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By:

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On the theme

Investigation of the effectiveness of WDM-PON system using two cascaded AWG waveguide arrays.

Publicly defended on 18 / 06 / 2025 in Tiaret before the jury composed of:

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I dedicate this work to…

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List of Acronyms

ASE Amplified Spontaneous Emission

ATM Asynchronous Transfer Mode

AWG Arrayed Waveguide Grating

BER Bit Error Rate

BPON Broadband Passive Optical Network

CD Chromatic Dispersion

CWDM Coarse Wavelength Division Multiplexing

DWDM Dense Wavelength Division Multiplexing

EPON Ethernet Passive Optical Network

FTTB Fiber to the Building

FTTC Fiber to the Curb

FTTH Fiber to the Home

FTTP Fiber to the Premises

FWM Four-Wave Mixing

GPON Gigabit Passive Optical Network

OLT Optical Line Terminal

ONT Optical Network Terminal

ONU Optical Network Unit

OSNR Optical Signal-to-Noise Ratio

P2MP Point-to-Multipoint

PMD Polarization Mode Dispersion

PON Passive Optical Network

RF Radio Frequency

SPM Self-Phase Modulation

TDMA Time Division Multiple Access

UDWDM Ultra-Dense Wavelength Division Multiplexing

VoIP Voice over IP

WDM Wavelength Division Multiplexing

WWDM Wide Wavelength Division Multiplexing

XPM Cross-Phase Modulation

General Introduction

In recent years, the rapid growth in demand for high-speed internet and advanced digital services such as high-definition video streaming, online gaming, and cloud computing has placed increasing pressure on telecommunication infrastructures. Passive Optical Networks (PON) have emerged as a promising and cost-effective solution to meet this demand, offering high bandwidth, long reach, and low maintenance requirements. Among the various PON technologies, Wavelength Division Multiplexing Passive Optical Networks (WDM-PON) have attracted significant attention due to their ability to assign a dedicated wavelength to each Optical Network Unit (ONU), resulting in enhanced bandwidth utilization, improved security, and superior quality of service compared to traditional Time Division Multiplexing (TDM)-based PONs.

Despite their numerous advantages, conventional WDM-PON systems often face challenges related to scalability, cost, and efficient wavelength management. In particular, the use of multiple wavelength-specific laser sources or tunable transmitters for each ONU can increase system complexity and deployment costs. To address these limitations, researchers have investigated alternative architectures that can improve spectral efficiency and reduce the hardware requirements of WDM-PON systems.

One promising solution involves the use of two cascaded Arrayed Waveguide Gratings (AWGs). AWGs are passive optical components capable of multiplexing and demultiplexing wavelengths with high precision, leveraging their periodic spectral response defined by the Free Spectral Range (FSR). When two AWGs are cascaded, their cyclic properties can be exploited to achieve structured wavelength routing, enabling efficient wavelength reuse, flexible ONU assignment, and simplified network design. This configuration holds the potential to reduce the number of required wavelength sources while enhancing overall system performance.

However, the use of cascaded AWGs introduces several technical challenges, such as increased insertion losses, wavelength alignment sensitivity, crosstalk, and dispersion effects, all of which can impair signal quality and limit the achievable transmission distance. Therefore, a thorough analysis is essential to assess the viability of this architecture in real-world scenarios.

The main objective of this thesis is to evaluate the performance and feasibility of a WDM-PON system that employs two cascaded AWG stages. The study focuses on analyzing the impact of this configuration on network performance indicators such as bandwidth allocation, reach, cost-effectiveness, and signal integrity. This is achieved through a combination of theoretical modeling and simulation using the OptiSystem software, with performance assessment based on key metrics including Q-factor, Bit Error Rate (BER), and eye diagram analysis. The investigation encompasses the design and configuration of all major components in the transmission chain, assessment of signal degradation due to dispersion and non-linearities. This work aims to provide valuable insights into the practical implementation of cascaded AWG-based WDM-PON systems and their potential role in next-generation optical access networks.

This thesis is divided into three main chapters, the first chapter is introducing the fundamental concepts of PON networks and their various types, with a particular focus on WDM-PON networks. It also provides a critical review of their advantages and disadvantages compared to other technologies.

The second chapter addresses the key components of the WDM-PON system, offering a detailed explanation of Arrayed Waveguide Gratings (AWGs), especially the technique of cascading two AWGs, alongside other essential components such as light sources and optical receivers. The third chapter is devoted to the practical and applied aspects of the study, presenting the methodology used for simulation with the OptiSystem software, analyzing performance results based on specified criteria, and discussing the impact of factors such as dispersion and crosstalk. The chapter concludes with suggestions for system performance improvement.

Finally, the thesis concludes with a general summary of the main findings and opens perspectives for future research in this field.

Chapter I: WDM-PON Networks

Introduction

With the rapid advancement of digital technology and the massive growth in data traffic, optical access networks have made significant progress in recent years. Among these, Passive Optical Networks (PONs) are considered a promising solution that meets the needs of next-generation access networks. These networks utilize passive optical components to transmit signals, thereby reducing the requirement for active equipment between the service provider and the end user.

This chapter will discuss the fundamental structure and working principle of PONs, along with their different types. We will then delve into Wavelength Division Multiplexing Passive Optical Networks (WDM-PONs), exploring their definition, operational mechanisms, and key benefits. Finally, we will examine the diverse applications of WDM-PON networks across various scenarios.

1 Presentation of PON Networks

1.1 Passive Optical Network (PON)

A Passive Optical Network (PON) is a fiber-optic network employing a point-to-multipoint (P2MP) architecture with optical splitters to distribute data from a single source to multiple end users. It is termed "passive" because it does not necessitate electrical power for the operation of the fiber or the distribution components.

Unlike active optical networks, power consumption in PONs is confined to the transmission and reception points, making them a cost-effective and energy-efficient option for network operation. These networks facilitate bidirectional data transmission, supporting both upstream and downstream traffic and ensuring continuous communication between users and central offices [1].

1.2 Architecture of PON networks

PON networks utilize a point-to-multipoint (P2MP) architecture. In this setup, passive optical splitters distribute the downstream signal from a single Optical Line Terminal (OLT) to multiple paths reaching end users. Conversely, these splitters combine the upstream signals originating from the end users to send them back to the same OLT.

This architecture is widely adopted due to its high efficiency in sharing optical fibers and its low power consumption, rendering it highly suitable for optical access networks.

A typical PON network originates from the OLT, situated at the service provider's site, commonly referred to as the central office or central point (sometimes also called the "exchange point" or "headend"). From the OLT, a main optical fiber cable extends to a passive optical splitter, with the option of deploying a backup fiber for redundancy.

Following the splitter, distribution optical fibers are used to transmit signals to drop terminals. These terminals can be located in various places, including outdoor cabinets, sealed underground enclosures, telephone poles, or even mounted on building walls. From these terminals, drop optical fibers provide the final individual connection between the terminal port and the end user's Optical Network Terminal (ONT) or Optical Network Unit (ONU).

In some network designs, multiple optical splitters are connected in series, a configuration known as a cascaded splitter architecture.

Signals transmitted through the optical fiber feeder system can be split to provide services for up to 256 users. ONU or ONT units at the user premises convert these optical signals, enabling users to access services such as the Internet. The number of times the downstream signal from the OLT is split before reaching the end user is referred to as the splitting ratio or split factor.

In more complex scenarios, such as when Radio Frequency (RF) video signals are broadcast in parallel with PON data services, or when additional PON services coexist on the same network, passive multiplexers are employed at the central office or central point. These multiplexers combine the wavelength of the video signal with the wavelengths of the additional services and then transmit them through the optical fiber feeder system originating from the OLT [1].

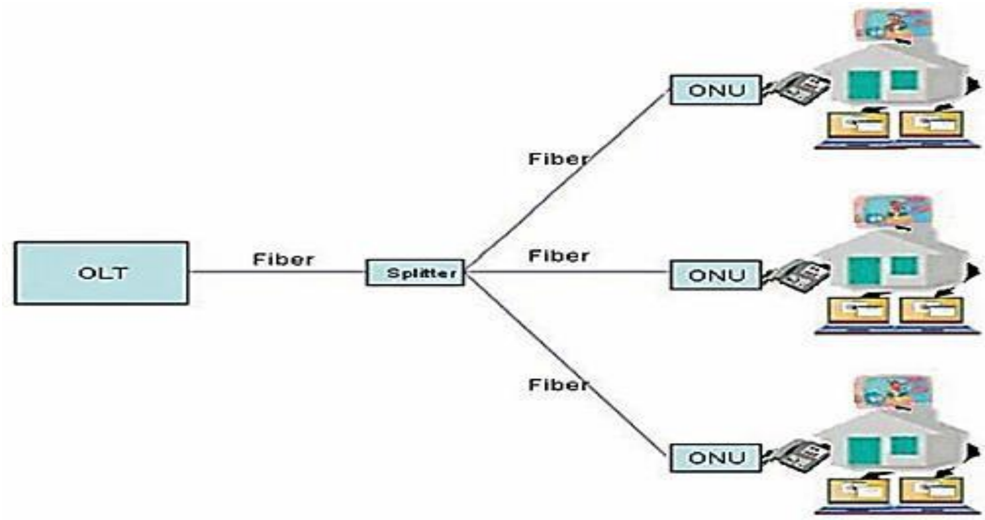


Figure 1: *PON architecture diagram. [1]*

1.3 Principle of PON networks

Wavelength Division Multiplexing (WDM) is a fundamental technique in the operation of PON networks. It is used to separate data streams based on different wavelengths (colors) of light emitted by lasers. A specific wavelength is allocated for downstream data transmission, while another is used for upstream transmission. These wavelengths vary according to the specific PON standard being used and can operate simultaneously on the same optical fiber.

On the other hand, Time Division Multiple Access (TDMA) technology, managed by the OLT, is employed to organize upstream data transmission. This technique assigns specific time slots for each end user, preventing wavelength or data collisions at the splitters or the OLT that could result from simultaneous data transmissions by multiple ONT/ONU units. This method is also known as burst mode transmission for upstream signals in PON networks.

1.4 Topology of PON networks

Three fundamental configurations are offered by PONs: the ring, the tree, and the bus. The tree structure is the most frequently adopted due to its ability to maintain stable signal power distribution. A dual ring topology can be implemented to enhance network redundancy and reliability. The bus topology allows for connecting all stations to a single medium; however, it presents challenges related to the distribution of the physical medium.

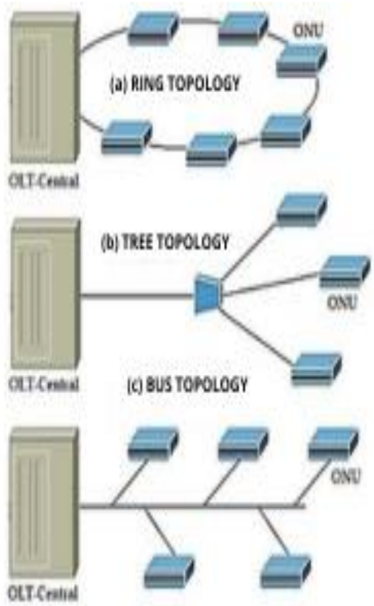


Figure 2: *Topology of PON network. [1]*

1.5 Types of PON networks.

Since the 1990s, Passive Optical Network (PON) technologies have continuously progressed, leading to the emergence of several versions with varying capabilities. Initial standards, such as APON and BPON, have been progressively replaced by more recent versions offering higher bandwidth and improved overall performance.

1.5.1 A-PON

APON stands for Asynchronous Transfer Mode Passive Optical Network (ATM-PON). As the first PON system, APON utilizes ATM technology to transmit information in fixed-size packets or cells. In APON, downstream transfer occurs through a continuous ATM stream at a rate of 155 Mbps or 622 Mbps. Upstream data is transmitted via ATM cell slices at 155 Mbps.

1.5.2 B-PON

BPON, also known as Broadband PON, is an optimized version of APON. It employs Wavelength Division Multiplexing (WDM) for downstream transmission, offering a transfer rate of up to 622 Mbps. It also supports various high-speed communication services, including ATM, Ethernet access, and video broadcasting. Currently, BPON is more widely adopted than APON .

1.5.3 E-PON

EPON, or Ethernet PON, uses Ethernet packets instead of ATM cells. EPON can support symmetrical speeds of up to 10 Gbps in both upstream and downstream directions. It is frequently deployed in Fiber to the Premises (FTTP) or Fiber to the Home (FTTH) structures to provide services to numerous users. Due to its advantages in terms of scalability, simplicity, convenience, multicast support, and the ability to provide full access to services, EPON has been widely adopted in many Asian regions for their access networks.

1.5.4 G-PON

Gigabit PON (G-PON) represents the evolution of BPON. It supports various transmission rates while utilizing the same underlying protocol. The maximum downstream transmission speed is 2.5 Gbps, and the maximum upstream speed is 1.25 Gbps. G-PON is also commonly used for FTTH networks. However, compared to EPON, its burst dimensions and additional physical layer overhead are considered inferior [1].

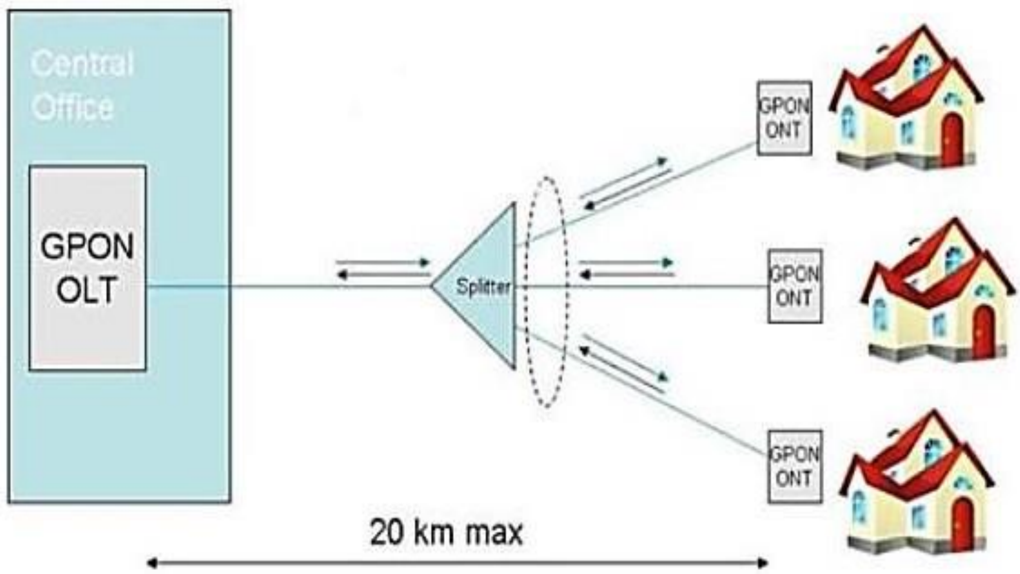


Figure 3: *Architecture of G-PON. [1]*

1.5.4.1 10G-EPON

The latest standard in the EPON family, known as 10G-EPON, enhances speeds to reach symmetrical rates of 10 Gbit/s in both upstream and downstream directions. It operates on different wavelengths within E-PON networks, using 1577 nm for downstream and 1270 nm for upstream. This wavelength plan allows both E-PON and 10G-EPON standards to operate simultaneously on the same PON network, facilitating smoother service upgrades and effectively increasing the capacity of existing networks.

1.5.4.2 *XG-PON*

The 10G version of G-PON is known as XG-PON. This new protocol supports a downstream speed of up to 10 Gbit/s and an upstream speed of 2.5 Gbit/s. Although the standards for optical fibers and data formatting remain consistent with the original G-PON, the wavelengths have been modified to 1577 nm for downstream and 1270 nm for upstream, mirroring the 10G-EPON standard. This wavelength adjustment enables G-PON and XG-PON to operate simultaneously on the same PON network.

1.5.4.3 *XGS-PON*

The enhanced version, known as XGS-PON, utilizes the same wavelengths as XG-PON but offers symmetrical speeds of up to 10 Gbit/s in both directions, significantly boosting network performance.

1.5.4.4 *NG-PON2*

NG-PON2 relies on Wavelength Division Multiplexing (WDM) technology, employing multiple wavelengths at 10 Gbit/s in both upstream and downstream directions, thereby enabling a symmetrical aggregate speed of up to 40 Gbit/s. Additionally, NG-PON2 uses different wavelengths from those employed in G-PON and XG/XGS-PON standards, allowing all three standards to coexist on the same PON network.

With the continuous increase in demand for higher speeds, XG-PON, XGS-PON, and NG-PON2 standards are expected to provide effective upgrade paths. These technologies are particularly beneficial for large networks with numerous users or enterprise networks, and they also enhance the performance of 5G wireless networks.

1.5.4.5 *50G-PON*

The ITU-T has selected a data rate of 50 Gbit/s for the new generation of G-PON networks. The first standard for asymmetric 50G-PON (50 Gbit/s downstream and 12.5 Gbit/s or 25 Gbit/s upstream) was published in 2021, followed by an amendment defining the symmetric 50 Gbit/s service in 2022.

The new standard utilizes wavelengths of 1286 nm for upstream and 1342 nm for downstream and is designed for coexistence with G-PON and XG(S)-PON networks. The 50G-PON standard represents a significant step forward in meeting the growing demands of residential applications and 5G fronthaul networks. Fully supported by PON equipment, devices, and chip suppliers, the first commercial deployments of the 50G-PON standard are anticipated.

1.5.5 Comparison between the different types of PON networks

Table 1 presents a comparison between the different types of PON networks, considering characteristics such as standard, upstream and downstream bandwidth, wavelengths, physical distance (ODN distance), maximum number of users (split ratio), guaranteed bandwidth per user, link budget, coexistence capabilities, and scope of application.

***Table 1:** Comparison between the different types of PON networks. [2]*

Characteristic	B-PON	E-PON	G-PON	10G-EPON	XG-PON	XGS-PON	NG-PON2	50G-PON
Standard	ITU-T G.983.1	IEEE 802.3ah	ITU-T G.984.x	IEEE 802.3av	ITU-T G.987.1	ITU-T G.9807.1	ITU-T G.989	ITU-T G.9804.x
Downstream (Mbps/Gbps)	622.08 Mbps	1.250 Gbps	2.488 Gbps	Sym.: 10 Gbps, Asym.: 10 Gbps	10 Gbps	10 Gbps	P2MP: 40 Gbps, P2P: 40 Gbps	50 Gbps
Upstream (Mbps/Gbps)	155.52 Mbps	1.250 Gbps	1.244 Gbps	Sym.: 10 Gbps, Asym.: 1 Gbps	2.5 Gbps	10 Gbps	P2MP: 10 Gbps, P2P: 40 Gbps	12.5/25/50 Gbps
Downstream Wavelength (nm)	1480 - 1580	1490	1490	Sym.: 1575 - 1580, Asym.: 1480 - 1500	1577	1577	P2MP: 1596-1603, P2P: 1603-1625	1342
Upstream Wavelength (nm)	1260 - 1360	1310	1310	Sym.: 1260 - 1280, Asym.: 1260 - 1360	1270	1270	P2MP: 1524-1544 (large), 1528-1540 (reduced), 1532-1540 (narrow), P2P: 1524-1625 (extended)	1286
Video Wavelength (nm)	1550	1550/IP	1550/IP	1550 - 1560/IP	1550/IP	1550/IP	1550 - 1560/IP	N/A
ODN Distance (km)	20	20	20	20	20 - 40	100	P2MP: 40, P2P: 20 - 60	20-40
Max Split Ratio	32/64	64	128	128	256	256	P2MP: 64	256
Guaranteed Throughput (Mbps)	19.44/4.86	19.44/19.44	19.44/9.76	Sym.: 78.125/78.125, Asym.: 78.125/7.81	78.125/19.44	39.06/39.06	P2MP: 625/156.25	TBD
Link Budget (dB)	5–20/10–25/15–30	21/23/26	20/25/30	26	14-29/16-31/18-33/20-35	28/29	14-29/16-31/18-33/20-35	29-32
Coexistence	N/A	10G EPON	XG-PON, XGS-PON, NG-PON2	EPON	GPON, XGS-PON, NG-PON2	GPON, XG-PON, NG-PON2	GPON, XGS-PON	GPON, XG(S)-PON
Scope of Application	ISDN, FTTH, FTTB, FTTCab, VoD	FTTH, FTTN, FTTC, Cellular Radio, Business	FTTH, FTTB, FTTC, IP-TV, VoD, High-Speed Internet	FTTH, FTTN, FTTC, Cellular Radio, Business	FTTCell, FTTH, FTTB, FTTO, FTTC/Cab, Business	FTTCell, FTTH, FTTB, FTTO, FTTC/Cab, Business	FTTCell, FTTH, FTTB, FTTO, FTTC/Cab, Business, TWDM PON, WDM PON, 5G Transport	Residential, 5G Fronthaul

1.6 Advantages and Disadvantages of Passive Optical Networks

Passive Optical Networks offer significant advantages, primarily the elimination of external active devices. All signal processing functions are performed within the OLT at the central office and the ONT/ONU at the user premises. This significantly reduces energy consumption and maintenance costs.

However, the adoption of a passive optical network also presents certain drawbacks. These include a limitation on signal range, which typically does not exceed 40 km, and vulnerability to failures, as a single point of failure can affect multiple users.

1.6.1 Advantages of PON Networks

- Energy Efficiency: The network infrastructure itself does not require a power source; energy is only consumed at the transmission and reception points (OLT and ONT/ONU).
- Easy Installation: The network does not necessitate cooling equipment, cable distribution cabinets, or intermediate electronic devices, simplifying deployment.
- Simplified Maintenance: Faults caused by passive and active components are generally easy to detect, facilitating faster and more efficient maintenance and repairs.
- Flexible Upgrades: The network can be readily upgraded by replacing only the terminal devices (OLT and ONT/ONU), while the passive fiber optic components and splitters remain unchanged.
- Low Economic Cost: Passive components are considerably less expensive than active ones, and the elimination of active equipment along the distribution path significantly reduces both installation and operational expenses.

1.6.2 Disadvantages of PON Networks

- Restricted Transmission Range: The transmission distance in a PON network is typically limited to between 20 and 40 km, whereas an active optical network can potentially cover distances up to 100 km.
- Vulnerability to Failures: A single feeder line and OLT serve multiple users (up to 128 in a P2MP architecture). With limited redundancy in the passive plant, an accidental fiber cut or an OLT failure can lead to widespread service disruption.

2 WDM-PON Operation

2.1 Wavelength Division Multiplexing (WDM)

Wavelength Division Multiplexing (WDM) is a technique aimed at optimizing the usable bandwidth in an optical fiber, thereby increasing network capacity. This method involves transmitting multiple signals simultaneously over a single optical fiber by merging them using a multiplexer. Each signal is assigned a distinct wavelength (color), allowing for the concurrent transmission of all signals rather than transmitting them sequentially or at different time intervals. Subsequently, a demultiplexer at the receiving end separates the combined signals, which are then detected by individual photodetectors.

The primary objective of a WDM system is to simultaneously boost data transmission capacity and extend transmission range. However, the use of this method can introduce complications such as crosstalk, four-wave mixing (FWM) nonlinear effects, and cross-phase modulation (XPM). These issues can arise from the narrow spacing between channels (e.g., 1.6 nm or 0.8 nm), which can lead to interference between neighboring channels. The ITU-T G.692 standard specifies the range of permitted wavelengths in the C-band transmission, typically from 1530 nm to 1565 nm. The relationship between wavelength spacing and frequency spacing can be calculated using the following formula [1]:

$$v = \frac{c}{\lambda} \rightarrow \Delta v = c\,\frac{\Delta\lambda}{\lambda^2} \qquad \textit{Equation 1}$$

Where:

- c: the speed of light [m/s].
- $\Delta\lambda$: the difference between the wavelengths [nm].
- Δv: the spacing between channels [GHz].

Optical components such as WDM couplers or multiplexers are used to perform wavelength-based multiplexing and demultiplexing.

2.1.1 Principle of WDM

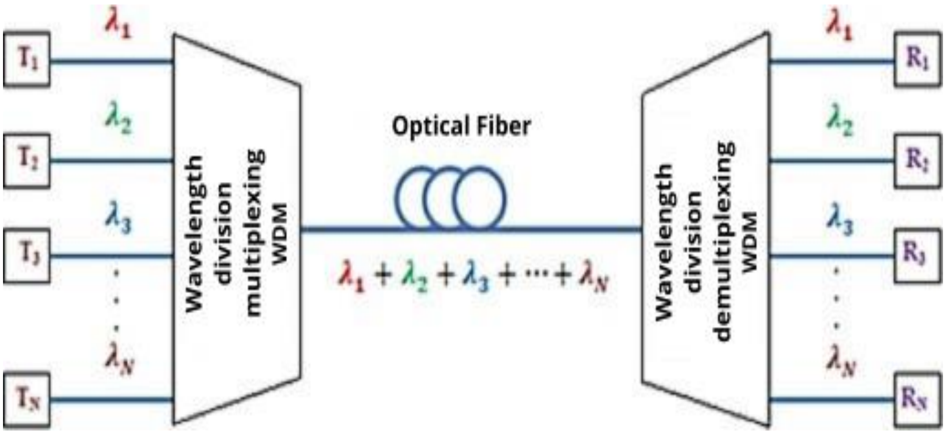


Figure 4: *Principle of WDM. [1]*

Figure 4 illustrates a traditional system employing the WDM multiplexing method. In terms of transmission, N channels, each with a nominal data rate D, are multiplexed. At the receiver, the combined signal with an aggregate rate of N×D is demultiplexed into N separate channels. This effectively means that the fiber carries multiple channels, equivalent to having N distinct fibers, each carrying a single channel. This process significantly increases network capacity without requiring changes to the physical fiber infrastructure.

2.1.2 Types of WDM

2.1.2.1 *DWDM*

Dense Wavelength Division Multiplexing (DWDM) is a technology that enables the simultaneous transmission of multiple optical signals on different wavelengths with much narrower spacing, typically less than 1 nm, operating primarily around 1550 nm.

The most commonly used frequency band in DWDM is the C-band (Conventional), which covers a frequency range from 191.560 to 195.942 THz (corresponding to wavelengths between 1530 and 1565 nm).

DWDM is often associated with optical amplifiers, such as erbium-doped fiber amplifiers (EDFAs), which can amplify all optical channels simultaneously without distorting the transmitted signals.

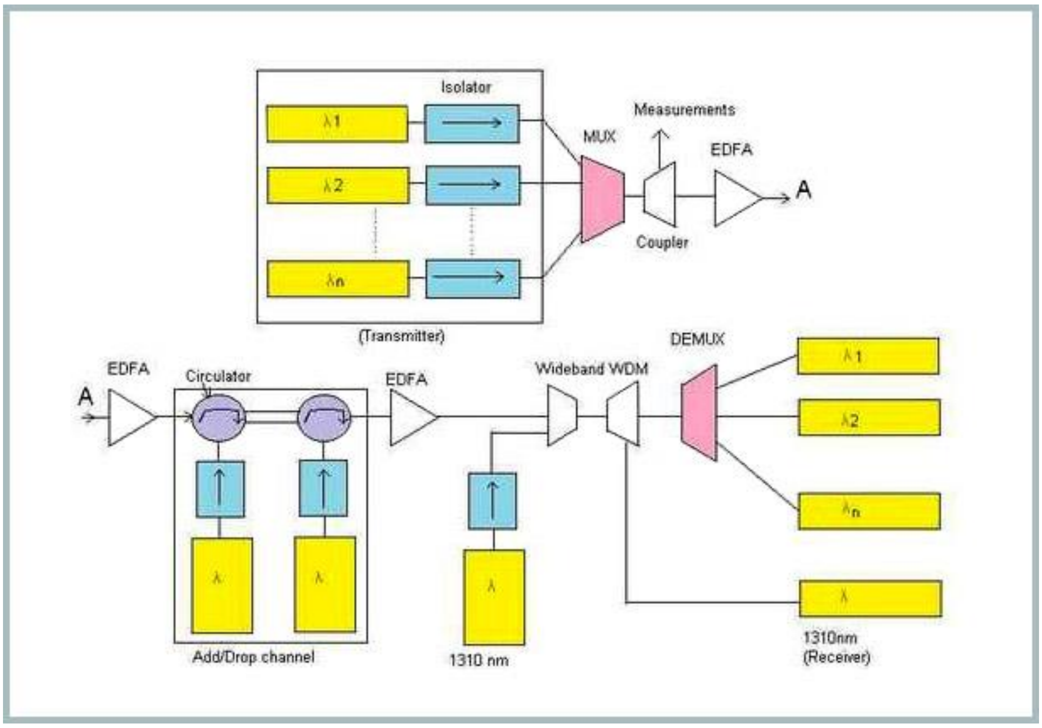


Figure 5: *DWDM system consisting of transmitter and receiver elements. [3]*

2.1.2.2 *UDWDM*

UDWDM (Ultra-Dense Wavelength Division Multiplexing) technology is an enhancement of DWDM, where the spacing between wavelengths is further reduced to 10 GHz (approximately 0.08 nm), enabling support for up to 400 optical channels.

2.1.2.3 *CWDM*

Coarse Wavelength Division Multiplexing (CWDM) utilizes wavelengths ranging from 1270 nm to 1610 nm, with a relatively wide 20 nm spacing between each wavelength. Up to 18 channels can be used within this range. This technology is cost-effective, making it particularly suitable for Metropolitan Area Networks (MANs).

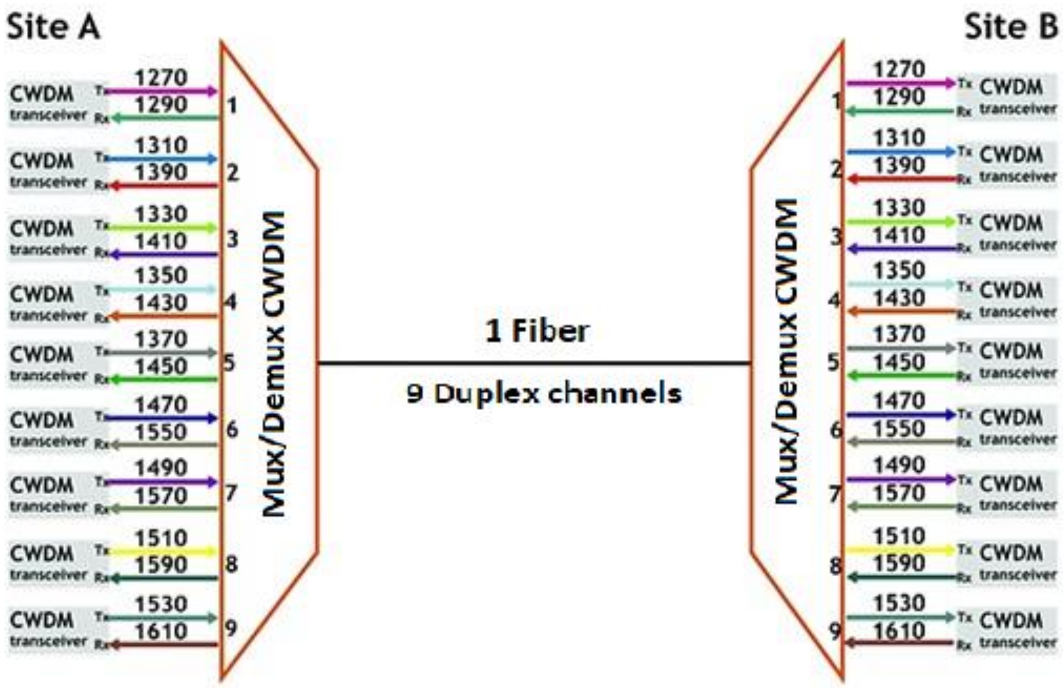


Figure 6: *Principle of CWDM Multiplexing. [2]*

2.1.2.4 WWDM

Wide Wavelength Division Multiplexing (WWDM) is a method that shares similarities with Coarse Wavelength Division Multiplexing (CWDM), but it is limited to the use of a maximum of four channels. WWDM operates over a range of wavelengths from 1275.7 nm to 1349.2 nm (O band) and supports four WWDM channels with a channel spacing of 24.5 nm. This type of multiplexing can be used for both multimode and single-mode fibers.

2.1.3 Comparison between the different types of WDM

Difference between DWDM, WWDM, UDWDM and CWDM

Type of Multiplexing	Channel Spacing (nm)	Number of Channels	Wavelength (nm)
WWDM	24.5	4	1275.7-1349.2
CWDM	20	18	1270-1610
DWDM	0.8	160	1530-1625
UDWDM	0.4 and 0.1	400	1625-1675

Table 2: *Comparison of different WDM types.*

2.2 WDM-PON

Wavelength Division Multiplexing Passive Optical Network (WDM-PON) is a type of optical multiplexing technology employed in optical access networks. Compared to systems such as 10G-EPON and XG-PON, WDM-PON offers significantly higher bandwidth and is considered a promising solution for next-generation passive optical networks. Unlike conventional Time Division Multiplexing (TDM) based PON systems, WDM-PON architecture provides several distinct advantages.

Primarily, WDM-PON assigns one or more specific wavelengths (λ1, λ2, λ3, etc.) to each user, enabling each subscriber to access a dedicated bandwidth channel. This wavelength-based allocation enhances both bandwidth scalability and user-specific service customization. Furthermore, since each user exclusively receives their designated wavelength, WDM-PON inherently provides improved security and supports incremental upgrades without affecting other users.

WDM-PON establishes point-to-point (P2P) connections between the Optical Line Terminal (OLT) and each Optical Network Unit (ONU), thereby eliminating the need for point-to-multipoint (P2MP) access control mechanisms found in other PON architectures.

WDM-PON is widely applicable in Fiber to the Curb (FTTC), Fiber to the Building (FTTB), and Fiber to the Home (FTTH) deployments, supporting the delivery of high-quality video, voice, and data services. Additionally, it satisfies the increasing bandwidth demands of mobile backhaul networks, such as those required by 3G and 4G LTE technologies. It can also serve as the foundation for a hybrid system, such as Time and Wavelength Division Multiplexed PON (TWDM-PON), which combines the strengths of both TDM-PON and WDM-PON technologies.

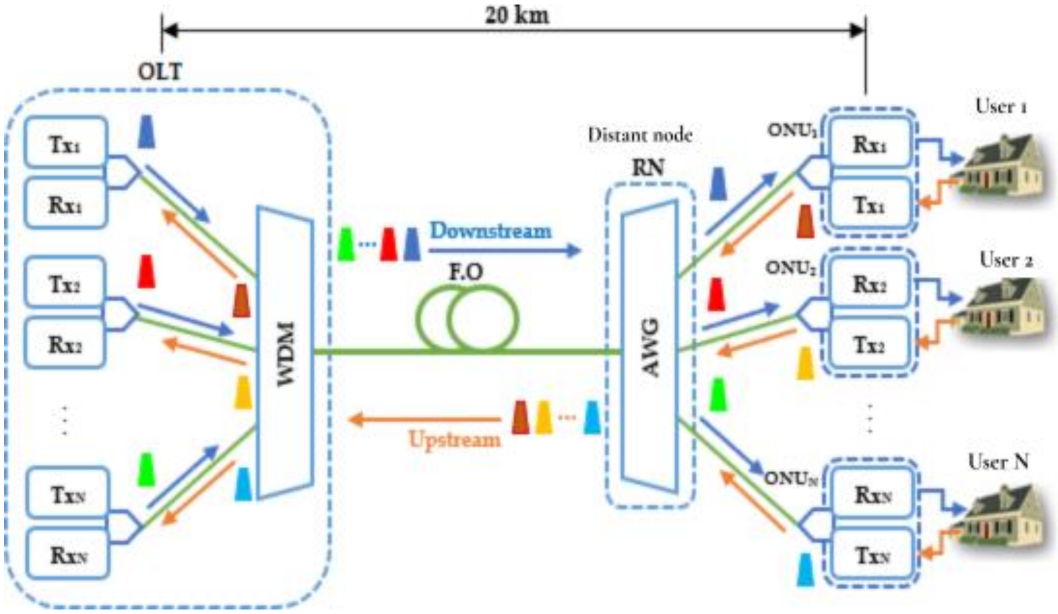


Figure 7: *A typical WDM PON architecture [2].*

2.2.1 Advantages compared to other PON technologies of WDM-PON

- **Dedicated Bandwidth per User:**

WDM-PON assigns a unique wavelength to each Optical Network Unit (ONU), ensuring that each user has a dedicated bandwidth channel. This contrasts with Time Division Multiplexing PONs (TDM-PONs) like GPON, where bandwidth is shared among users.

- **Enhanced Security**

By providing separate wavelengths for each user, WDM-PON inherently enhances data security [6]. This separation reduces the risk of data interception compared to shared-bandwidth systems.

- **Scalability and Flexibility**

WDM-PON systems are highly scalable. Adding new users involves assigning additional wavelengths without requiring significant changes to the existing infrastructure. This flexibility makes it easier to expand the network as demand grows [7].

- **Higher Aggregate Bandwidth**

By utilizing multiple wavelengths simultaneously, WDM-PON can achieve higher total bandwidth compared to TDM-PON systems [8]. This capability is crucial for supporting bandwidth-intensive applications.

- **Support for Diverse Services**

WDM-PON's architecture allows for the allocation of specific wavelengths to different services, such as internet, IPTV, and Voice over IP (VoIP). This separation ensures quality of service and simplifies network management.

- **Reduced Latency**

With dedicated wavelengths, WDM-PON minimizes contention and scheduling delays inherent in shared systems, leading to lower latency. This feature is particularly beneficial for real-time applications like video conferencing and online gaming.

- **Efficient Fiber Utilization**

WDM-PON enables multiple wavelengths to coexist on a single fiber, maximizing the utilization of the fiber infrastructure. This efficiency can lead to cost savings in deployment and maintenance.

- **Future-Proofing the Network**

The architecture of WDM-PON is well-suited for future upgrades. As bandwidth demands increase, additional wavelengths can be added to accommodate new services without overhauling the existing network.

2.2.2 Applications of WDM-PON Networks

WDM-PON (Wavelength Division Multiplexing - Passive Optical Network) networks are innovative solutions designed to meet the growing demands for bandwidth and flexibility in modern communication systems. These networks support a wide variety of application scenarios in both urban and rural environments due to their ability to deliver high-speed and reliable connections.

2.2.2.1 Application scenarios

WDM-PON networks are versatile and can be used in a range of contexts, including:

➢ **FTTx (Fiber to the x)**

- **FTTH (Fiber to the Home):** WDM-PON is ideal for direct connections between each home and the central network. It enables high-bandwidth services such as video streaming, online gaming, and cloud applications.
- **FTTB (Fiber to the Building):** In commercial or residential buildings, WDM-PON offers secure and reliable connections for multiple users, which is essential for businesses requiring fast and secure communications.
- **FTTC (Fiber to the Curb):** This setup is useful in areas where installing fiber directly to homes is impractical. WDM-PON can provide high-speed connectivity from a nearby central point to users.

➢ **5G Backhaul and Fronthaul**

With the rise of 5G networks, WDM-PON plays a critical role in both backhaul (connecting cell towers to the core network) and fronthaul (connecting baseband units to remote radio heads). These networks require high-capacity transmission to support low-latency, high-bandwidth applications such as virtual reality and autonomous vehicles.

WDM-PON meets these demands by offering dedicated and reliable transmission channels, which are essential for maintaining the quality of 5G services.

➢ **Local Networks and Network Convergence**

In enterprise networks or campus networks, WDM-PON can be used to integrate various local services. It offers a unified infrastructure for multiple applications, simplifying management and reducing operational costs. This convergence also enables better resource management and optimized use of available bandwidth.

2.2.2.2 *Benefits for urban and rural coverage*

WDM-PON networks provide several key benefits for both urban and rural deployments:

- **Urban Coverage**

  High Bandwidth: Urban areas require networks capable of handling increasing bandwidth demand due to the growing number of users and data-intensive applications. WDM-PON fulfills these needs by providing high-speed connections, allowing urban users to access services like 4K video streaming, online gaming, and cloud platforms without interruption.

  Security and Reliability: By using dedicated wavelength channels, WDM-PON enhances security for urban connections. Each user receives a unique channel, minimizing risks of interference or eavesdropping. Reliability is also improved through potential automatic rerouting capabilities in case of failures, ensuring continuous availability of critical services.

- **Rural Coverage**

  Extended Reach: In rural areas, communication infrastructure is often limited, and the distance between users and central network nodes can be significant. WDM-PON can extend the network reach using advanced optical components like Arrayed Waveguide Gratings (AWGs), which help reduce optical losses over long distances. This makes it possible to deliver high-quality services even in remote locations.

  Cost Reduction: Installing networks in rural regions can be expensive due to long distances and lack of existing infrastructure. WDM-PON reduces costs by minimizing the number of fibers needed to cover an area. By transmitting multiple channels over a single fiber, several users can be served using less equipment, which lowers both installation and maintenance costs. This makes internet access more affordable for rural communities, helping bridge the digital divide between urban and rural areas.

Conclusion

With the rapid advancement of digital technology and the massive increase in data traffic, optical access networks have seen significant progress in recent years, including Passive Optical Networks (PONs). These networks represent a promising solution for next-generation access networks, providing both efficiency and high bandwidth transmission capabilities. This chapter has provided an overview of PON and WDM-PON technologies, their architectures, types, advantages, disadvantages, and applications, setting the stage for a more detailed investigation into specific components and system effectiveness.

Chapter II: Key Components of the WDM-PON System

Introduction

In Wavelength Division Multiplexing Passive Optical Networks (WDM-PONs), several key components play crucial roles in ensuring efficient data transmission and network performance. This chapter focuses on the fundamental elements of WDM-PON systems, particularly the Arrayed Waveguide Grating (AWG), which serves as a core component for wavelength multiplexing and demultiplexing. Additionally, we explore the characteristics and functions of light sources, including lasers, which are essential for optical signal generation. By understanding these components, we gain insight into how WDM-PON systems achieve high-capacity and cost-effective optical communication.

1 AWG (Arrayed Waveguide Grating) Network

1.1 Arrayed Waveguide Grating (AWG)

The Arrayed Waveguide Grating (AWG) is a fundamental optical component in Wavelength Division Multiplexing (WDM) systems used in optical communication networks. It is utilized for separating and combining optical channels that carry signals with different wavelengths. An AWG operates based on the principle of optical wave interference and diffraction, which states that different wavelengths propagate through the device along different paths and can be spatially separated or combined. Consequently, by assigning a slightly different wavelength to each channel in an optical communication network, multiple signals can be transmitted through a single optical fiber with minimal channel interference.

1.2 Structure of AWGs

A typical AWG consists of five main parts:

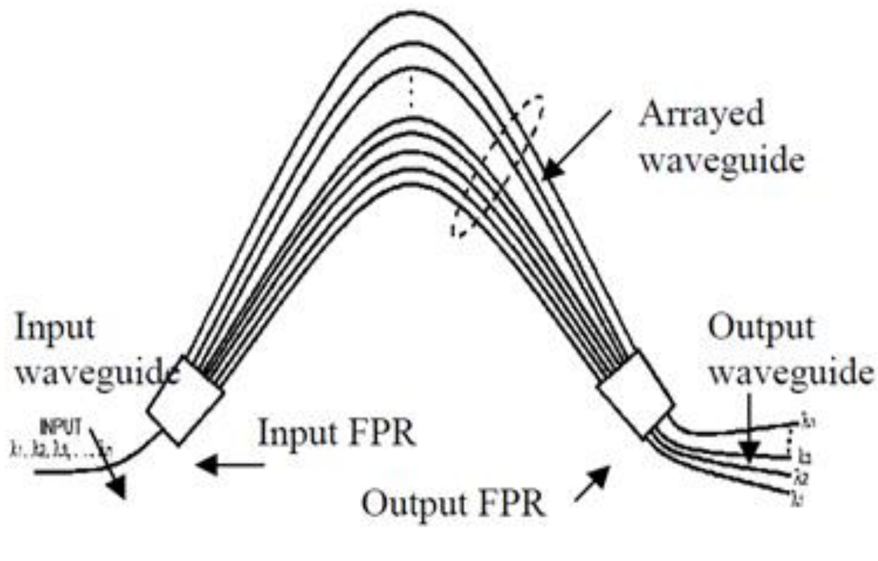


Figure 8: *AWG Structure. [4]*

1. **Input Waveguide:** This component guides the incoming optical signal (which may contain multiple wavelengths) into the device.
2. **First Free Propagation Region (FPR):** In this region, the optical waves from the input waveguide diffract and spread out before entering the arrayed waveguide.

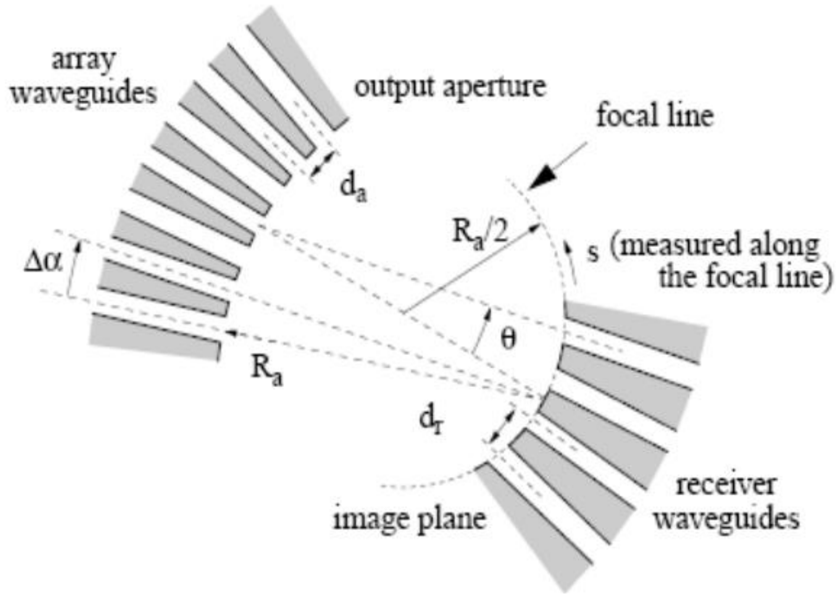


Figure 9: *Output free propagation region (FPR). [4]*

3. **Arrayed Waveguide:** This is the core of the AWG, composed of multiple waveguides of precisely controlled, varying lengths. A fixed length difference (ΔL) between adjacent waveguides is designed to cause the light waves to experience different phase shifts, leading to diffraction at specific angles depending on the wavelength.
4. **Second Free Propagation Region (FPR):** This region collects the light waves from the arrayed waveguide. Due to the phase differences accumulated in the array, the light waves interfere constructively at different spatial locations in this region, corresponding to their respective wavelengths.
5. **Output Waveguides:** These waveguides are positioned in the second FPR to capture the spatially separated wavelengths, directing each wavelength to a specific output port.

1.3 Operation of AWGs

The first FPR couples light diffracted from the input waveguide into the arrayed waveguide. The optical path length difference (ΔL) between neighboring array waveguides is designed to be an integer (m) multiple of the demultiplexer's center wavelength (λ_c). This path difference introduces a wavelength-dependent phase shift between light waves traveling through adjacent waveguides in the array. [4]

$$\Delta L = m\lambda_c / n_{eff} \qquad \textit{Equation 2}$$

Where:

- ΔL: Path length difference between adjacent waveguides.
- m: Diffraction order (an integer).
- λ_c: Center wavelength.
- n_{eff} : Effective refractive index of the waveguide mode. [4]

Consequently, at the center wavelength (λ_c), the phase shifts are such that light constructively interferes at the center of the second FPR, where the central output waveguide is typically located (assuming the input waveguide is centered in the input plane).

If the input wavelength deviates from the central wavelength, phase shifts in the array branches change linearly with the wavelength deviation due to the constant path length difference between adjacent waveguides. This results in a slanted wavefront at the output aperture of the arrayed waveguide. As a result, the focal point in the second FPR shifts spatially away from the center. The various wavelength channels are thus separated spatially by positioning receiver waveguides appropriately along the image plane in the second FPR.

1.4 Optical properties of AWGs

Focusing: Focusing is achieved by selecting the length difference (ΔL) between neighboring array waveguides such that it equals an integer number of wavelengths (as described above). At a distance R_a from the array apertures, the array functions as a lens with image and object planes. Typical instances of Rowland-type mountings are the phased array's input and output apertures. As illustrated in Figure [Reference Figure Showing Rowland Mounting], the focus line of such a mounting, which defines the image plane, follows a circle with radius $R_a/2$.[4]

Dispersion: It is evident from Figure 8 that the dispersion angle θ caused by a phase difference ΔΦ between neighboring waveguides.

$$\theta = arcsin\left(\frac{(\Delta\Phi - 2m\pi)/\beta_{FPR}}{d_a}\right) = \frac{\Delta\Phi - m2\pi}{\beta_{FPR} d_a} \qquad \textit{Equation 3}$$

Where

- $\Delta\Phi = \beta\ \Delta L$
- B and β_{FPR}: are the propagation constants in the array waveguide and Free Propagation Reion (FPR).
- d_a: is the lateral spacing (on centre lines) of the waveguides in the array aperture. [4]

Free Spectral Range (FSR): The free spectral range (FSR), sometimes referred to as demultiplexer periodicity, is a crucial aspect of an AWG. This periodicity arises from the possibility of constructive interference at the output FPR for multiple wavelengths separated by the FSR.

Insertion Loss and Non-uniformity: Ineffective coupling between the first FPR and the arrayed waveguides (AWs) at the interface is a primary reason for insertion loss in an AWG. Due to reciprocity, the coupling efficiency between the second AW-FPR interface and the output waveguides also contributes to loss. Coupling efficiency is significantly influenced by the separation of the AWs at these interfaces, with smaller separations generally increasing efficiency.

Channel Bandwidth:

If the wavelength is changed the focal field of the PHASAR moves along the receiver waveguides. The frequency response of the different channels follows from the overlap of this field with the modal fields of the receiver waveguides. If we assume that the focal field is a good replica of the modal field at the input, and that the input and output waveguides are identical, the (logarithmic) transmission $T(\Delta f)$ around the channel maximum Tf_c follows as the overlap of the modal field with itself, displaced over a distance $\Delta s\ (\Delta f) = D\Delta f$ (Smit, 1996).

$$T(\Delta f) = Tf_c + 20\,log \int_{-\infty}^{+\infty} U\,(s)U(s - D\Delta f)ds \quad \textit{Equation 4}$$

Where

- U(s) is the normalized modal field
- D is the dispersion
- Tf_c is the transmission in dB at the channel maximum. [4]

Channel Crosstalk: Crosstalk, the unwanted leakage of signal power from one channel into adjacent channels, can arise from numerous mechanisms, including receiver crosstalk, truncation (finite aperture size), mode conversion, coupling within the array, phase transfer incoherence, and background radiation. The first four can often be minimized through effective design. The latter two are more challenging to reduce and often result from imperfections in the fabrication process. The coupling between the receiver sides of the star coupler (second FPR) is a significant source of crosstalk. Crosstalk can be estimated using the overlap between the waveguide mode profile and the exponential tails of the propagation field. [4]

Polarization Dependence: An AWG is considered polarization independent if the propagation constants for the fundamental Transverse Electric (TE) and Transverse Magnetic (TM) modes are equivalent in the array waveguides. Polarization dispersion, or the shift (Δf_{pol}) of the spectral response between the TE and TM modes, is caused by waveguide birefringence, which is a difference in the effective refractive index for the two polarizations.

Channel Spacing and Number of Ports: The most crucial factors in designing an AWG wavelength multiplexer are the number of channels (N) and the wavelength channel separation (Δλ). According to the ITU-T grid standard, the wavelength channel spacing Δλ is typically chosen to be 50 GHz, 100 GHz, or 200 GHz. The specific requirements of the network type (WDM, DWDM, or CWDM) and its users define the number of wavelength channels needed. AWGs typically come in two varieties: 1xN (one input, N outputs) and NxN (N inputs, N outputs). The number of wavelength channels N is often chosen as a power of 2, such as 16, 32, 64, or 128.[4]

1.5 Advantages of AWGs

- Can meet specific customer requirements.
- Reliable, well characterized, high volume manufacturing platform.
- Reduced system tradeoffs.
- Allows laser source and system tradeoffs.
- Higher value added configurations for system evolution.
- High stability and reliability, confidence in long term use.

2 Cascading of Two AWGs

2.1 Waveguide cascade architecture

We mainly distinguish two types of cascade structures for AWGs

2.1.1 Conventionally Cascaded AWGs

This approach is referred to as the "conventional" method and is frequently used for high-density Wavelength Division Multiplexing (WDM) systems. It is based on using two stages of conventional AWG structures with different resolutions and FSR values: a primary AWG stage and a secondary AWG stage, as shown conceptually in Figure [Figure 9a].

The primary AWG, typically a 1xN device, slices the entire spectrum of interest into N wide sub-passbands. The N secondary AWGs, which are 1xM devices, then further reslice these wide passbands into narrower passbands. This configuration aims to achieve a narrow overall channel spacing and a wide effective FSR for the entire cascaded arrangement (as illustrated conceptually in Figure [Figure 9]). Each secondary AWG has a center wavelength that aligns with the associated primary filter passband. The total passband loss of the cascaded configuration is the sum of the losses from the primary and secondary filters.

Additionally, the Gaussian-like transmission response of the AWG can introduce extra loss for the corresponding secondary AWG passbands, particularly at the passband crossing locations of the primary AWG. Therefore, a primary filter with a transfer function that approximates a rectangular shape (flat-top response) as much as possible is preferred. Various approaches to implementing a rectangular transfer function will be discussed later.

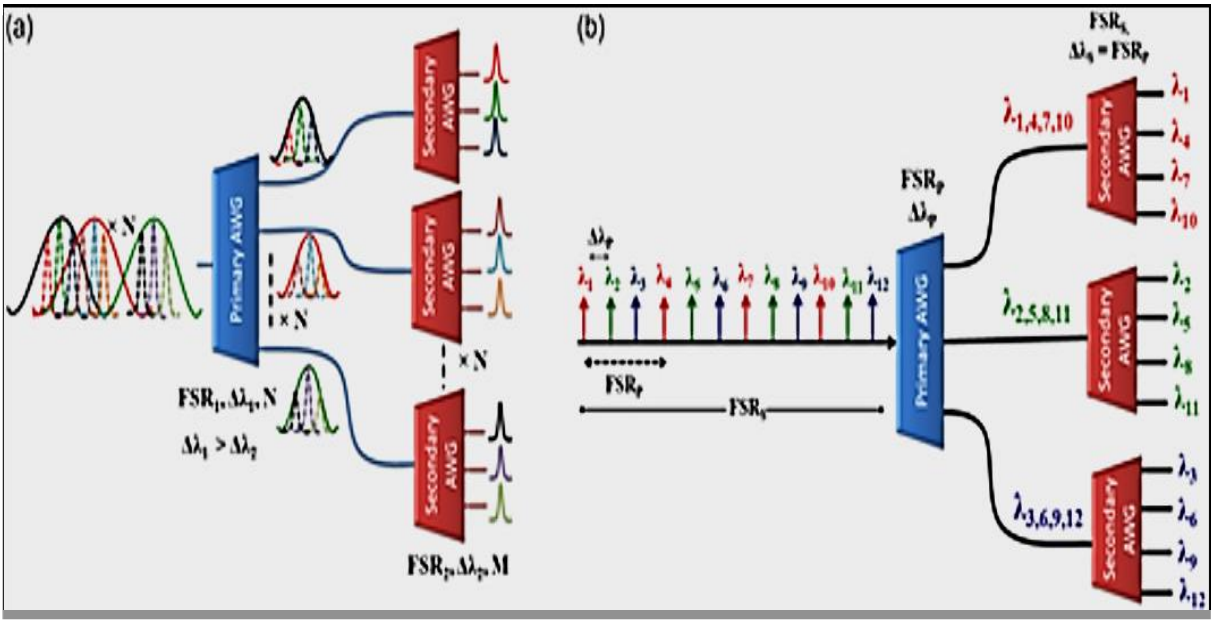


Figure 10: *Schematic diagram of the (a) conventionally cascaded and (b) cyclic FSR nature-based AWG configurations.*

a) N and M indicate the number of primary and secondary filter output waveguides, respectively.

b) FSRP and FSRS indicate the FSR of the primary and secondary AWGs, respectively, while ΔλP and ΔλS are the channel spacings of the primary and secondary AWGs, respectively. ΔλS equals FSRP. The combined system has a free spectral range FSRS and a resolution ΔλP. [5]

2.1.2 Cascaded AWG Systems Based on Cyclic FSR Nature (Interleaved AWGs)

A cyclic transmission characteristic of an AWG is that all wavelengths with a spacing equal to the FSR are simultaneously routed to a single output waveguide. A new cascading strategy that leverages this periodic routing aspect of the AWG can offer a considerably reduced system size and potentially better overall performance (i.e., interleaved configuration) compared to the size and loss issues of the standard cascaded method. In this design, instead of the primary AWG having wide flat passbands, it might have narrow, tightly spaced passbands (equal to the ultimate intended channel spacing) that repeat N times across the desired wavelength range, exploiting the frequency-cyclic nature of the AWG as indicated in Figure [Figure 9b]. The channel spacing of the secondary AWGs should match the FSR of the primary AWG (ΔλS=FSRP).

2.2 Potential problems

Increased Insertion Loss: Each AWG in the cascade contributes insertion loss. Cascading two or more AWGs results in a cumulative increase in the total insertion loss experienced by the optical signal [6]. This can significantly reduce the optical power budget, limiting the achievable transmission distance or requiring higher power sources and more sensitive receivers.

Accumulated Crosstalk: Crosstalk, the unwanted leakage of signal power between channels, is present in individual AWGs. In a cascaded configuration, the crosstalk from each stage accumulates [6]. This can lead to a significant degradation in the signal quality, particularly for channels that are passed through multiple stages with non-ideal isolation. Accumulated crosstalk can increase the Bit Error Rate (BER) and limit the system's capacity.

Complexity in Design and Fabrication: Designing and fabricating cascaded AWG structures with precise control over waveguide lengths, gaps, and refractive indices is more complex than for a single AWG. Achieving optimal performance requires tight tolerances during the manufacturing process, which can increase fabrication costs and reduce yield [11, 13].

Challenges in Passband Alignment: In cascaded architectures, especially those aiming for narrow channel spacing or specific filtering characteristics, precisely aligning the passbands of the cascaded AWG stages is critical [5, 9]. Misalignment can lead to increased insertion loss, distorted passband shapes, and increased crosstalk. Thermal stability and packaging become crucial to maintain alignment under varying environmental conditions [13, 16].

Degradation of Passband Shape: The cascading process can alter the overall passband shape compared to that of a single AWG. The combination of multiple filter responses can lead to narrower effective bandwidths, increased ripple within the passband, or steeper roll-offs, which can affect signal integrity, especially for high-speed modulated signals [5].

Increased Polarization Dependence: If the individual AWGs in the cascade exhibit polarization dependence, cascading them can potentially exacerbate this issue, leading to larger variations in insertion loss and spectral response between TE and TM polarizations [4, 12]. This requires careful design or compensation techniques to ensure polarization-independent operation.

Sensitivity to Environmental Variations: Cascaded AWG systems can be more sensitive to environmental factors such as temperature fluctuations compared to single AWGs. Temperature changes can affect the refractive index and physical dimensions of the waveguides, leading to shifts in the center wavelength and passband characteristics, which can cause misalignment between stages and performance degradation [13, 16].

2.3 Solutions

Addressing the potential problems associated with cascading AWGs requires a combination of advanced design techniques, improved fabrication processes, and system-level mitigation strategies:

- **Advanced AWG Designs:**

Flat-Top AWGs: Designing AWGs with flatter passbands in each stage can help minimize the impact of passband narrowing and ripple when cascaded. Various techniques, such as using wider input waveguides or multimode interference (MMI) couplers, can be employed to achieve flat-top responses [5, 11].

Optimized Cascade Architectures: Careful selection of the cascade architecture (e.g., conventional vs. interleaved) and optimization of the parameters of each AWG stage (e.g., FSR, resolution, passband shape) can help minimize cumulative losses and crosstalk [5].

Improved Fabrication Techniques: Utilizing high-precision fabrication processes, such as deep UV photolithography or e-beam lithography, can help achieve tighter tolerances in waveguide dimensions and reduce fabrication flaws, thereby minimizing insertion loss, crosstalk, and non-uniformity [13, 14].

Loss Reduction Techniques: Implementing techniques to reduce insertion loss in individual AWGs, such as optimizing fiber-to-waveguide coupling, using low-loss waveguide materials, and minimizing scattering losses, can help manage the overall loss budget in a cascaded system [16].

- **Crosstalk Mitigation:**

Improved AWG Design: Designing individual AWGs with lower intrinsic crosstalk through optimized layout and apodization techniques [4, 13].

Filter Design: Using cascaded filters with steeper roll-offs to improve out-of-band rejection and reduce adjacent-channel crosstalk [5].

- **Passband Alignment and Stability:**

Precise Manufacturing: Ensuring high precision during fabrication to minimize initial misalignment [13, 14].

Thermal Control and Packaging: Employing active or passive thermal stabilization techniques and robust packaging to minimize wavelength shifts due to temperature variations and maintain alignment between cascaded stages [16].

Tunable AWGs: Utilizing tunable AWGs where the center wavelength can be adjusted to compensate for manufacturing variations or environmental drifts [16].

Polarization Dependence Compensation: Incorporating polarization diversity schemes or designing polarization-independent AWGs through careful control of waveguide geometry and material birefringence can mitigate the effects of polarization dependence in cascaded systems [4, 12].

System-Level Optimization: Optimizing system parameters such as channel spacing, modulation format, and forward error correction (FEC) can help improve overall performance and tolerance to the impairments introduced by cascaded AWGs [17].

By implementing these solutions, the challenges associated with cascading AWGs can be effectively managed, enabling the realization of high-performance WDM-PON systems with increased capacity and functionality.

3 Other Components

3.1 Light sources (Lasers)

The term "Laser" is an acronym for Light Amplification by Stimulated Emission of Radiation. A laser is a device that emits coherent light, meaning the light waves have the same frequency, direction of vibration (polarization), and a fixed phase relationship. Excellent laser light sources are essential for high-performance optical communication systems.

3.1.1 Types of Optical Module Lasers

DFB, FP, and VCSEL lasers are common types used in optical modules. They can be driven with or without direct electrical modulation to transmit messages. Lasers that are directly modulated are known as Directly Modulated Lasers (DMLs).

- **VCSEL Lasers:** The Vertical Cavity Surface Emitting Laser (VCSEL) is a semiconductor laser that emits light perpendicular to the chip surface. VCSELs can produce high-quality laser beams, offer increased coupling efficiency into fibers, and can support high modulation speeds. Low-cost VCSEL-based transceivers can be manufactured because VCSELs are generally simpler to fabricate than FP and DFB lasers. The primary application for VCSELs is in short-distance optical links.
- **FP Laser:** The Fabry-Perot (FP) laser is a semiconductor light-emitting device that utilizes an FP cavity as a resonant cavity. It typically emits multi-longitudinal mode coherent light. FP lasers have a horizontal cavity structure and are of the edge-emitting type.
- **DFB Laser:** The Distributed Feedback (DFB) laser is based on the FP laser but incorporates a Bragg grating integrated into the active layer or gain medium within the resonant cavity. This grating acts as a mode selection structure, enabling single-mode operation (emission at a single wavelength). DFB lasers also have a horizontal cavity structure and are classified as edge-emitting.

3.2 Optical receivers

Optical receivers are crucial components in WDM-PON systems responsible for converting the incoming optical signal back into an electrical signal that can be processed by electronic circuits. A typical optical receiver consists of a photodetector and subsequent electronic amplification and processing stages.

3.2.1 Photodetector:

This is the primary component that converts photons from the optical signal into electrical current. Optical detectors generally use the PN junction. The image below shows the PN junction.

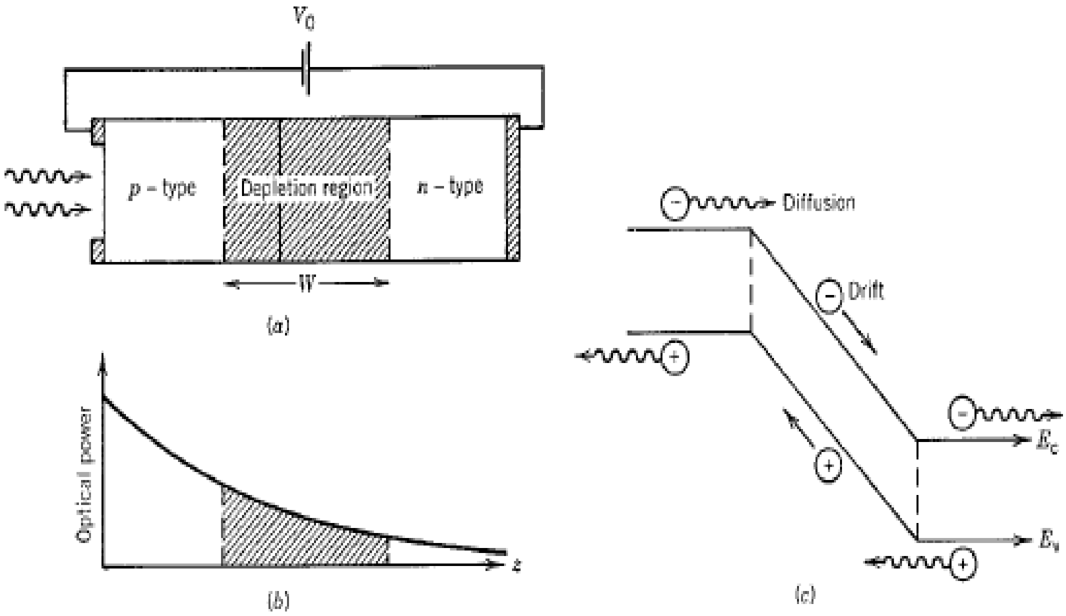


Figure 11: *(a) a photodiode under voltage bias (b) variation of optical power inside the photodiode (c) energy band diagram shows the movement of carriers by the current derived or by the diffusion current [10].*

- PIN Photodiodes: These are widely used due to their linearity, low dark current, and relatively high speed. They are suitable for a range of data rates and are often preferred for their simplicity and cost-effectiveness [15].
  A simple way to increase the width of the depletion region is to insert an undoped SC layer between the PN junction.

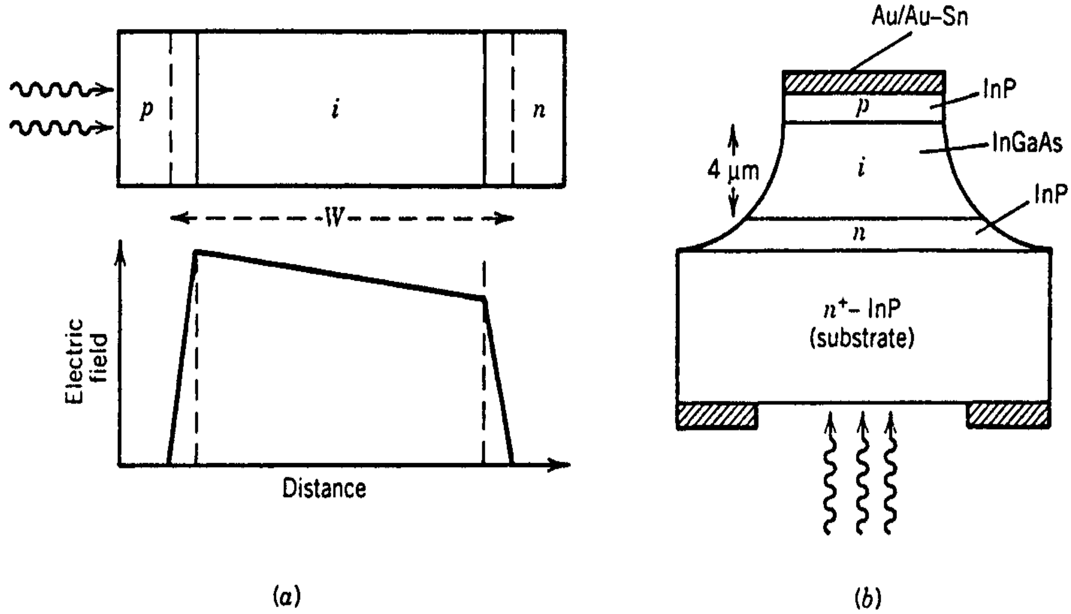


***Figure 12:** (a) a photodiode with the distribution of an electric field under reverse bias (b) Design of a PIN photodiode with InGaAs [10].*

As a result, the large electric field exists in layer (i). • The main difference compared to the PN photodiode is that the current derived from the photocurrent dominates over the diffusion current because a large part of the incident power is absorbed inside the i-region of the PIN photodiode.

The main difference compared to the PN photodiode is that the drift current of a photocurrent dominates over the diffusion current because most of the incident power is absorbed within the i-region of the PIN photodiode.

The main difference compared to the PN photodiode is that the drift current of a photocurrent dominates over the diffusion current because most of the incident power is absorbed inside the i-region of the PIN photodiode. The optimal value of the depletion region w of the PIN photodiode will depend on a trade-off between speed and sensitivity.

- Avalanche Photodiodes (APDs): APDs provide internal gain through the avalanche effect, making them more sensitive than PIN photodiodes. They are often used in applications requiring longer reach or higher data rates where signal power is limited, as they can detect lower light levels [16].

The avalanche photodiode can have higher values of R (sensitivity), as they are designed to provide current gain. And they are used when the optical power arriving at the receiver is limited. Avalanche photodiodes differ in their designs from PIN photodiodes in one single aspect: an additional layer is added where secondary electron-hole pairs are generated under the effect of impact ionization.

The following figure shows the structure of the APD with a variable electric field in the different layers. Under reverse bias, a strong electric field exists in the P-type layer placed between the i-type and n+ type layers. This layer is called This layer is called the multiplication layer; however, secondary e- - hole pairs are generated here under the effect of impact ionization.

The multiplication layer, however, secondary e- - hole pairs are generated here under the effect of impact ionization. And the layer i acts as the depletion region where most of the incident photons are absorbed and the primary e- - hole pairs are generated.

So, the e- generated in region i through the gain region and the secondary e- - hole pairs are responsible for the current gain. [10]

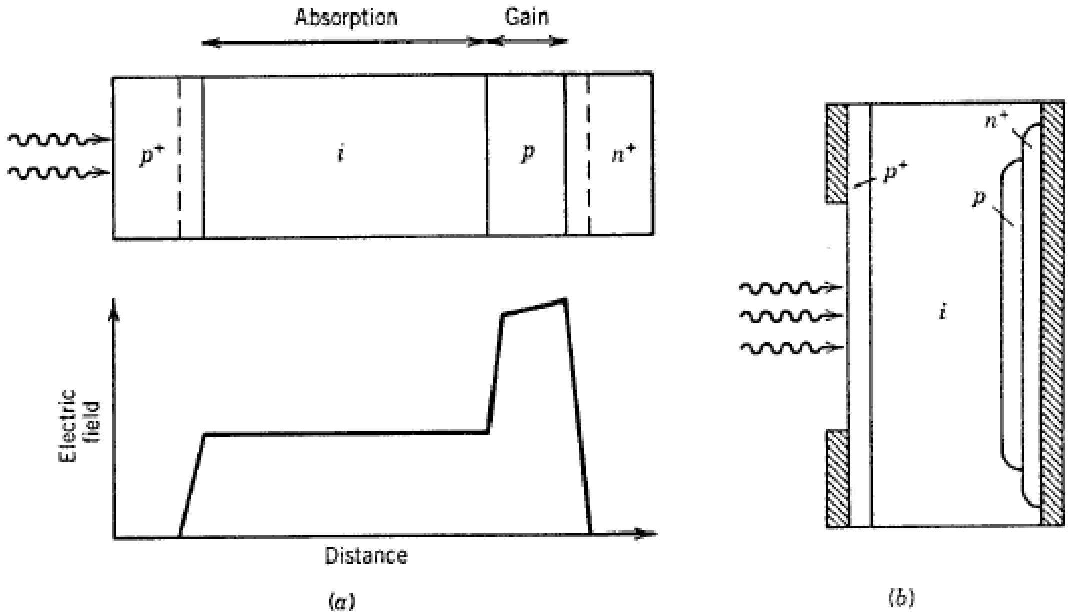


Figure 13: *an APD photodiode with the distribution of an electric field in the different layers under reverse bias, (b): A design of a silicon range of an APD photodiode.[10]*

Conclusion

This chapter has provided an overview of the key components that form the backbone of WDM-PON systems. We discussed the Arrayed Waveguide Grating (AWG) in detail, covering its structure, operation, optical properties, and advantages as a core wavelength multiplexer/demultiplexer. We also explored the challenges and potential solutions associated with cascading multiple AWGs to achieve higher channel counts or finer spectral resolution. Finally, we introduced the essential role of light sources, particularly lasers, and optical receivers in the transmission and reception of optical signals. Understanding the characteristics and limitations of these components is crucial for analyzing and optimizing the overall performance and effectiveness of WDM-PON systems, which will be further investigated in the subsequent chapters.

Chapter III: Simulation and Results

Introduction

In this chapter, we present the various simulations carried out to evaluate the performance of an optical transmission system. The main objective is to analyze the impact of several key parameters such as transmission distance, laser power, modulation format, chromatic dispersion (CD), as well as nonlinear effects like Self-Phase Modulation (SPM) and Cross-Phase Modulation (XPM).

The OptiSystem simulator was used due to its flexibility and accuracy in modeling optical communication networks. Simulations were performed for both NRZ (Non-Return to Zero) and RZ (Return to Zero) signals in order to assess their respective behaviors under different scenarios.

Several performance metrics were studied, including the quality factor (Q-Factor), eye diagram, and bit error rate (BER), which help determine the reliability and transmission quality of the proposed system.

1 Simulation Tool

1.1 OptiSystem

Figure 14: *OptiSystem.*

In this study, we utilized OptiSystem simulation software, developed by Optiwave Systems Inc., to design, model, and analyze the performance of the proposed WDM-PON system based on two cascaded AWG waveguide arrays.

OptiSystem is specifically developed for the design, testing, and optimization of optical communication systems. It offers an intuitive graphical interface that allows users to model sophisticated optical links without requiring extensive programming knowledge.

One of the major strengths of OptiSystem lies in its extensive library of optical components, which includes modules for:

- Lasers
- Modulators
- Single-mode and multi-mode optical fibers
- Optical amplifiers (EDFA, SOA)
- WDM filters and multiplexers
- Photodetectors and Avalanche Photodiodes (APDs)
- Specialized passive components such as Arrayed Waveguide Gratings (AWGs).

The accurate modeling of these components ensures that the simulations closely represent real-world system behavior, which is critical for obtaining credible and reproducible results.
Moreover, OptiSystem provides a suite of advanced performance analysis tools, allowing for the evaluation of important system parameters such as:

- Bit Error Rate (BER)
- Optical Signal-to-Noise Ratio (OSNR)
- Eye Diagram analysis
- Quality Factor (Q-Factor)
- Transmission power and attenuation

These features made OptiSystem particularly suitable for simulating and optimizing the architecture proposed in this study, especially in assessing the behavior of cascaded AWGs under various network conditions.
Due to its flexibility, accuracy, and user-friendliness, OptiSystem has become a widely adopted platform in both academic and industrial research related to optical communications.
In our project, we employed OptiSystem version 20, selected for its specialized modules for WDM system design and its ability to accurately simulate cascaded AWG-based architectures.

1.2 OptiSystem Software Interface Description

The graphical user interface which appears when you open OptiSystem (see Figure 15).

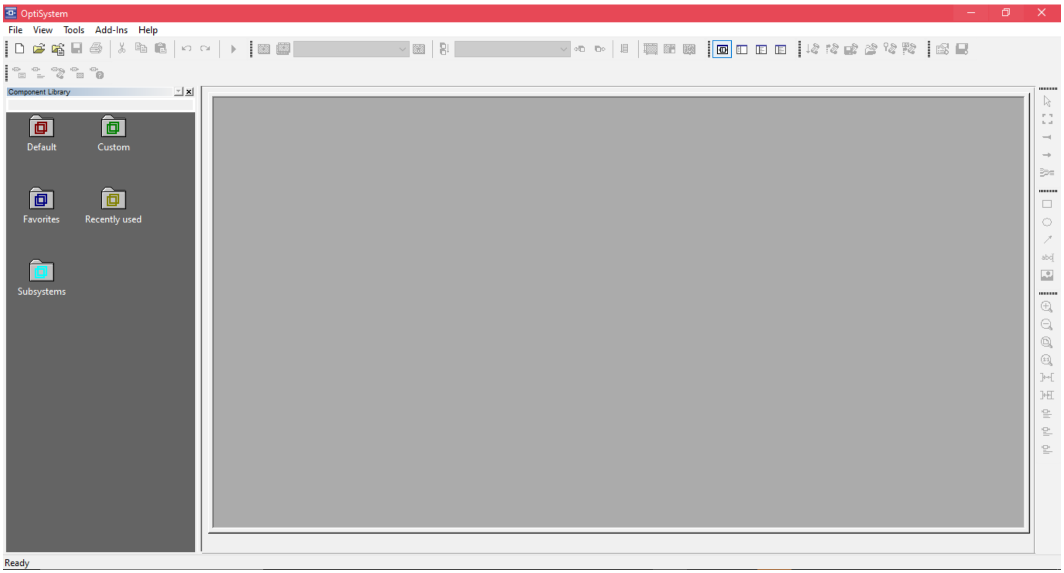


Figure 15: *OptiSystem graphical user interface (GUI).*

Main parts of the GUI:

The OptiSystem GUI contains the following main windows:

• Project layout

The main working area where you insert components into the layout, edit components, and create connections between components (see Figure 15).

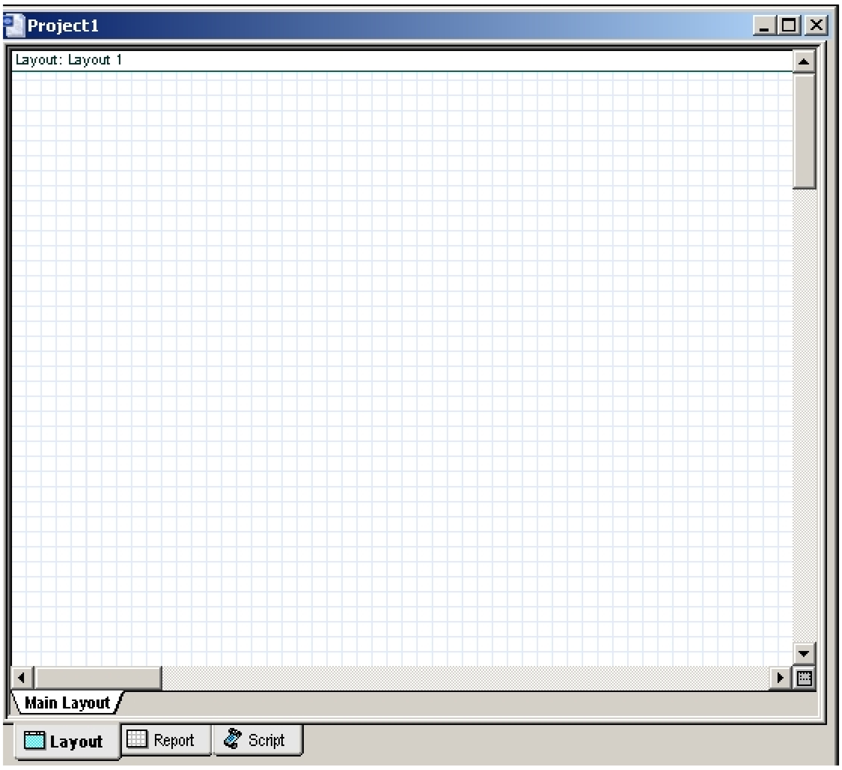


Figure 16: Project layout window.

• Dockers

Dockers, which are found in the main layout, can be used to show details about the current project:

— Component Library

Utilize components to generate the system design (see Figure 16).

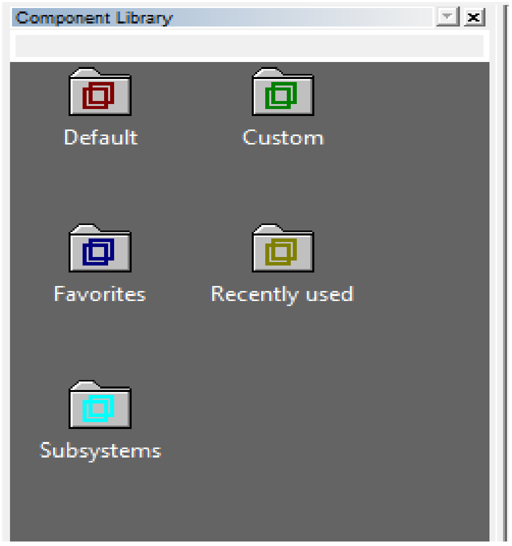


Figure 17: Component Library window.

— Project Browser

Navigate through the current project and organize the project to accomplish results more efficiently (refer to Figure 18).

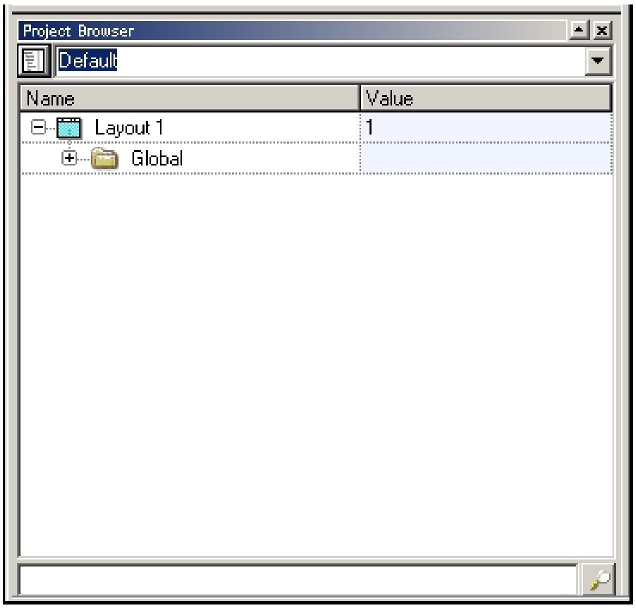


***Figure 18:** Project Browser window.*

— Description

Display detailed information about the current project (see Figure 19).

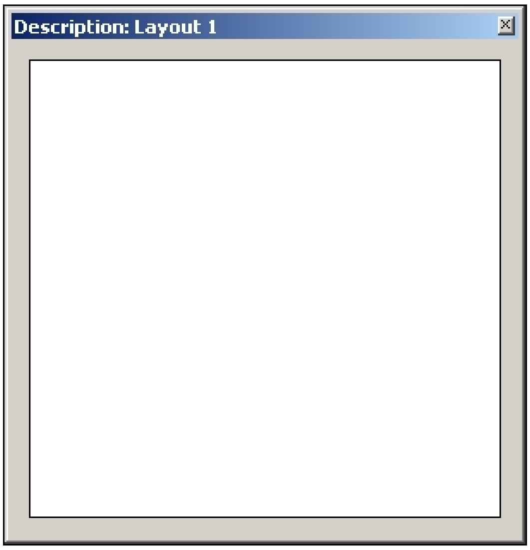


***Figure 19:** Description window.*

- Menu bar

Contains the menus that are available in OptiSystem (see Figure 20).

Figure 20: Menu bar.

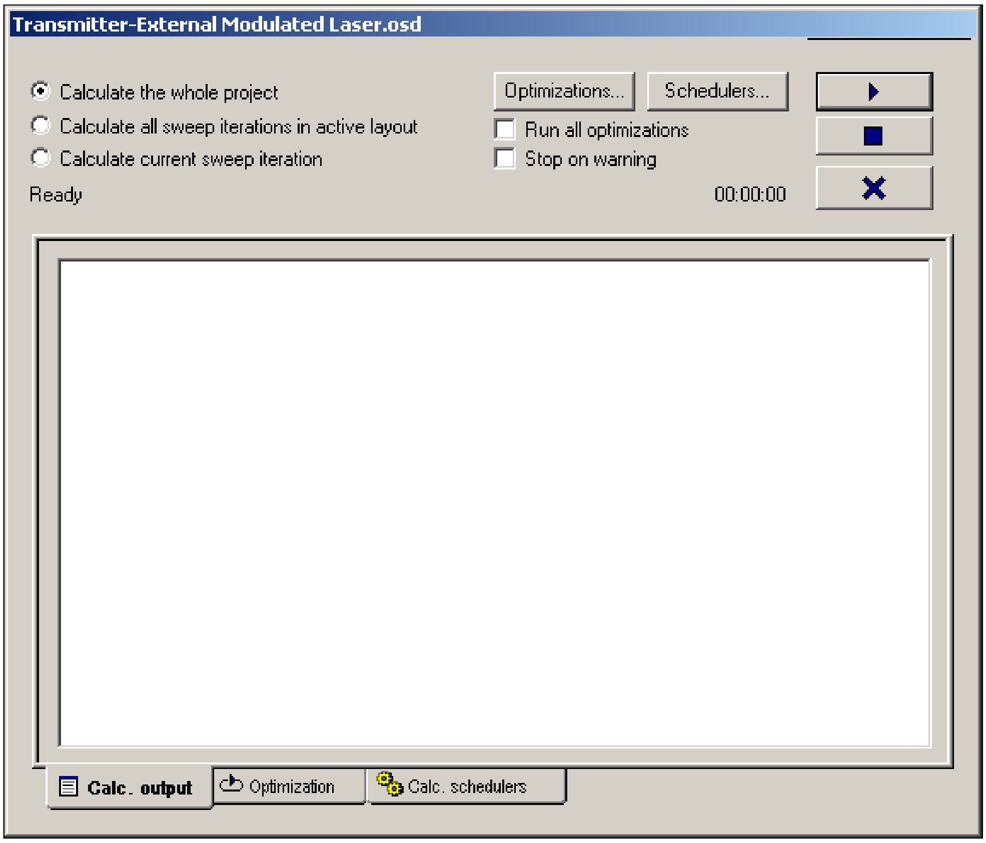


Figure 21: Running the simulation

2 Justification of tool selection

We selected OptiSystem for the modeling of the WDM-PON system as it possesses dedicated focus on the area of optical communication networks. In contrast with Python or MATLAB, it does not require complicated coding and employs an intuitive drag-and-drop environment. Its extensive library of real-world optical devices ensures realistic modeling of components including lasers, modulators, and AWGs. The built-in analysis tools such as BER and eye diagrams help evaluate system performance efficiently. OptiSystem's accuracy and speed made it ideal for our design and testing needs. It saved time while ensuring reliable results.

3 Performance criteria

3.1 Attenuation

In the domain of fiber optics, attenuation refers to the loss of transmission over long distances. This loss is expressed as the logarithmic ratio of the input optical power P_i and the output optical power P_0 in units of decibels.

In fiber optic communications, attenuation is generally expressed in decibels per unit length (i.e. dB/km) [2]:

$$\alpha_{dB}L = 10\ log_{10} \frac{P_i}{P_0} \quad \textit{Equation 5}$$

Where:

α_{dB} is the signal attenuation per unit length in dB, and L: is the fiber length.

The attenuation varies with the wavelength of the light. A typical single-mode fiber offers an attenuation of:

- 2,0 à 2,5 dB/km → 850 nm;
- 0,4 à 0,5 dB/km → 1300 nm;
- 0,25 à 0,30 dB/km → 1550 nm.

3.2 Quality Factor (Q-Factor)

The Q factor is a critical parameter for assessing signal quality in a WDM-PON (Wavelength Division Multiplexing Passive Optical Network) system, as it reflects the signal's resistance to interference and noise. In WDM-PON networks, the Q factor is used to evaluate the reliability of optical transmission, especially over long distances spanning several kilometers. [19]

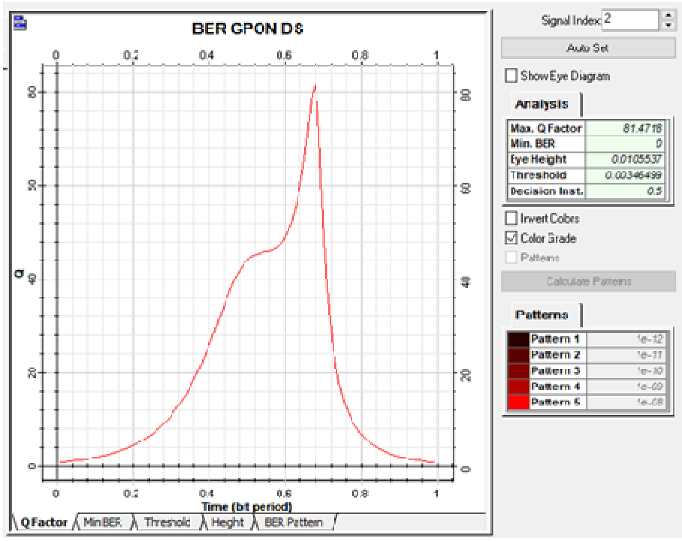


Figure 22: *Q factor.*

3.3 Eye Diagram

The eye diagram is a "visual" method for evaluating the quality of a signal. It is created by superimposing all the binary symbols of the emitted signal. If the signal is of good quality, the eye diagram will be more open, the quality factor will be higher, and the detection of error-free signal will be easier. Thus, the eye diagram is an excellent visual tool to evaluate the signal quality, but it depends on the response of the photodiode and the oscilloscope used [1].

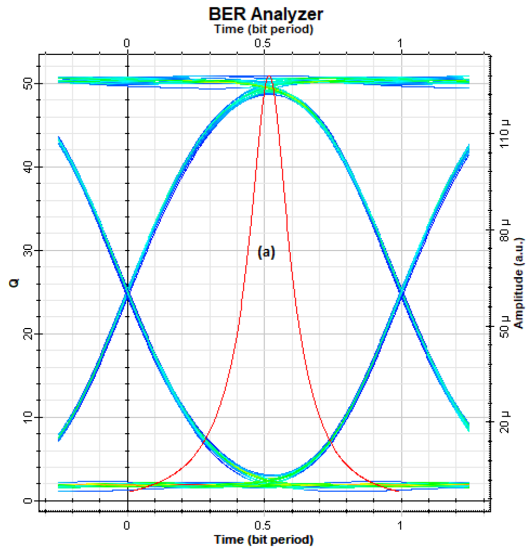


Figure 23: *Eye diagram.*

3.4 Optical Signal-to-Noise Ratio (OSNR)

The optical signal-to-noise ratio, or OSNR, measures how much optical noise interferes with optical signals. Within a legitimate bandwidth, it is the ratio of noise power to service signal power.

The main justification for having a small number of optical amplifiers (OAs) in a network is that the signal's optical signal to noise ratio (OSNR) decreases when it is amplified by an OA, such as EDFA. [18]

$$OSNR = 10.Log10\ (Ps/Pn) \qquad \textit{Equation 6}$$

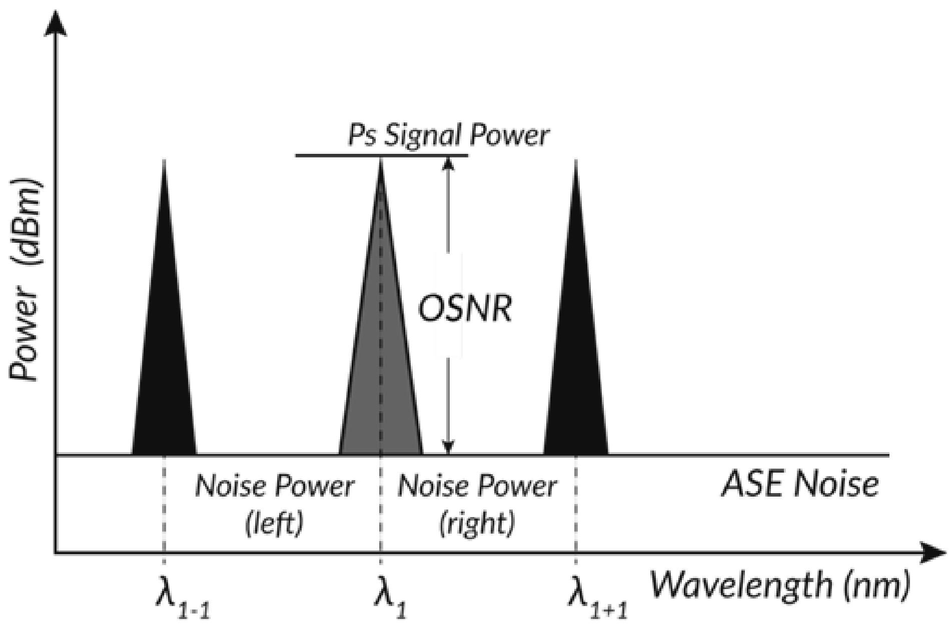


Figure 24: *OSNR.[18]*

3.5 Bit Error Rate (BER)

The transfer of data in a digital format implies that it is communicated as sequences of binary data. To assess the quality of a binary digital transmission, it is essential to compare the sent sequence of symbols with the received one. This comparison is achieved by calculating the number of incorrect bits, which refers to the instances where a "0" is detected for a transmitted "1" symbol, or vice versa. The binary error rate (BER) is then defined as the number of incorrect bits divided by the total number of bits transmitted. [1]

$$BER = \frac{nombre\ de\ bits\ erronés}{nombre\ de\ bits\ totals\ envoyés} \quad \textit{Equation 7}$$

In the domain of optical communication systems, a system is deemed of high quality when the binary error rate (BER) is inferior to or equal to 10^-9, with a quality factor (Q) superior or equal to 6, depending on the specific system. In our optical network, the eye diagram serves as an indicator mirroring the network's performance and determines any degradation that may impact the quality of service. It is crucial to acknowledge that a fully open eye corresponds to a better quality factor Q, and conversely.

3.6 Transmission distance

The Transmission Distance refers to the maximum distance at which an optical signal can be transmitted while maintaining an acceptable level of service quality, adhering to loss and degradation limitations. This distance is influenced by several factors, such as:

- The power of the transmitter and the receiver's sensitivity.
- The optical cable attenuation standard (dB/km).
- Losses incurred due to connectors, optical butt joints (OBJ), and other passive components.
- Chromatic dispersion of the signal.

Generally, for WDM-PON networks, the transmission distance can reach:

- About 20 to 40 km, depending on the quality of the installation, the transmitter power, and the noise tolerance
- With the use of repeaters or optical amplifiers, this distance can be extended

It is crucial to properly dimension the transmission distance during network planning to ensure optimal performance and to stay within the technical limits of the technology used.

3.7 Power laser

Laser power refers to the amount of energy emitted by the laser source per unit time, typically measured in milliWatts (mW) or decibels-milliWatts (dBm). It plays a crucial role in determining the quality of transmission and the network's range.

An appropriate laser power must balance several factors:

- **Range:** Higher power enables coverage of longer distances by compensating for losses due to fiber attenuation and passive component insertion.
- **Signal Quality:** Excessively high power can induce interference or saturate the receiver, whereas insufficient power may result in signal degradation or increased error rates.
- **Energy Efficiency:** Proper calibration of laser power reduces electrical consumption while maintaining optimal performance.

In WDM-PON systems, the laser power must adhere to regulatory standards to prevent damage to components and ensure compliance with safety guidelines. These laser sources are often modulated in amplitude, phase, or frequency to transmit data effectively.

4 Architecture proposed

In this system, there are three main stages: the transmitter stage, the transmission medium, and the receiver stage. The system is based on a Passive Optical Network (PON) architecture and supports bidirectional communication, consisting of a downstream (OLT to ONU) and an upstream (ONU to OLT) direction. The performance of the system will be evaluated in both directions by analyzing the impact of key parameters such as link length, transmission power, and modulation format on the WDM-PON system.

The simulated WDM-PON system consists of eight downstream channels and eight upstream channels. The Optical Line Terminal (OLT) transmits multiple wavelengths simultaneously over a single optical fiber link, with distances ranging from 20 km to 70 km and varying launch powers from -10 dBm to 10 dBm. The data rate per channel is 2.5 Gbps, leading to a total aggregate rate of 8 × 2.5 Gbps, as detailed in the system specifications.

The architecture includes two cascaded Arrayed Waveguide Gratings (AWGs) to manage wavelength multiplexing and demultiplexing. The first AWG acts as a multiplexer/demultiplexer at the central office, while the second AWG is placed closer to the end users to route individual wavelengths to their respective Optical Network Units (ONUs). These AWGs allow for efficient wavelength routing without the need for active switching components.

At the receiver side, each ONU is equipped with a wavelength-selective filter or demultiplexer to extract and process only the signal corresponding to its assigned wavelength. The modulation format used throughout the system is NRZ (Non-Return-to-Zero), which provides a good balance between complexity and performance.

This architecture enables point-to-point (P2P) connections between the OLT and each ONU using dedicated wavelengths, eliminating the need for access control mechanisms typically required in TDM-PON systems. The use of two cascaded AWGs enhances spectral efficiency and allows for scalable deployment in dense wavelength environments.

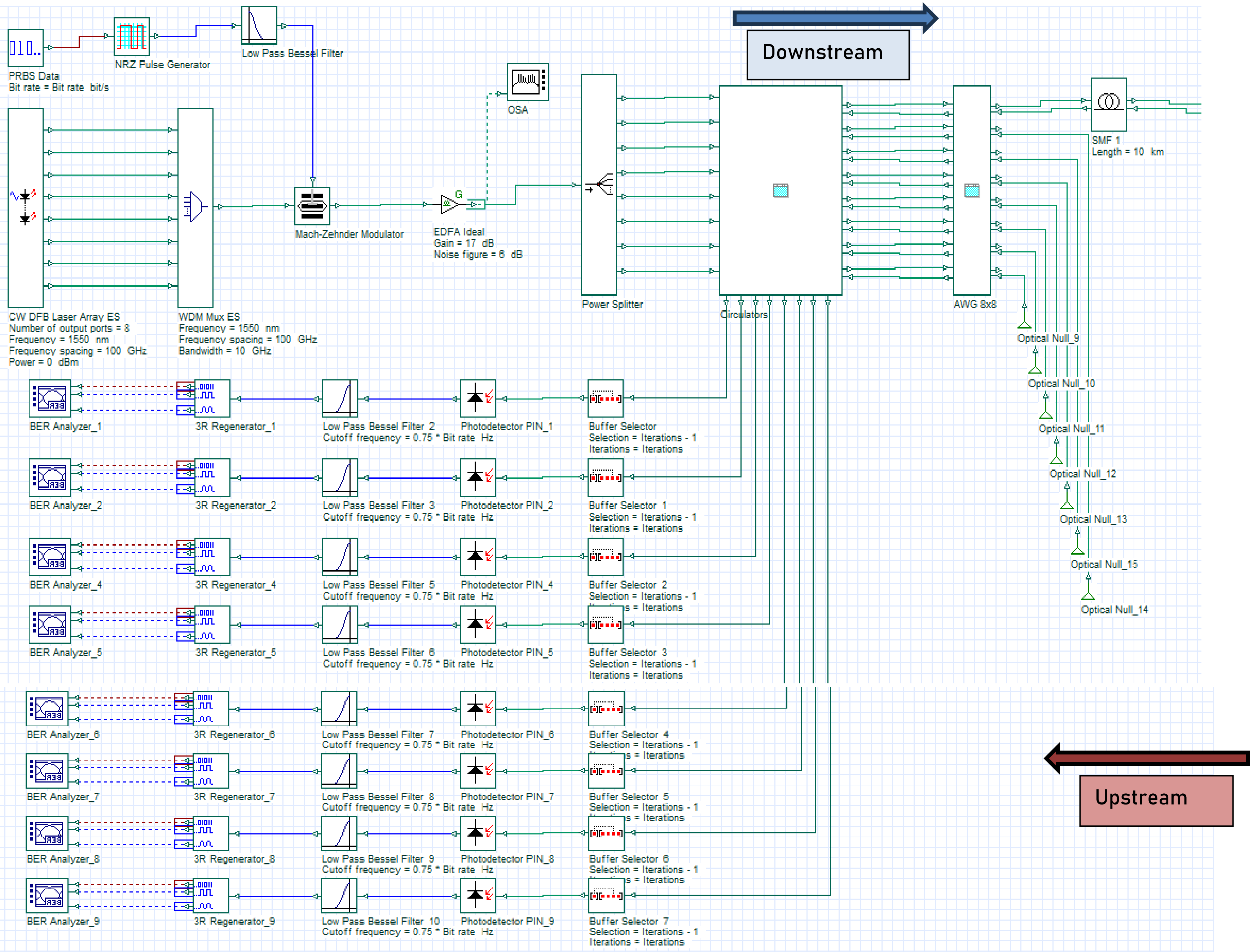


Figure 25: *Diagram of the WDM-PON System for Eight Users (OLT).*

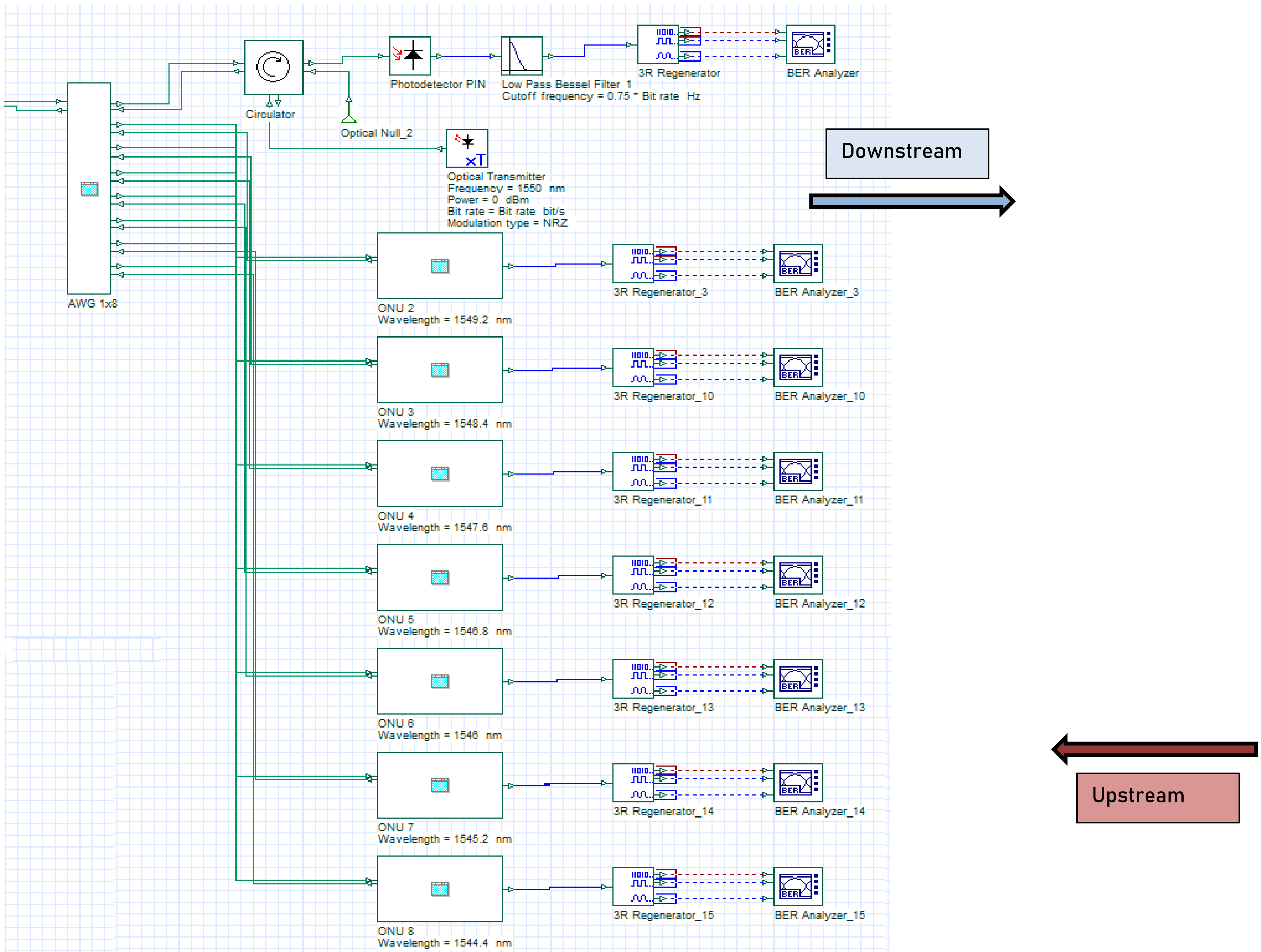
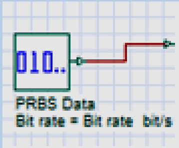
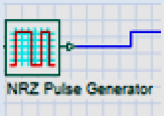
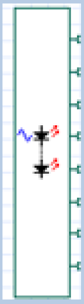
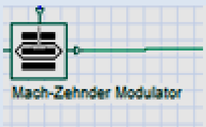
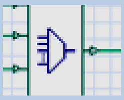
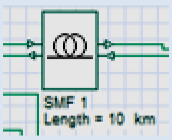


Figure 26: *Diagram of the WDM-PON System for Eight Users (ONU).*

5 Components of the system

In the table below, we define the elements that constitute the architecture of the proposed system.

Component	Block in OptiSystem	Function
Bit generator pseudo-random PRBS		It is a device that produces a sequence binary sequence of random or pseudo-random bits. This sequence is used as a source of data to be transmitted over the optical link.
Type of coding (modulation format)		Improve the robustness and integrity of the data transmitted in an optical transmission chain.
Laser CW (Continuous Wave Laser)		The CW laser is a source of continuous optical light. continuous. It generates a beam of light coherent that serves as an optical signal carrying the data to be transmitted. The frequency and the laser power can vary depending on the transmission system requirements.
Mach-Zehnder modulator		The Mach-Zehnder modulator is a device optical device that modifies the intensity of light in function of the electrical signal applied to it.
WDM Mux		Allows multiplexing several optical signals at different wavelengths (colors) on a single optical fiber.
Fiber optic bidirectional		Allowing both technologies to use the same fiber optic infrastructure while separating the optical signals through the use of different wavelengths.

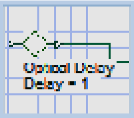
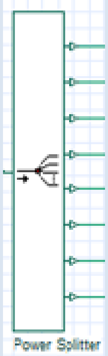
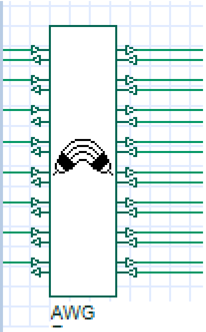
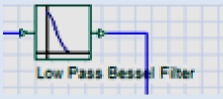
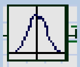
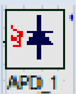
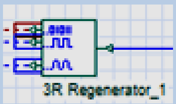
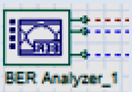
Optical Delay		Facilitates the access technique for customers in the upstream direction.
Power Splitter		Passive component that splits the multiplexed optical signal into multiple equal-power paths, enabling simultaneous distribution of the signal to several circulators at the input of an AWG network.
AWG		Passive optical component used to demultiplex or multiplex WDM signals by precisely separating or combining wavelengths based on their frequency.
Bessel Low-Pass Filter		Allowing the extraction of useful information.
Band-pass filter Bessel		Used to filter optical signals with a large bandwidth, while maintaining a relatively narrow impulse response.
Optical receiver (PIN Photodiode)		Allows to convert the optical signal into electric, and to adjust the decision threshold based on the received data packets.
3R Regenerator		It's a 3R type repeater, its role is to resynchronize the optical signal.
Bit Error Rate (BER) Analyzer		This component allows us to see the eye diagram and compare the bits delivered and received in order to assess the system performance.

Table 3: *The elements that constitute the architecture of the proposed system.*

6 Parameters of system

The table below shows the parameters used in our system:

Parameters	Values
Bit rate	2.5 Gbps/canal (downstream), 2.5 Gbps/canal (upstream)
Pulse generator	NRZ/RZ
Laser Power	-15 dBm to +15 dBm
Length of the fiber	10 km, 20 km, 30 km, 40 km, 50 km, 60 km, 70 km.
Chromatic dispersion CD	17 ps/nm/km.
Attenuation	0.24 dB/km.
EDFA Gain	17 dB.
Number of users	8 channels
Wavelength (downstream)	1550 nm/channel
Wavelength (upstream)	
The video (broadcast)	1550 nm.
Spacing between channels	0.8 nm.

Table 4: *Parameters of WDM-PON system.*

7 Impact of Fiber Length (NRZ Modulation)

This simulation aims to evaluate the effect of increasing fiber length on the performance of a WDM-PON system using NRZ modulation. The transmission power is fixed at 0 dBm, and the fiber spans from 10 km to 70 km. Chromatic dispersion is taken into account, while nonlinear effects are excluded.

7.1 Downstream Transmission

Length (km)	Q factor Down	BER down	Image
10	50,91	0	(a)
20	42,96	0	(b)
30	28,81	6,04e-183	(c)
40	17,53	3,80e-69	(d)
50	10,26	4,86e-25	(e)
60	8,15	1,72e-16	(f)
70	3,44	0,00028	(g)

Table 5: *Downstream transmission – Q factor and BER as a function of fiber length (Power = 0 dBm, NRZ, With CD, Without Nonlinear Effects).*

In the **downstream direction**, the system performs well up to **60 km**. The Q factor remains high ($Q > 8$), and the Bit Error Rate (BER) is almost zero. However, at **70 km**, performance drops significantly: **Q = 3.44** and **BER = 2.8×10^{-4}**, which exceeds acceptable limits for reliable communication. Eye diagrams clearly show this degradation, with the eye becoming nearly closed at longer distances.

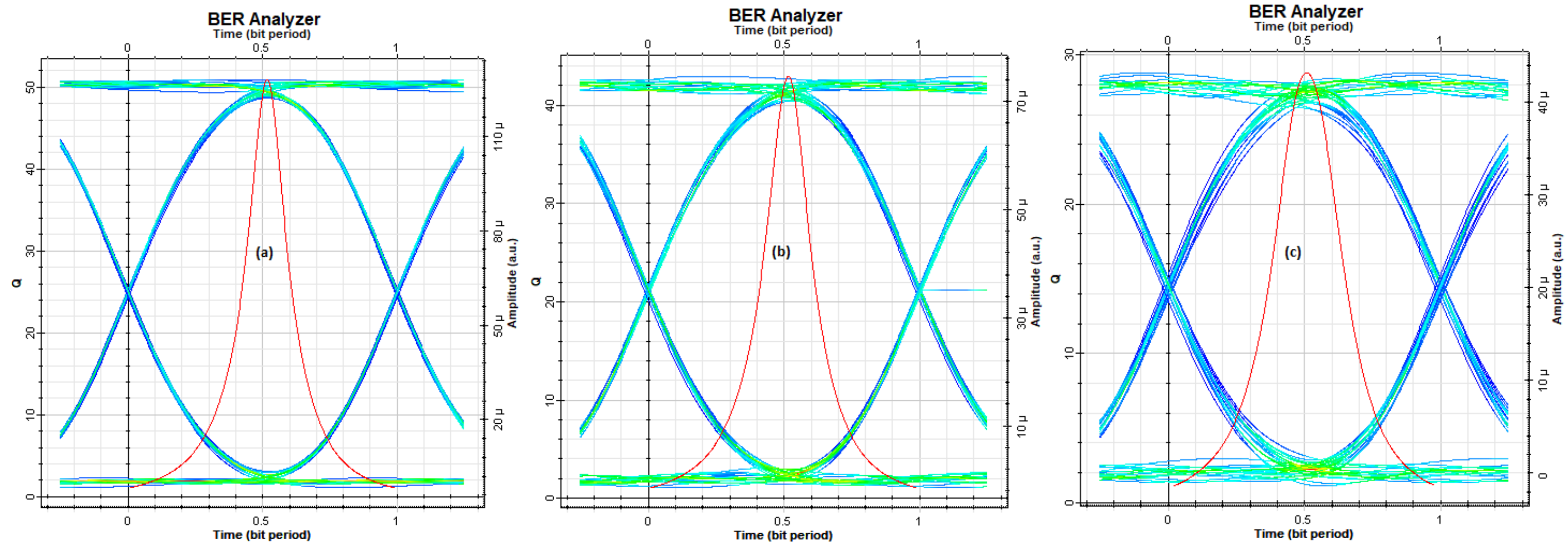


***Figure 27:** Eye diagram of the downstream signal for a fiber length of 10 km(a) Eye diagram of the downstream signal for a fiber length of 20 km(b) Eye diagram of the downstream signal for a fiber length of 30 km(c).*

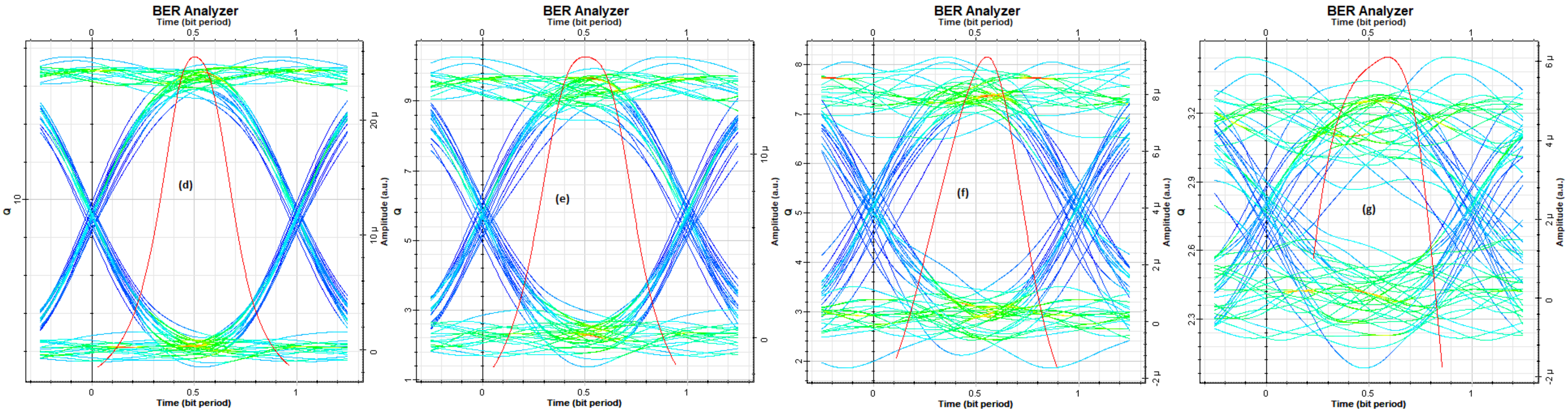


***Figure 28:** Eye diagram of the downstream signal for a fiber length of 40 km(d) Eye diagram of the downstream signal for a fiber length of 50 km(e) Eye diagram of the downstream signal for a fiber length of 60 km(f) Eye diagram of the downstream signal for a fiber length of 70km(g)*

7.2 Upstream Transmission

Length (km)	Q factor up	BER up	Image
10	43,46	0	(a)
20	26,56	9,57e-156	(b)
30	15,98	7,89e-58	(c)
40	9,54	7,07e-22	(d)
50	5,68	6,40e-09	(e)
60	3,40	0,00032	(f)
70	2,06	0,019	(g)

Table 6: *Upstream transmission – Q factor and BER as a function of fiber length (Power = 0 dBm, NRZ, With CD, Without Nonlinear Effects)*

In the **upstream direction**, the quality drops more quickly. The system maintains acceptable performance up to **50 km** (**Q = 5.68**, **BER = 6.4×10^{-9}**), but beyond this point, signal quality degrades. At **70 km**, the Q factor falls to **2.06**, and the BER reaches **1.9×10^{-2}**, indicating serious transmission issues.

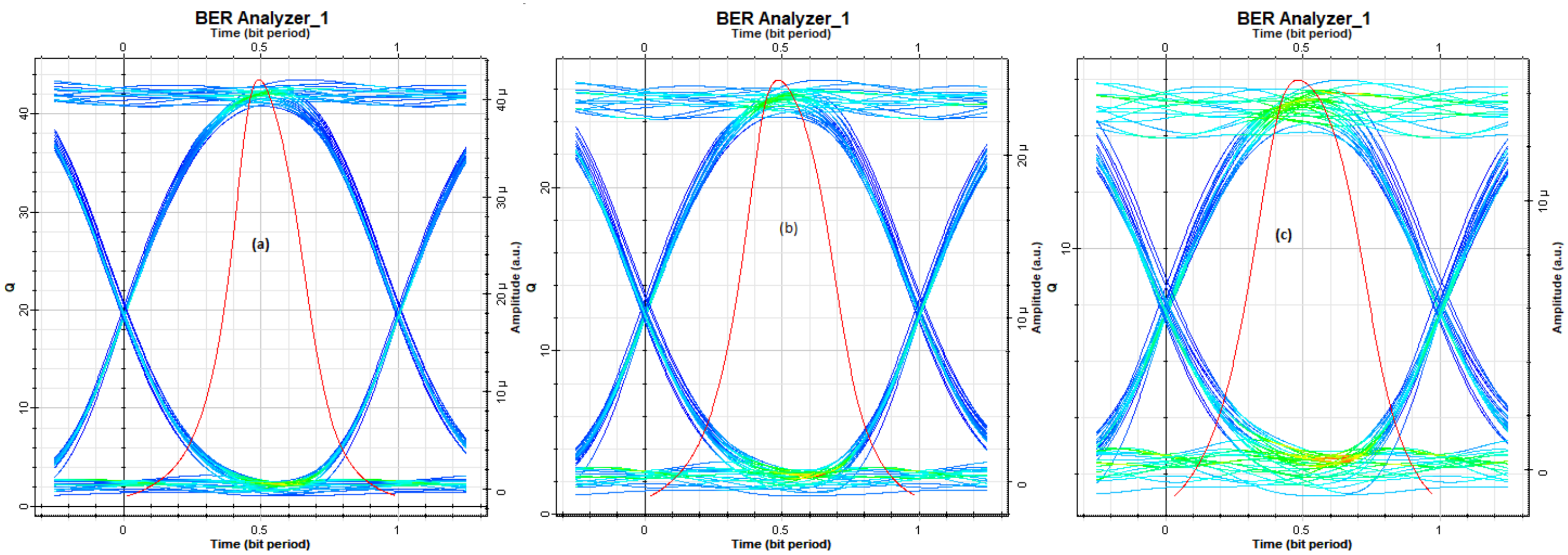


Figure 29: *Eye diagram of the upstream signal for a fiber length of 10 km(a) Eye diagram of the upstream signal for a fiber length of 20 km(b) Eye diagram of the upstream signal for a fiber length of 30 km(c).*

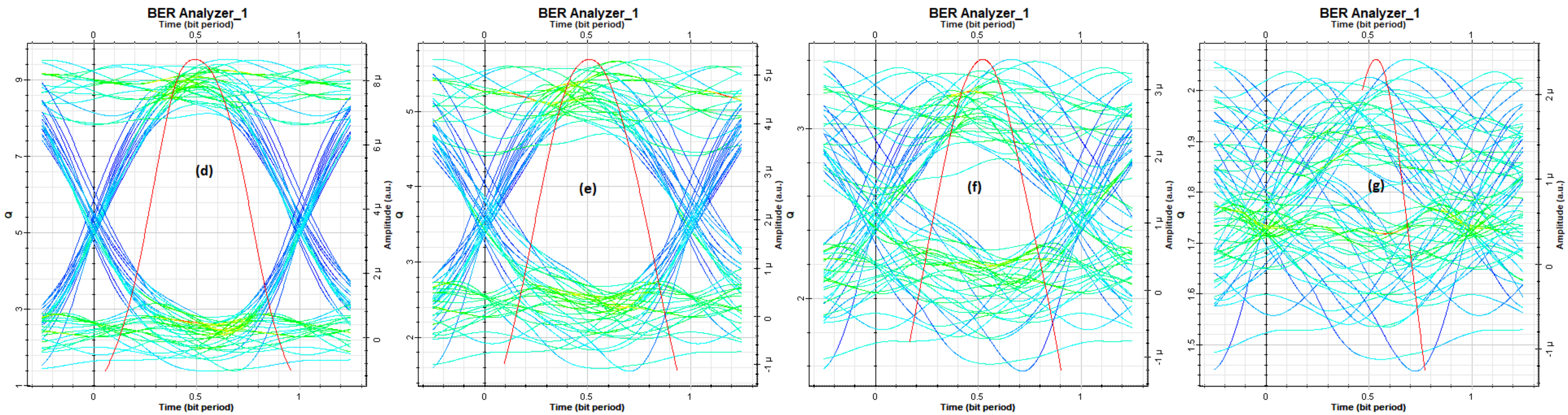


Figure 30: *Eye diagram of the upstream signal for a fiber length of 40 km(d) Eye diagram of the upstream signal for a fiber length of 50 km(e) Eye diagram of the upstream signal for a fiber length of 60 km(f) Eye diagram of the upstream signal for a fiber length of 70km(g)*

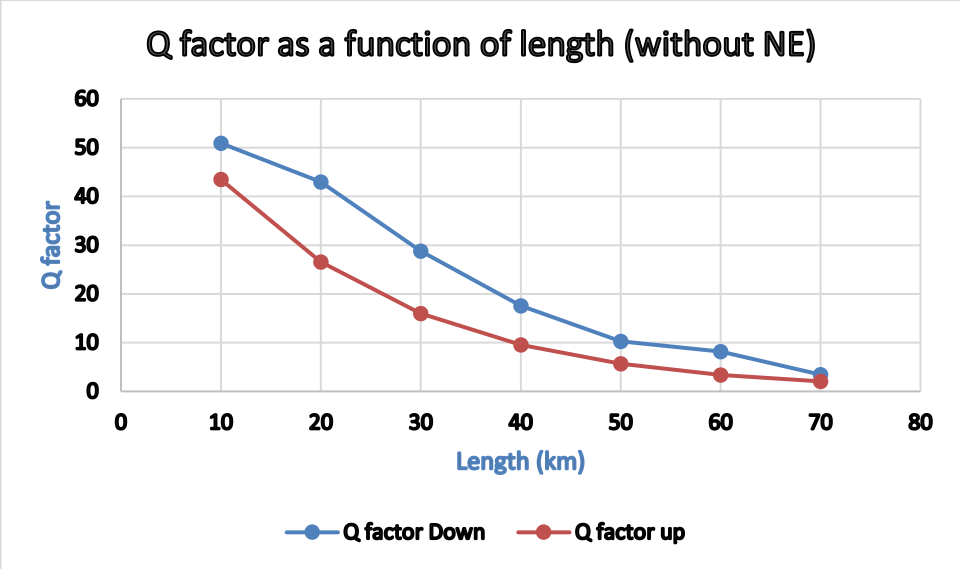


Figure 31: *Evolution of the Q factor vs. fiber length – Downstream and Upstream (Power = 0 dBm, NRZ, With CD)*

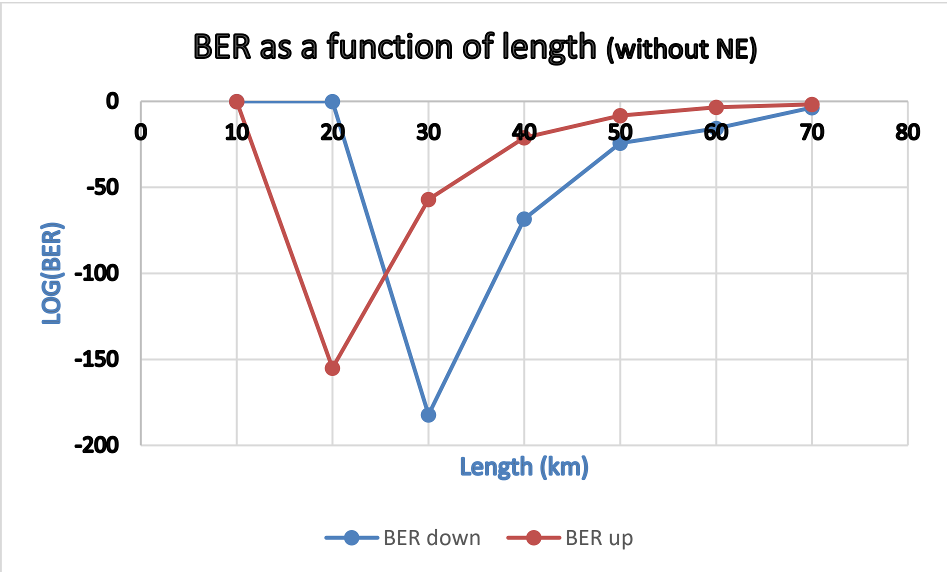


Figure 32: *Bit Error Rate (BER) vs. fiber length – Downstream and Upstream (Power = 0 dBm, NRZ, With CD)*

The Q factor and BER curves show a clear trend: **as fiber length increases, signal quality decreases**, with a stronger impact in the upstream direction than in the downstream.

Fiber length is a critical factor in the performance of the WDM-PON system. Without compensation, the system can operate reliably up to **60 km downstream** and **50 km upstream**. Beyond these distances, performance degrades significantly. To maintain good transmission quality, it is necessary to implement solutions such as **optical amplification** or **chromatic dispersion compensation**.

8 Impact of Non-linear Effects (NRZ Modulation)

This simulation investigates the combined impact of chromatic dispersion (CD) and nonlinear optical effects (SPM, XPM) on the performance of a WDM-PON system using NRZ modulation at a fixed launch power of 0 dBm.

8.1 Downstream Transmission

Length (km)	Q factor Down	BER Down	Image
10	37,68	4,57e-311	(a)
20	33,62	3,70e-248	(b)
30	29,15	3,46e-187	(c)
40	17,96	1,99e-72	(d)
50	12,26	7,12e-35	(e)
60	7,95	8,96e-16	(f)
70	3,77	8,14e-05	(g)

Table 7: *Downstream transmission: Q factor and BER as a function of fiber length (NRZ, Power = 0 dBm, With CD, With Nonlinear Effects)*

In the downstream direction, the system maintains reliable performance up to 60 km, with a Q factor of 7.95 and a BER of 8.96×10^{-16}, remaining within acceptable quality thresholds ($Q \geq 5.5$, $BER \leq 10^{-9}$). At 70 km, the Q factor drops to 3.77 and the BER increases to 8.14×10^{-5}, indicating significant degradation due to the combined effects of dispersion and nonlinearities. Eye diagrams confirm this, showing progressive narrowing and signal distortion with increasing distance.

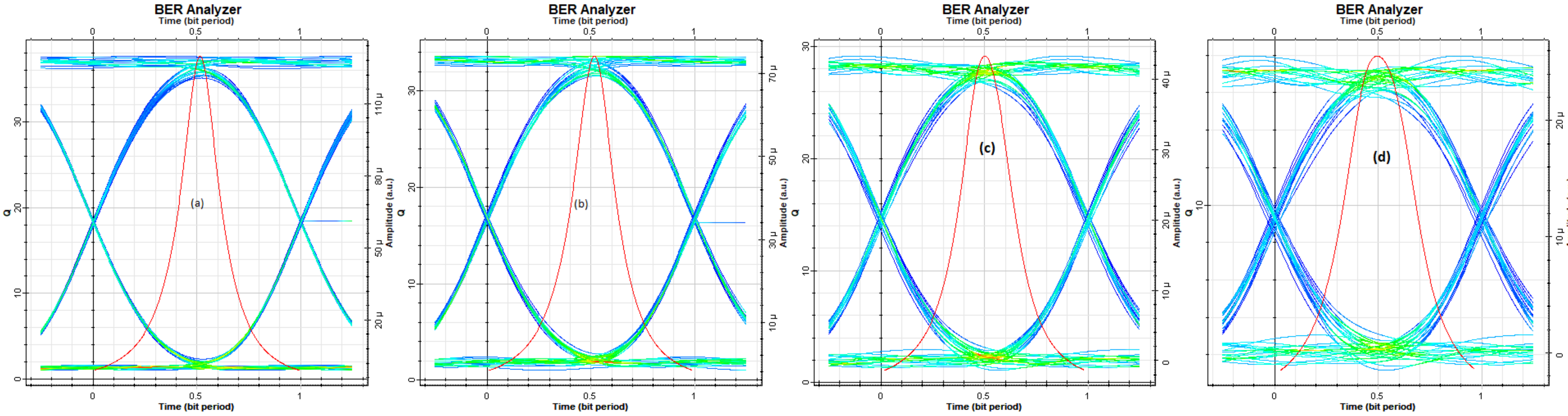


Figure 33: *Eye diagram of the downstream signal for a fiber length of 10 km(a)Eye diagram of the downstream signal for a fiber length of 20 km(b) Eye diagram of the downstream signal for a fiber length of 30 km(c).*

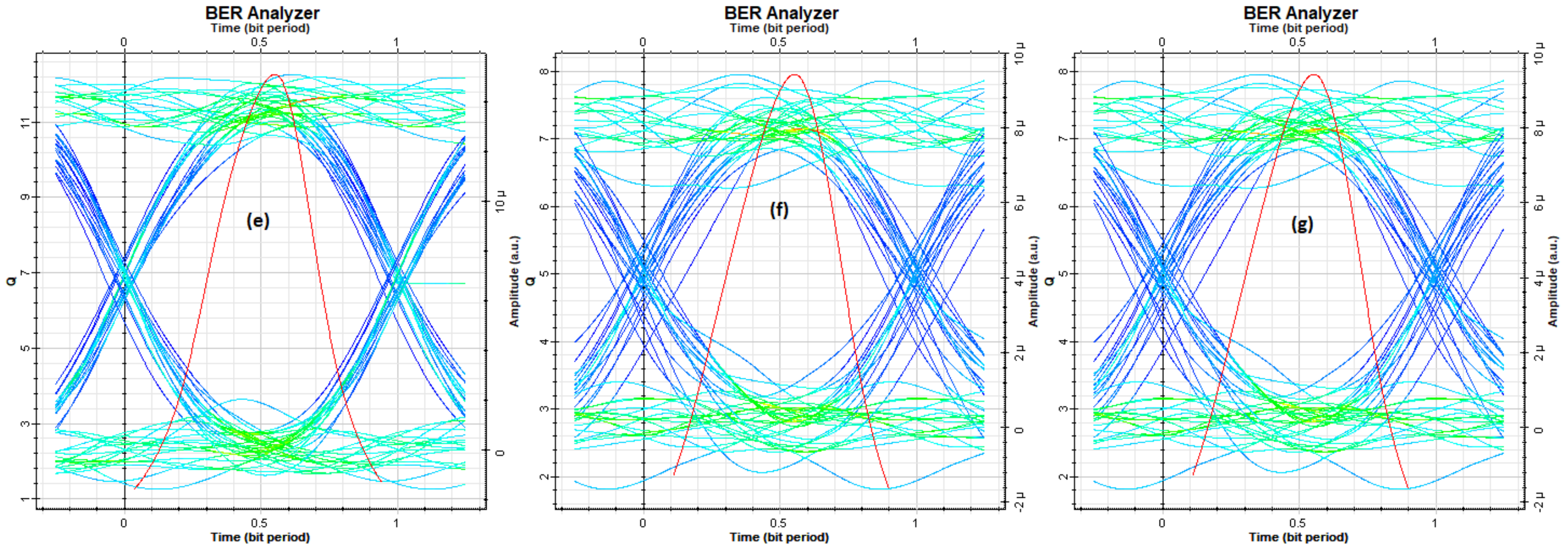


Figure 34: *Eye diagram of the downstream signal for a fiber length of 40 km(d)Eye diagram of the downstream signal for a fiber length of 50 km(e)Eye diagram of the downstream signal for a fiber length of 60 km(f)Eye diagram of the downstream signal for a fiber length of 70km(g)*

8.2 Upstream Transmission

Length (km)	Q factor up	BER up	Image
10	42,12	0	(a)
20	26,44	2,04e-15	(b)
30	15,81	1,23e-56	(c)
40	9,58	4,65e-22	(d)
50	5,85	2,29e-09	(e)
60	2,77	0,002	(f)
70	0	1	(g)

Table 8: *Upstream transmission: Q factor and BER as a function of fiber length (NRZ, Power = 0 dBm, With CD, With Nonlinear Effects)*

In the upstream direction, the impact of these impairments is more severe. Acceptable performance is maintained up to 50 km ($Q = 5.85$, $BER = 2.29 \times 10^{-9}$), but rapidly deteriorates beyond that. At 60 km, Q drops to 2.77 and BER exceeds 10^{-3}, while at 70 km, transmission fails entirely ($Q = 0$, $BER = 1$).

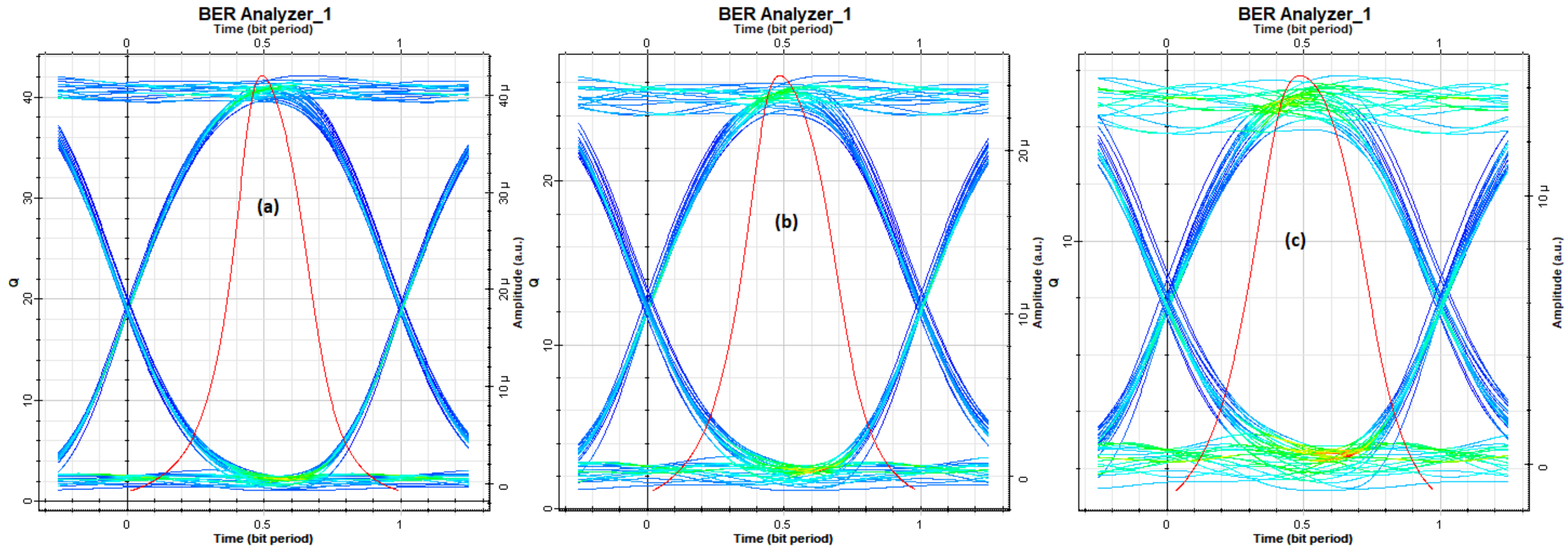


Figure 35: *Eye diagram of the upstream signal for a fiber length of 10 km(a) Eye diagram of the upstream signal for a fiber length of 20 km(b) Eye diagram of the upstream signal for a fiber length of 30 km(c).*

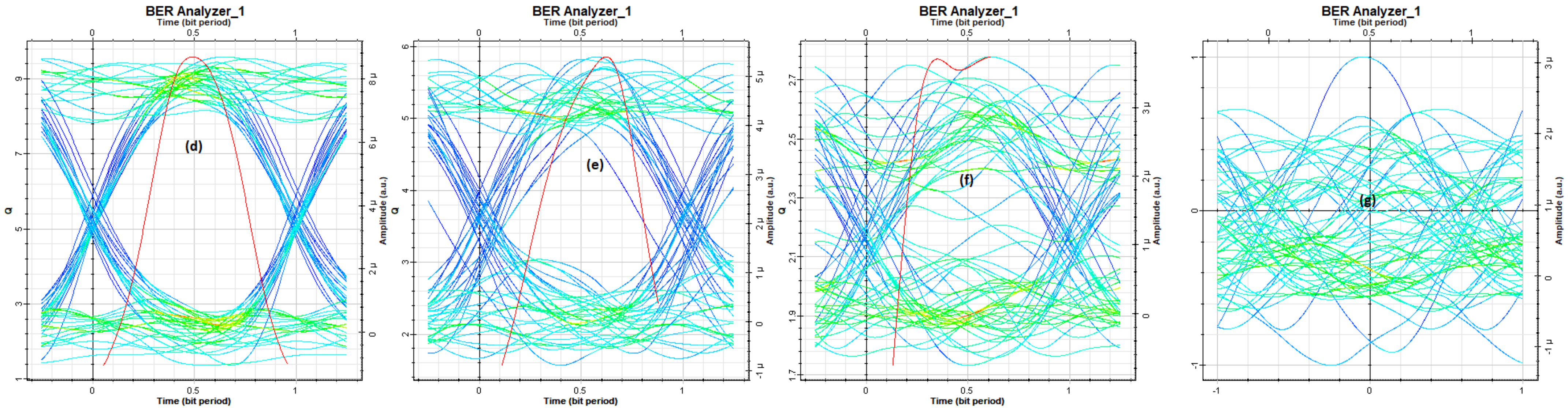


Figure 36: *Eye diagram of the upstream signal for a fiber length of 40 km(d) Eye diagram of the upstream signal for a fiber length of 50 km(e)Eye diagram of the upstream signal for a fiber length of 60 km(f) Eye diagram of the upstream signal for a fiber length of 70km(g)*

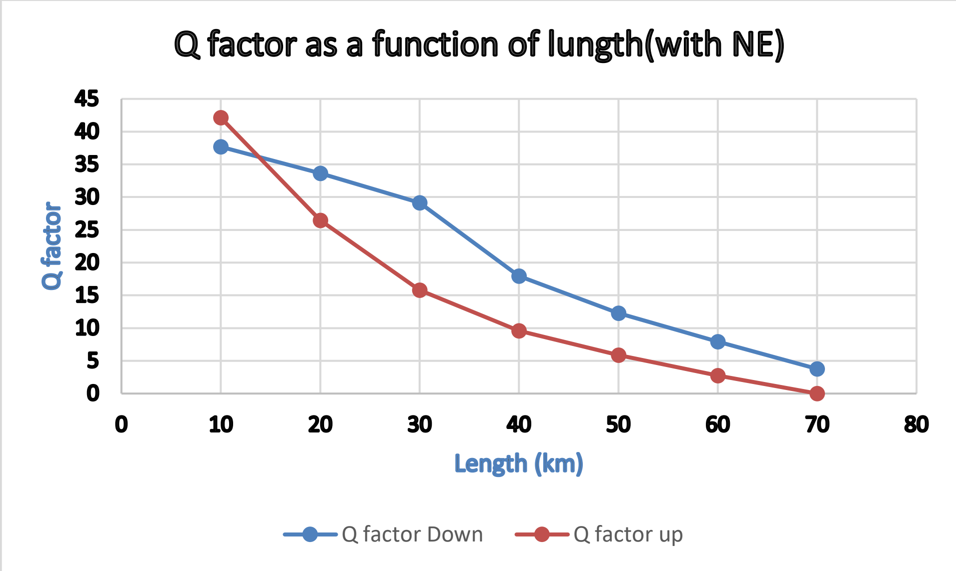


Figure 37: *Variation of Q factor versus fiber length for downstream and upstream directions (NRZ, With CD, With Nonlinear Effects)*

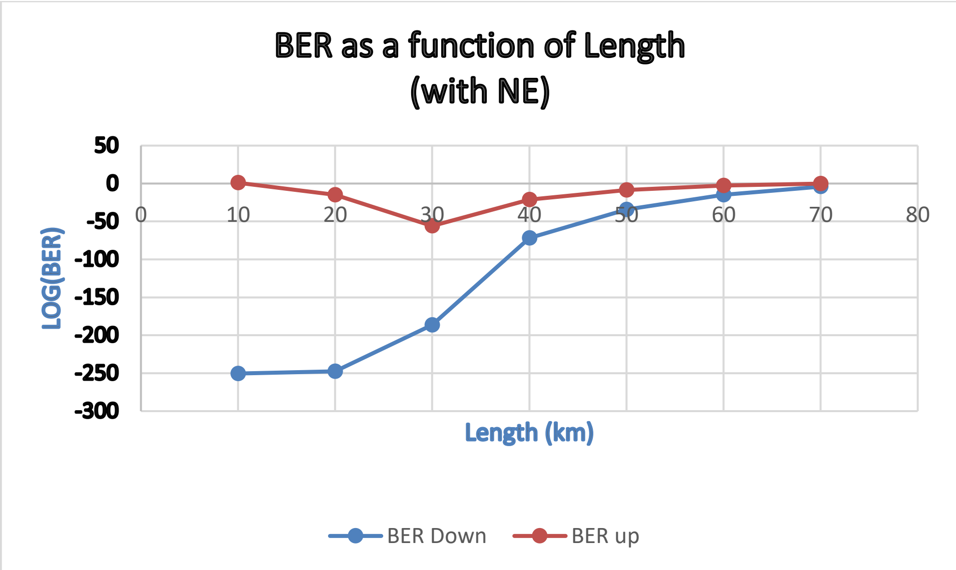


Figure 38: *Variation of BER versus fiber length for downstream and upstream directions (NRZ, With CD, With Nonlinear Effects)*

The Q factor and BER curves show a clear trend: as fiber length increases, signal quality decreases, with a stronger impact in the upstream direction than in the downstream. This highlights the upstream path's higher sensitivity to the joint effects of CD and nonlinearities.

The results demonstrate that the **combined effects of chromatic dispersion and nonlinearities** significantly limit system reach under NRZ modulation. Without compensation, the WDM-PON system can operate effectively **up to 60 km downstream** and **50 km upstream**. Beyond these distances, the system exceeds acceptable error rates. Implementing **dispersion compensation** or **nonlinearity mitigation** is essential for ensuring reliable long-distance transmission.

9 Impact of Power (NRZ Modulation)

In this simulation, we studied the effect of varying the transmitter power on the performance of a WDM-PON system using NRZ modulation. The fiber length was fixed at **50 km**, and chromatic dispersion was included. Simulations were conducted both **with and without nonlinear effects (SPM and XPM)** to evaluate their influence on system behavior. The transmitted optical power was varied from **–10 dBm to +10 dBm**, and for each power level, we analyzed the system performance in both **downstream and upstream directions**. Key performance metrics such as the **Q factor**, **Bit Error Rate (BER)**, and **eye diagrams** were recorded to assess signal quality at each configuration.

9.1 Without Nonlinear Effects (NE)

9.1.1 Downstream Transmission

Power (dBm)	Q factor down	BER down	Image
-10	0	1	(a)
-5	3,28	0,0005	(b)
0	13,51	6,12e-42	(c)
5	29,47	3,30e-191	(d)
10	56,07	0	(e)

Table 9: *Downstream transmission: Q factor and BER as a function of power (NRZ, Length = 50 km, With CD, Without Nonlinear Effects)*

In the downstream direction, the system shows a clear dependence on transmission power when nonlinear effects are absent. At –10 dBm, the signal is completely degraded (Q = 0, BER = 1), and the eye diagram is fully closed. From –5 dBm, the transmission becomes acceptable (Q = 6.17, BER ≈ 10^{-10}), with a partially open eye. As the power increases to 0 dBm and higher, signal quality improves significantly. At +10 dBm, the system reaches optimal performance (Q = 56.07, BER = 0), and the eye diagram is wide open, indicating strong signal integrity.

These results demonstrate that, without the presence of nonlinear effects, the downstream link can achieve high reliability over 50 km using moderate power levels.

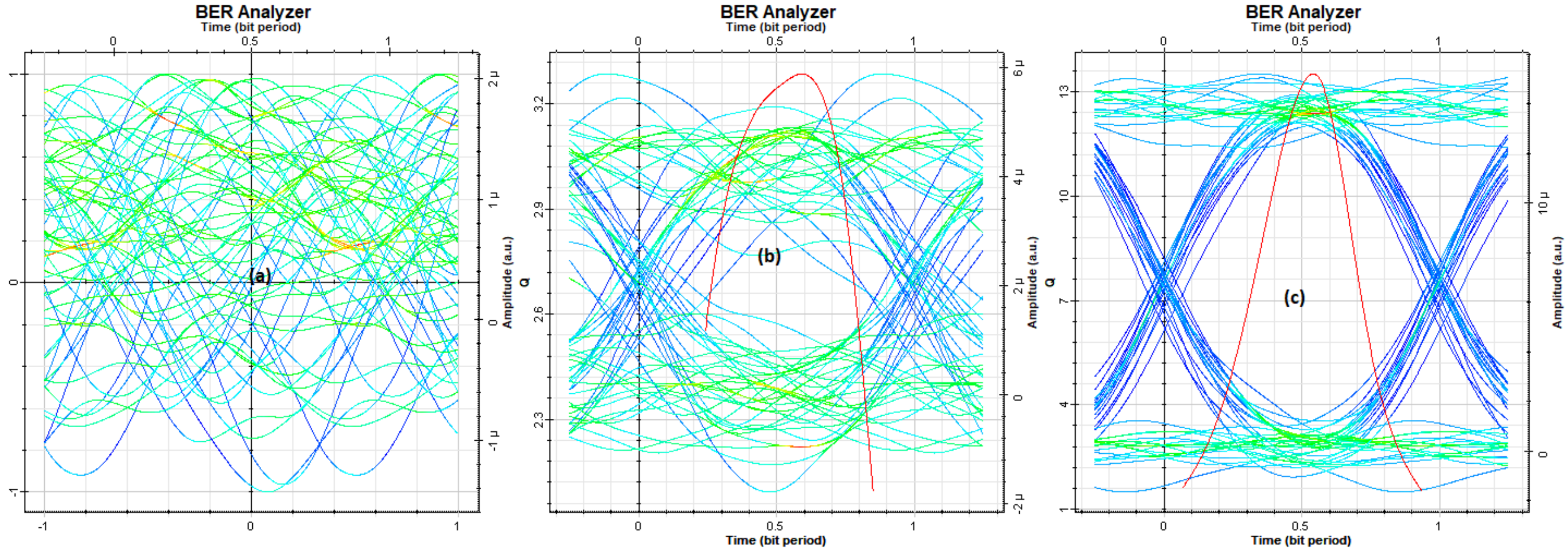


Figure 39: *Eye diagram of the downstream signal for a power of -10 dBm (a)Eye diagram of the downstream signal for a power of -10 dbm for a power of -5 dBm (b) Eye diagram of the downstream signal for a power of 0 dBm (c).*

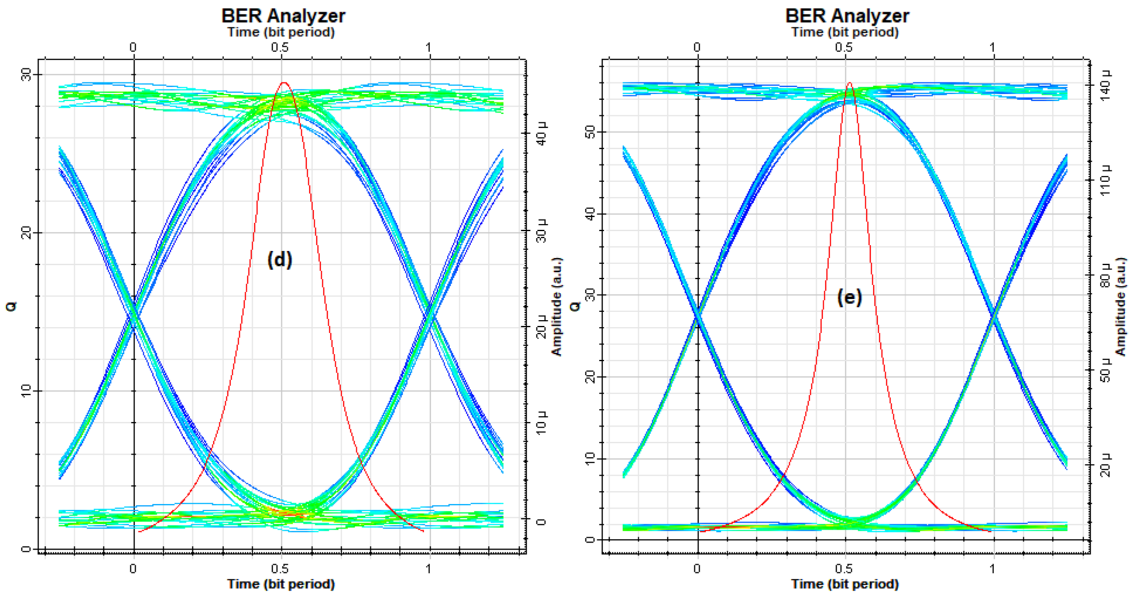


Figure 40: *Eye diagram of the downstream signal for a power of 5 dBm (d) Eye diagram of the downstream signal for a power of 10 dBm (e)*

9.1.2 Upstream Transmission

Power (dBm)	Q factor up	BER up	Image
-10	0	1	(a)
-5	1,96	0,024	(b)
0	4,76	9,27e-07	(c)
5	15,89	3,36e-57	(d)
10	33,88	5,21e-252	(e)

Table 10: *Upstream transmission: Q factor and BER as a function of power (NRZ, Length = 50 km, With CD, Without Nonlinear Effects)*

In the upstream direction, the system exhibits greater sensitivity to low transmission power, even in the absence of nonlinear effects. At –10 dBm and –5 dBm, the transmission completely fails (Q = 0 and 1.96 respectively), with closed eye diagrams indicating unreadable signals. At 0 dBm, performance improves but remains below the acceptable threshold (Q = 4.76, BER = 9.27×10^{-7}). Only from +5 dBm does the system achieve reliable transmission (Q = 15.89, BER = 3.36×10^{-57}), with a clearly open eye diagram. At +10 dBm, the upstream link reaches excellent quality (Q = 33.88, BER = 0). These results confirm that, compared to the downstream path, the upstream direction requires **higher transmission power** to ensure stable operation over a 50 km link, even when nonlinear effects are not present.

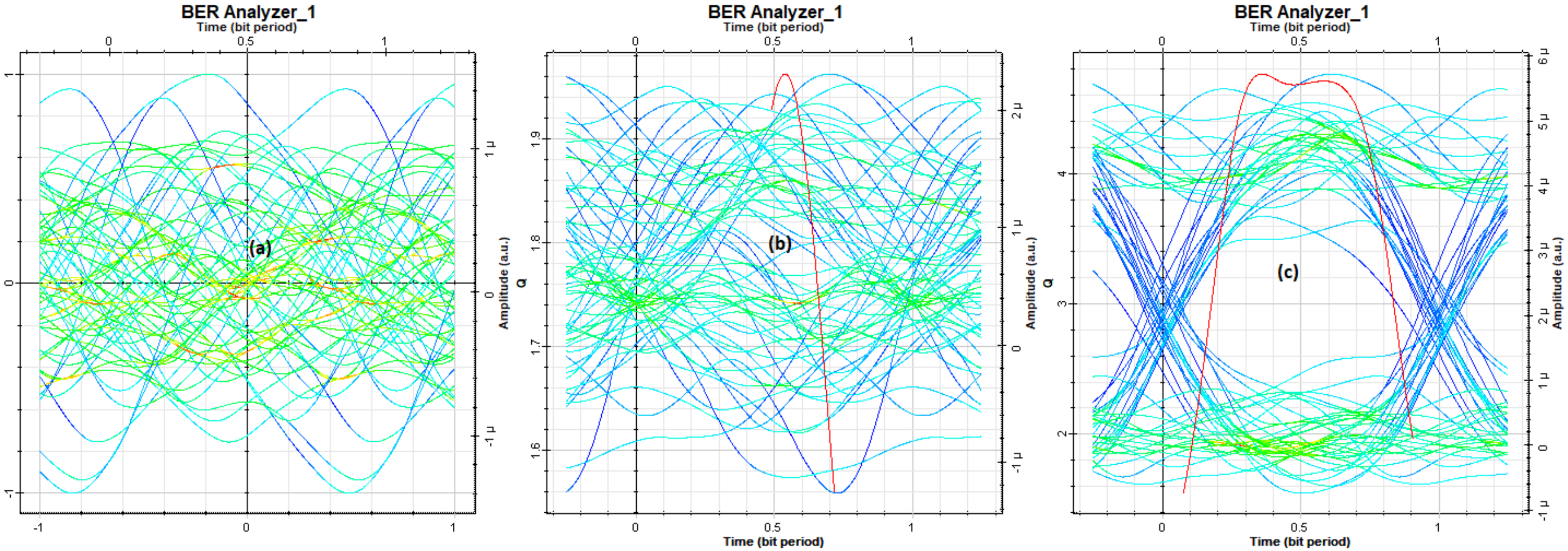


Figure 41: *Eye diagram of the upstream signal for a power of -10 dBm (a) Eye diagram of the upstream signal for a power of -5 dBm (b) Eye diagram of the upstream signal for a power of 0 dBm (c).*

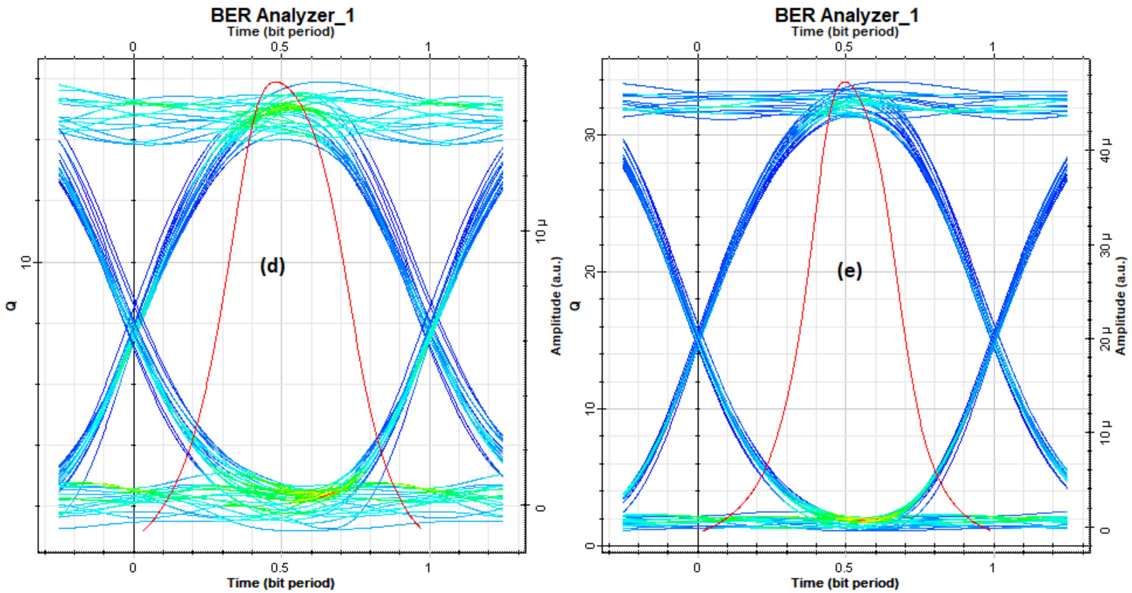


Figure 42: *Eye diagram of the upstream signal for a power of 5 dBm (d) Eye diagram of the upstream signal for a power of 10 dBm (e)*

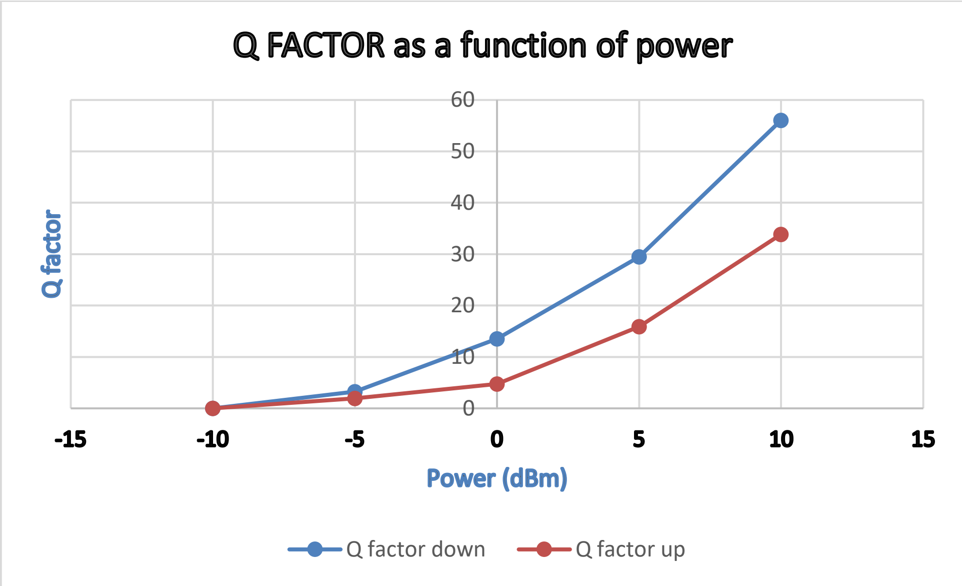


Figure 43: *Q factor vs. transmission power – Downstream and Upstream (NRZ, L = 50 km, Without Nonlinear Effects)*

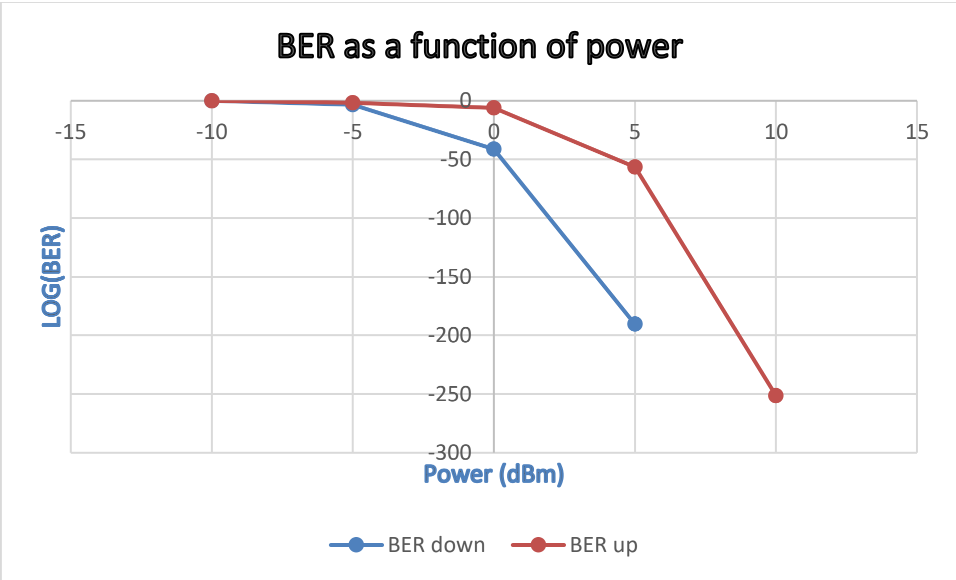


Figure 44: *Bit Error Rate (BER) vs. transmission power – Downstream and Upstream (NRZ, L= 50 km, Without Nonlinear Effects)*

The Q factor and BER curves as a function of transmission power clearly demonstrate a rapid performance improvement once the power exceeds 0 dBm. In the downstream direction, the progression is gradual and steady, while in the upstream, the improvement is more abrupt, with a **critical threshold around +5 dBm**. These observations highlight the importance of **power optimization** to balance the performance in both transmission directions.

9.2 With Nonlinear Effects (NE)

9.2.1 Downstream Transmission

Power (dBm)	Q factor down	BER down	Image
-10	0	1	(a)
-5	4,61	1,95e-06	(b)
0	10,34	2,10e-25	(c)
5	25,28	2,46e-141	(d)
10	74,93	0	(e)

Table 11: *Downstream transmission: Q factor and BER as a function of power (NRZ, Length = 50 km, With CD, With Nonlinear Effects)*

In the downstream direction, the results clearly show that the transmission power has a strong influence on system performance, even in the presence of nonlinear effects. At low power levels such as –10 dBm and –5 dBm, the Q factor remains below the acceptable threshold, and the eye diagrams appear completely closed, indicating poor signal quality and high distortion. Starting from 0 dBm, the system reaches acceptable performance (Q = 10.34, BER = 2.10×10^{-25}), with noticeable improvement in the eye opening. As the power increases to +5 dBm and +10 dBm, the Q factor rises significantly, reaching a value of 74.93 with a BER of 0 at +10 dBm. The corresponding eye diagrams confirm a clean and wide-open eye, reflecting excellent signal clarity.

Despite the presence of nonlinear effects, the downstream transmission remains robust and benefits from increased power, making it possible to maintain high performance over a 50 km fiber link when proper power levels are applied.

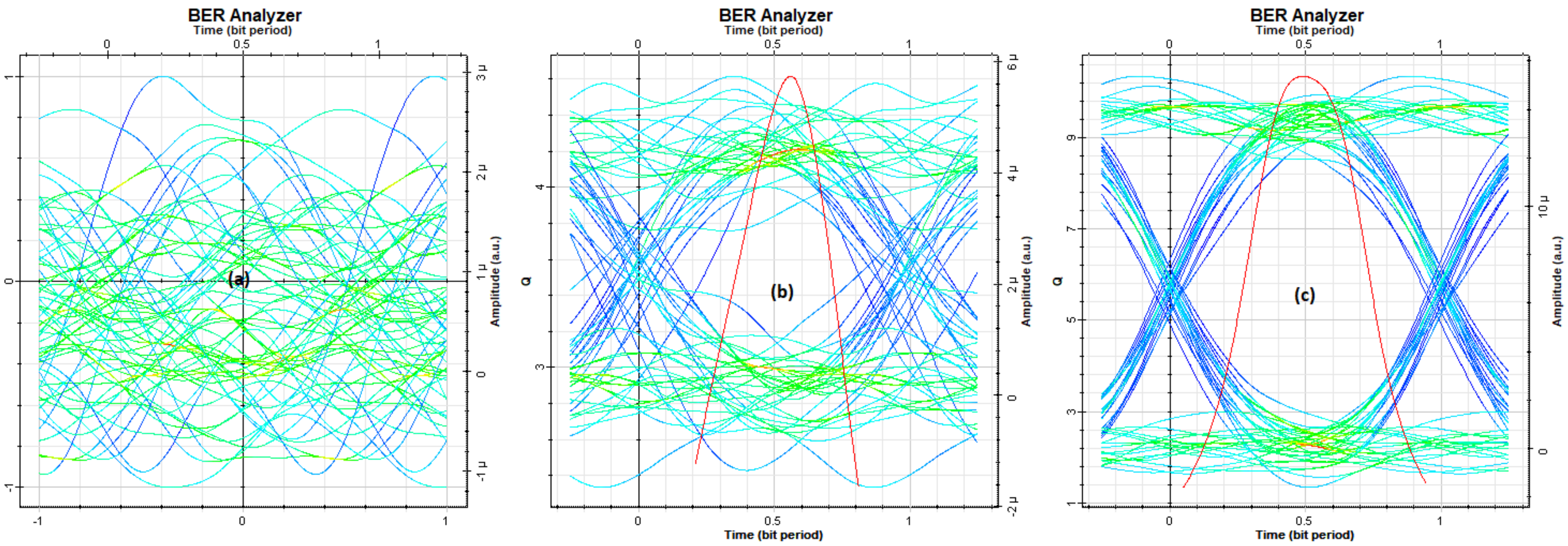


Figure 45: *Eye diagram of the downstream signal for a power of -10 dBm (a) Eye diagram of the downstream signal for a power of -5 dBm (b) Eye diagram of the downstream signal for a power of 0 dBm (c).*

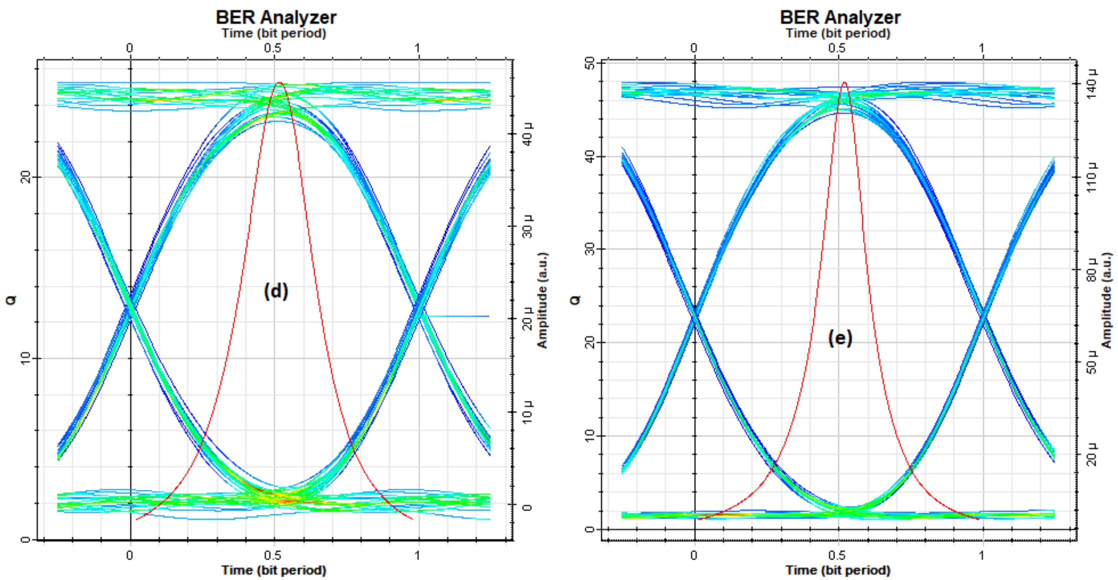


Figure 46: *Eye diagram of the downstream signal for a power of 5 dBm (d) Eye diagram of the downstream signal for a power of 10 dBm (e)*

9.2.2 Upstream Transmission

Power (dBm)	Q factor up	BER up	Image
-10	0	1	(a)
-5	0	1	(b)
0	5,74	4,53e-09	(c)
5	14,002	7,36e-45	(d)
10	33,62	3,39e-248	(e)

Table 12: *Upstream transmission: Q factor and BER as a function of power (NRZ, Length = 50 km, With CD, With Nonlinear Effects)*

In the upstream direction, the system shows a much higher sensitivity to transmission power in the presence of nonlinear effects.

At low power levels (–10 dBm and –5 dBm), the system fails completely, with a Q factor of 0 and a BER of 1, indicating total signal degradation. The eye diagrams at these levels are fully closed, confirming that the signal is unrecoverable. At 0 dBm, the performance reaches the minimum acceptable limit (Q = 5.74, BER = 4.53×10^{-9}), but the eye remains narrow and susceptible to distortion. A significant improvement is observed from +5 dBm, where the Q factor increases to 14.00 and the eye becomes clearly open. At +10 dBm, the system achieves excellent performance (Q = 33.62, BER ≈ 0), with an eye diagram indicating good signal integrity, though slightly more affected by nonlinear phase noise compared to downstream.

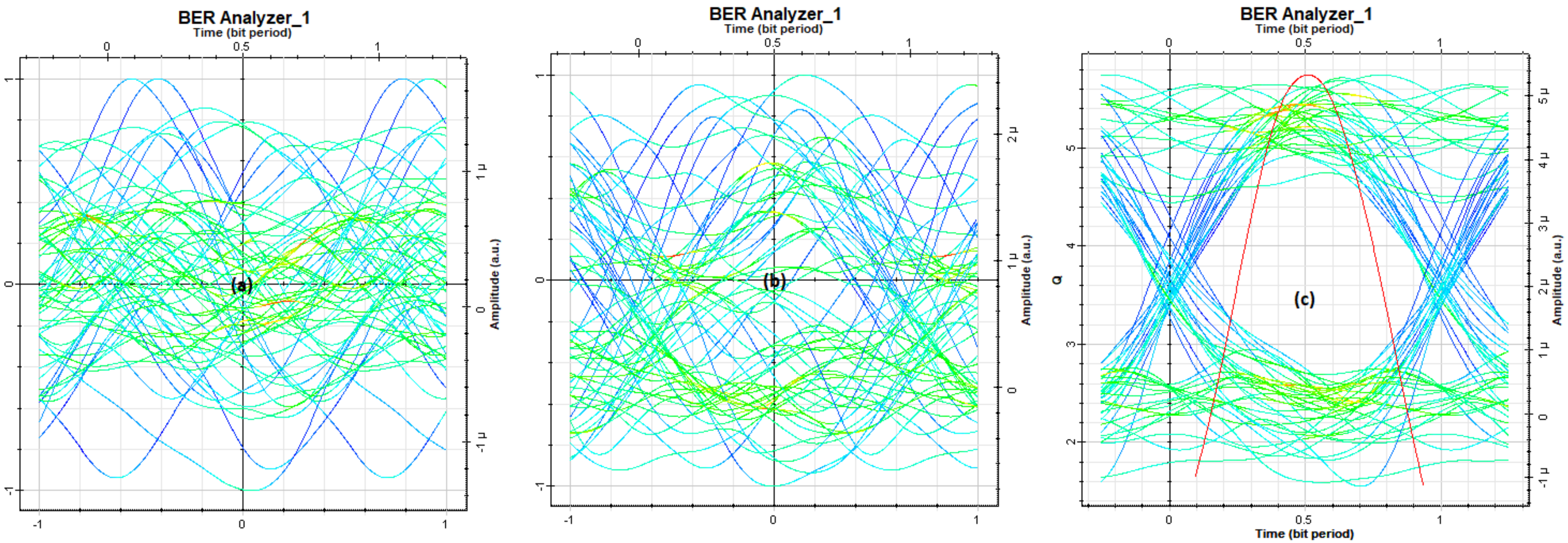


Figure 47: *Eye diagram of the upstream signal for a power of -10 dBm (a) Eye diagram of the upstream signal for a power of -5 dBm (b) Eye diagram of the upstream signal for a power of 0 dBm (c).*

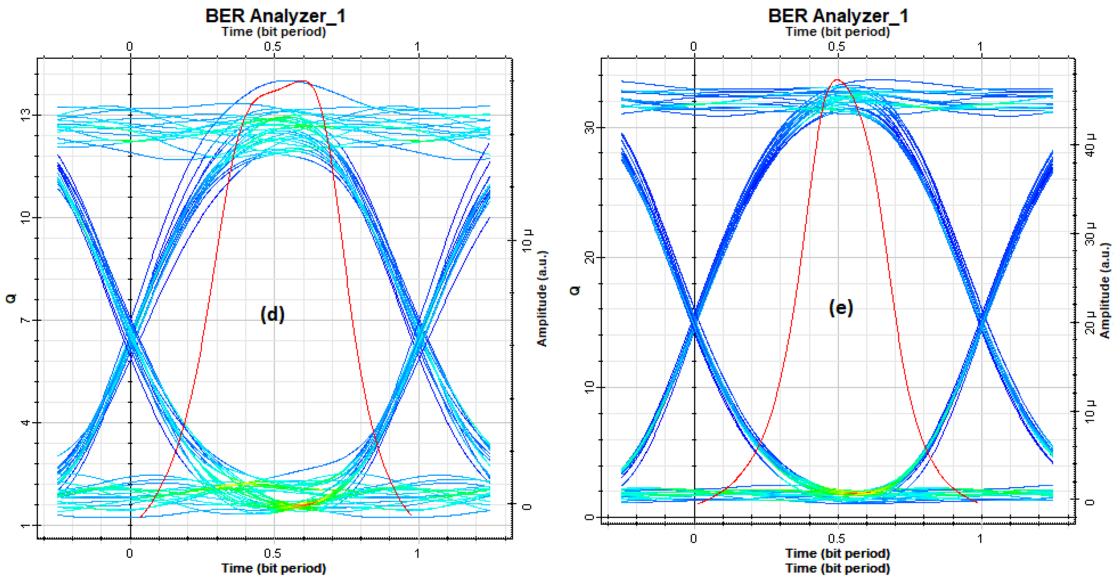


Figure 48: *Eye diagram of the upstream signal for a power of 5 dBm (d) Eye diagram of the upstream signal for a power of 10 dBm (e).*

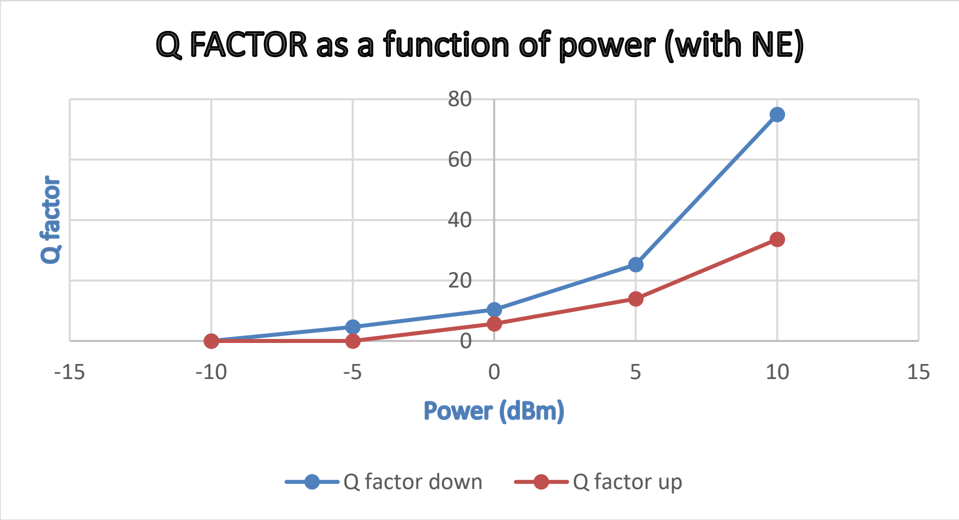


Figure 49: *Q factor vs. transmission power – Downstream and Upstream (NRZ, L = 50 km, With Nonlinear Effects)*

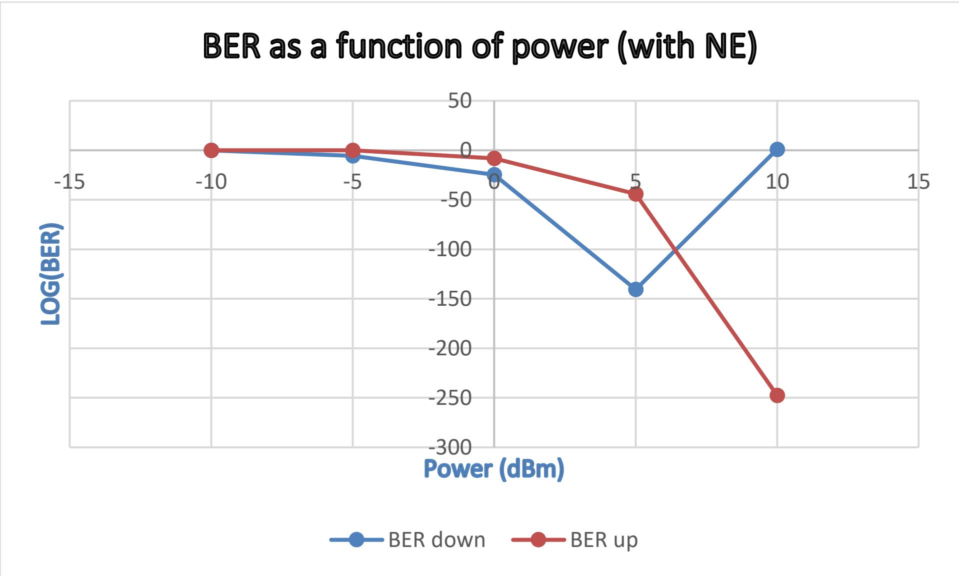


Figure 50: *Bit Error Rate (BER) vs. transmission power – Downstream and Upstream (NRZ, L = 50 km, Without Nonlinear Effects)*

The Q factor and BER curves show that system performance improves with increasing transmission power. In the downstream, the improvement is gradual, while in the upstream, performance shifts sharply from failure to acceptable quality between 0 dBm and +5 dBm. These trends confirm that the upstream direction is more sensitive to low power and nonlinear effects, and that proper power adjustment is essential for stable operation.

The simulation results clearly demonstrate that power is a critical factor influencing WDM-PON system performance. In the absence of nonlinear effects, both downstream and upstream links show steady improvement as the power level increases. Reliable transmission is achieved from –5 dBm in the downstream and +5 dBm in the upstream. However, when nonlinear effects (SPM, XPM) are present, system sensitivity increases, particularly in the upstream direction. Under these conditions, acceptable performance begins at 0 dBm downstream and requires at least +5 dBm upstream. Overall, ensuring sufficient optical power is essential to maintain signal quality over 50 km fiber links, especially when nonlinear impairments are involved.

10 Impact of Fiber Length (RZ Modulation)

10.1 Downstream Transmission

Length (km)	Q factor down	BER down	Image
10	58,98	0	(a)
20	36,99	6,68e-300	(b)
30	22,55	5,44e-113	(c)
40	14,74	1,57e-49	(d)
50	8,66	1,86e-18	(e)
60	5,02	2,55e-07	(f)
70	2,99	0,001	(g)

Table 13: *Downstream transmission – Q factor and BER as a function of fiber length (Power = 0 dBm, RZ, With CD, Without Nonlinear Effects)*

In the downstream direction, the WDM-PON system shows strong performance when using RZ modulation with chromatic dispersion. The Q factor remains well above acceptable levels up to 50 km, and the BER is extremely low (e.g., 8.66 at 50 km with BER = 1.86×10^{-18}). At 60 km, the Q factor drops to 5.02, which is just above the acceptable threshold, and the BER remains within limits. However, at 70 km, the system performance degrades significantly (Q = 2.99, BER = 0.001), and the eye diagram is largely closed. These results confirm that RZ modulation provides good dispersion tolerance, allowing reliable downstream transmission up to 60 km without compensation.

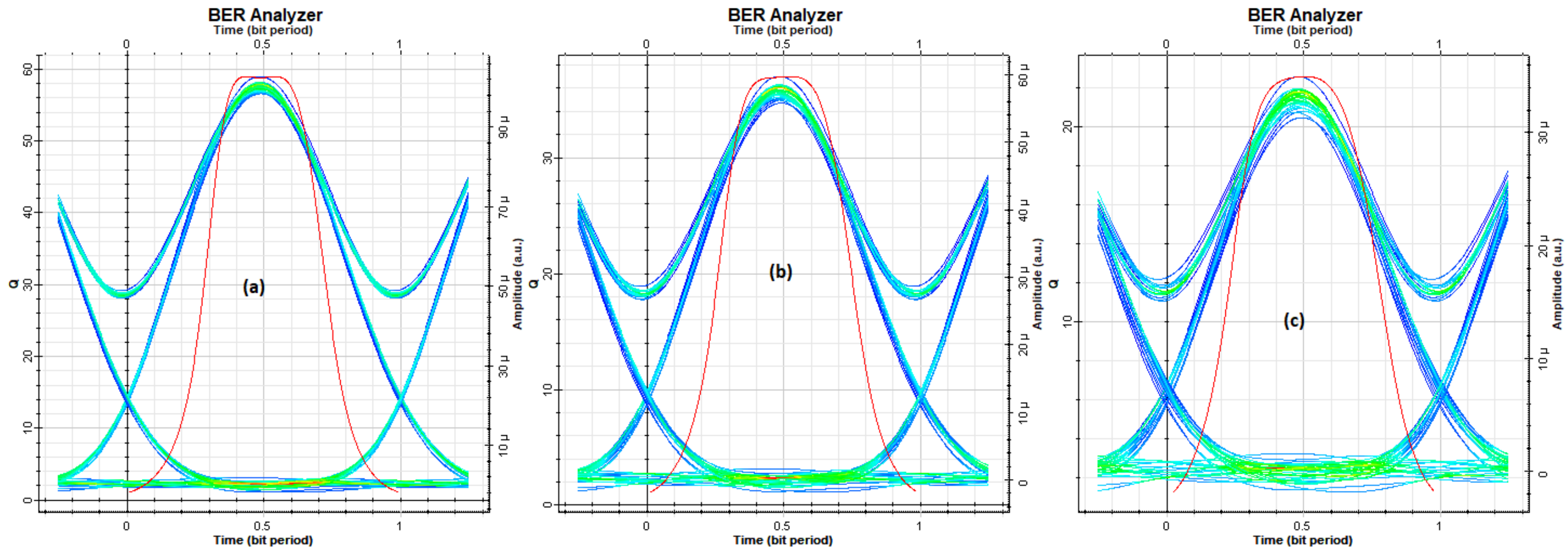


Figure 51: *Eye diagram of the downstream signal for a fiber length of 10 km(a)Eye diagram of the downstream signal for a fiber length of 20 km(b)Eye diagram of the downstream signal for a fiber length of 30 km(c).*

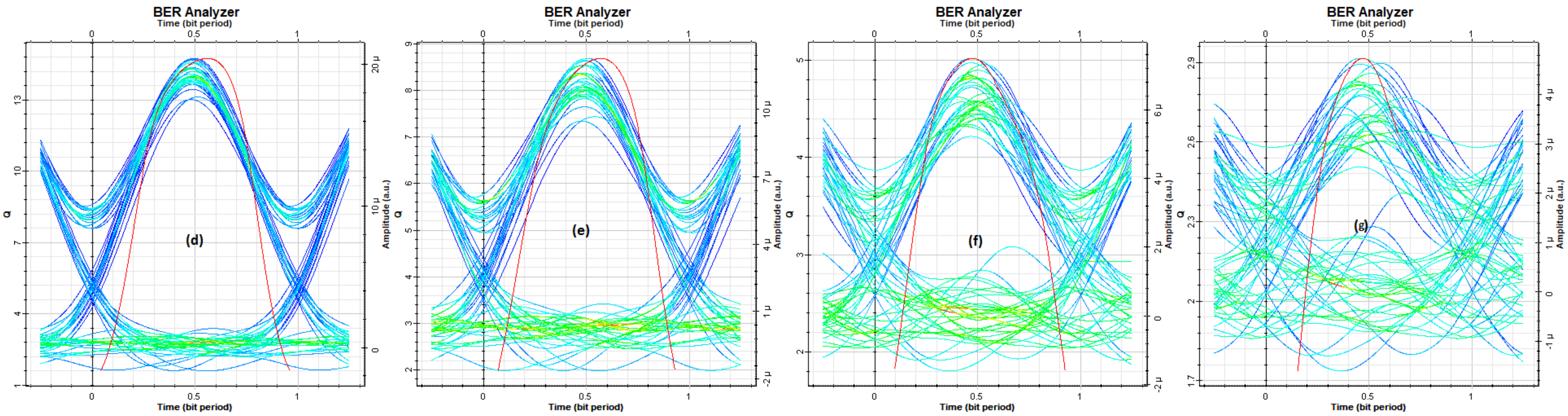


Figure 52: *Eye diagram of the downstream signal for a fiber length of 40 km(d)Eye diagram of the downstream signal for a fiber length of 50 km(e)Eye diagram of the downstream signal for a fiber length of 60 km(f)Eye diagram of the downstream signal for a fiber legth 70km(g)*

10.2 Upstream Transmission

Length (km)	Q factor up	BER up	Image
10	29,58	5,50e-192	(a)
20	17,55	2,61e-69	(b)
30	10,28	14,12e-25	(c)
40	6,27	1,72e-10	(d)
50	3,61	0,00015	(e)
60	0	1	(f)
70	0	1	(g)

Table 14: *Upstream transmission – Q factor and BER as a function of fiber length (Power = 0 dBm, RZ, With CD, Without Nonlinear Effects)*

In the upstream direction, the WDM-PON system shows good performance up to 40 km when using RZ modulation. At this distance, the Q factor is 6.27 and the BER is 1.72×10^{-10}, which remains within acceptable limits. However, at 50 km, the signal quality drops below the required threshold (Q = 3.61, BER = 1.5×10^{-4}), and beyond this point, the system fails completely. At 60 km and 70 km, both the Q factor and BER indicate total degradation (Q = 0, BER = 1), with fully closed eye diagrams. These results highlight that while RZ modulation improves dispersion tolerance compared to NRZ, the upstream link remains more vulnerable to distance and requires additional compensation to operate reliably beyond 40 km.

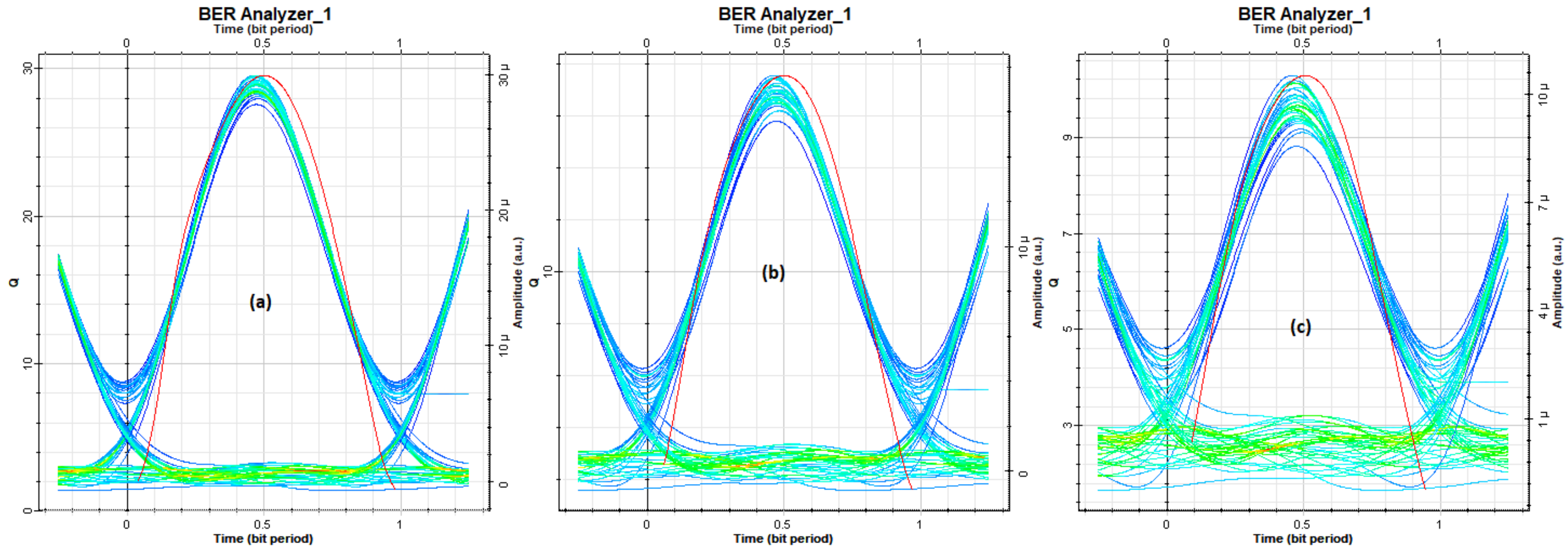


Figure 53: *Eye diagram of the upstream signal for a fiber length of 10 km(a)Eye diagram of the upstream signal for a fiber length of 20 km(b)Eye diagram of the upstream signal for a fiber length of 30 km(c).*

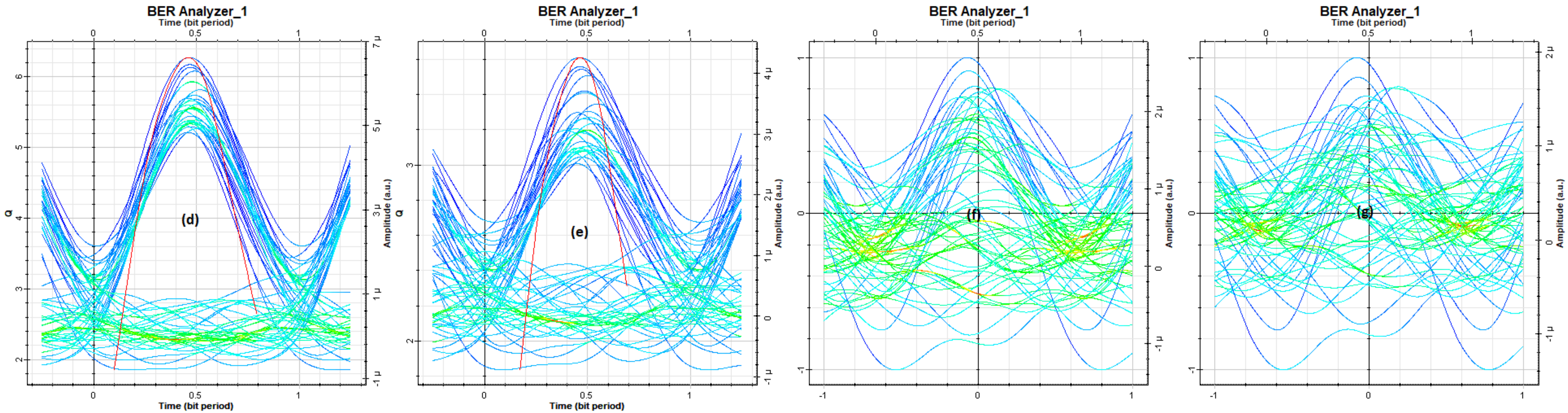


Figure 54: *Eye diagram of the upstream signal for a fiber length of 40 km(d)Eye diagram of the upstream signal for a fiber length of 50 km(e)Eye diagram of the upstream signal for a fiber length of 60 km(f)Eye diagram of the upstream signal for a fiber length of 70km(g)*

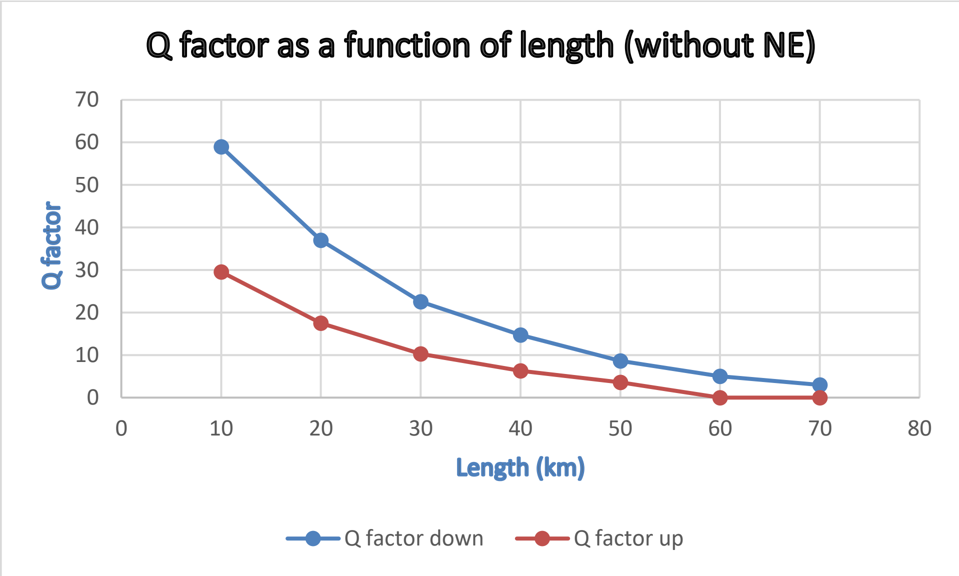


Figure 55: *Evolution of the Q factor vs. fiber length – Downstream and Upstream (Power = 0 dBm, RZ, With CD)*

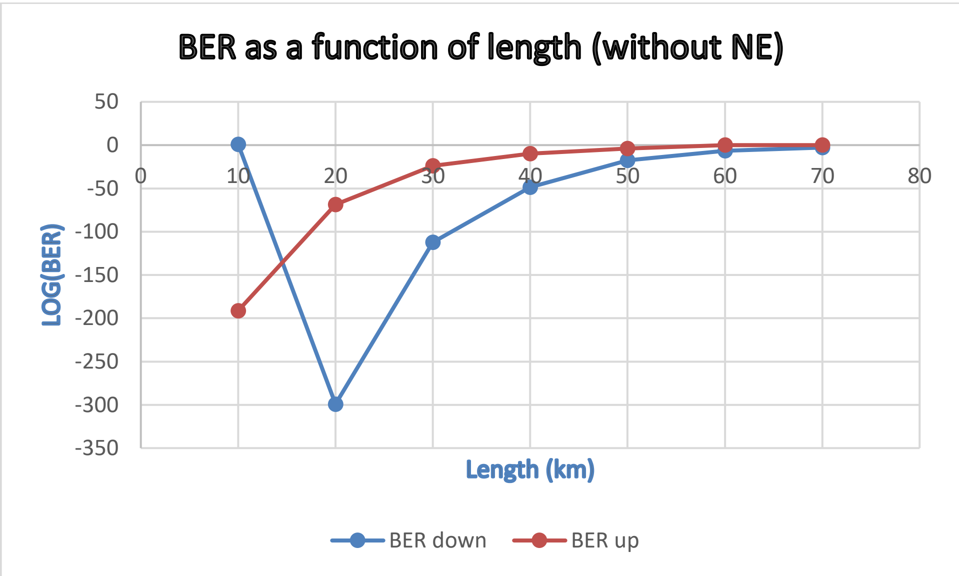


Figure 56: *Bit Error Rate (BER) vs. fiber length – Downstream and Upstream (Power = 0 dBm, RZ, With CD)*

The Q factor and BER curves for RZ modulation show a gradual decline in performance with increasing fiber length. Downstream remains acceptable up to 60 km, while upstream degrades more rapidly and fails beyond 40 km. This confirms that RZ improves dispersion tolerance, but the upstream path remains more limited in distance.

The use of RZ modulation improves system performance under chromatic dispersion compared to NRZ, especially in the downstream direction. The WDM-PON system maintains reliable transmission up to **60 km downstream** and **40 km upstream**. Beyond these distances, the signal quality degrades significantly, particularly in the upstream direction, where the system fails entirely at 60 km. These results confirm that while RZ enhances dispersion tolerance, **distance remains a limiting factor**, and additional measures such as dispersion compensation are needed to support longer reach, especially upstream.

11 Impact of Non-linear Effects (RZ Modulation)

11.1 Downstream Transmission

Length (km)	Q factor down	BER down	Image
10	54,90	0	(a)
20	34,05	2,01e-254	(b)
30	24,28	1,57e-130	(c)
40	14,42	1,77e-47	(d)
50	8,43	1,70e-47	(e)
60	4.97	3,26e-07	(f)
70	2,80	0,02	(g)

Table 15: *Downstream transmission: Q factor and BER as a function of fiber length (RZ, Power = 0 dBm, With CD, With Nonlinear Effects)*

The downstream results show strong performance with RZ modulation despite the presence of nonlinear effects. The Q factor remains high up to 50 km (Q = 8.43, BER = 1.70e-47). At 60 km, the system approaches the limit with Q = 4.97 and BER = 3.26e-07, still marginally acceptable. At 70 km, performance drops below threshold (Q = 2.80, BER = 0.02), and the eye diagram becomes significantly closed. These values indicate that RZ modulation helps mitigate nonlinear effects in the downstream path, ensuring stable operation up to 60 km

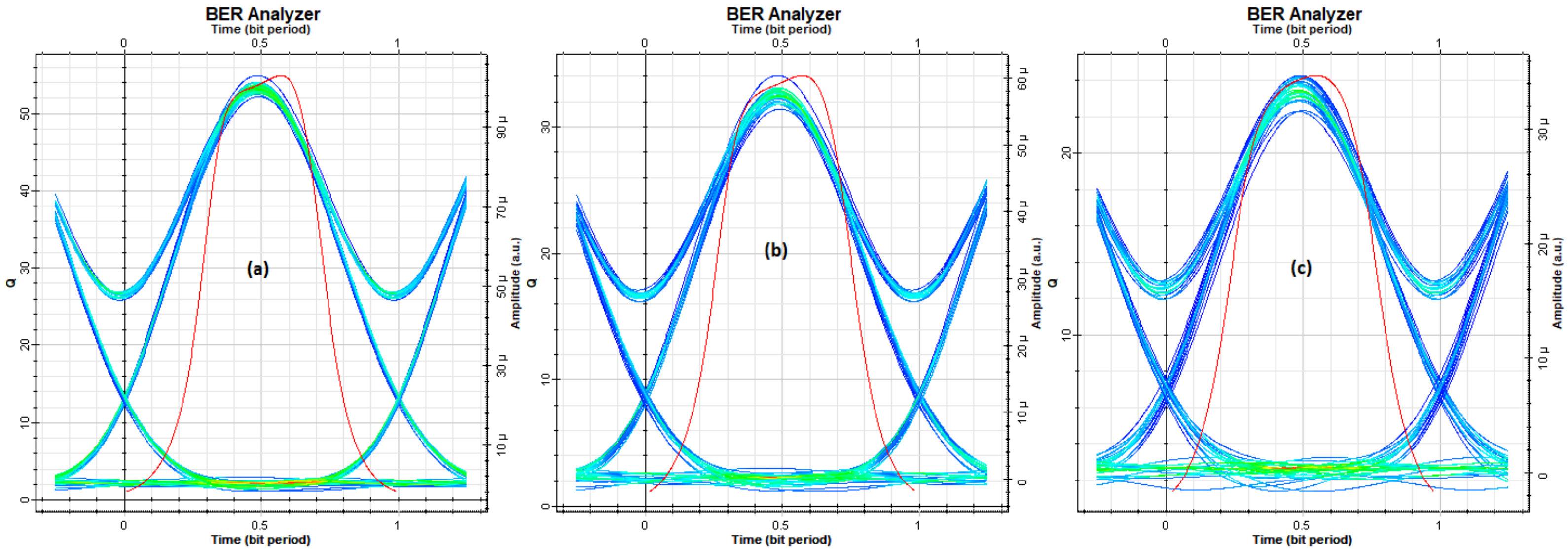


Figure 57: *Eye diagram of the downstream signal for a fiber length of 10 km(a)Eye diagram of the downstream signal for a fiber length of 20 km(b)Eye diagram of the downstream signal for a fiber length of 30 km(c).*

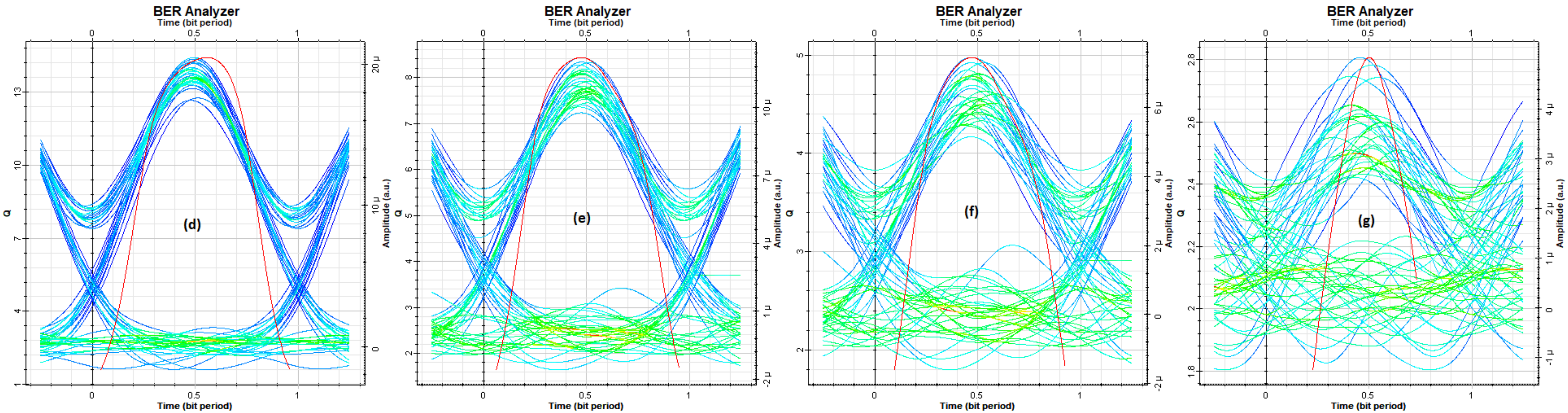


Figure 58: *Eye diagram of the downstream signal for a fiber length of 40 km(d)Eye diagram of the downstream signal for a fiber length of 50 km(e)Eye diagram of the downstream signal for a fiber length of 60 km(f)Eye diagram of the downstream signal for a fiber le*

11.2 Upstream Transmission

Length (km)	Q factor up	BER up	Image
10	29,60	5,91e-193	(a)
20	17,50	6,80e-69	(b)
30	10,67	6,46e-27	(c)
40	6,23	2,16e-10	(d)
50	3,12	0,000	(e)
60	0	1	(f)
70	0	1	(g)

Table 16: *Upstream transmission: Q factor and BER as a function of fiber length (RZ, Power = 0 dBm, With CD, With Nonlinear Effects)*

In the upstream direction, the system is more affected by nonlinearities. It maintains acceptable performance only up to 40 km, with Q = 6.23 and BER = 2.16e-10. At 50 km, quality degrades rapidly (Q = 3.12, BER ≈ 0.000), and at 60–70 km, the system completely fails (Q = 0, BER = 1). Eye diagrams confirm this decline, with complete eye closure beyond 50 km. This highlights the higher sensitivity of the upstream path to nonlinear effects, even when using a robust format like RZ.

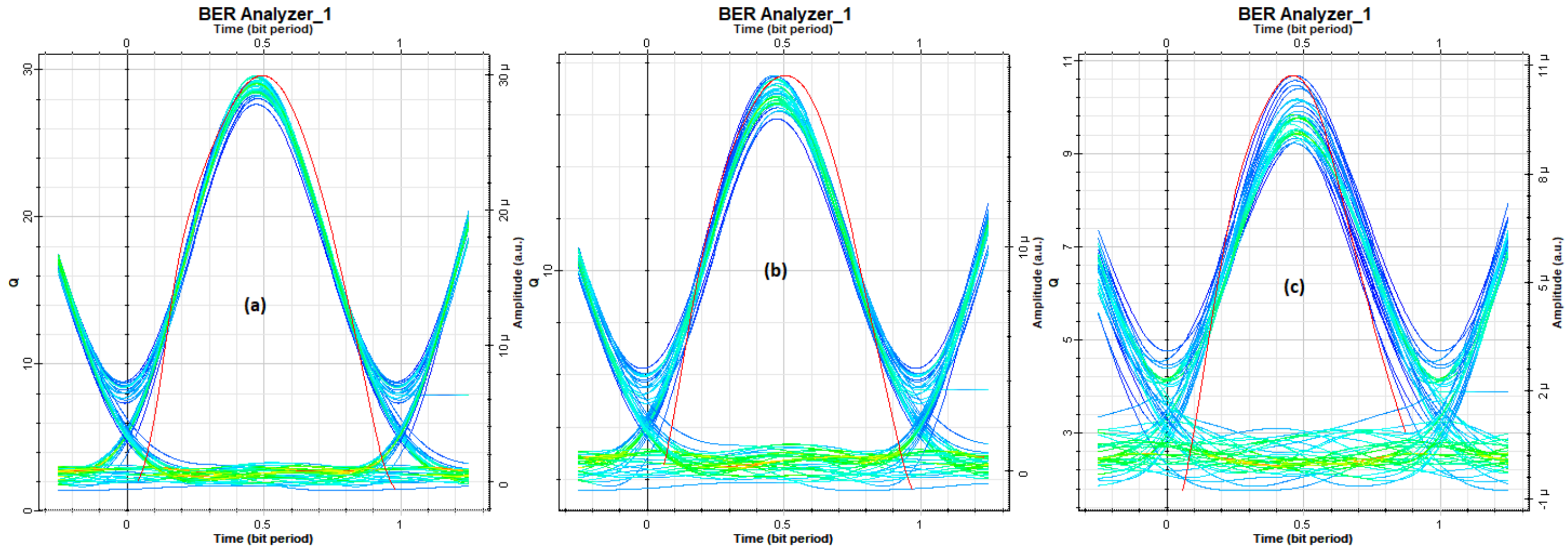


Figure 59: *Eye diagram of the upstream signal for a fiber length of 10 km(a)Eye diagram of the upstream signal for a fiber length of 20 km(b)Eye diagram of the upstream signal for a fiber length of 30 km(c).*

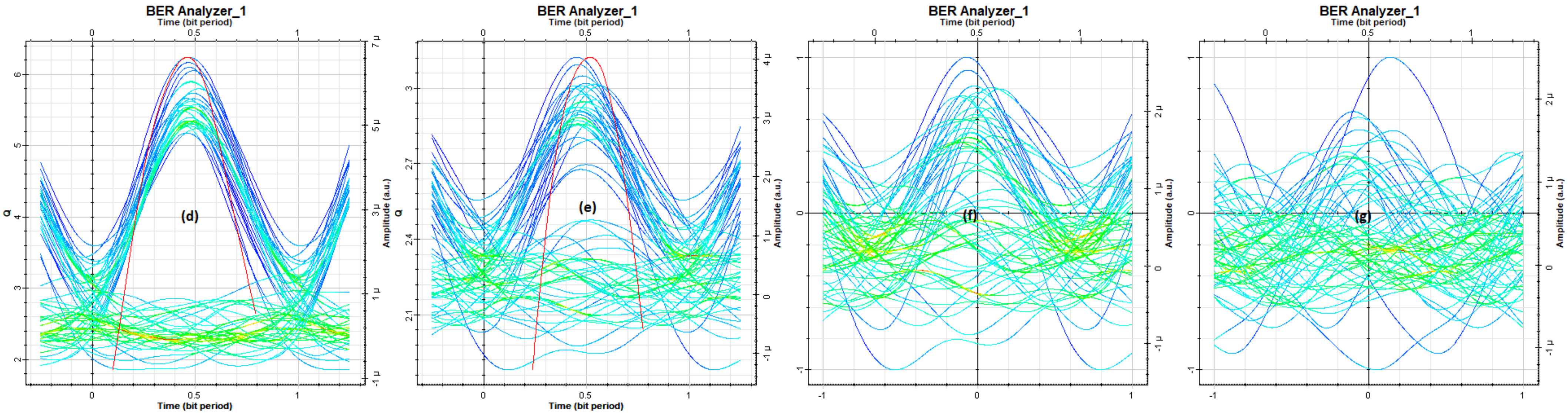


Figure 60: *Eye diagram of the upstream signal for a fiber length of 40 km(d)Eye diagram of the upstream signal for a fiber length of 50 km(e)Eye diagram of the upstream signal for a fiber length of 60 km(f)Eye diagram of the upstream signal for a fiber length of 70km(g)*

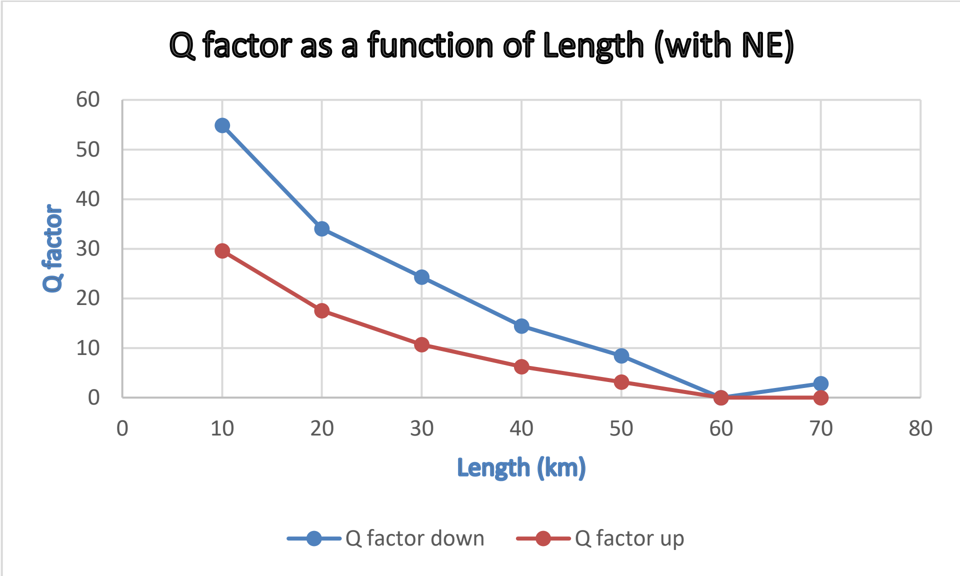


Figure 61: *Variation of Q factor versus fiber length for downstream and upstream directions*

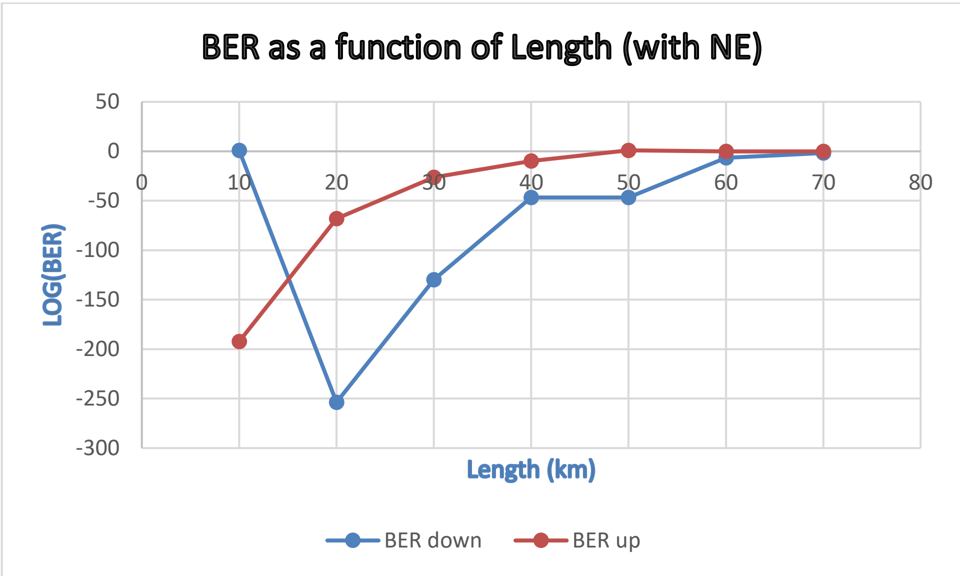


Figure 62: *Variation of BER versus fiber length for downstream and upstream directions*

As the transmission distance increases, a noticeable degradation in Q factor and BER is observed. Downstream performance decreases gradually and remains within acceptable limits until 60 km, while upstream quality drops more sharply after 40 km. The divergence between the two paths emphasizes that nonlinear effects have a stronger impact on upstream transmission, especially as distance increases.

Under the combined influence of nonlinear effects and chromatic dispersion, RZ modulation allows stable transmission up to 60 km downstream and 40 km upstream. Beyond these distances, the signal quality degrades noticeably, especially in the upstream direction, where transmission becomes unreliable. These findings confirm that although RZ provides enhanced resilience, range limitations still exist in nonlinear conditions, with upstream transmission remaining the most sensitive link in the system.

12 Impact of Power (RZ Modulation)

12.1 Without Nonlinear Effects (NE)

12.1.1 Downstream Transmission

Power (dBm)	Q factor down	BER down	Image
-10	0	1	(a)
-5	2,61	0,004	(b)
0	8,68	1,68e-18	(c)
5	25,11	1,67e-139	(d)
10	72,72	0	(e)

Table 17: *Downstream transmission: Q factor and BER as a function of power (RZ, Length = 50 km, With CD, Without Nonlinear Effects)*

In the downstream direction, without nonlinear effects, the system shows a clear improvement in performance as optical power increases. At low power levels (-10 dBm and -5 dBm), the system fails or performs poorly, with Q factors of 0 and 2.61, and high BER values. However, starting from 0 dBm, transmission becomes reliable, with a Q factor of 8.68 and a BER of 1.68×10^{-18}. At higher powers (+5 dBm and +10 dBm), performance becomes excellent, with Q factors above 25 and negligible BER. Eye diagrams confirm this progression, showing a wide-open eye at higher powers. These results confirm that downstream transmission becomes fully stable and efficient from 0 dBm and beyond.

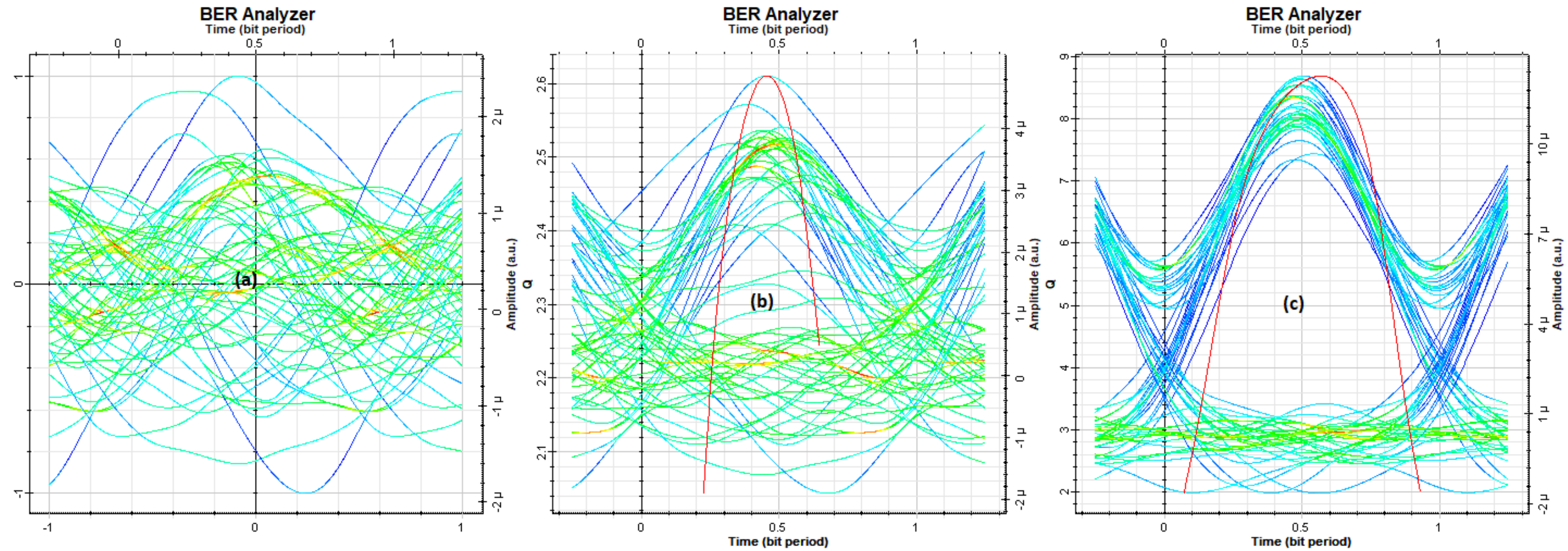


Figure 63: *Eye diagram of the downstream signal for a power of -10 dBm (a)Eye diagram of the downstream signal for a power of -5 dBm (b)Eye diagram of the downstream signal for a power of 0 dBm (c).*

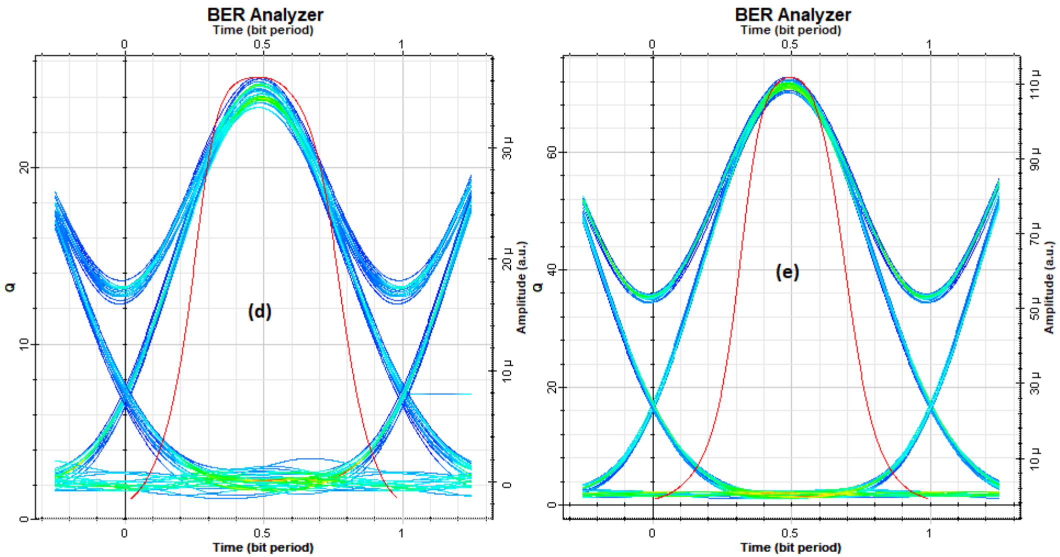


Figure 64: *Eye diagram of the downstream signal for a power of 5 dBm (d) Eye diagram of the downstream signal for a power of 10 dBm (e)*

12.1.2 Upstream Transmission

Power (dBm)	Q factor up	BER up	Image
-10	0	1	(a)
-5	0	1	(b)
0	3,61	0,000	(c)
5	10,24	6,48e-25	(d)
10	31,26	7,85e-215	(e)

Table 18: *Upstream transmission: Q factor and BER as a function of power (RZ, Length = 50 km, With CD, Without Nonlinear Effects)*

The upstream direction is more sensitive to low power levels. At -10 dBm and -5 dBm, the system fails completely, with closed eye diagrams and BER = 1. At 0 dBm, performance improves, but the Q factor remains below acceptable limits (Q = 3.61). From +5 dBm, signal quality becomes acceptable, with Q = 10.24 and BER = 6.48×10^{-25}. At +10 dBm, the system performs excellently with Q = 31.26 and a fully open eye. These results indicate that upstream transmission requires at least +5 dBm to meet the minimum quality standards.

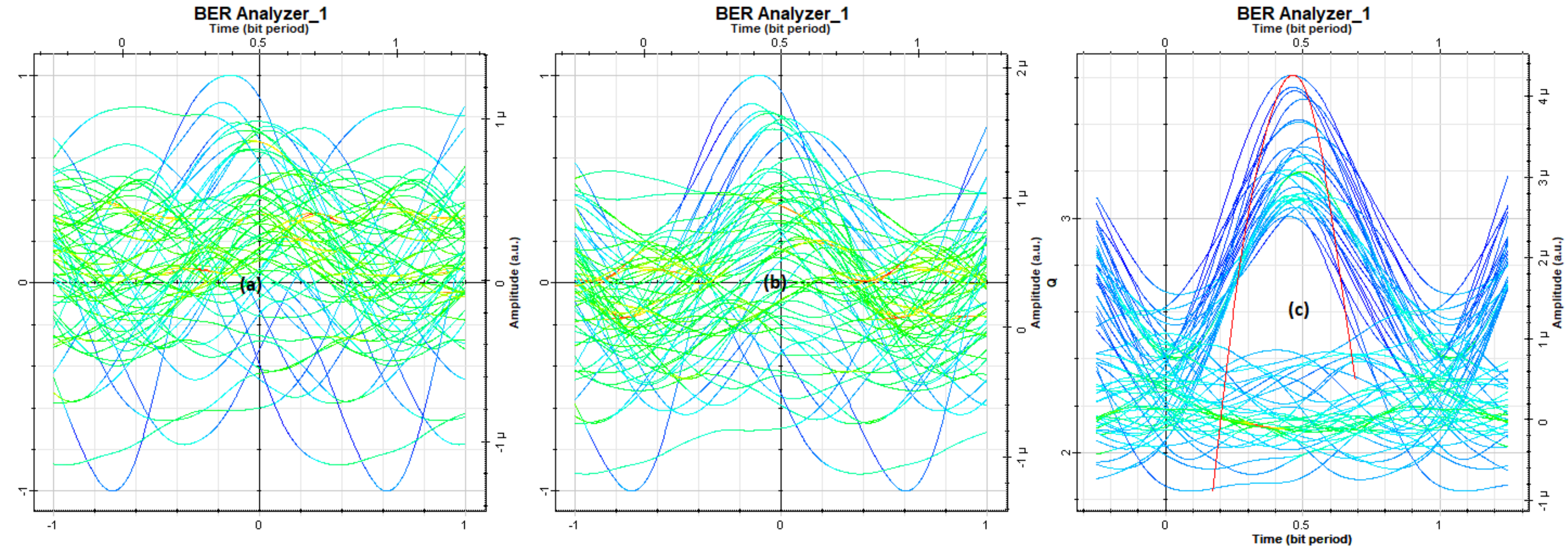


Figure 65: *Eye diagram of the upstream signal for a power of -10 dBm (a)Eye diagram of the upstream signal for a power of -5 dBm (b)Eye diagram of the upstream signal for a power of 0 dBm (c).*

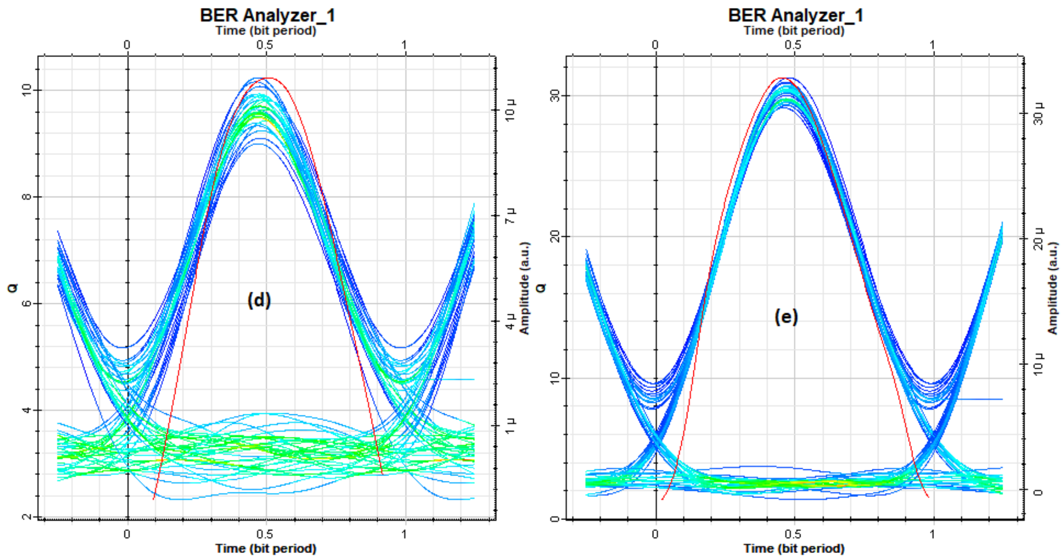


Figure 66: *Eye diagram of the upstream signal for a power of 5 dBm (d) Eye diagram of the upstream signal for a power of 10 dBm (e)*

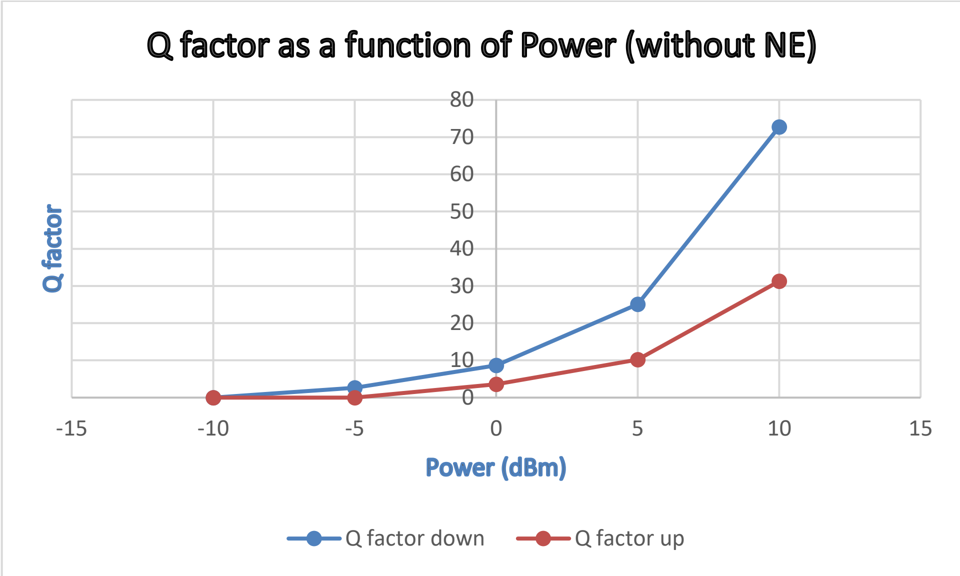


Figure 67: *Q factor vs. transmission power – Downstream and Upstream (RZ, L = 50 km, Without Nonlinear Effects)*

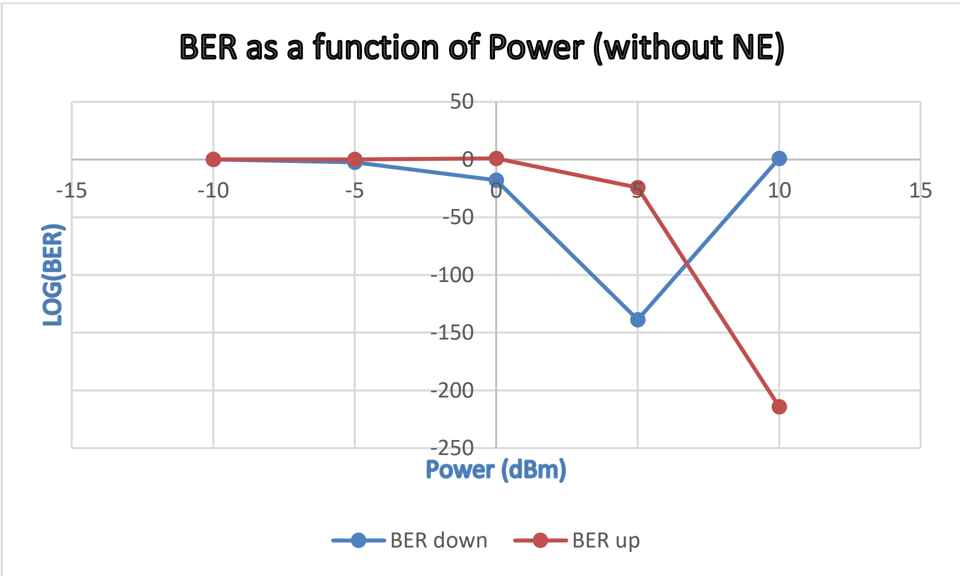


Figure 68: *Bit Error Rate (BER) vs. transmission power – Downstream and Upstream (RZ, L = 50 km, Without Nonlinear Effects)*

In the absence of nonlinear effects, the WDM-PON system using RZ modulation shows strong performance improvement as optical power increases. Downstream transmission becomes reliable from 0 dBm, while upstream requires at least +5 dBm to meet quality thresholds. Overall, higher launch power significantly enhances system performance, confirming that RZ modulation effectively supports dispersion-limited transmission over 50 km without additional compensation.

12.2 With Nonlinear Effects (NE)

12.2.1 Downstream Transmission

Power (dBm)	Q factor down	BER down	Image
-10	0	1	(a)
-5	2,61	0,004	(b)
0	7,79	3,19e-15	(c)
5	23,62	9,51e-124	(d)
10	55,87	0	(e)

Table 19: *Downstream transmission: Q factor and BER as a function of power (RZ, Length = 50 km, With CD, With Nonlinear Effects)*

When nonlinear effects are included, the downstream direction remains stable and robust. At 0 dBm, the Q factor is 7.79 (slightly lower than the 8.68 observed without nonlinearities), and the BER remains very low (3.19×10^{-15}). At +5 dBm and +10 dBm, the system achieves high performance, with Q = 55.87 and BER = 0 at +10 dBm. These results confirm that RZ modulation effectively mitigates the impact of nonlinear effects in the downstream path and ensures reliable transmission from 0 dBm onward.

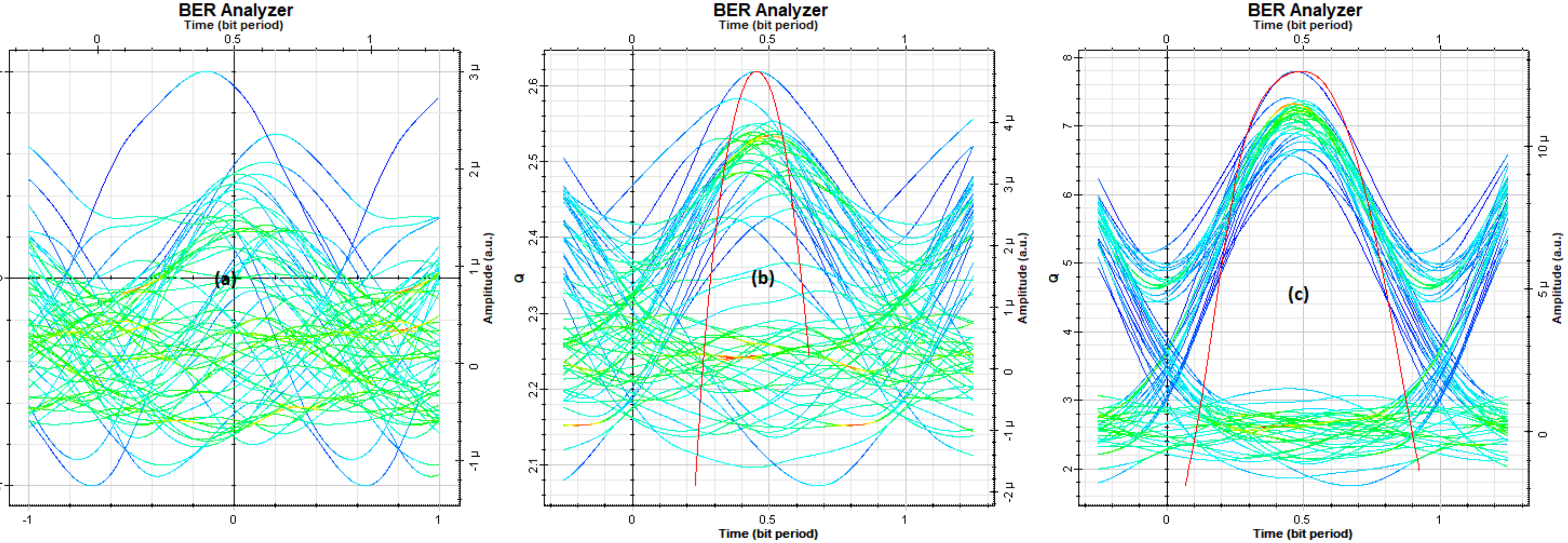


Figure 69: *Eye diagram of the downstream signal for a power of -10 dBm (a)Eye diagram of the downstream signal for a power of -5 dBm (b)Eye diagram of the downstream signal for a power of 0 dBm (c).*

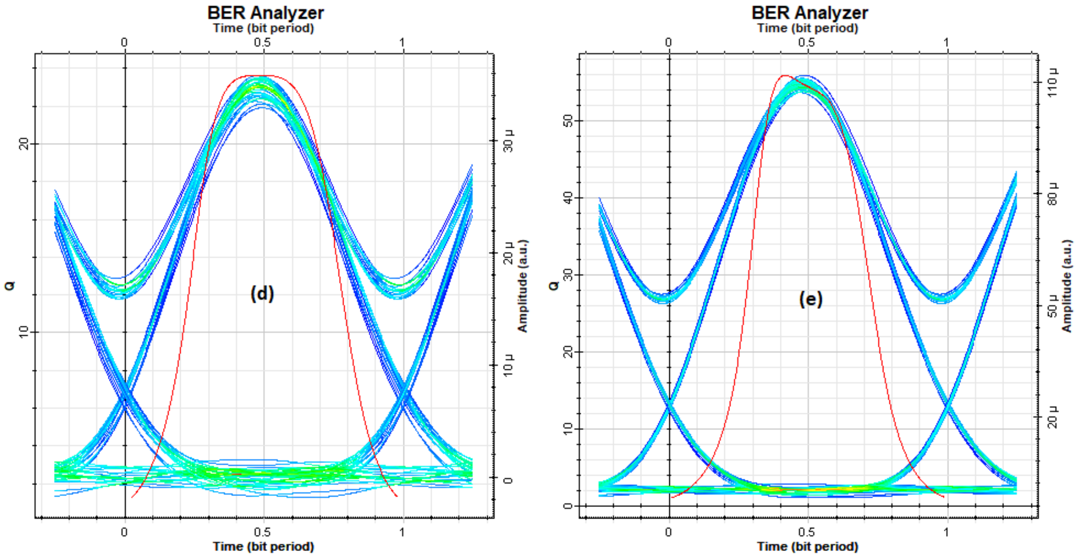


Figure 70: *Eye diagram of the downstream signal for a power of 5 dBm (d) Eye diagram of the downstream signal for a power of 10 dBm (e)*

12.2.2 Upstream Transmission

Power (dBm)	Q factor up	BER up	Image
-10	0	1	(a)
-5	0	1	(b)
0	3,41	0,0003	(c)
5	10,72	4,001e-27	(d)
10	30,46	3,74e-204	(e)

Table 20: *Upstream transmission: Q factor and BER as a function of power (RZ, Length = 50 km, With CD, With Nonlinear Effects)*

Upstream transmission remains the most affected by nonlinear effects. At -10 dBm and -5 dBm, the system fails entirely. At 0 dBm, performance improves slightly (Q = 3.41), but the BER (3×10^{-4}) remains above acceptable levels. From +5 dBm, the signal becomes stable, with a Q factor of 10.72 and BER = 4×10^{-27}, and at +10 dBm, it reaches excellent levels (Q = 30.46). Despite RZ's resilience, these results show that nonlinearities have a stronger impact upstream, and a power of at least +5 dBm is required for reliable transmission.

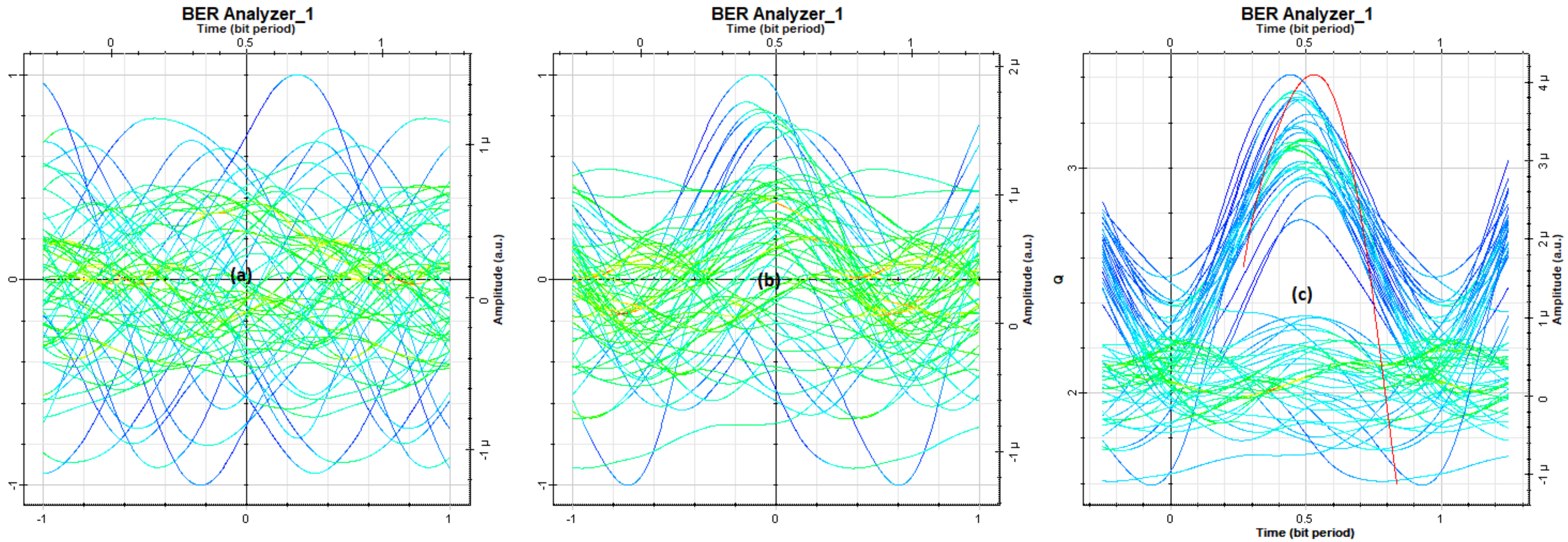


Figure 71: *Eye diagram of the upstream signal for a power of -10 dBm (a)Eye diagram of the upstream signal for a power of -5 dBm (b)Eye diagram of the upstream signal for a power of 0 dBm (c).*

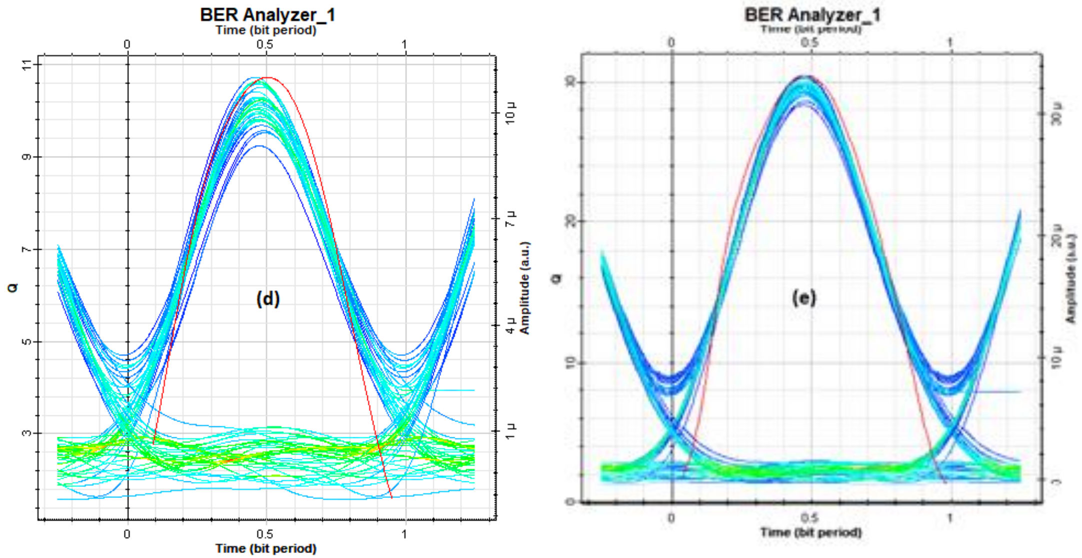


Figure 72: *Eye diagram of the upstream signal for a power of 5 dBm (d) Eye diagram of the upstream signal for a power of 10 dBm (e)*

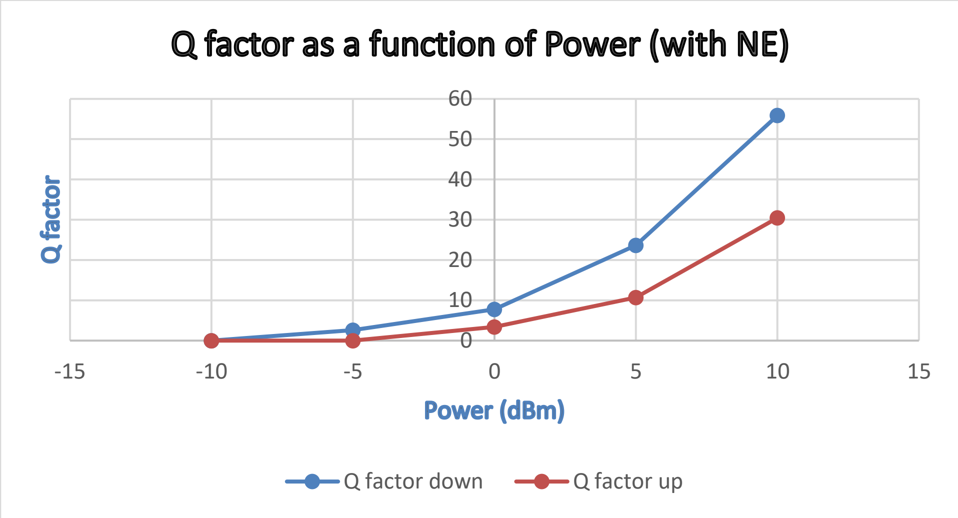


Figure 73: *Q factor vs. transmission power – Downstream and Upstream (RZ, L = 50 km, With Nonlinear Effects)*

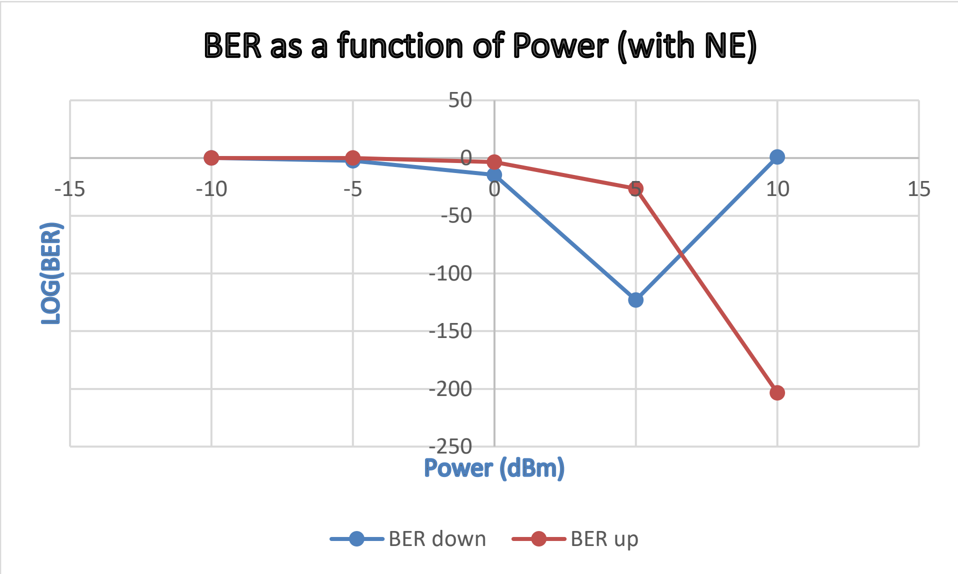


Figure 74: *Bit Error Rate (BER) vs. transmission power – Downstream and Upstream (RZ, L = 50 km, Without Nonlinear Effects)*

RZ modulation improves system robustness under dispersion and nonlinear conditions. In the downstream direction, reliable operation is achieved from 0 dBm, while upstream transmission requires at least +5 dBm to meet quality criteria. Although nonlinear effects slightly degrade performance, particularly upstream, sufficient optical power ensures stable and high-quality transmission in both directions over 50 km.

Scenario	Metric	NRZ Format	RZ Format
Impact of Length (L) (Without Nonlinear Effects)	$L_{max\text{-}Down}$	60 km	50 km
	$L_{max\text{-}Up}$	50 km	40 km
	$Q_{\text{-}Down}$	8.15	8.66
	$Q_{\text{-}Up}$	5.68	6.27
	$BER_{\text{-}Down}$	1.72×10^{-16}	1.86×10^{-18}
	$BER_{\text{-}Up}$	6.40×10^{-9}	1.72×10^{-10}
Impact of Power (Without Nonlinear Effects)	$P_{min\text{-}Down}$	0 dBm	0 dBm
	$P_{min\text{-}Up}$	5 dBm	5 dBm
	$Q_{\text{-}Down}$	13.51	8.68
	$Q_{\text{-}Up}$	15.89	10.24
	$BER_{\text{-}Down}$	6.12×10^{-42}	1.68×10^{-18}
	$BER_{\text{-}Up}$	3.36×10^{-57}	6.48×10^{-25}
Impact of Nonlinear Effects (With Nonlinear Effects)	$L_{max\text{-}Down}$	60 km	50 km
	$L_{max\text{-}Up}$	50 km	40 km
	$Q_{\text{-}Down}$	7.95	8.43
	$Q_{\text{-}Up}$	5.85	6.23
	$BER_{\text{-}Down}$	8.96×10^{-16}	1.70×10^{-47}
	$BER_{\text{-}Up}$	2.29×10^{-9}	2.16×10^{-10}
	$P_{min\text{-}Down}$	0 dBm	0 dBm
	$P_{min\text{-}Up}$	0 dBm	5 dBm
	$Q_{\text{-}Down}$	10.34	7.79
	$Q_{\text{-}Up}$	5.74	10.72
	$BER_{\text{-}Down}$	2.10×10^{-25}	6.48×10^{-25}
	$BER_{\text{-}Up}$	4.53×10^{-9}	4.001×10^{-27}

Table 21: *Comparative Performance Analysis of NRZ and RZ Modulation Formats under Different Transmission Conditions in a WDM-PON System*

The table shows that NRZ works well in terms of distance and power, making it suitable for networks that need long reach. On the other hand, RZ, even though it doesn't reach as far, offers better signal quality and is more resistant to noise and nonlinear effects. So, choosing between the two depends on whether you prioritize distance or signal performance**.**

13 Suggestions for Improvement

Suggestions for Improvement Proposals to Improve the Effectiveness of the WDM-PON System:

- **Optimization of Component Parameters**: Fine-tuning key parameters such as laser power, receiver sensitivity, and filter bandwidth can significantly enhance system performance and reduce signal degradation.
- **Use of Advanced Modulation Formats:** Implementing modulation formats such as DPSK or QAM instead of NRZ or RZ could improve spectral efficiency and resistance to dispersion and nonlinear effects.
- **Dynamic Wavelength Allocation:** Employing dynamic wavelength assignment strategies can optimize bandwidth utilization and enhance network scalability and flexibility.

- **Hybrid TDM/WDM Architecture:** Combining WDM with time-division multiplexing (TDM) can improve user density support while maintaining high transmission speeds.
- **Improved Dispersion Compensation Techniques:** Integrating dispersion compensating fibers (DCF) or using electronic dispersion compensation (EDC) can mitigate the effects of chromatic dispersion over long distances.
- **Incorporation of Optical Amplifiers:** Utilizing optical amplifiers such as EDFAs (Erbium-Doped Fiber Amplifiers) at appropriate points in the network can extend the transmission reach and improve signal quality.
- **Use of Forward Error Correction (FEC):** Adding FEC can significantly reduce the BER and enhance the robustness of the system against noise and signal impairments.
- **Network Monitoring and Dynamic Reconfiguration:** Integrating intelligent monitoring systems can enable real-time fault detection and allow for automatic rerouting or reconfiguration to maintain service continuity

Conclusion

In summary, the simulations carried out using the OptiSystem software made it possible to precisely evaluate the impact of several fundamental parameters on the performance of an optical transmission system.

The results showed that transmission distance, laser power, modulation format, as well as dispersion phenomena and nonlinear effects such as SPM **(**Self-Phase Modulation) and XPM (Cross-Phase Modulation), significantly affect the quality of the transmitted signal.

The analysis of performance metrics such as the quality factor (Q-Factor), bit error rate (BER), and eye diagram allowed for a quantification of these impacts and the identification of optimal operating conditions.

These results confirm the importance of precise parameter tuning and highlight the relevance of simulation-based approaches in designing reliable and high-performance optical networks, particularly in the context of WDM architectures.

General Conclusion and Perspectives

This thesis explores the feasibility of using a two-stage cascaded Arrayed Waveguide Grating (AWG) architecture within Wavelength Division Multiplexing Passive Optical Networks (WDM-PON), aiming to meet the growing demand for higher capacity, better scalability, and lower deployment costs in optical access networks. The proposed architecture leverages the spectral periodicity property of AWGs, allowing for wavelength reuse and a reduction in the number of required laser sources, while enabling greater flexibility in wavelength assignment to Optical Network Units (ONUs). Performance was evaluated through theoretical modeling and simulation using the OptiSystem software, analyzing key performance indicators such as the Q-factor, Bit Error Rate (BER), and Eye Diagram analysis to assess the effects of attenuation, chromatic dispersion, inter-channel interference, and nonlinearities. The results confirmed that the proposed architecture can achieve acceptable performance levels that meet next-generation network requirements, provided that parameters are properly optimized.

The main scientific contribution of this work lies in the proposal and evaluation of a new WDM-PON architecture that enhances spectral efficiency and reduces costs without the need for tunable transmitters. The study also provides a practical framework for assessing the trade-offs between the benefits and technical challenges of cascaded AWGs, offering valuable insights into the practical considerations for deploying such systems.

Future research perspectives include experimental validation of the proposed system in real-world environments and studying the effects of thermal and mechanical factors. Further investigation could also explore the integration of advanced digital signal processing techniques such as Forward Error Correction (FEC), dispersion compensation, and the use of artificial intelligence to enhance system resilience against impairments. Promising directions also include combining this architecture with emerging concepts such as Software-Defined Networking (SDN), energy-efficient designs, and quantum-resistant communications. Future studies focusing on scalability, power consumption, and economic aspects will be essential to assess the suitability of this architecture for high-capacity fiber optic networks of the future.

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ملخص:

سعيًا نحو تطوير شبكات النفاذ البصري وتحقيق الاستجابة لمتطلبات السرعة العالية والخدمات الحديثة مثل الفيديو حسب الطلب والبث بجودة فائقة، تم التوجه نحو أنظمة WDM-PON كخيار فعال يلبي هذه الاحتياجات. في هذا العمل، نركز على دراسة وتحليل أداء شبكة WDM-PON باستخدام نوعين من تقنيات التشكيل هما RZ وNRZ، مع الاستفادة من مرشحين ضوئيين من نوع AWG موصولين على التوالي لتعزيز التحكم في الأطوال الموجية. تم تقييم النظام بناءً على مؤشرات الأداء الأساسية، مثل معدل الخطأ في البتات (BER) ومعامل الجودة(Q) ، وذلك في بيئات خالية من التأثيرات غير الخطية وأخرى تتضمنها. وقد تم تغيير القدرة البصرية من –10 dBm إلى +dBm10 ، وتغيير طول الألياف من 10 كم إلى 70 كم، بهدف تحديد أفضل إعداد ممكن لتحقيق أداء قوي واستقرار في النقل على مسافات طويلة.

Summary:

In order to improve the capacity and flexibility of Passive Optical Networks (PON) while supporting higher data rates and future services such as ultra-high-definition video and cloud-based applications, WDM-PON systems have emerged as a promising solution. In this work, we evaluate the performance of a WDM-PON architecture based on RZ and NRZ modulation formats, using two cascaded AWG filters to enhance wavelength management. The analysis focuses on key parameters such as the bit error rate (BER) and quality factor (Q), under both linear and nonlinear transmission conditions. Optical power levels are varied from –10 dBm to +10 dBm, and fiber lengths range from 10 km to 70 km, in order to identify the optimal configuration that ensures high system performance and long-reach capability.

Résumé :

Afin d'améliorer la capacité et la flexibilité des réseaux optiques passifs (PON), tout en répondant aux exigences croissantes en matière de débits élevés et de services avancés tels que la vidéo en très haute définition (4K, 8K) et les applications cloud, les systèmes WDM-PON s'imposent comme une solution prometteuse. Dans ce travail, nous évaluons les performances d'une architecture WDM-PON basée sur les formats de modulation RZ et NRZ, en utilisant deux filtres AWG en cascade pour une meilleure gestion des longueurs d'onde. L’analyse porte principalement sur deux indicateurs clés : le taux d’erreur binaire (BER) et le facteur de qualité (Q), en tenant compte des conditions de transmission linéaires et non linéaires. La puissance optique est variée de –10 dBm à +10 dBm, et la longueur de la fibre de 10 km à 70 km, afin d’identifier la configuration optimale assurant une performance élevée et une portée étendue du système.