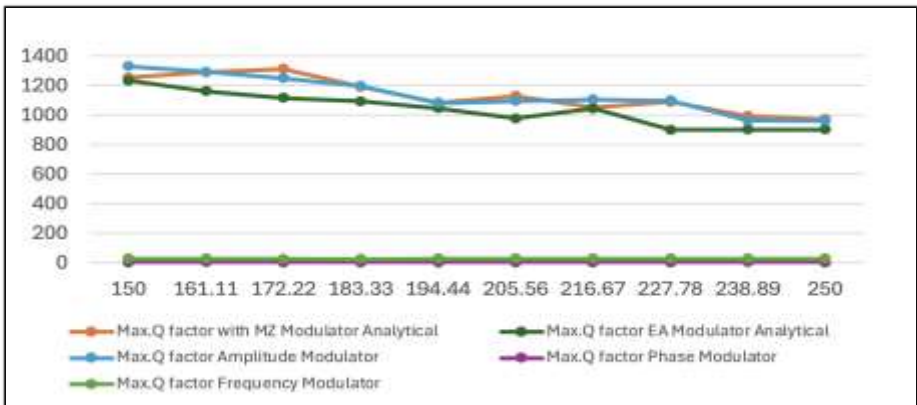


Figure 4.98: The Relationship Between the Quality Factor and Frequencies with The RZ Pulse Bit Generator.

As shown in Figure 4.96, the relationship between frequency in THz on x-axis and the maximum Q-Factor on y-axis. It was noted that the AM modulator has the best reading at 150 THz and the MZ modulator raise at 172.22 THz and decline as the frequency increases. The best reading using MZ Modulator with 150 THz with Q-Factor 1329.16.

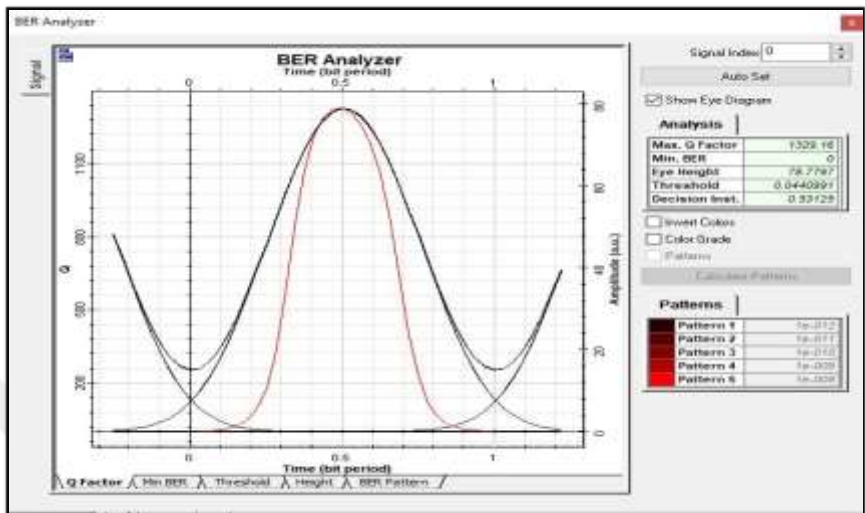


Figure 4.99: The BER and EYE Diagram of MZ Modulator.

As given in Figure 4.97, shows eye diagram which shows distortion in signal quality, and the red curved line indicates somewhat bad reading for the signal.

4.2.4.2 Responding to changes in the power of the laser source in dBm

A. NRZ Pulse Bit Generator

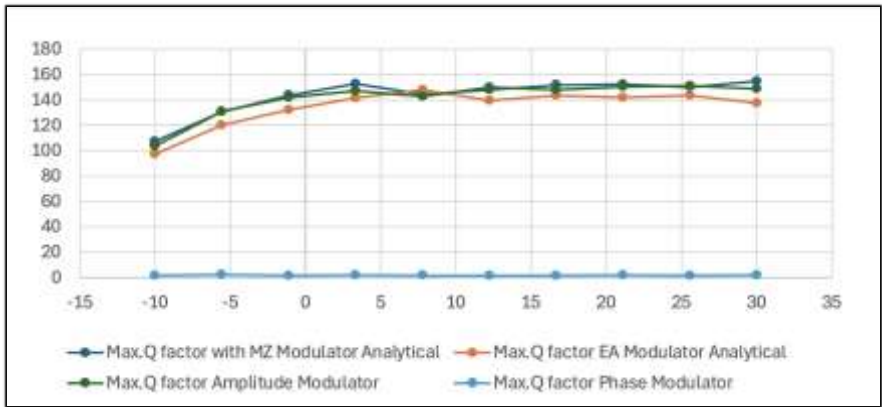


Figure 4.100: The Relationship Between the Quality Factor and Power Laser with The NRZ Pulse Bit Generator.

As shown in Figure 4.98, which demonstrated maximum Q-Factors on vertical axis of different types of modulators against values on the horizontal axis varied from -15 to 35. The best reading using MZ Modulator with 30dBm with Q-Factor 154.793

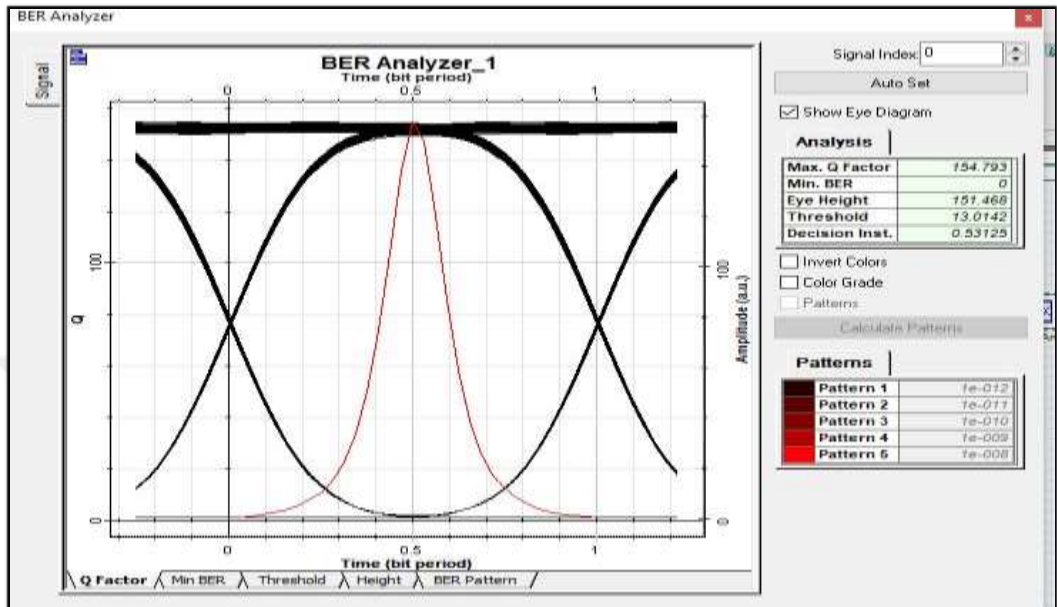


Figure 4.101: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.99, shows the eye diagram which indicates a distortion in the signal which in turn effect the quality of the signal, and the red curved line shows a good reading in the signal.

B. RZ Pulse Bit Generator

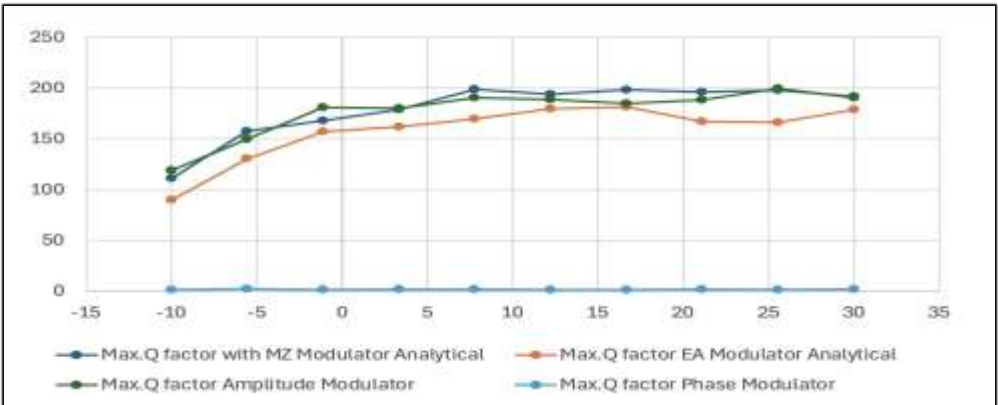


Figure 4.102: The Relationship Between the Quality Factor and Power Laser with The RZ Pulse Bit Generator.

As shown in Figure 4.100, the relationship between several variables over a period from -15 to 35 the horizontal axis represented laser power, while the vertical axis represented the Q-factor values of the modulators. It observed that the values started from -10 and fluctuated around the 7.5 to 30 dBm. The best reading using AM Modulator with 30dBm with Q-Factor 198.26 as in the figure below.

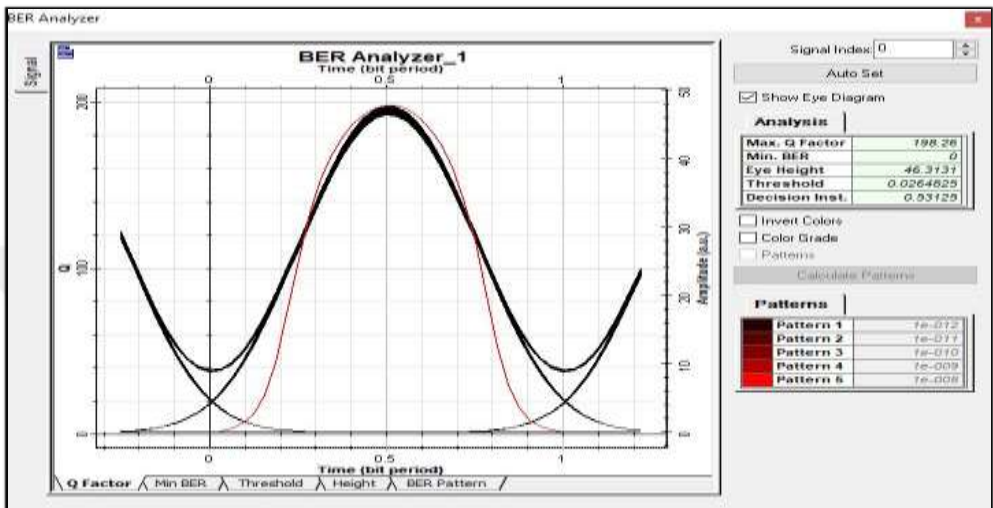


Figure 4.103: The BER and EYE Diagram of AM Modulator.

As shown in Figure 4.101, shows the eye diagram that indicates that there is a distortion in the signal which mean bad signal, and the red curved line indicates bad reading of the signal.

4.2.5 Heavy Rain 19.28 Responding to Changes in Distances in Km

A. NRZ Pulse Bit Generator

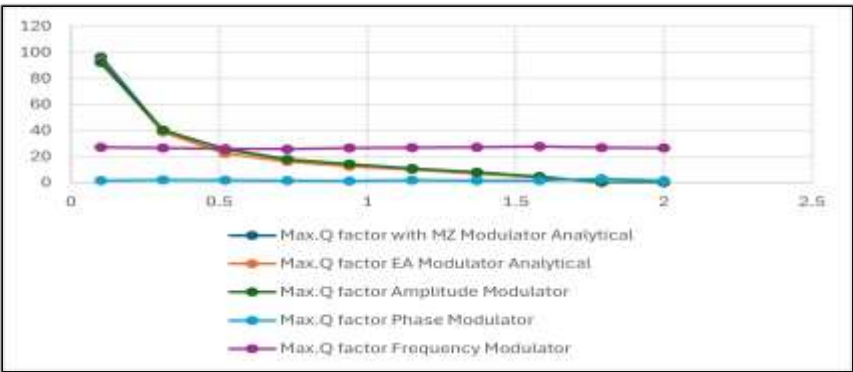


Figure 4.104: The Relationship Between the Quality Factor and Distances with The NRZ Pulse Bit Generator.

As shown in Figure 4.102, the data showed that the maximum Q-Factors on y-axis started with high values and sharply decreased as the distance increased on x-axis except for the phase and frequency modulator which showed relative stability in its values. The best reading using MZ Modulator Analytical with 0.1km with Q-Factor 93.2693

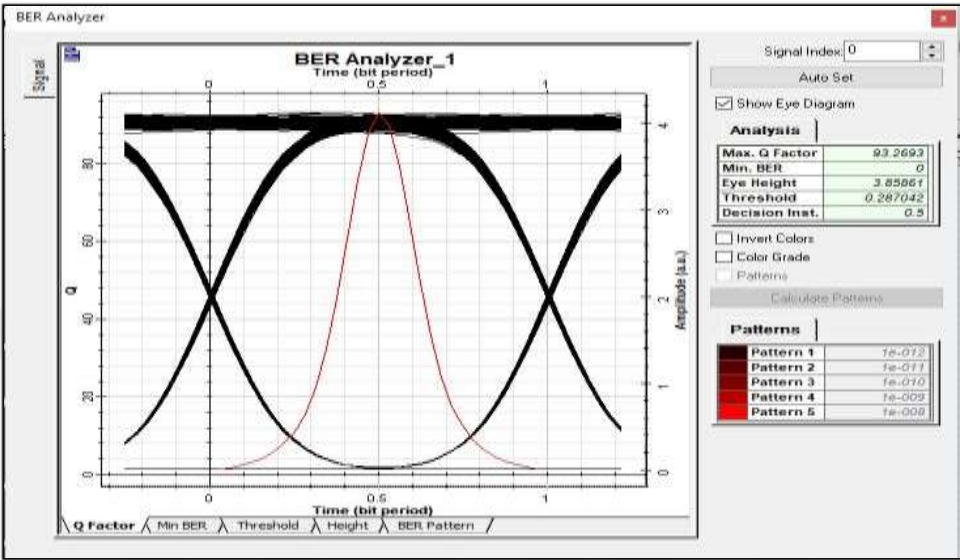


Figure 4.105: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.103, shows the eye diagram which has good open eye shape but has distortion which effect the signal quality, and the red curved line shows good reading for the signal.

B. RZ Pulse Bit Generator

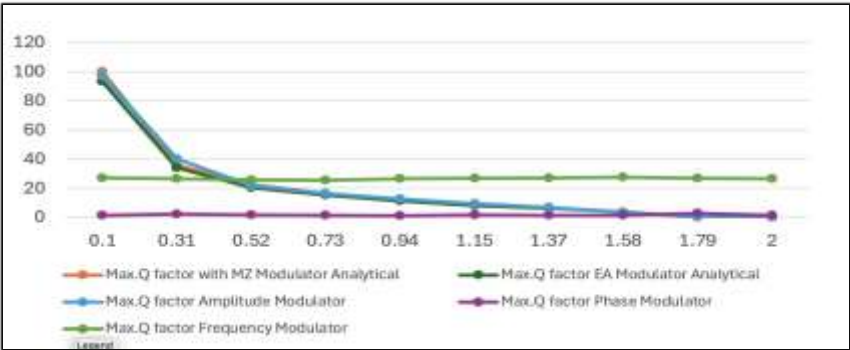


Figure 4.106: The Relationship Between the Quality Factor and Distances with The RZ Pulse Bit Generator.

As shown in Figure 4.104, the relationship between the maximum Q-factor and different types of modulators the horizontal axis represented values from 0.1 to 2 while the vertical axis represented values from 0 to 120. The graph showed that the initial values of the maximum Q-factor were very high then rapidly decreased to stabilize at shallow values after the 0.5 points on the horizontal axis The best reading using AM modulator with 0.1km with Q-Factor 101.417

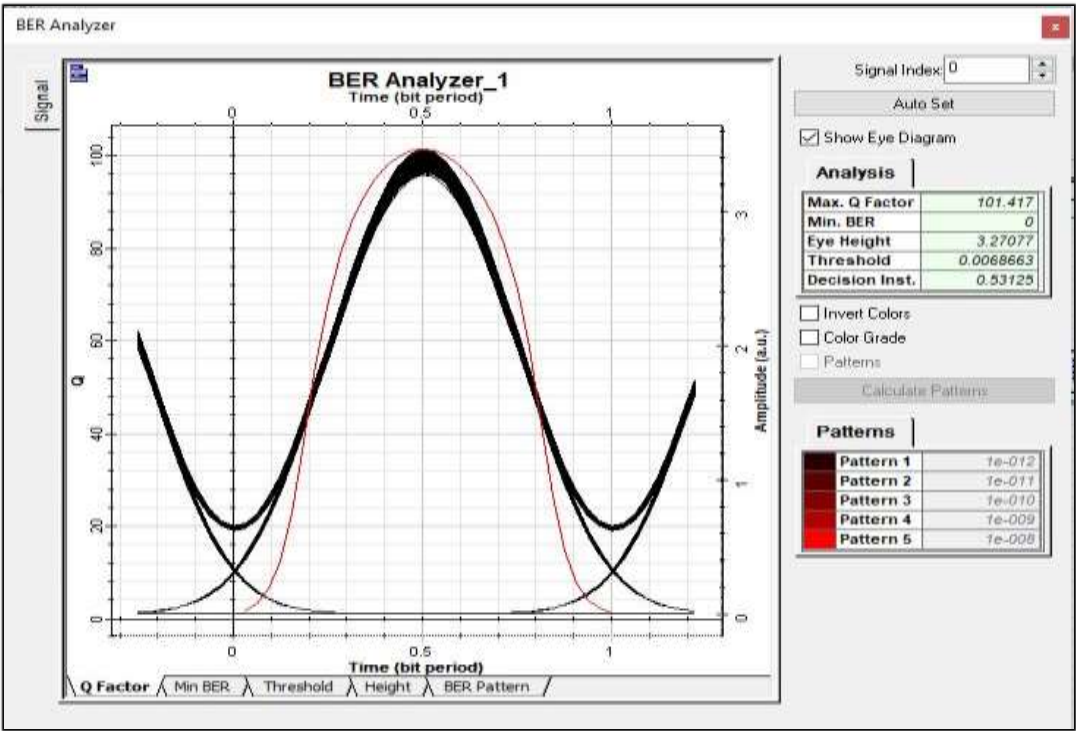


Figure 4.107: The BER and EYE Diagram of AM Modulator.

As shown in Figure 4.105, shows the eye diagram which has bad signal quality, and the red curved line has also bad reading.

4.2.6 Responding to Changes in Frequencies in THz

A. NRZ Pulse Bit Generator

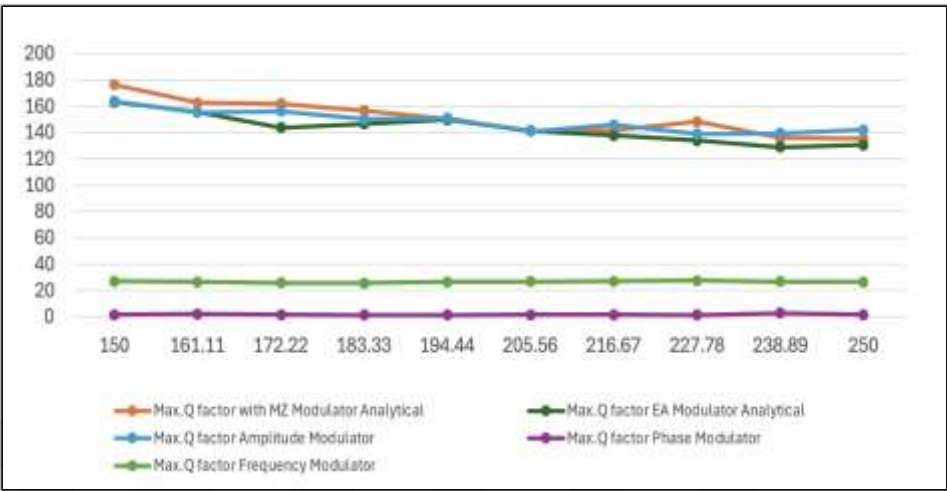


Figure 4.108: The Relationship Between the Quality Factor and Frequencies with The NRZ Pulse Bit Generator.

As shown in Figure 4.106, the graph showed that the initial values of the maximum Q-Factor on y-axis were very high then rapidly decreased as the frequency increased on x-axis. The best reading using MZ modulator Analytical with 150 THz with Q-Factor 176.344

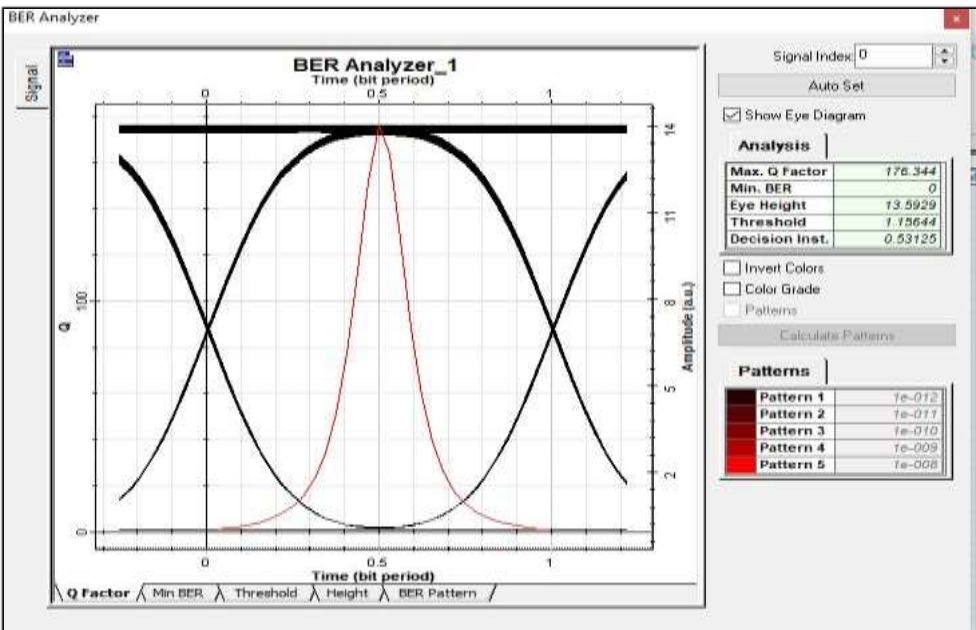


Figure 4.109: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.107, showed open eye diagram compressed vertically with distortion in the signal which indicate not very good signal quality, and the red curved line showed good reading for the signal.

B. RZ Pulse Bit Generator

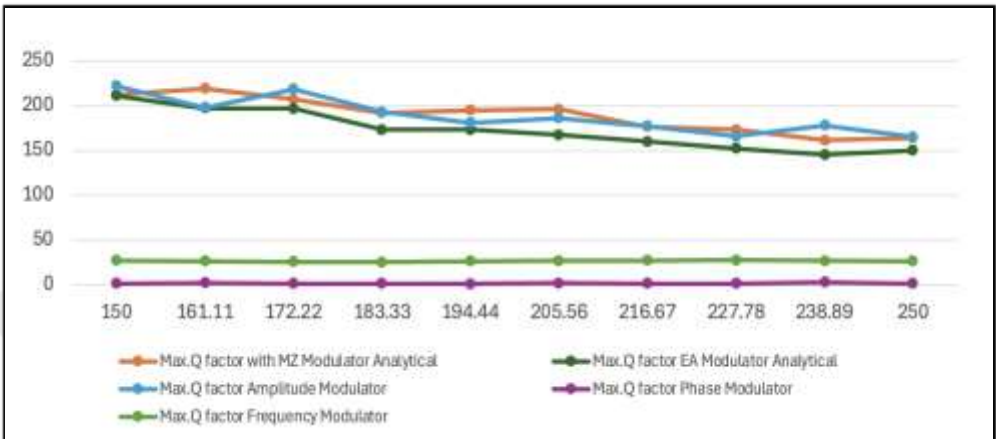


Figure 4.110: The Relationship Between the Quality Factor and Frequencies with The RZ Pulse Bit Generator.

As shown in Figure 4.108, It was observed that the maximum Q-factor on y-axis had extremely high values at low frequency on x-axis and then decreased abruptly. The best reading using AM modulator with 150 THz with Q-Factor 231.195

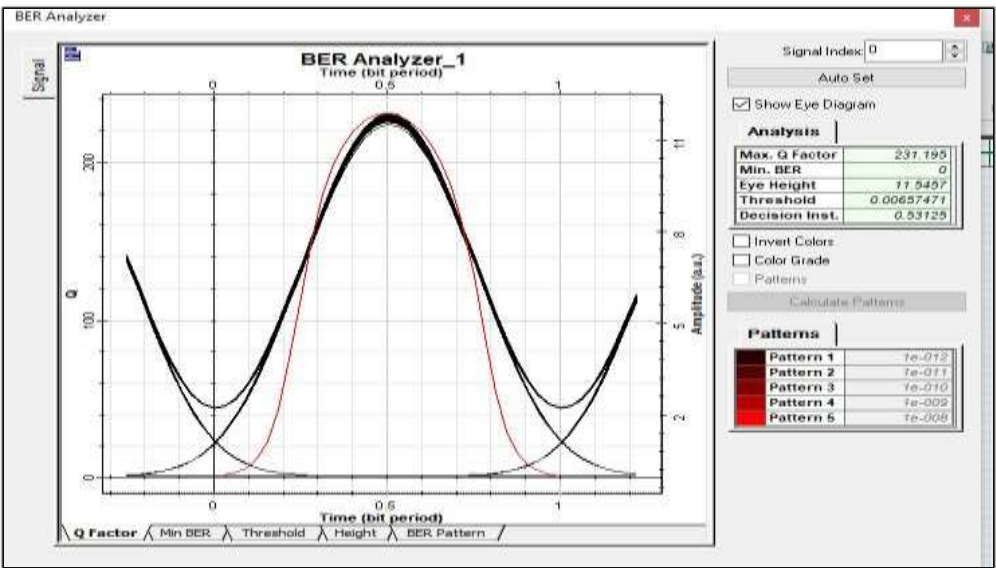


Figure 4.111: The BER and EYE Diagram of MZ Modulator.

As given in Figure 4.109, showed the eye diagram compressed vertically which mean bad signal quality and the red curved line BER indicates bad reading.

4.2.7 Responding to Changes in the Power of the Laser Source

A. NRZ Pulse Bit Generator

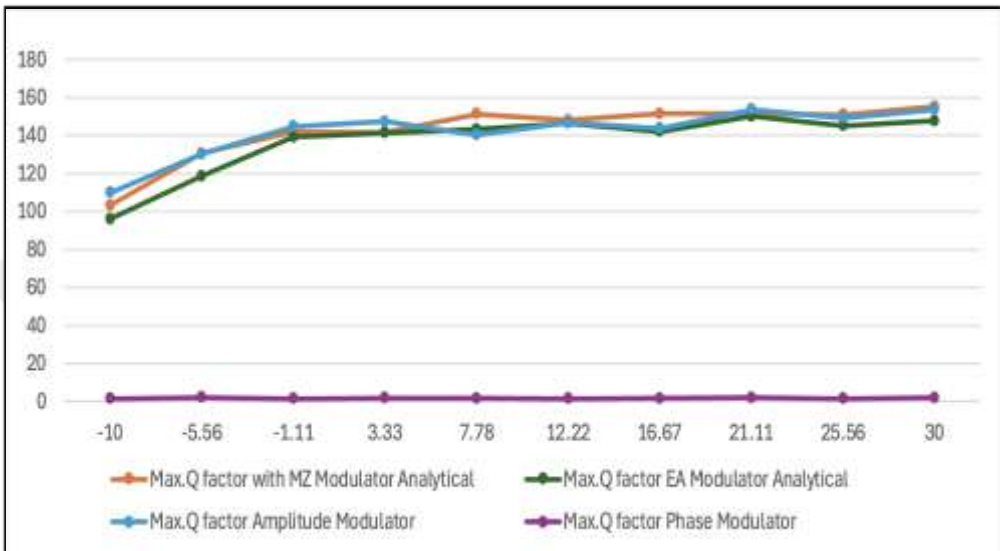


Figure 4.112: The Relationship Between the Quality Factor and Power Laser with The NRZ Pulse Bit Generator.

As shown in Figure 4.110, the dependence of the maximum quality factor on laser power in dBm for different modulator types. Laser power goes linearly with the horizontal axis value, while typically the maximum Q-factor for all modulator types rises with the increasing laser power to a maximum and then levels off or decreases slightly. The MZ modulator shows the highest maximum Q-factor 153.693 with 30dBm.

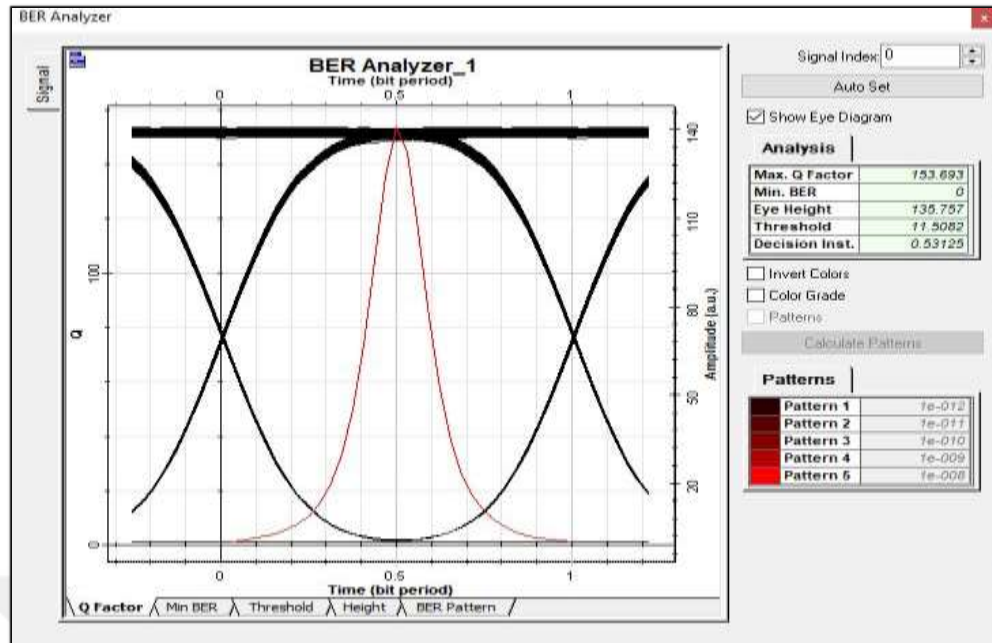


Figure 4.113: The BER and EYE Diagram of MZ Modulator.

As given in Figure 4.111, showed open eye diagram with distortion that mean lower signal quality and the red curve line showed good reading for the signal.

B. RZ Pulse Bit Generator

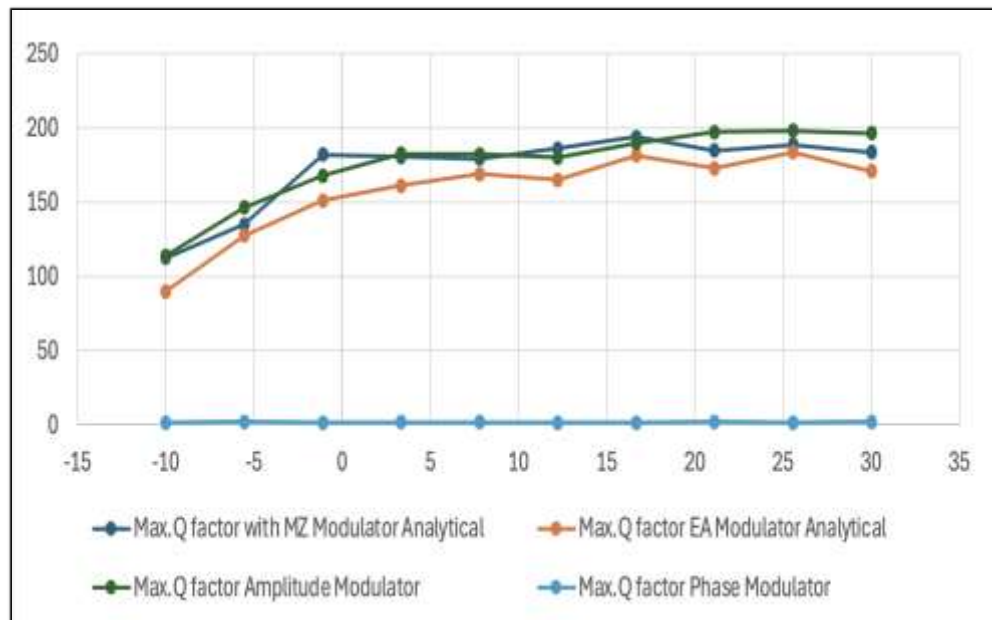


Figure 4.114: The Relationship Between the Quality Factor and Power Laser with The RZ Pulse Bit Generator.

As shown in Figure 4.112, shows Q-factor on y-axis and the laser power on x-axis, the best reading was using the AM Modulator with 25.56 dBm with Q-Factor 183.934.

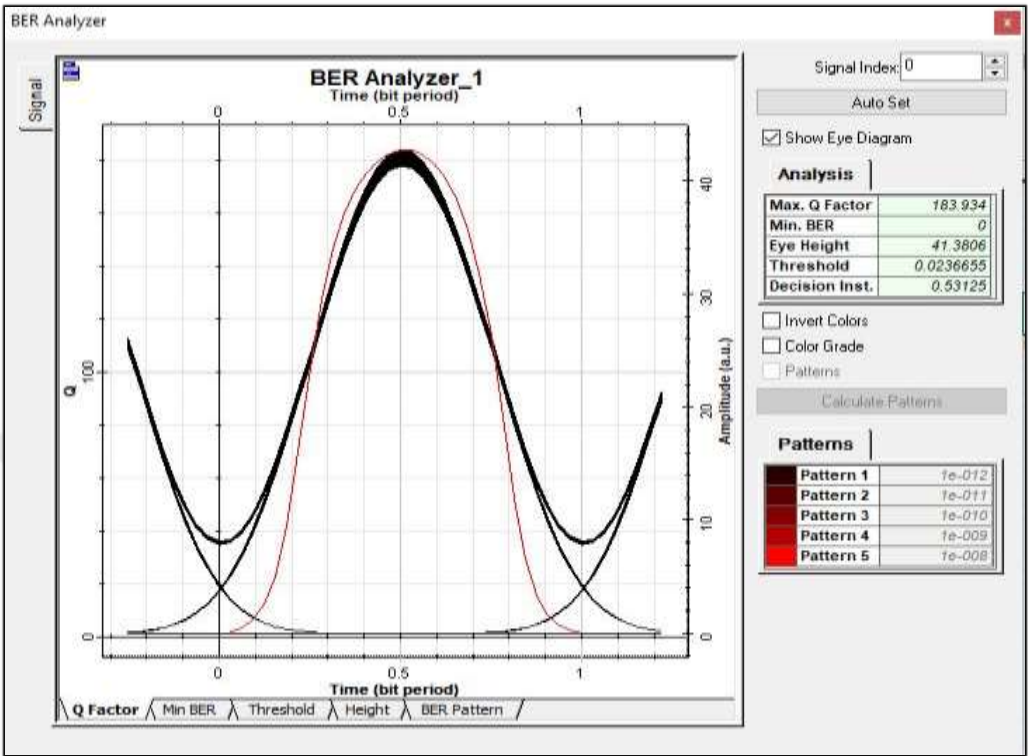


Figure 4.115: The BER and EYE Diagram of AM Modulator.

As shown in Figure 4.113, showed not completely open eye diagram which indicates bad signal quality, and the red curved line showed bad reading for the signal.

4.3 OWC OPTICAL POWER COMMUNICATION CHANNEL

According to Table 3.9, all distances were used. According to Table 3.10, all power of the laser was used, and Figure 3.9 was used.

4.3.1 Sea Water 500 dB/Km Using 490 Nm

4.3.1.1 Responding to changes in distances in Km

A. NRZ Pulse Bit Generator

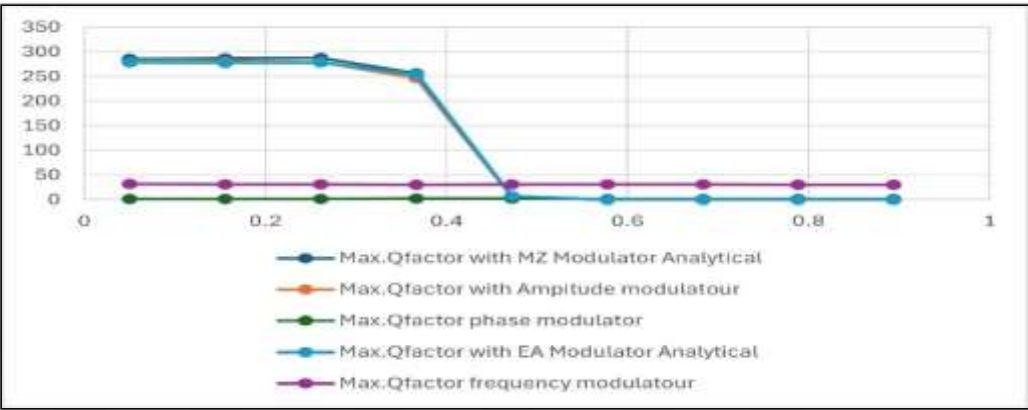


Figure 4.116: The Relationship Between the Quality Factor and Distances with The NRZ Pulse Bit Generator.

As shown in Figure 4.114, it depicts the relationship between the Q-factor on y-axis and the distance on x-axis. From the graph, we see that the Q-Factor changes considerably with respect to the distance of the horizontal axis. Some factors held a relatively constant Q-Factor, while for other factors the Q-Factor dropped significantly to certain values. The best reading using MZ modulator with 0.27km with Q-Factor 284.857

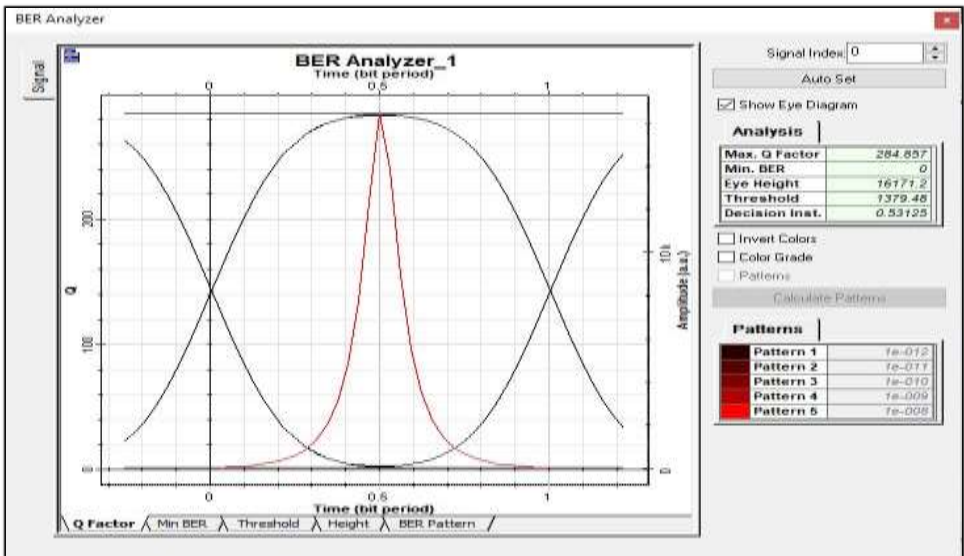


Figure 4.117: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.115, shows the eye diagram which is completely open meaning the signal quality is good and the red curved line indicates that the reading also good for the signal.

B. RZ Pulse Bit Generator

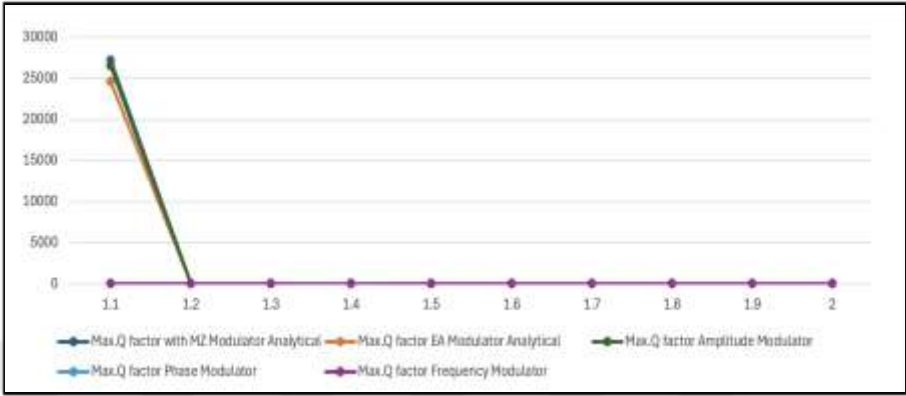


Figure 4.118: The Relationship Between the Quality Factor and Distances with The RZ Pulse Bit Generator.

As shown in Figure 4.116, all curves exhibit a sharp decrease in the maximum Q-Factor on y-axis with increasing distance on x-axis. The Mach-Zehnder and electro-optic modulators was the highest reading. The frequency and phase modulators exhibit the lowest maximum Q-Factor values. The best reading using MZ Modulator Analytical with 0.17 km with Q-Factor 27140.8

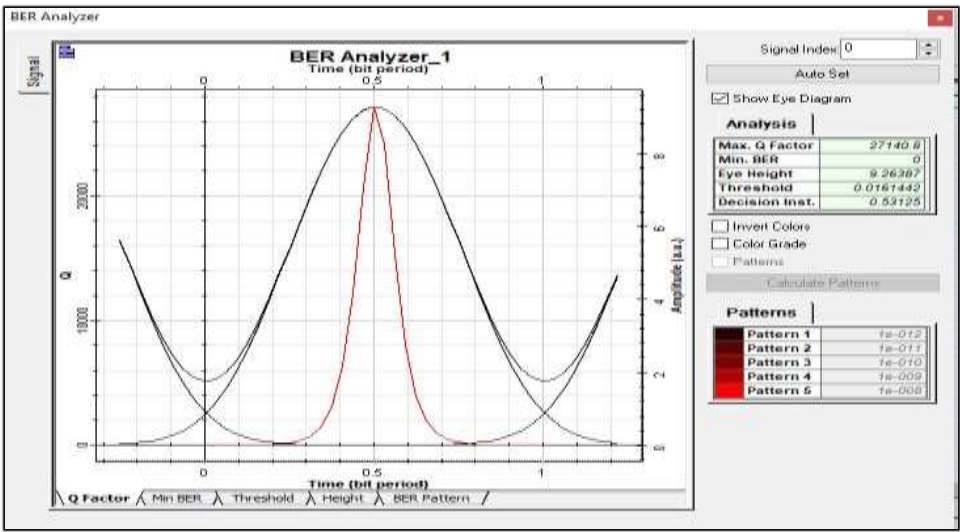


Figure 4.119: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.117, shows the eye diagram which has a distortion and compressed vertically which indicated bad signal quality and the red curved line BER indicate good reading.

4.3.1.2 Responding to changes in the power of the laser source

A. NRZ Pulse Bit Generator

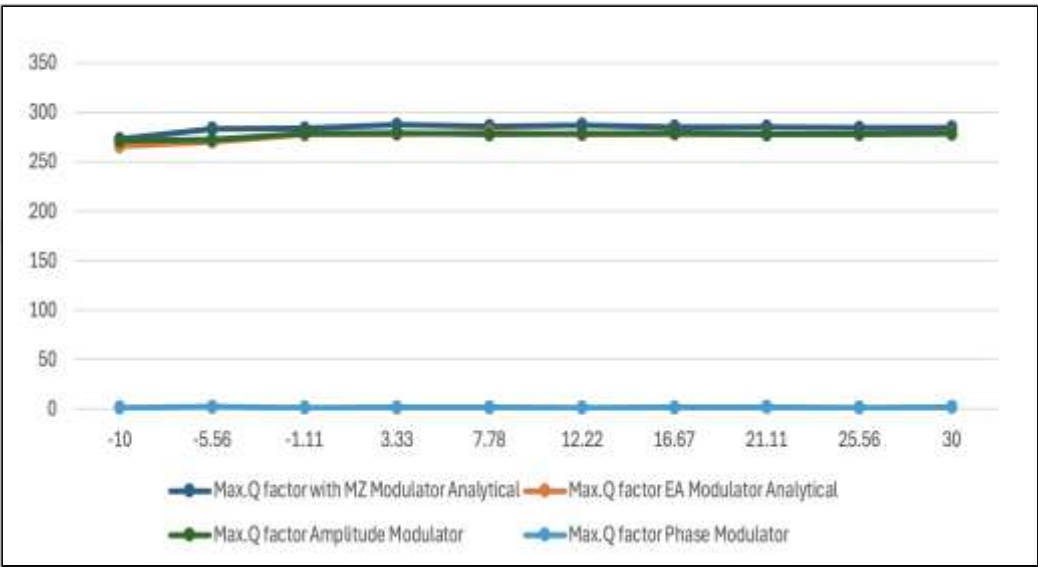


Figure 4.120: The Relationship Between the Quality Factor and Power of The Laser Source with The NRZ Pulse Bit Generator.

As shown in Figure 4.118, results indicate that changes in laser power on x-axis do not significantly affect the maximum Q-Factor on y-axis for the modulator types tested. However, different modulator types exhibit varying maximum Q-Factor values, which remain relatively stable with changes in laser power. The beat reading was with MZ modulator of 287.612

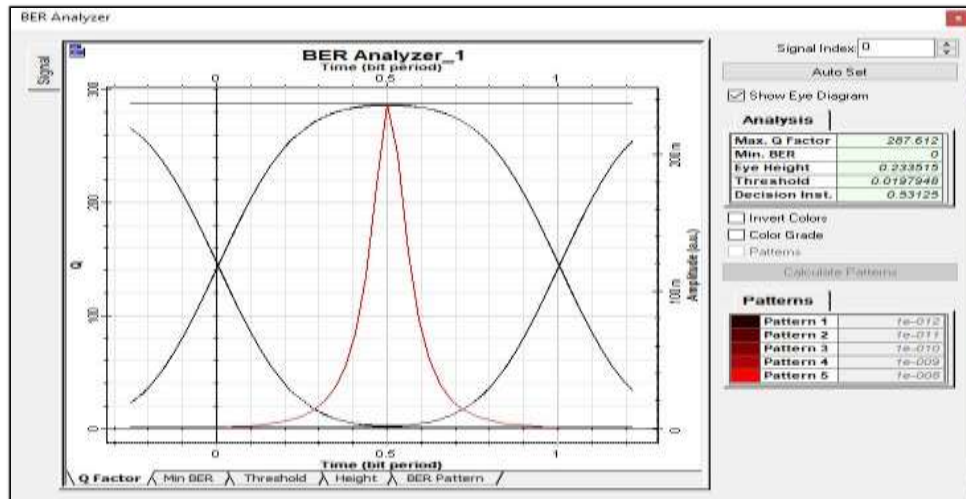


Figure 4.121: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4,119, shows the eye diagram and the red curved line BER, the eye diagram indicates open eye, but it seems somewhat compressed vertically which mean the signal quality is not as good as it wanted, and the red curved line give good reading.

B. RZ Pulse Bit Generator

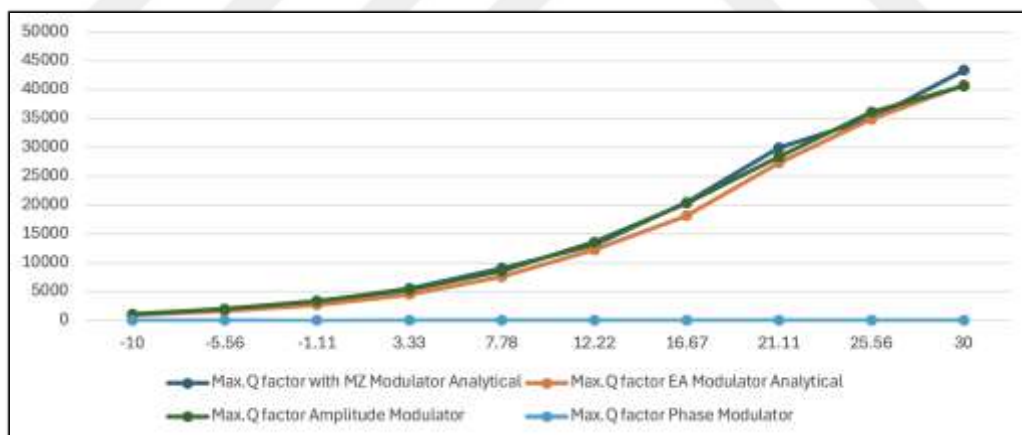


Figure 4.122: The Relationship Between the Quality Factor and Power of The Laser Source with The RZ Pulse Bit Generator.

As shown in Figure 4.120, these results indicated that increasing laser power on x-axis generally improved the quality of the modulators on y-axis, except for the phase modulator, which seemed insensitive to changes in laser power. The best reading using MZ modulator Analytical with 30dBm with Q-Factor 43365.6.

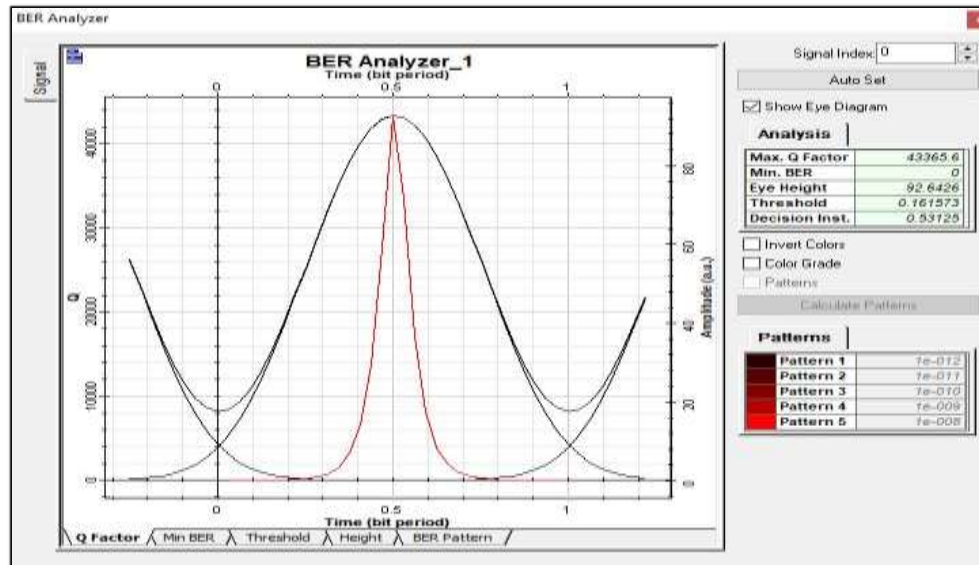


Figure 4.123: The BER and EYE Diagram of MZ Modulator.

As shown on Figure 4.121, shows that the eye diagram is compressed vertically and not open which indicates bad signal quality and the red curved line BER indicates good reading for the signal.

4.3.2 Still Water 87 dB/Km Using 532 Nm

4.3.2.1 Responding to changes in distances in M

A. NRZ Pulse Bit Generator

In this section, still water 87 dB/Km using 532 nm was studied.

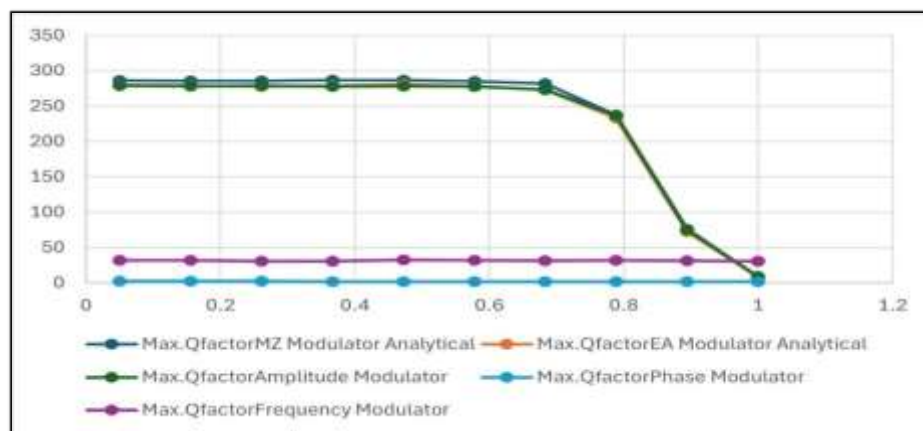


Figure 4.124: The Relationship Between the Quality Factor and Distances in Km with The NRZ Pulse Bit Generator.

As shown in Figure 4.122, MZ and AM shows constant maximum Q-Factor on vertical axis with increasing distance on horizontal axis. The best reading is using MZ Modulator Analytical with 0.47km with Q-Factor 285.608.

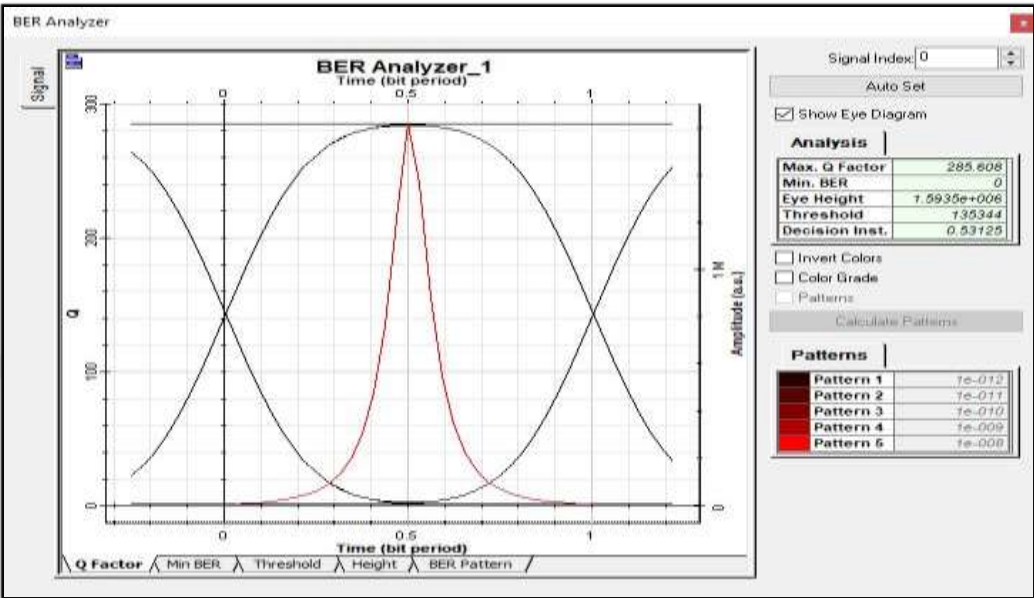


Figure 4.125: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.123, indicates that the eye diagram is open, and the signal quality is good and the red curved line BER indicates good reading for the signal.

B. RZ Pulse Bit Generator

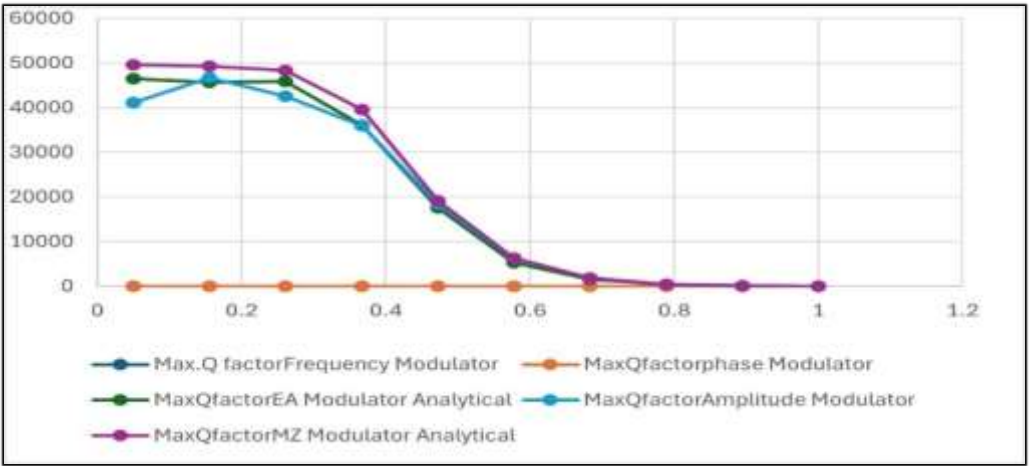


Figure 4.126: The Relationship Between the Quality Factor and Distances in Km with The RZ Pulse Bit Generator.

As given in Figure 4.124, shows the results suggested that increasing the distance on horizontal axis will decrease the Q-factor on vertical axis. However, the best reading using MZ Modulator Analytical with 0.16 km with Q-Factor 49610.3.

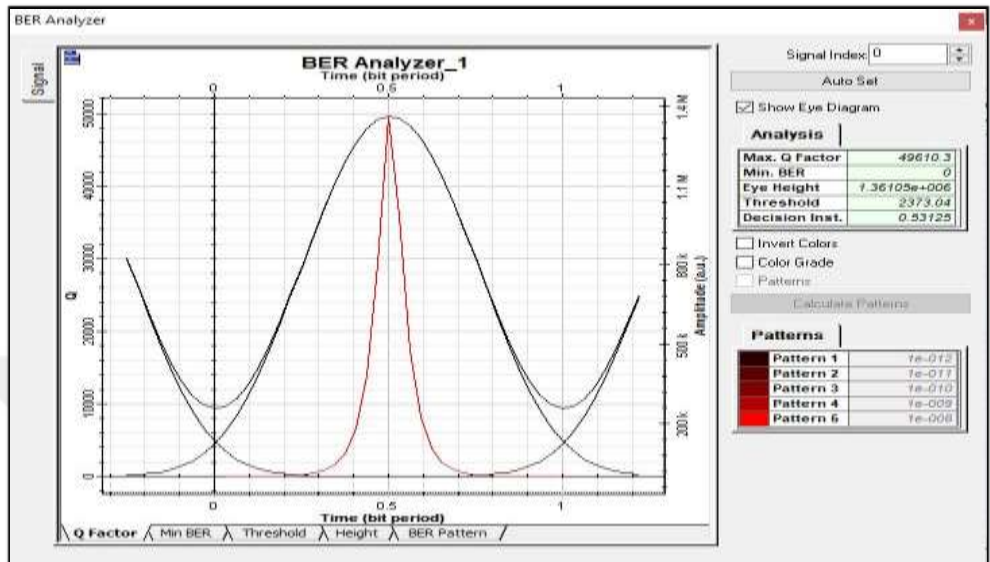


Figure 4.127: The BER and EYE Diagram of MZ Modulator.

As given in Figure 4.125, indicates bad eye diagram and signal quality and the red curved line BER indicates good reading.

4.3.2.2 Responding to changes in the power of the laser source in dBm

A. NRZ Pulse Bit Generator

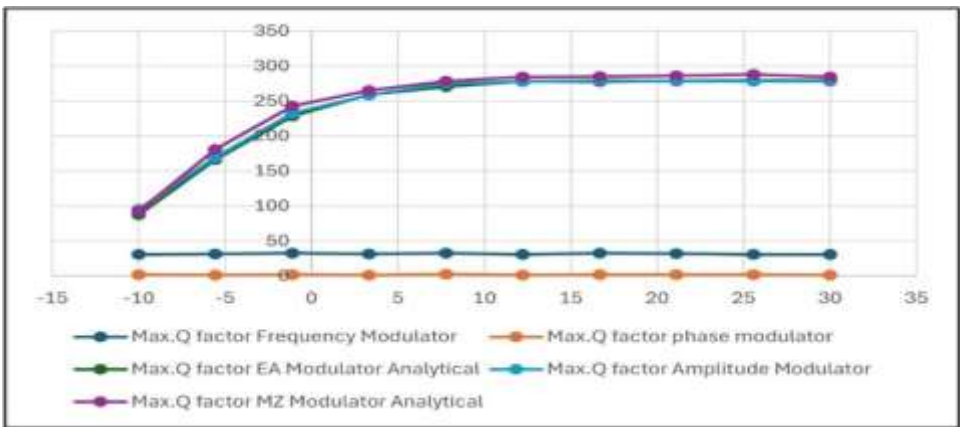


Figure 4.128: The Relationship Between the Quality Factor and Power Laser with The NRZ Pulse Bit Generator.

As shown in 4.126, the best reading using MZ Modulator Analytical with 25.56 dBm with Q-Factor 286.554.

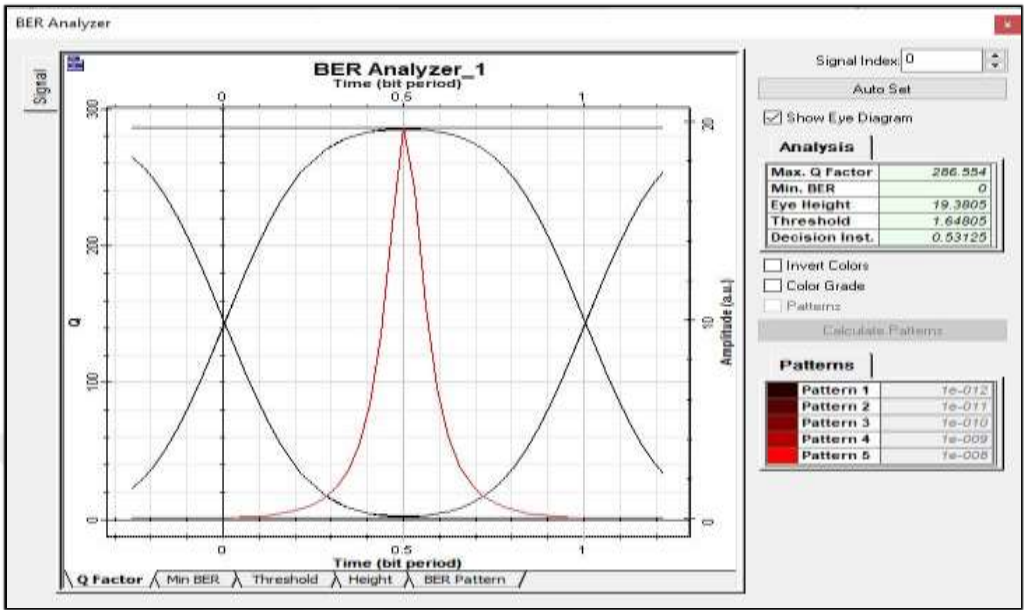


Figure 4.129: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.127, shows good eye diagram and signal quality and the red curved line BER shows good reading.

B. RZ Pulse Bit Generator

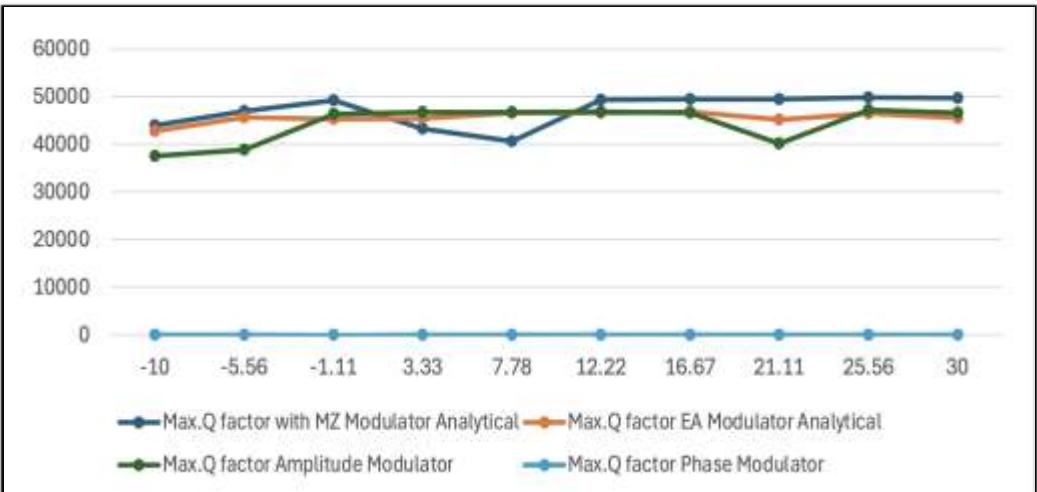


Figure 4.130: The Relationship Between the Quality Factor and Power Laser with The RZ Pulse Bit Generator.

As shown in Figure 4.128, The rate of increase in the maximum Q-Factor on y-axis varies between different modulator types as it increases for MZ and AM as the power increases on x-axis. The best reading using MZ Modulator Analytical with 30 dBm with Q-Factor 49633.9.

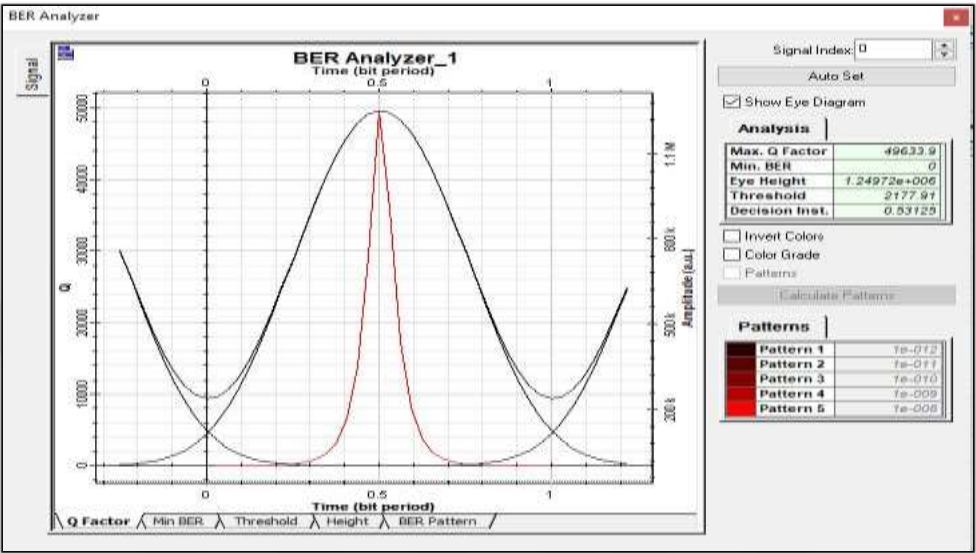


Figure 4.131: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.129, indicates bad eye diagram and signal quality and the red curved line BER indicates good reading for the signal.

4.3.2.3 River water 200 dB/km using 490nm responding to changes in distances in Km

A. NRZ Pulse Bit Generator

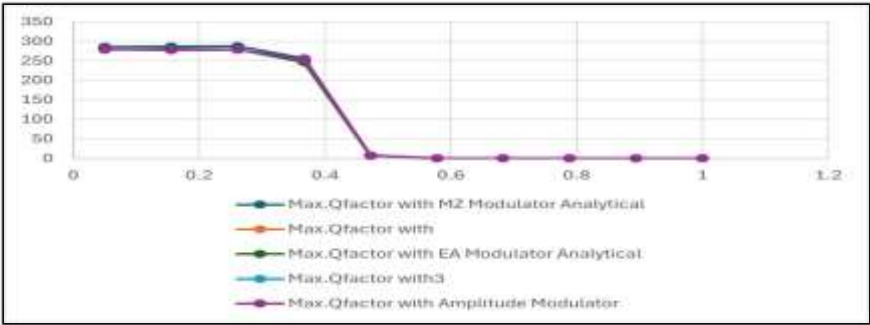


Figure 4.132: The Relationship Between the Quality Factor and Distances in Km with The NRZ Pulse Bit Generator.

As shown in Figure 4.130, the relationship between Q-Factor on y-axis and the distances on x-axis. The best reading using MZ Modulator Analytical with 0.26 km with Q-Factor 285.692.

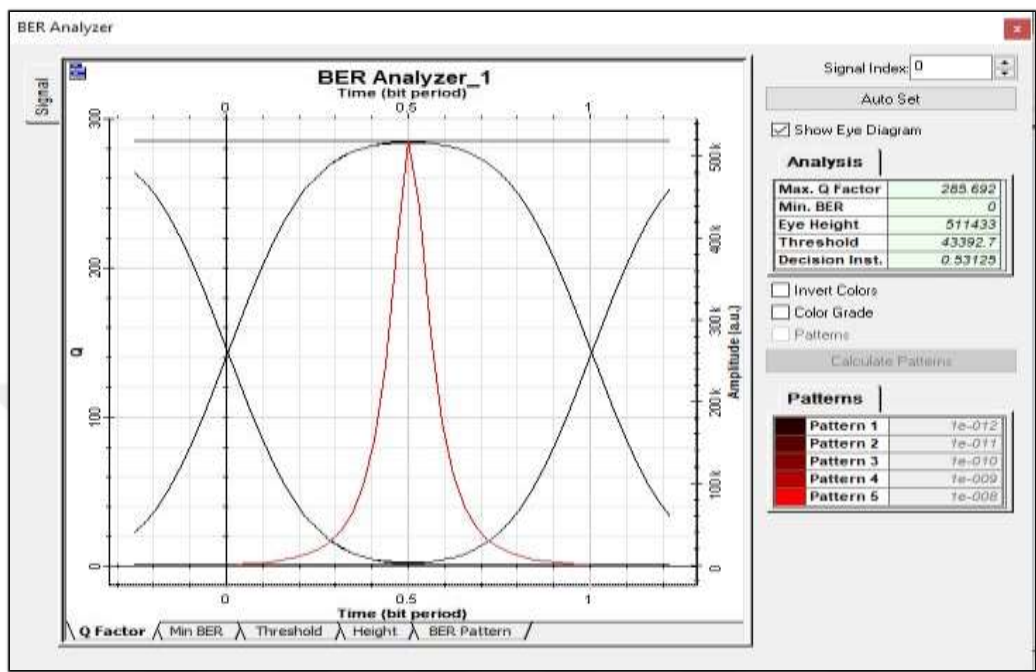


Figure 4.133: The BER and EYE Diagram of MZ Modulator.

As given in Figure 4.131, shows good eye diagram and signal quality and the red curved line BER shows good reading for the signal.

B. RZ Pulse Bit Generator

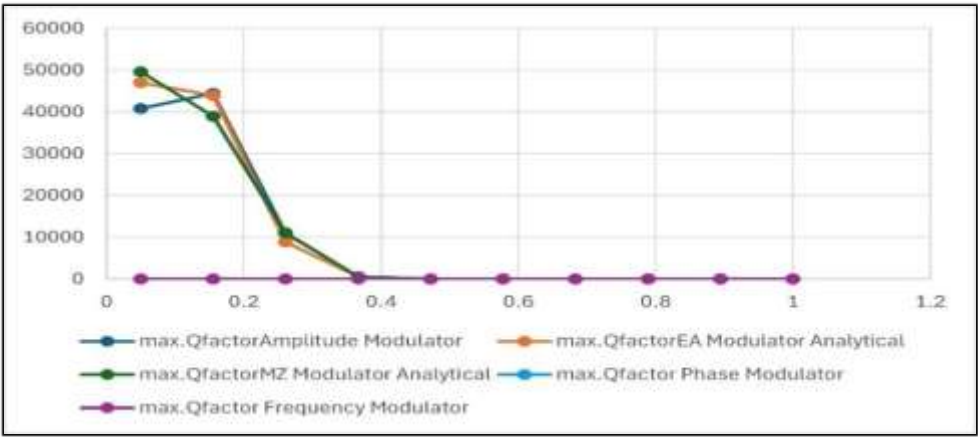


Figure 4.134: The Relationship Between the Quality Factor and Distances in Km with The RZ Pulse Bit Generator.

As shown in Figure 4.132, the best reading using MZ Modulator Analytical with 0.05 km with Q-Factor 49233.5.

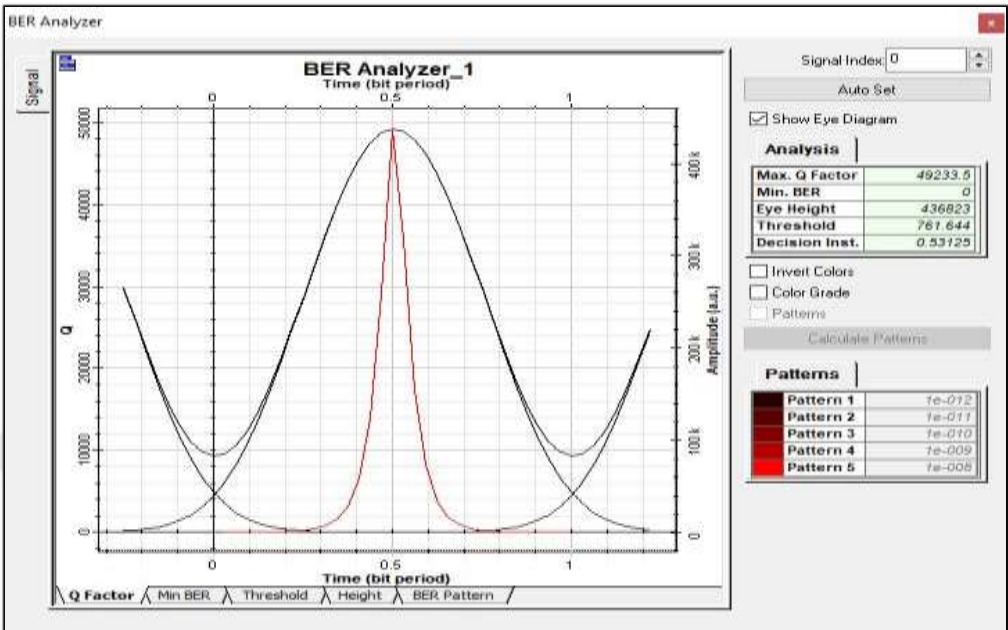


Figure 4.135: The BER and EYE Diagram of MZ Modulator.

As given in Figure 4.133, shows bad eye diagram and signal quality while the red curved line indicated good reading for the signal.

4.3.2.4 Responding to changes in the power of the laser source

A. NRZ Pulse Bit Generator

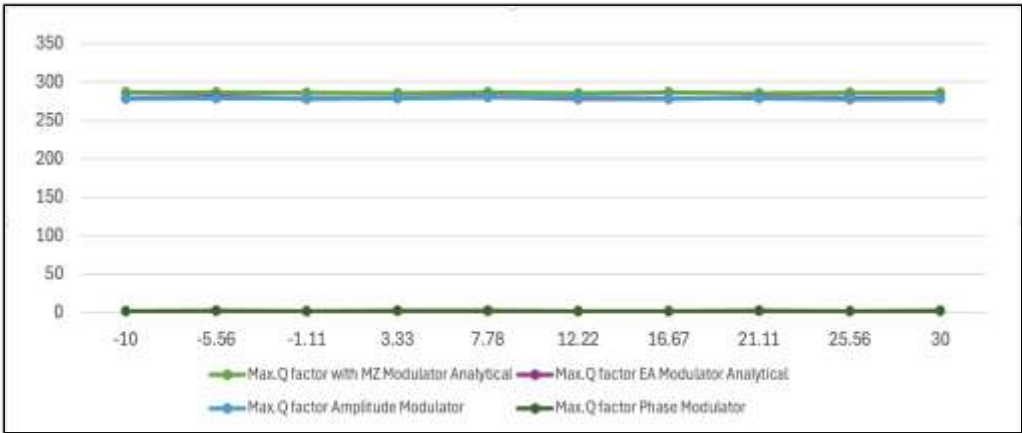


Figure 4.136: The Relationship Between the Quality Factor and Power Laser with The NRZ Pulse Bit Generator.

As shown in Figure 4.134, the relationship between laser power x-axis and Q-Factor y-axis. Results indicate that changes in laser power do not significantly affect the maximum Q-Factor for the modulator types tested. However, different modulator types exhibit varying maximum Q-Factor values, which remain relatively stable with changes in laser power. The best result was with MZ modulator with a Q-factor of 286.764. at 16.67

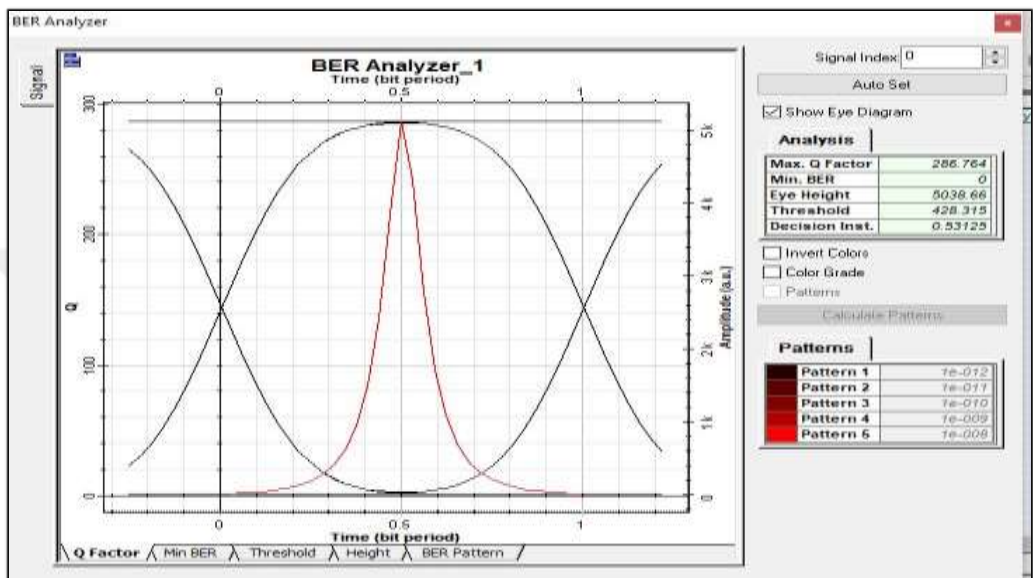


Figure 4.137: The BER and EYE Diagram of MZ Modulator.

As given in Figure 4.135, showed open eye diagram with good signal quality, and the red curved line showed good reading for the signal.

B. RZ Pulse Bit Generator

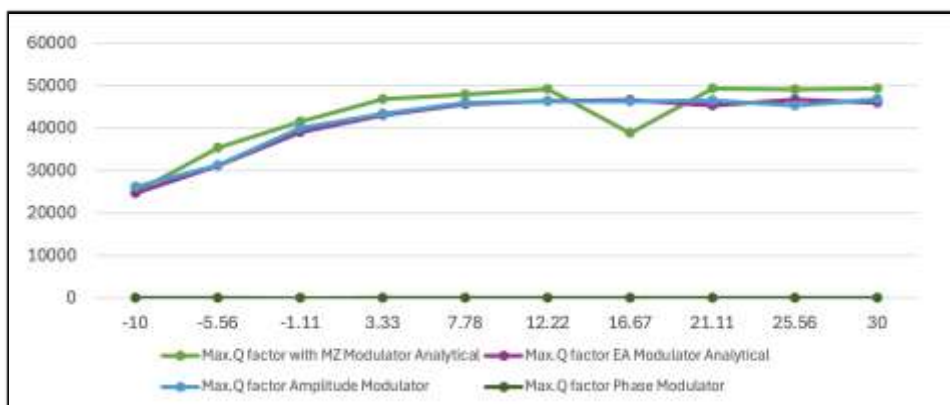


Figure 4.138: The Relationship Between the Quality Factor and Power Laser with The NRZ Pulse Bit Generator.

As shown in Figure 4.136, the relationship between laser power x-axis and Q-Factor y-axis. All modulators except PM modulator have slightly increased with increasing laser power. The best reading using MZ Modulator with 30dBm with Q-Factor 49373.

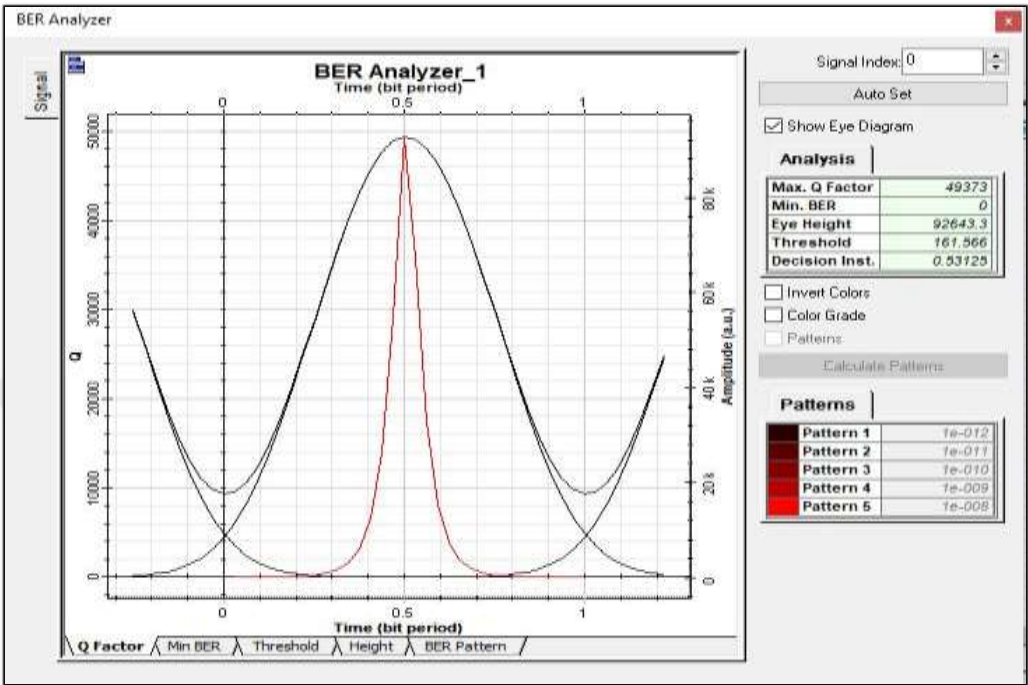


Figure 4.139: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.137, showed bad eye diagram and signal quality, the red curved line BER showed good reading for the signal.

4.4 THE NETWORK FROM THE SHIP TO THE SUBMARINE

According to Figure (3,13) (a) image, Figure (3.8) and Figure (3.9) using (FSO) and (OWC) as wireless optical fiber the distance from the satellite to the ship is 100 km. FSO was used with pure attenuation as shown in the design. The FSO network outlet has become the network input from the ship to the submarine underwater. The sea attenuation 87 dB/km has been adopted and 532 nm as frequency.

4.4.1 Responding to Changes in Distances in Meter

According To Properties Table 3.9

A. NRZ Pulse Bit Generator

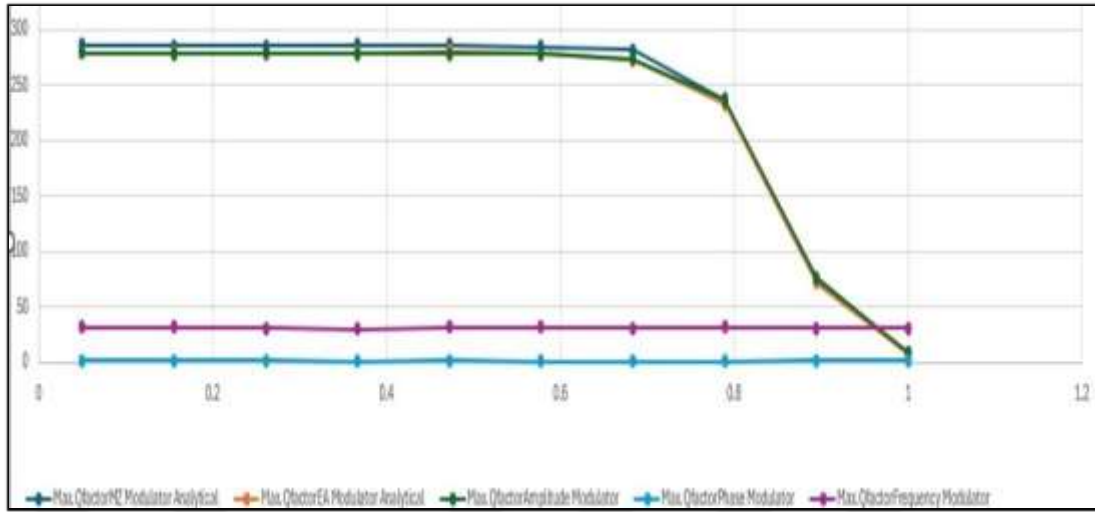


Figure 4.140: The Relationship Between the Quality Factor and Distances with The NRZ Pulse Bit Generator.

As shown in Figure 4.138, the relation between the distance x-axis and the Q-factor y-axis. The best reading was using an MZ Modulator with 0.5km with Q-Factor 286.097.

B. RZ Pulse Bit Generator

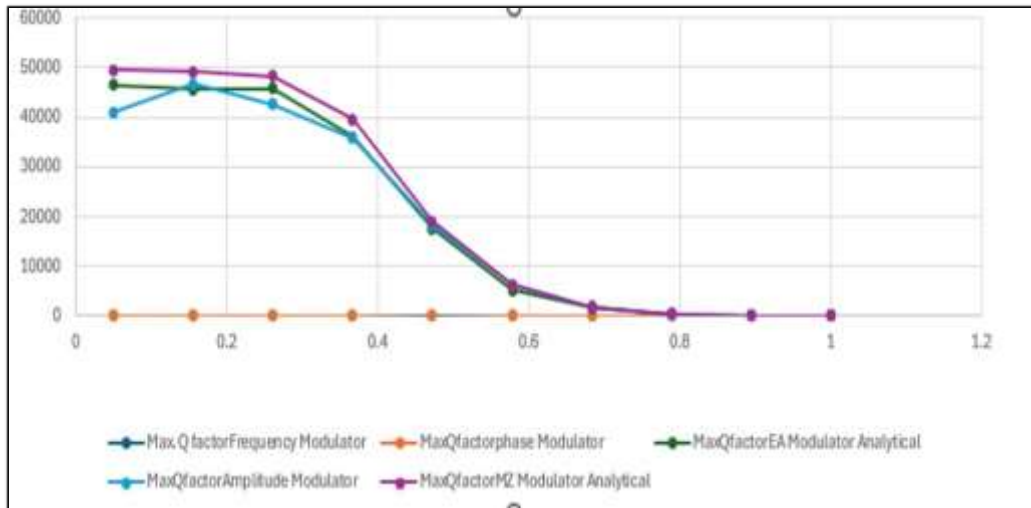


Figure 4.141: The Relationship Between the Quality Factor and Distances with The RZ Pulse Bit Generator.

As shown in Figure 4.139, The relationship between the Q-factor y-axis and the distance x-axis. The best reading was using an MZ Modulator with 0.5 km with Q-Factor 49567.2.

4.4.2 Responding to Changes in the Power of the Laser Source

A. NRZ Pulse Bit Generator

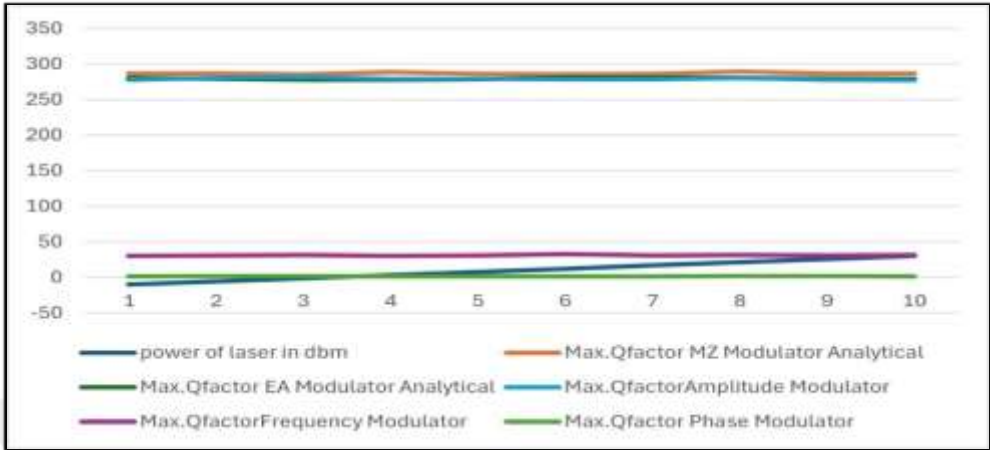


Figure 4.142: The Relationship Between the Quality Factor and Power of The Laser with The NRZ Pulse Bit Generator.

As shown in Figure 4.140, The relationship between the Q-factor y-axis and laser power x-axis. These results suggest that increasing the input power generally improves the quality of the modulators slightly up to a certain point, after which the quality stabilizes. However, different modulator types exhibit varying capabilities in achieving very high maximum Q-Factor values and the input power threshold at which this stabilization occurs.

B. RZ Pulse Bit Generator

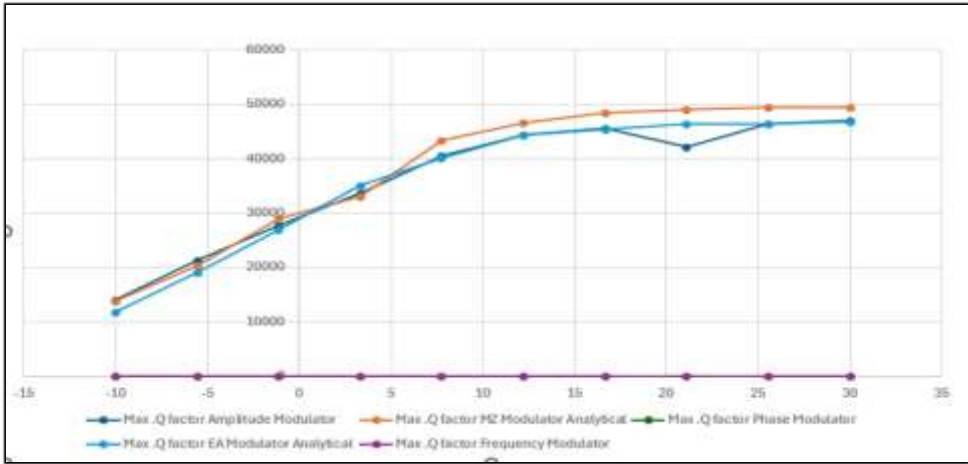


Figure 4.143: The Relationship Between the Quality Factor and Power of The Laser with The RZ Pulse Bit Generator.

As shown in Figure 4.141, the relationship between the laser source power on horizontal axis and the Q-factor on vertical axis. The best reading was using an MZ Modulator with 30 dBm with a Q-Factor of 49464.4.

4.5 NETWORK USING THE LINE OF SIGHT

According to Figure 3.13, Figure 3.14 (b) and Figure 3.16.

4.5.1 Responding To Changes in Distances In M

A. NRZ Pulse Bit Generator

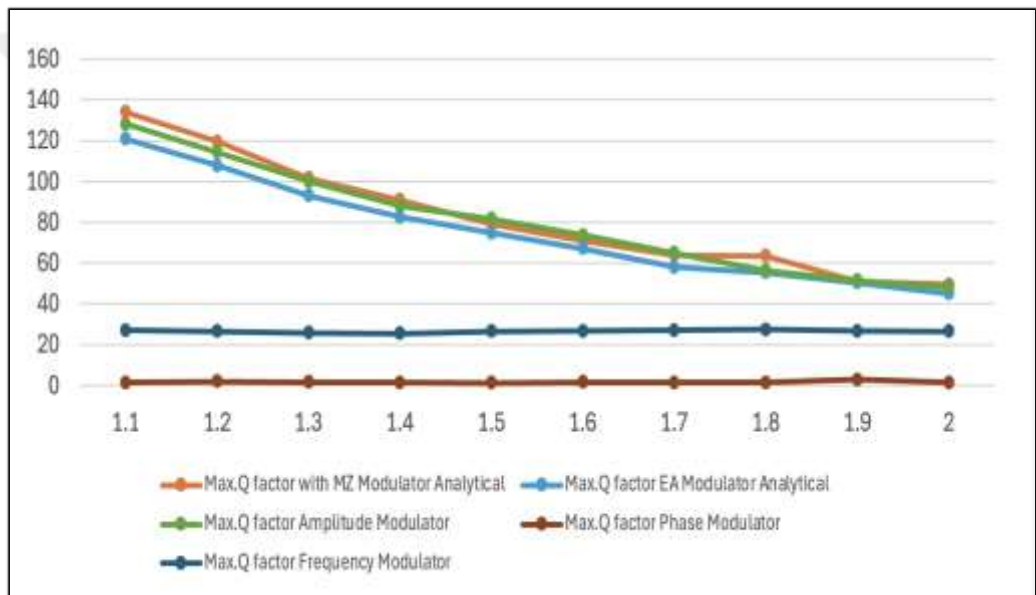


Figure 4.144: The Relationship Between the Quality Factor and Distances with The NRZ Pulse Bit Generator.

As shown in Figure 4.142, the relationship between Q-factor on vertical axis and the distance on horizontal axis. The modulators represented by colored lines. The best reading using an MZ Modulator with 1 m with Q-Factor 137.705.

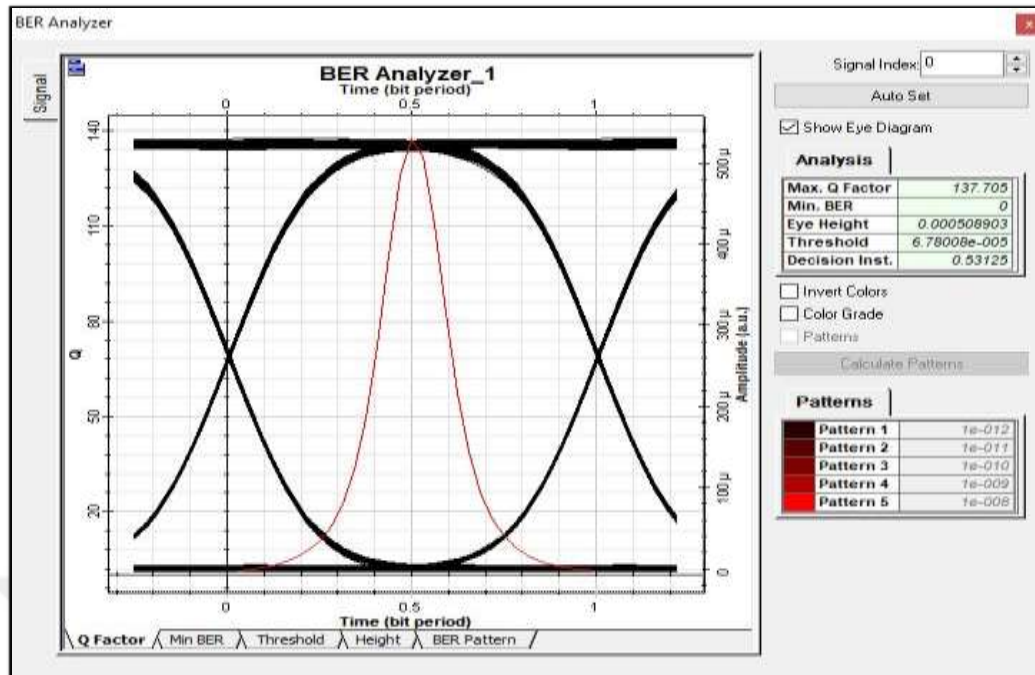


Figure 4.145: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.143, showed open eye but there is a distortion meaning somewhat bad signal quality, and the red curved line BER showed good reading for the signal.

B. RZ Pulse Bit Generator

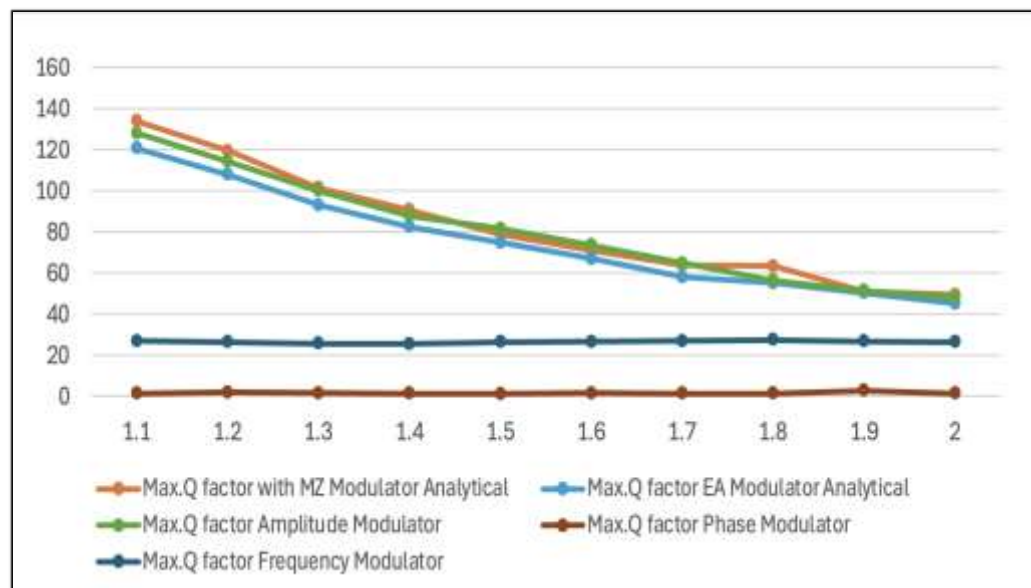


Figure 4.146: The Relationship Between the Quality Factor and Distances with The RZ Pulse Bit Generator.

As shown in Figure 4.144, the relationship between the distance on horizontal axis and Q-factor on vertical axis. Each curve represents a different modulator. The best reading using an MZ Modulator with 1 m with Q-Factor 131.485.

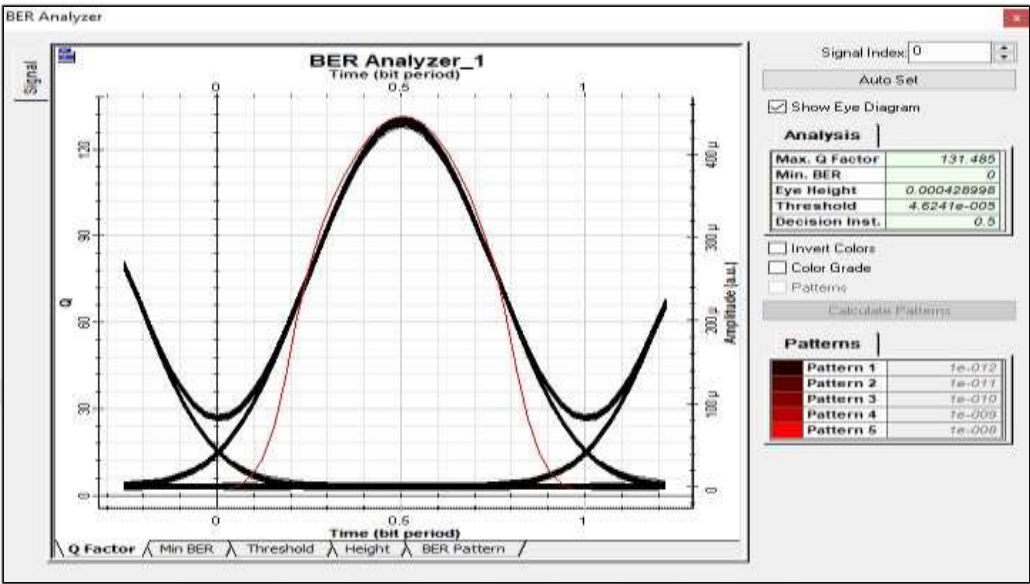


Figure 4.147: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.145, indicates bad eye diagram with distortion and signal quality, the red curved line BER showed also bad reading for the signal.

4.5.2 Responding to Changes in the Power of the Laser Source from -10 to 30 dBm

A. NRZ Pulse Bit Generator

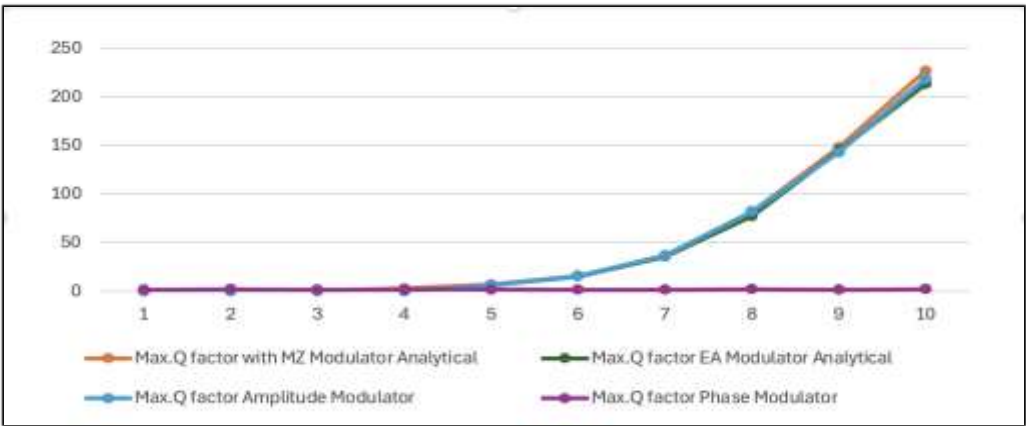


Figure 4.148: The Relationship Between the Quality Factor and Power Laser with The NRZ Pulse Bit Generator.

As shown in 4.146, the relationship between the Q-factor on y-axis and the distance on x-axis. Each curve represents a different modulator. The best reading using an MZ Modulator with 30dBm, with Q-Factor 226.493.

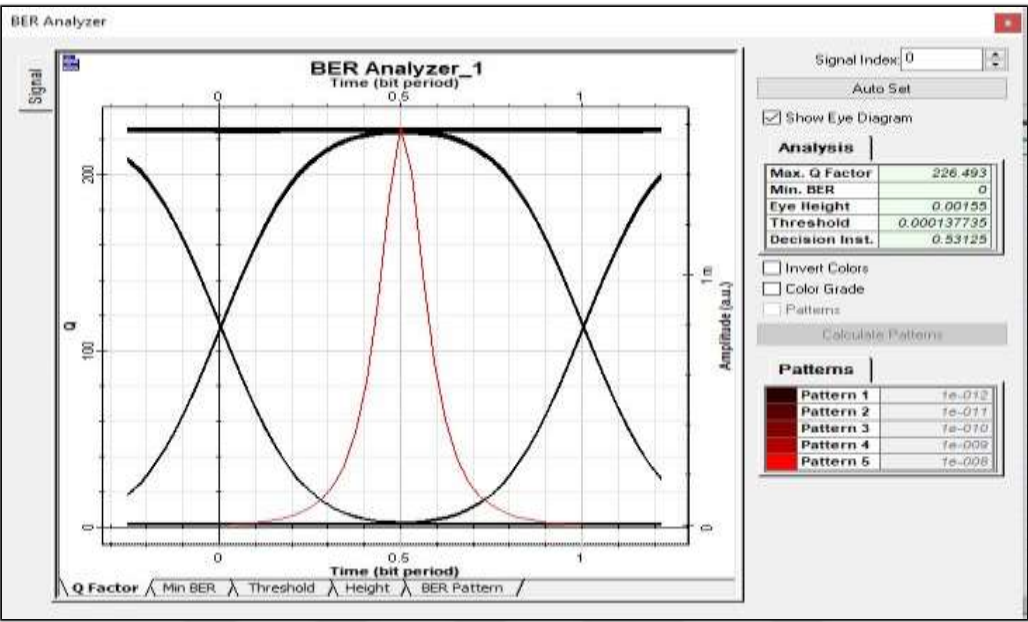


Figure 4.149: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.147, showed open eye diagram with some distortion, and the red curved line BER indicates good reading for the signal.

B. RZ Pulse Bit Generator

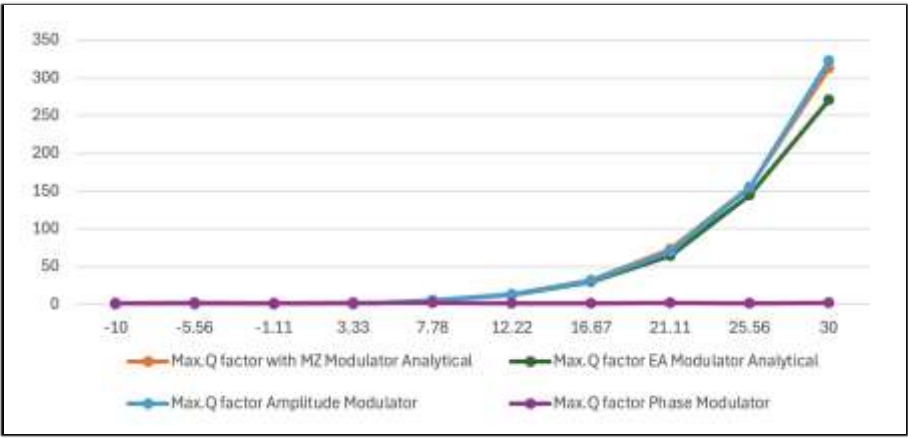


Figure 4.150: The Relationship Between the Quality Factor and Power Laser with The RZ Pulse Bit Generator.

As shown in 4.148, the relationship between laser power on x-axis and Q-Factor on y-axis. Each curve represented a different modulator. The best reading using an MZ Modulator with 30 dBm with Q-Factor 322.706.

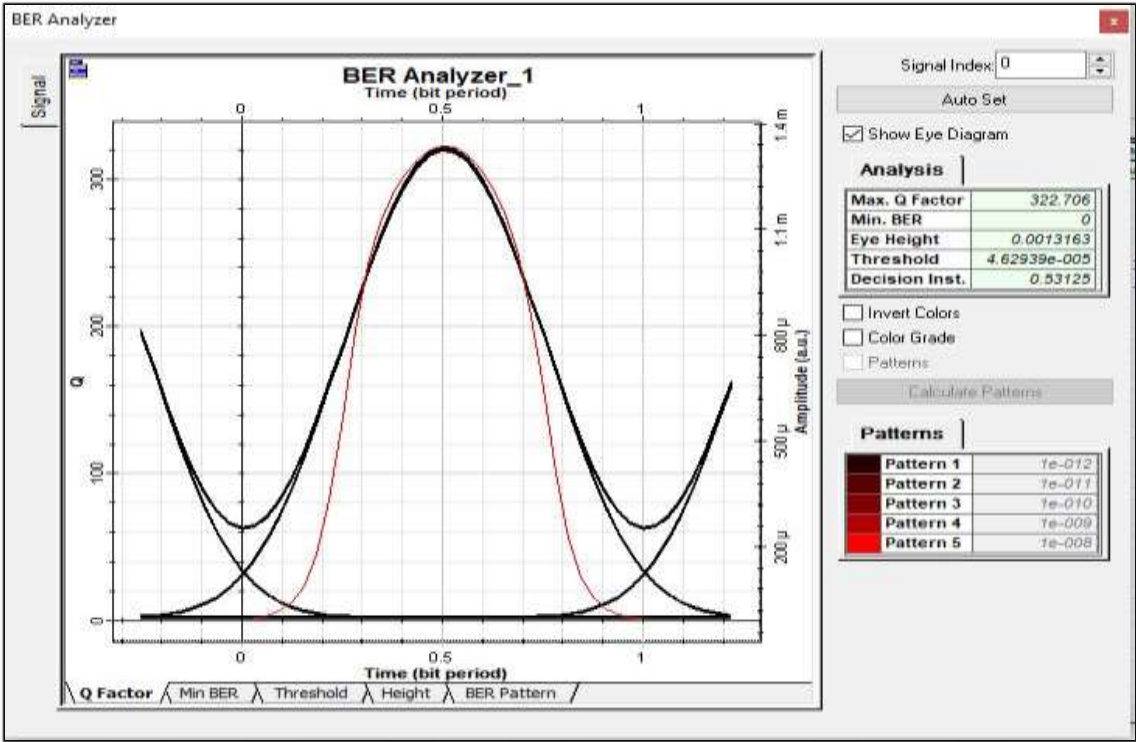


Figure 4.151: The BER and EYE Diagram of MZ Modulator.

As shown in Figure 4.149, indicates bad eye diagram and some distortion, and the red curved line BER indicates bad reading also for the signal.

4.6 THE INTERIOR NETWORK ON THE SHIP

According to Figure 3.13, Figure 3.14 and Figure 3.13 (b).

4.6.1 Responding to Changes in Distances in Meter

A. NRZ Pulse Bit Generator

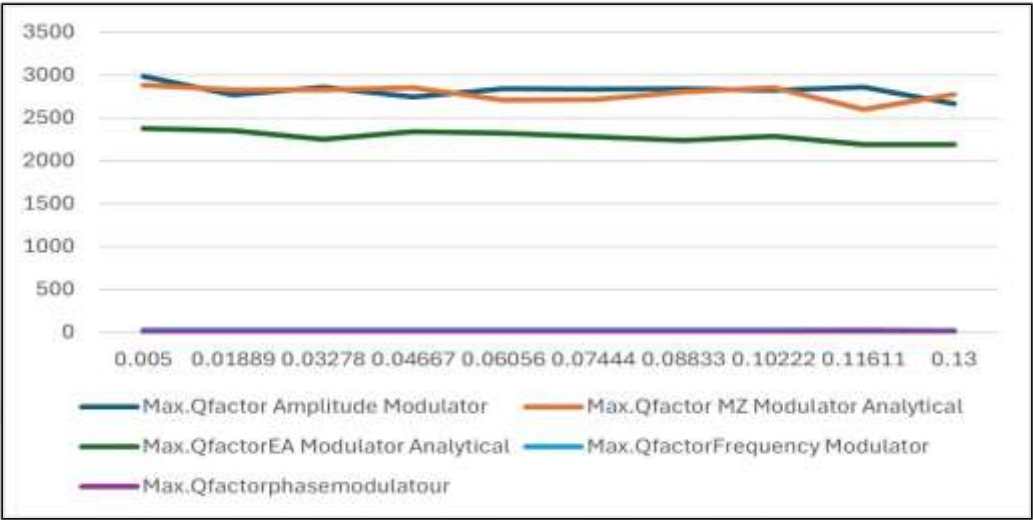


Figure 4.152: The Relationship Between the Quality Factor and Distances with The NRZ Pulse Bit Generator.

As shown in Figure 4.150, the relationship between Q-factor vertical axis, and the distance horizontal axis. Each curve represents a different modulator. The best reading is using an Amplitude Modulator with 0.005km with Q-Factor 2979.72.

B. RZ Pulse Bit Generator

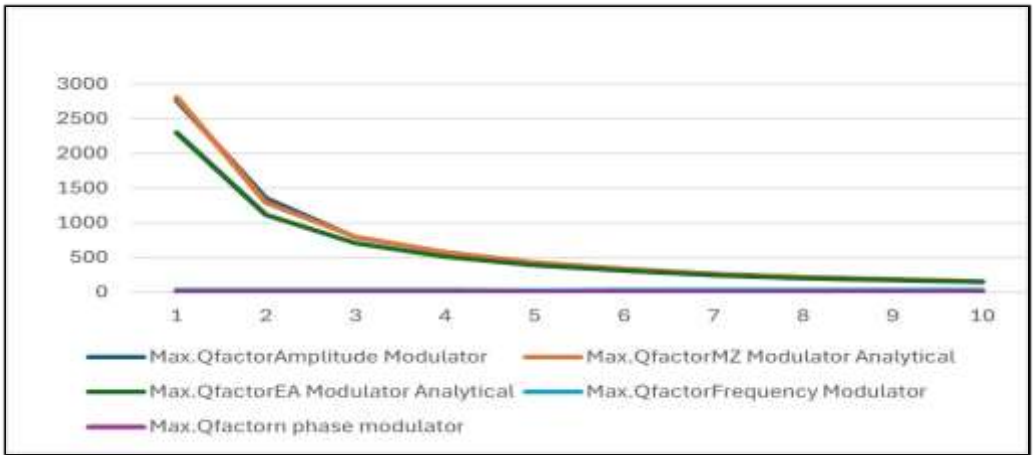


Figure 4.153: The Relationship Between the Quality Factor and Distances with The RZ Pulse Bit Generator.

As shown in Figure 4.151, the relationship between the Q-factor and the distances. The best reading using an Amplitude Modulator with 1 m with Q-Factor 2763.78.

4.6.2 Responding to Changes in Frequencies in THz

According to reference frequency in the Table 3.4.

A. NRZ Pulse Bit Generator

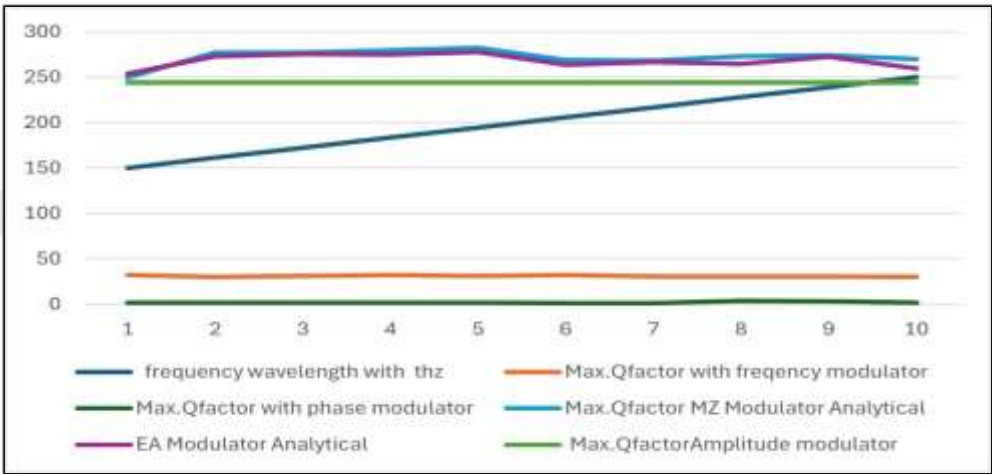


Figure 4.154: The Relationship Between the Quality Factor and Frequencies with The NRZ Pulse Bit Generator.

As shown in Figure 4.152, the relationship between the frequency (x-axis), and the Q-factor (y-axis). The best reading using an MZ Modulator with 194.44 THz with Q-Factor 282.345.

B. RZ Pulse Bit Generator

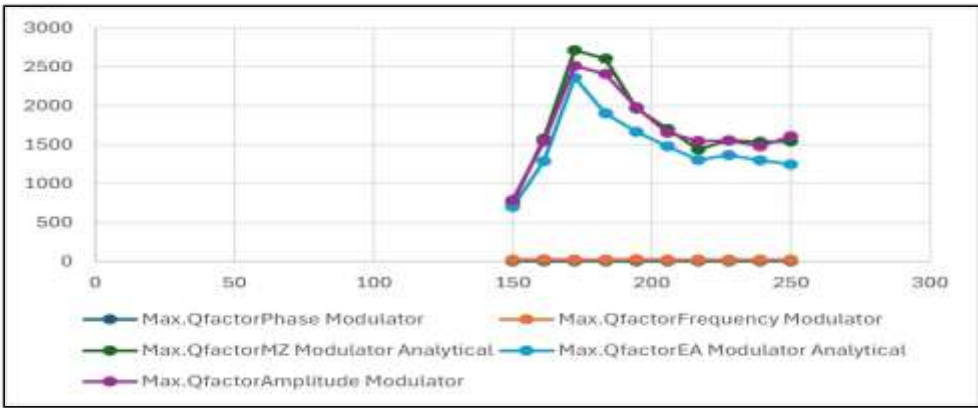


Figure 4.155: The Relationship Between the Quality Factor and Frequencies with The RZ Pulse Bit Generator.

As shown in Figure 4.153, the relationship between the Q-factor (y-axis), and the frequency (x-axis). The best reading using an MZ Modulator with 172.22 THz with Q-Factor 2714.53.

4.6.3 Responding to Changes in the Power of the Laser Source Numbers from -10 to 30 dBm in Ascending Order Were Used

A. NRZ Pulse Bit Generator

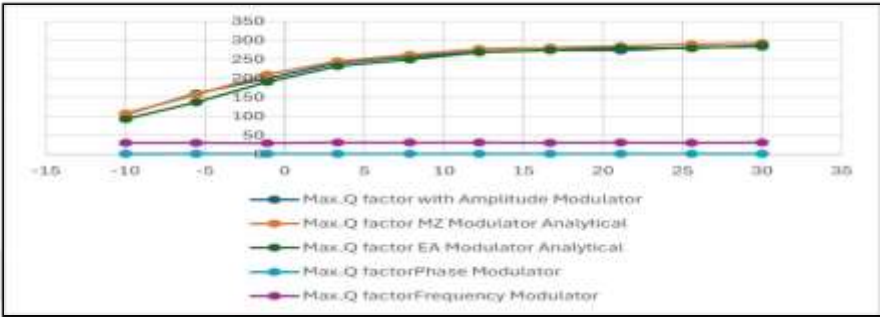


Figure 4.156: The Relationship Between the Quality Factor and Power Laser with The NRZ Pulse Bit Generator.

As shown in Figure 4.154, the relationship between the Q-factor (y-axis), and laser power (x-axis). The best reading using an MZ Modulator with 30 dBm with Q-Factor 292.696.

B. RZ Pulse Bit Generator

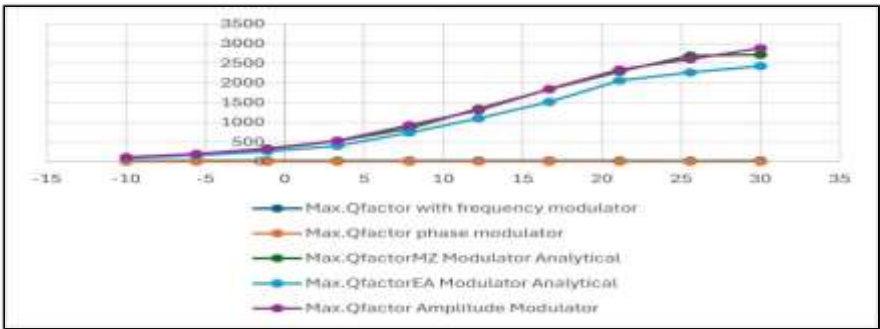


Figure 4.157: The Relationship Between the Quality Factor and Power Laser with The RZ Pulse Bit Generator.

As shown in Figure 4.155, the relationship between the Q-factor vertical axis and the laser power horizontal axis. The best reading using an Amplitude Modulator with 30 dBm with Q-Factor 2881.78.

5. CONCLUSION

It came out that for optical fiber on the land, a very basic medium like clean air had been used. The system parameters like fiber length, laser frequency, and source power were varied in a systematic way to be able to compare these conditions. The study disclosed that with a systematic variation of fiber length, the EA modulator showed the highest quality factor. Similarly, systematic variation of frequency gave the highest quality factor for EA modulation. The Mach-Zehnder (MZ) modulator surpassed the other modulators when it was measured using a quality factor scale concerning source laser power adjustment.

This work showed direct proportional relationships between variations in fiber length, frequency, and source laser power, and an increase in Q-Factor. RZ pulse bit generator was a good enough bit generator in both cases and unfailingly computed maximum quality factors. FSO, OWC, network from satellite to submarine, network from ship to submarine, interior network on the ship the quality factor is directly proportional to the distance, frequency, and power of the laser source and increases directly with increasing distances, frequencies, and laser source powers. The values always were the greatest first and diminished subsequently.

NRZ pulse bit generator at times came out bad while RZ pulse bit generator had the best quality factor results in all cases. It was also observed that the rate of attenuation (weather conditions) increased with quality factors generally tending to decrease. The rate MZ Modulator Analytical had the best readings in all cases, followed by the modulator EA Modulator Analytical.

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