

# T183004\_Fajal kader\_Thesis Report Book-1

*by liuc Central Library*

---

**Submission date:** 19-Aug-2023 09:21AM (UTC+0530)

**Submission ID:** 2147838849

**File name:** T183004\_Fajal\_kader\_Thesis\_Report\_Book-1.pdf (1.78M)

**Word count:** 20837

**Character count:** 131794



**BACHELOR OF SCIENCE IN ELECTRONIC AND  
TELECOMMUNICATION ENGINEERING**

**Design, Simulation and Investigation of DWDM  
Optical Transmission Systems**

**Submitted by:**

**Fajal Kader**

**ID: T183004**

**Supervised by:**

**Engr. Abdul Gafur**

**Associate Professor**

**Department of ETE**

**International Islamic University Chittagong**

**Department of Electronic and Telecommunication Engineering**

**International Islamic University Chittagong**

**Kumira, Sitakunda, Chittagong – 4314**

**July 2023**

## **Certificate of Approval**

The thesis is titled “**Design, Simulation and Investigation of DWDM optical transmission systems**” Submitted by Fajal Kader, ID: T183004 in fulfillment of the requirement for the degree of Bachelor of Science in Electronic and Telecommunication Engineering (ETE) is accepted as to style and content by:

---

Supervisor

Engr. Abdul Gafur

Associate Professor

Department of Electronic and Telecommunications Engineering

International Islamic University of Chittagong

## **Declaration of Candidate**

It is thus stated that I have completed this thesis and that no part of it has been submitted Else where to grant a degree or certificate in any other institution.

---

Fajal Kader

Matric ID: T183004

## **Acknowledgment**

All praises and thanks to Allah, the Lord of the world, the Most Beneficent, the Most Merciful, to complete this thesis without Whose help it would not be possible for us.

We appreciate our gratitude to our honorable thesis supervisor Engr. Abdul Gafur, Associate Professor, Department of Electronics & Telecommunication Engineering, International Islamic University Chittagong for his useful ideas and assistance for the thesis work. He has given us guidelines to correct our work.

We also appreciate the Department of ETE faculty members' generous assistance. All authors and researchers whose work we consulted in order to design and conduct this study are owed to us.

Finally, we want to express our sincere gratitude to our parents for their support and inspiration, which have kept us motivated during this four-year trip, particularly this research.

## Abstract

This study reported the performance evaluation of various distributors and exchange elements configurations in the optical fiber communication system. With the increasing demand for high-speed data transfer, Dense Wavelength Division Multiplexing (DWDM) technology has become an attractive solution for optical communication systems. This paper presents the design and performance analysis of a DWDM-based optical communication system with different channels. The system consists of multiple channels, each transmitting data at a different wavelength, which are combined into a single optical fiber using a multiplexer. A demultiplexer separates the channels at the receiving end, and each channel's data is recovered separately. We analyze the performance of the system by measuring its bit error rate (BER), Quality Factor, and signal-to-noise ratio (SNR) under different conditions. We also examine how varying the channel spacing affects the system's performance. Our results demonstrate that the proposed system can achieve high data rates and excellent performance with low BER and high SNR, making it a promising candidate for high-speed optical communication systems.

# Table of Contents

<b>1</b>	Certificate of Approval .....	ii
	Declaration of Candidate .....	iii
	Acknowledgment .....	iv
	Abstract .....	iv
	Table of Contents .....	vi
	List of Figures .....	x
	List of Tables .....	xii
	List of Abbreviations .....	xv
	Chapter 1 .....	1
	Introduction .....	1
<b>1.1</b>	Introduction .....	1
<b>1.2</b>	History of optical communication System .....	2
<b>1.3</b>	Background of optical communication System .....	3
<b>1.4</b>	Working Principle of optical communication System .....	4
<b>1.5</b>	Recent work of optical communication System .....	4
<b>1.6</b>	Advantage of optical communication systems based on a different channel.....	5
1.6.1	Fiber Optic Communication: .....	5
1.6.2	Free-Space Optical Communication: .....	6
1.6.3	Visible Light Communication: .....	6
1.6.4	Coherent Optical Communication: .....	7
1.6.5	Quantum Optical Communication: .....	7
<b>1.7</b>	Low Power Consumption: .....	8
<b>1.8</b>	Scalability: .....	8
<b>1.9</b>	Immunity to Crosstalk: .....	8
<b>1.10</b>	Enhanced Signal Quality: .....	8
<b>1.11</b>	Multiplexing and Multimode Capabilities: .....	8
<b>1.12</b>	limitation of optical communication systems with different channels .....	9
1.12.1	Attenuation and Losses: .....	9
1.12.2	Dispersion: .....	9
1.12.3	Nonlinear Effects: .....	9
1.12.4	Power Budget Constraints: .....	9
1.12.5	Crosstalk and Interference: .....	10
1.12.6	Noise: .....	10

1.12.7	Channel Capacity Limitations:.....	10
1.12.8	Signal Quality and Regeneration:.....	10
18	Wavelength Division Multiplexing (WDM): .....	10
	Dense Wavelength Division Multiplexing (DWDM) : .....	11
1.13	How many types of DWDM .....	13
1.13.a	Coarse Wavelength Division Multiplexing (CWDM): .....	13
1.13.b	Long Wavelength Division Multiplexing (LWDM): .....	13
1.13.c	Ultra-Dense Wavelength Division Multiplexing (UDWDM): .....	13
1.13.d	Coherent Wavelength Division Multiplexing (Coherent WDM): .....	13
1.13.e	Hybrid Dense Wavelength Division Multiplexing (HDWDM): .....	14
1.13.f	Colorless, Directionless, and Contentionless (CDC) DWDM: .....	14
1.13.g	Gridless DWDM:.....	14
1.13.h	FlexGrid DWDM: .....	15
1.14	The name of different channels in optical communication .....	15
1.14.a	Single-Mode Fiber (SMF): .....	15
1.14.b	Multimode Fiber (MMF): .....	15
1.14.c	Free-Space Optical (FSO) Communication: .....	15
1.14.d	Coaxial Cable:.....	16
1.14.e	Waveguides:.....	16
1.14.f	Plastic Optical Fiber (POF):.....	16
1.14.g	Optical Satellite Communication: .....	16
1.14.h	Quantum Channels: .....	16
1.14.i	Submarine Optical Cable:.....	16
1.14.j	Terrestrial Optical Networks:.....	16
1.14.k	Intra-Chip Optical Communication: .....	17
1.14.l	Optical Wireless Communication:.....	17
1.14.m	Orbital Angular Momentum (OAM) Channels: .....	17
1.14.n	Mode-Division Multiplexing (MDM): .....	17
1.14.o	Space-Division Multiplexing (SDM):.....	17
1.14.p	Polarization-Division Multiplexing (PDM):.....	17
1.14.q	Coherent Optical Communication: .....	18
1.14.r	Optical Frequency Division Multiplexing (OFDM):.....	18
1.14.s	Quantum Key Distribution (QKD):.....	18
1.15	Objective of Research: .....	19
	Chapter 2.....	21
	Literature review.....	21

2.1	Literature review.....	21
2.2	Design of DWDM-based Optical Communication System: .....	23
2.3	Performance Analysis of DWDM-based Optical Communication System:.....	23
2.4	Different Channels in DWDM-based Optical Communication System:.....	23
	Channel Spacing in DWDM-based Optical Communication System:.....	24
2.5	Optical Amplification in DWDM-based Optical Communication System: .....	27
2.6	Filter Design in DWDM-based Optical Communication System:.....	28
2.7	Mode-division Multiplexing in DWDM-based Optical Communication System:.....	28
2.8	Polarization-based Multiplexing in DWDM-based Optical Communication System: ..	28
2.9	Coherent Detection in DWDM-based Optical Communication System: .....	28
2.10	Nonlinear Effects in DWDM-based Optical Communication System: .....	28
2.11	Network Topology in DWDM-based Optical Communication System: .....	29
2.12	System Optimization in DWDM-based Optical Communication System:.....	29
2.13	Metro and Data Center Interconnect in DWDM-based Optical Communication System:.....	29
2.14	Roadmap for Future DWDM-based Optical Communication System: .....	29
2.15	Cost-effective Design in DWDM-based Optical Communication System:.....	30
	Chapter 3.....	32
	System Model .....	32
3.1	Introduction to Optisystem.....	32
3.2	CW Laser .....	32
3.3	Pseudo-Random Bit Sequence Generator .....	34
3.4	NRZ Pulse Generator.....	36
3.5	Mach-Zehnder Modulator .....	37
3.6	Transmission Line Library.....	38
3.7	PIN Photodiode: .....	39
3.8	3R Regenerator .....	40
3.9	BER Analyzer .....	40
3.10	Optical Spectrum Analyzer.....	41
3.11	wavelength division multiplexing (WDM) MUX :.....	42
3.12	DWDM Demux .....	43
3.13	Optical Amplifier .....	44
3.14	Optical Fiber.....	45
3.15	DWDM system in optisystem .....	46
3.16	Proposed System in optisystem using 4 Channel .....	47
3.17	Proposed System in Optisystem using 8 Channel.....	47

3.18	Proposed System in Optisystem using 16 Channel.....	48
	Chapter 4.....	51
	Result Analysis .....	51
4.1	Proposed System performance analysis using different channel.....	51
4.2	Q Factor Analysis.....	54
4.3	Bit Error Rate Analysis.....	58
4.4	Eye Diagram Analysis .....	60
4.5	Comparison With Existing Work.....	62
	Chapter 5.....	64
	Conclusion.....	64
5.1	Conclusion.....	64
5.2	Achievement .....	64
5.3	Limitation .....	65
5.4	Future Work.....	65
	References .....	67

## List of Figures

FIGURE 1. 1 BLOCK DIAGRAM OF WDM.....	11
FIGURE 1. 2 BLOCK DIAGRAM OF DWDM SYSTEM.....	12
FIGURE 1. 3 BLOCK DIAGRAM OF CWDM.....	13
<b>1</b> FIGURE 2. 1 BASIC BUILDING BLOCK OF OPTICAL DWDM TRANSMISSION.....	26
FIGURE 2. 2 BLOCK DIAGRAM OF OPTICAL AMPLIFICATION IN DWDM.....	27
FIGURE 3. 1: CW LASER IN OPTISYSTEM.....	33
FIGURE 3. 2: PRBS IN OPTISYSTEM.....	35
FIGURE 3. 3: NRZ PULSE GENERATOR IN OPTISYSTEM.....	37
FIGURE 3. 4: MACH-ZEHNDER MODULATOR IN OPTISYSTEM.....	38
FIGURE 3. 5: PIN PHOTODIODE IN OPTISYSTEM.....	39
FIGURE 3. 6: 3R REGENERATOR IN OPTISYSTEM.....	40
FIGURE 3. 7: BER ANALYZER IN OPTISYSTEM.....	41
FIGURE 3. 8: OPTICAL SPECTRUM ANALYZER IN OPTISYSTEM.....	42
FIGURE 3. 9 : WDM MUX IN OPTISYSTEM.....	43
FIGURE 3. 10: DWDM DEMUX IN OPTISYSTEM.....	44
FIGURE 3. 11: OPTICAL AMPLIFIER IN OPTISYSTEM.....	45
FIGURE 3. 12: OPTICAL FIBER IN OPTISYSTEM.....	46
FIGURE 3. 13 : 16 CHANNEL DWDM IN OPTISYSTEM.....	49
FIGURE 3. 14: 8 CHANNEL DWDM IN OPTISYSTEM.....	48
FIGURE 3. 15: 4 CHANNEL DWDM IN OPTISYSTEM.....	47
<b>1</b> FIGURE 4. 1: PROPOSED SYSTEM PERFORMANCE FOR Q FACTOR AND BER USING DIFFERENT CHANNELS.....	51
FIGURE 4. 2: OPTICAL SPECTRUM ANALYZER FOR 4 CHANNEL.....	52
<b>11</b> FIGURE 4. 3: OSA FOR 8 CHANNEL.....	53

FIGURE 4. 4: OSA FOR 16 CHANNELS.....	53
FIGURE 4. 5: Q FACTOR FOR 4 CHANNELS.....	55
FIGURE 4. 6: Q FACTOR FOR 8 CHANNELS.....	55
FIGURE 4. 7: Q FACTOR FOR 16 CHANNELS.....	56
FIGURE 4. 8: BAR DIAGRAM OF Q-FACTOR FOR 4, 8, AND 16 CHANNELS.....	57
FIGURE 4. 9: BER FOR 4 CHANNEL.....	58
FIGURE 4. 10: BER FOR 8 CHANNEL.....	59
FIGURE 4. 11: BER FOR 16 CHANNEL.....	59
FIGURE 4. 12: BER FOR 4, 8, AND 16 CHANNELS.....	60
FIGURE 4. 13: EYE DIAGRAM FOR 4 CHANNEL.....	60
FIGURE 4. 14: EYE DIAGRAM FOR 8 CHANNELS.....	61
FIGURE 4. 15: EYE DIAGRAM FOR 16 CHANNEL.....	61
FIGURE 4. 16: EYE FOR 4, 8, AND 16 CHANNELS.....	62

## List of Tables

<b>1</b>	<b>TABLE 2 1: REQUIRED PARAMETERS AND VALUES</b> .....	24
	<b>TABLE 2 2: SIMULATION PARAMETER</b> .....	26
	<b>TABLE 2 4: COMPARISON BETWEEN DIFFERENT TECHNIQUES</b> .....	27
	<b>TABLE 4 1 Q FACTOR VALUES FOR DIFFERENT CHANNELS</b> .....	57
	<b>TABLE 4 2: BIT ERROR RATE FOR DIFFERENT CHANNELS</b> .....	60
	<b>TABLE 4 3: EYE DIAGRAM FOR DIFFERENT CHANNELS</b> .....	62
	<b>TABLE 4 4: COMPARISON WITH EXISTING WORK</b> .....	62

## List of Symbols

<b>1</b> Hz	Hertz
THz	Terahertz
GHz	Gigahertz
f	Frequency
$\omega$	Angular frequency
$\lambda$	Wavelength
$\pi$	Pi
B	Byte
MB	Megabyte
s	Second
ps or s <sup>-1</sup>	Per second
MBps	Megabyte per second
Gbps	Gigabyte per second
m	Meter
mm	Millimeter
cm	Centimeter
km	Kilometer
$\mu$ m	Micrometer
nm	nanometer
m <sup>-1</sup>	Per Meter
ms <sup>-1</sup>	Meter per second
cm <sup>-1</sup>	Per Centimeter
<b>1</b> g/cm <sup>3</sup>	Gram per centimeter cube
kJ/m	Kilo joule per meter
ps/THz/cm	Per second per terahertz per centimeter
dB/m	Decibel per meter
dB/cm	Decibel per centimeter
dB/km	Decibel per kilometer
%	Percentage
d	Diameter

<sup>1</sup>  
r

w

a

b

$\eta$

$\Lambda$  Speed of light

$^{\circ}\text{C}$

$\eta$

a

b

W

<sup>1</sup>

Radius

Width

The major diameter of the ellipse

The minor diameter of the pipe

Ellipticity

Pitch

Degree Celsius

Ellipticity

<sup>1</sup>  
The major diameter of ellipse

The minor diameter of ellipse

Watt

## List of Abbreviations

WDM	Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
PRE	Power Amplifier
AMP	Amplifier
SMF	Single Mode Fiber
MOF	Micro-structured Optical Fiber
PM	Polarization Maintaining
0D	Zero-Dimensional
NRZ	Non-return to zero
RZ	Return To Zero
FSO	Free Space Channel
3D	Three-Dimensional
MSF	Micro Steel Fiber
MCF	Multi-core Fiber
M-TIR	Modified Total Internal Reflection
COC	Cyclic Olefin Copolymers
TFE	Tetra-fluoro-Ethylene
PTFE	Polytetrafluoroethylene
MMA	Methyl Methacrylate
SOA	Semiconductor Optical Amplifiers
EDFA	Erbium Doped Fiber Amplifier
UV	Ultraviolet
PC-PCF	Porous-Core Photonic Crystal Fiber
EML	Effective Material Loss
Y-pol	Y-polarization
PS	Partially Slotted
FS	Fully Slotted
LFM	Localized-function Method

# Chapter 1

## Introduction

### 1.1 Introduction

When it comes to features and benefits over conventional electrical transmission, optical technology is a game-changer. It has a high data rate and ample storage. The optical transmission system is composed of the transmitter and multiplexer. Modern optical networks' transmission layer optical link design has never been easier owing to Opti-System, an all-in-one optical network design and testing system [1][2]. Optical signals of various wavelengths (1300–1600 nm) can travel apart from one another without interfering. Wavelength division multiplexing (WDM) is a method for spreading various wavelengths over a single fiber. A different light source with a different wavelength produces each input. The advancement of the Erbium Doped Fiber Amplifier (EDFA) propelled WDM to DWDM, the next stage. Without the creation of EDFAs, DWDM implementation would not have been feasible. These amplifiers are compatible with optical fibers that run in the same 1550nm wavelength window since they operate close to that range of wavelengths. Special optical components and optical modules, such as a low chirp integrated laser, EDFAs, a multiplexer, and a demultiplexer, are needed to implement DWDM in an optical communication network. To the transmitting fiber, an optical multiplexer couples light from several sources. Before photo identification of individual signals, an optical demultiplexer is needed at the receiving station to separate the various carriers. The demultiplexer must operate within a tight spectrum window with distinct wavelength cut-offs to prevent erroneous signals from entering the receiving channel. Crosstalk levels must not exceed -30dB. The capacity boost, transparency, wavelength switching, and routing are some features of DWDM.

Due to the big bandwidth, high data rate, and affordable, dependable optical communication links available recently, the need for optical fiber technology is growing every day in the telecommunications industry[3]. DWDM technology is now being adopted to improve optical fiber networks' ability to transmit data and use ACCEPTED manuscripts effectively[4][5].

## 1.2 History of optical communication System

Optical communication has been an important technology for centuries, expanding from the use of mirrors and semaphore arms to the development of optical fibers and laser technology for transmitting vast amounts of data at high speeds over long distances. In the mid-1960s, the first digital optical communication system was developed using light-emitting diodes (LEDs) and infrared light to transmit digital signals over short distances between electronic devices. This laid the foundation for the widespread use of optical communication in the telecommunications industry. The 1970s saw the development of optical fibers as a means of transmitting light signals over long distances. The early optical fibers were made of glass and had a high signal loss, but research in the 1980s led to the development of low-loss optical fibers with high bandwidth. Additionally, high-power lasers provided a tremendous boost in the optical signal power and enabled optical fibers to transmit signals over long distances[6][7]. Today, optical communication is a critical component of many industries, including telecommunications, data centers, medical equipment, and space exploration. Optical communication systems are designed to transmit signals over long distances with minimal signal loss and interference. Single-mode fiber optic cable has become the best channel for long-distance optical communication due to its lower signal attenuation, allowing for signals to be transmitted at high speeds and across large distances[8]. The development of advanced optical components, such as optical amplifiers, optical switches, and wavelength-division multiplexing (WDM), has enabled increased capacity and bandwidth in optical communication systems. Optical amplifiers, such as erbium-doped fiber amplifiers (EDFAs), amplify optical signals inside the fiber, while optical switches and WDM allow multiple signals to be transmitted simultaneously over a single fiber [9][10]. Optical communication technology has come a long way since ancient times, with the development of digital optical communication systems, optical fibers, lasers, and advanced optical components. It has had a significant impact on the way we communicate and receive data, and its importance is only expected to grow in the future. Ongoing research and development in the field will continue to drive innovation and improve the performance of optical communication systems.

### 1.3 Background of optical communication System

Optical communication systems have revolutionized the telecommunications industry, offering a high-speed, reliable, and cost-effective method of transmitting data over long distances. The channel used for data transmission can have a significant impact on the performance of the communication system. Multimode fiber, with its larger core diameter, supports the transmission of multiple modes of light, making it a cost-effective and easy-to-install option for short-range communication. Single-mode fiber, with its smaller core diameter, supports higher bandwidth and longer transmission distances, making it ideal for long-haul communication[11].

The continuous advancements in optical communication have opened up new opportunities in various fields, including aerospace, transportation, healthcare, and security. The channel chosen for data transmission is pivotal to the system's overall performance, and research is ongoing to improve the speed, bandwidth, and transmission distance of each channel. Multimode fiber has widespread availability and remains a popular choice for short-range communication. However, it is prone to dispersion and attenuation, which can limit data transmission speed and reduce signal quality. Single-mode fiber, with its lower dispersion and attenuation rates, offers improved bandwidth and transmission distances, making it ideal for long-distance communication applications. Free space optical communication has the potential to revolutionize communication in remote areas where cables and other communication infrastructure are not available. However, the channel can suffer from atmospheric turbulence, which can cause weakening or scattering of the optical signals. Overcoming these challenges requires advanced adaptive optics techniques to stabilize the optical beam and ensure reliable and consistent performance. Optical power-line communication offers an alternative to traditional copper-wire-based communication systems, leveraging existing powerline infrastructure to carry signals. However, the channel can be impacted by signal attenuation, noise, and interference from other devices on the same powerline. Developing new modulation and filtering technologies can help to improve the quality and reliability of the transmission. Advanced research is being carried out, leveraging the principles of quantum physics to develop quantum optical communication systems that enable ultra-secure communication by exploiting the unique properties of quantum particles. These systems have the potential to provide secure communication solutions that are resistant to potential attacks by eavesdroppers,

making them ideal for advanced military communications and other applications that require high levels of security [12] [13].

#### **1.4 Working Principle of optical communication System**

Optical communication is a critical component of modern telecommunications systems, offering high-speed and reliable data transmission over long distances. A proper understanding of the working principles of different channels is essential for optimizing system performance. Multimode fiber and single-mode fiber are widely used channels for optical communication. Multimode fiber has a larger core diameter and can suffer from modal dispersion, while single-mode fiber has a smaller core diameter, ensuring signals propagate through the fiber in only one mode, minimizing attenuation, distortion, and signal degradation over long distances[14].

Free space optical communication has many challenges, including the impact of atmospheric turbulence, beam divergence, and beam noise. Adaptive optics techniques, beam shaping, and error correction codes can be used to improve the channel's performance. Optical power-line communication uses existing powerline infrastructure, making it ideal for urban areas and smart grid applications. However, this channel can suffer from signal attenuation and interference from other devices on the powerline. To overcome these problems, modulation and filtering techniques can be used to improve signal quality, and advanced powerline coupling and impedance matching can be employed to reduce signal degradation.

The working principles of different optical communication channels are crucial to optimizing system performance. Advances in technology are being made to improve each channel's working principle and improve their performance. Optical communication is an evolving field, and research, development, and innovative solutions are ongoing to improve the efficiency, speed, and reliability of data transmission [15].

#### **1.5 Recent work of optical communication System**

Recent work in optical communication systems has focused on improving the performance of existing technologies and exploring new applications.

One exciting field of the development of metasurfaces, which are surfaces that manipulate light at a subwavelength scale. Metasurfaces can be used in optical communication systems to enable more efficient light transmission, allowing for higher data rates and improving signal quality over a range of wavelengths. Recent studies have shown that

metasurfaces can be used to design compact and advanced optical components, including multiplexers, switches, and receivers [16].

Machine learning and artificial intelligence techniques are also being applied to optical communication systems to improve system efficiency and performance. Some recent studies have shown that machine learning can be employed to predict the performance of optical communication systems, allowing for optimization and improved signal quality. Quantum mechanics to improve communication security. Quantum key distribution (QKD) uses the principles of quantum mechanics to generate a secure key that can be used for secure communication. QKD has the potential to provide unbreakable encryption and can be used in applications where security is a top priority, such as military and government communications [17].

Overall, recent work in optical communication systems has focused on improving the performance of existing technologies and exploring new applications. Meta surfaces, artificial intelligence, and quantum mechanics are just a few examples of exciting new developments in this field.

### 1.6 Advantage of optical communication systems based on a different channel

Optical communication systems offer several advantages over other communication channels, such as electrical and wireless channels. Here are the advantages of optical communication systems based on different channels:

#### 1.6.1 Fiber Optic Communication:

Fiber optic communication is based on transmitting data through optical fibers, which are thin strands of glass or plastic. The advantages of fiber optic communication include:

**High Bandwidth:** Fiber optics provide a significantly higher bandwidth compared to electrical cables. This enables the transmission of large amounts of data at high speeds, making it suitable for applications requiring high data rates, such as video streaming and cloud computing.

**Low Attenuation:** Optical fibers have low signal attenuation, which means that the transmitted signals can travel longer distances without a significant loss of signal strength. This allows for long-distance communication without the need for repeaters, reducing costs and signal degradation.

**Immunity to Electromagnetic Interference:** Unlike electrical cables, optical fibers are immune to electromagnetic interference (EMI). This makes fiber optic communication

more reliable in environments with high EMI, such as industrial facilities or areas with heavy electrical equipment.

#### **1.6.2 Free-Space Optical Communication:**

Free-space optical communication (FSO) involves the transmission of data through open air or outer space using laser beams. The advantages of FSO communication include:

**High Data Rates:** FSO systems can achieve extremely high data rates, rivaling or even surpassing traditional wired communication. This makes FSO suitable for applications requiring high-speed data transfer, such as point-to-point links or backhaul connections.

**Immunity to Interference:** FSO communication is immune to radio frequency interference (RFI) and electromagnetic interference (EMI) since it operates in the optical spectrum. This allows for secure and reliable communication without concerns about signal jamming or interception.

**No Spectrum Licensing:** FSO communication does not require spectrum licensing, unlike radio frequency-based wireless communication systems. This makes it a cost-effective solution, especially in densely populated areas where radio spectrum is scarce or expensive.

#### **1.6.3 Visible Light Communication:**

Visible Light Communication (VLC) utilizes the visible light spectrum for data transmission, often through light-emitting diodes (LEDs). The advantages of VLC include:

**Ubiquitous Infrastructure:** VLC leverages existing lighting infrastructure, such as LED bulbs, for communication purposes. This widespread infrastructure enables the deployment of VLC systems in various indoor environments like homes, offices, and public spaces without requiring additional infrastructure.

**High Security:** VLC offers a high level of security since visible light does not penetrate through walls. This property makes VLC communication inherently secure against eavesdropping or unauthorized access from outside the premises.

**Immunity to RF Interference:** VLC operates in the visible light spectrum, which is separate from radio frequencies used by other wireless systems. This immunity to RF interference ensures reliable communication in environments with heavy wireless traffic or congested radio spectrum.

#### **1.6.4 Coherent Optical Communication:**

Coherent optical communication utilizes advanced modulation and detection techniques to achieve high spectral efficiency. The advantages of coherent optical communication include:

**Increased Capacity:** Coherent optical systems can achieve higher data transmission rates by efficiently utilizing the available spectrum. This enables the transmission of a larger amount of data within the same bandwidth, resulting in increased capacity and improved network scalability.

**Longer Transmission Distances:** Coherent optical systems employ sophisticated signal processing techniques, such as digital signal processing and forward error correction, which help compensate for signal impairments. This allows for longer transmission distances without significant degradation in signal quality.

**Flexibility in Wavelength Allocation:** Coherent optical communication systems can dynamically allocate different wavelengths to different data channels, enabling wavelength-division multiplexing (WDM). This flexibility maximizes the utilization of the optical spectrum, allowing for efficient multiplexing of multiple channels over a single fiber [18].

#### **1.6.5 Quantum Optical Communication:**

Quantum optical communication involves the use of quantum phenomena to transmit information securely and reliably. The advantages of quantum optical communication include:

**Quantum Key Distribution (QKD):** Quantum optical systems enable secure key distribution using QKD protocols. QKD provides unconditional security by leveraging the principles of quantum mechanics, ensuring that any eavesdropping attempt can be detected.

**Resistance to Eavesdropping:** Quantum communication is intrinsically secure against eavesdropping due to the no-cloning theorem, which states that it is impossible to create an identical copy of an unknown quantum state. This property makes quantum optical communication highly resistant to interception or tampering.

**Quantum Entanglement for Enhanced Communication:** Quantum optical communication can exploit quantum entanglement to enhance communication capabilities. Entangled particles can be used to transmit information instantaneously, enabling faster-than-light communication in certain scenarios[19][20].

### **1.7 Low Power Consumption:**

Optical communication systems require significantly less power compared to traditional electrical communication systems. This is because optical signals experience lower losses and require fewer amplification stages, resulting in reduced power consumption. Lower power consumption is particularly beneficial in energy-constrained environments and helps in achieving higher energy efficiency in data transmission.

### **1.8 Scalability:**

Optical communication systems offer excellent scalability, allowing for seamless expansion and upgrading of network infrastructure. Optical fibers can accommodate a large number of wavelength channels through WDM technology, providing virtually unlimited capacity for future growth. This scalability is vital in meeting the ever-increasing demand for higher data rates and accommodating emerging technologies like 5G, the Internet of Things (IoT), and cloud computing.

### **1.9 Immunity to Crosstalk:**

Optical communication systems are immune to crosstalk, which is the interference that occurs when signals from different channels or wires overlap. Unlike electrical systems, optical signals do not interfere with each other, allowing for dense packing of optical channels without cross-interference. This attribute is particularly advantageous in high-density communication environments, such as data centers or submarine communication systems.

### **1.10 Enhanced Signal Quality:**

Optical communication systems offer superior signal quality compared to other communication channels. Optical signals are less susceptible to noise, distortion, and degradation over long distances, ensuring high-fidelity transmission. Additionally, optical fibers exhibit lower signal dispersion, enabling the transmission of high-speed signals over longer distances without significant degradation.

### **1.11 Multiplexing and Multimode Capabilities:**

Optical communication systems support various multiplexing techniques, such as time-division multiplexing (TDM) and wavelength-division multiplexing (WDM). These techniques allow multiple independent data channels to be combined and transmitted simultaneously, increasing overall system capacity. Moreover, optical fibers can support multimode transmission, where multiple modes of light propagate

through the fiber simultaneously. This multimode capability enables efficient utilization of fiber bandwidth, enhancing overall system performance [21][22].

## **1.12 limitation of optical communication systems with different channels**

### **1.12.1 Attenuation and Losses:**

Optical signals experience attenuation and losses as they propagate through different channels, such as optical fibers or free space. These losses can be due to fiber material properties, bending losses, scattering, or absorption. Attenuation limits the distance over which signals can be transmitted without significant degradation. Losses can also limit the overall system performance in terms of signal quality and data rate [23].

### **1.12.2 Dispersion:**

Dispersion refers to the spreading of optical signals as they propagate through the transmission medium. Different channels can have varying dispersion characteristics, such as chromatic dispersion (resulting from different wavelengths traveling at different speeds) and polarization mode dispersion (caused by different polarizations of light experiencing different velocities). Dispersion can cause pulse broadening, leading to inter-symbol interference and limiting the achievable data rate and transmission distance [24].

### **1.12.3 Nonlinear Effects:**

Nonlinear effects can occur in optical communication systems when the signal power becomes relatively high. These effects include self-phase modulation, four-wave mixing, stimulated Raman scattering, and stimulated Brillouin scattering. They can distort the transmitted signals and introduce noise, limiting the system's performance.

### **1.12.4 Power Budget Constraints:**

Optical communication systems have power budget constraints that limit the number of channels or the distance over which signals can be transmitted. These constraints depend on the available optical power, receiver sensitivity, and the losses encountered in the transmission medium. [25].

### 1.12.5 Crosstalk and Interference:

In multi-channel optical communication systems, crosstalk and interference can arise when signals from different channels interfere with each other due to inadequate isolation or channel spacing. This can degrade the signal quality and increase the error rate.

### 1.12.6 Noise:

Optical communication systems are susceptible to various sources of noise, such as thermal noise, shot noise, and spontaneous emission noise. These noise sources can degrade the signal-to-noise ratio (SNR) and limit the system's ability to accurately detect and interpret the transmitted information [26].

### 1.12.7 Channel Capacity Limitations:

The channel capacity of optical communication systems is finite, and limited by factors such as the available bandwidth, modulation schemes, and noise levels. As the number of channels increases, the available capacity must be shared among them, potentially reducing the achievable data rates per channel [27].

### 1.12.8 Signal Quality and Regeneration:

In long-haul optical communication systems with multiple channels, the signal quality can degrade due to cumulative impairments. Signal regeneration and amplification become necessary to restore and boost the signal quality periodically. However, the regeneration process introduces additional complexity, cost, and potential limitations in terms of signal fidelity and timing.

These limitations highlight the complex challenges faced in optical communication systems with different channels. The provided references offer further insights into these topics, exploring advanced techniques, mitigation strategies, and research advancements in the field of optical communications.

### 28 Wavelength Division Multiplexing (WDM):

Wavelength Division Multiplexing (WDM) is a highly advanced technology used in optical communication systems for transmitting multiple data signals over a single optical fiber. This technology allows for the efficient utilization of the available bandwidth, making it possible to transmit vast amounts of data at high speeds over long distances. In fiber-optic communications, wavelength-division multiplexing (WDM) is crucial for multiplexing optical carrier messages onto a single optical fiber. It is possible to use a single fiber strand for both capacity growth and bidirectional transmission. In

WDM systems, multiplexers and demultiplexers are used to combine and separate signals. Theoretically, both objectives might be achieved simultaneously by creating an optical add-drop multiplexer with the appropriate fiber type. For a long time, optical filtering devices called Etalons (Fabry-Pérot interferometers in thin-film coated optical glass) have been employed [28].

### Wavelength Division Multiplexing (WDM)

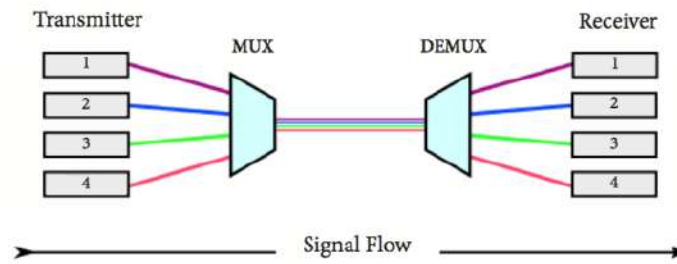


Figure 1. 1 Block diagram of WDM System [29]

WDM networks typically use single-mode fiber cables with a 9-meter diameter. 50 or 62.5 m multi-mode fibers, also referred to as premises cable, can be utilized in some WDM variations. Based on their wavelength patterns, conventional/coarse (CWDM) and dense (DWDM) wavelength division multiplexing systems are two different types of WDM systems [30].

### Dense Wavelength Division Multiplexing (DWDM) :

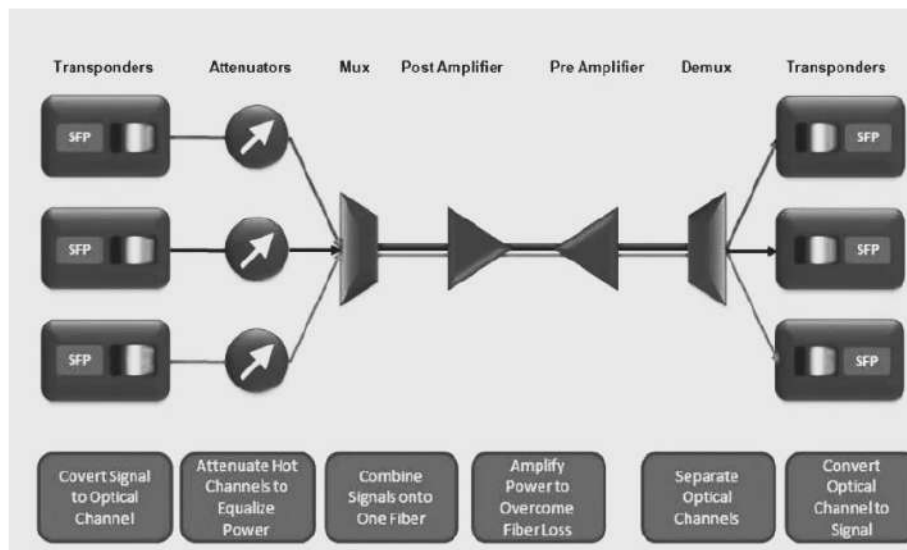
Dense Wavelength Division Multiplexing (DWDM) is a type of Wavelength Division Multiplexing (WDM) technology used in optical communication systems. A method called dense wavelength division multiplexing (DWDM) makes it possible to transmit many information streams simultaneously over a single cable. This offers a workable solution for increasing the capacity of current networks without adding new fiber.

The method used the most frequently for backbone lines is DWDM [32]. It uses very narrow channel spacing (around 0.8-1.6 nm) and supports a large number of channels (up to 160 channels or more), making it an efficient and cost-effective technology for high-bandwidth applications. These systems employ gaps as small as 0.1 nm or even 0.2 nm.

However, when spacing values get smaller, more transmission route parts—especially DFB (Distributed Feedback) lasers—are needed[33]. Tens or even hundreds of parallel optical lines may be transmitted via DWDM systems.

DWDM is characterized by its normalized frequency of 193.1 THz. For optimal performance, the wavelength cannot depart from the normalized wavelength by more than 0.16 nm [34]. DWDM systems allow for the transmission of vast amounts of data over long distances by multiplexing multiple data streams onto a single optical fiber. The data streams are transmitted at different wavelengths on the same fiber without interfering with each other. This technology enables optical networks to operate at much higher speeds, improving network efficiency and reducing costs. DWDM technology has revolutionized optical communication systems and has had a significant impact on the telecommunications industry. It has made it possible to transmit large amounts of data over long distances, making it suitable for applications such as long-haul and submarine communication systems, data centers, and high-speed internet backbone networks.

One of the critical components of DWDM systems is the optical amplifier, which amplifies the optical signal to compensate for signal losses. The most commonly used optical amplifier in DWDM systems is the erbium-doped fiber amplifier (EDFA), which provides high gain and low noise while maintaining compatibility with standard single-mode fiber [35].



76 **Figure 1. 2 Block diagram of DWDM system [36]**

### 1.13 How many types of DWDM

Dense Wavelength Division Multiplexing (DWDM) is a technology used in optical communications to transmit multiple signals simultaneously over a single optical fiber. There are several types of DWDM based on different characteristics and functionalities. However, it's important to note that specific implementations and variations may exist beyond the general types mentioned here.

#### 1.13.a Coarse Wavelength Division Multiplexing (CWDM):

CWDM is a simplified version of DWDM that uses wider channel spacing between wavelengths. It typically operates in the 1270 nm to 1610 nm wavelength range, with a channel spacing of 20 nm. CWDM is suitable for shorter distances and smaller networks where the number of channels is limited.

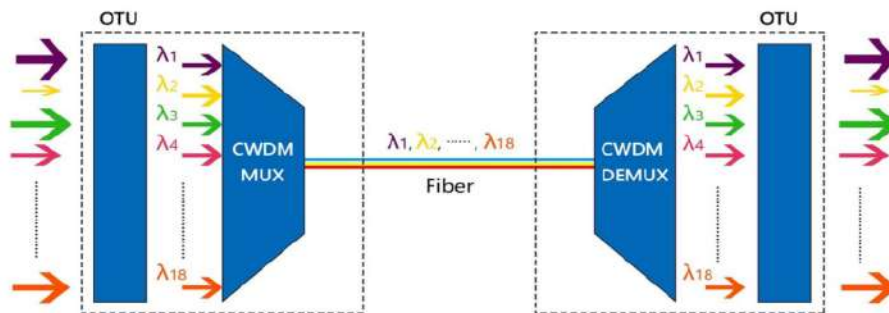


Figure 1. 3 Block Diagram of CWDM [37]

#### 1.13.b Long Wavelength Division Multiplexing (LWDM):

LWDM is a variation of DWDM that operates in the long wavelength range, typically around 1550 nm. It offers a more cost-effective solution compared to traditional DWDM for transmitting a limited number of channels over shorter distances.

#### 1.13.c Ultra-Dense Wavelength Division Multiplexing (UDWDM):

UDWDM is an advanced form of DWDM that allows for a higher number of channels to be transmitted over a single fiber by reducing the channel spacing. UDWDM typically employs channel spacing of 6.25 GHz or less, enabling the transmission of more than 80 channels over a single fiber.

#### 1.13.d Coherent Wavelength Division Multiplexing (Coherent WDM):

Coherent WDM is a technique that utilizes advanced modulation and detection schemes, such as coherent detection, to improve the spectral efficiency and

transmission capacity of DWDM systems. It enables the transmission of multiple wavelengths on a single fiber, achieving higher data rates and longer distances.

**1.13.e Hybrid Dense Wavelength Division Multiplexing (HDWDM):**

HDWDM combines both DWDM and CWDM technologies to create a hybrid system that supports a larger number of channels. It allows for the transmission of a mix of densely spaced channels (DWDM) and widely spaced channels (CWDM) over the same fiber, providing flexibility and scalability.

**1.13.f Colorless, Directionless, and Contentionless (CDC) DWDM:**

CDC DWDM is an advanced technology that enhances the flexibility and efficiency of optical networks. It allows any wavelength to be added or dropped at any network node (colorless), enables bi-directional transmission on any wavelength (directionless), and provides contentions access to wavelengths without interference (contentions). CDC DWDM facilitates dynamic and reconfigurable optical networks.

**1.13.g Gridless DWDM:**

Gridless DWDM is a flexible approach that allows for the use of arbitrary channel spacings rather than being restricted to fixed channel grids. It enables more efficient use of the available optical spectrum by optimizing channel spacing according to the specific requirements of the network, thereby maximizing spectral efficiency.

### **1.13.h FlexGrid DWDM:**

FlexGrid DWDM is an advanced variant of DWDM that introduces flexible and dynamically adjustable channel spacing. Unlike traditional fixed grid systems, FlexGrid DWDM allows for variable channel spacing, enabling optimal utilization of the available spectrum and improved spectral efficiency. With FlexGrid DWDM, channel spacing can be adjusted on a per-wavelength basis, accommodating varying data rates and transmission requirements. This flexibility enables network operators to allocate bandwidth more efficiently, adapt to changing traffic demands, and optimize network capacity. FlexGrid DWDM systems often utilize advanced modulation formats and coherent detection techniques to achieve higher data rates and longer transmission distances. By dynamically allocating channel spacing based on specific needs, FlexGrid DWDM provides enhanced scalability and future-proofing capabilities for optical networks. FlexGrid DWDM represents a significant advancement in optical networking technology, offering increased flexibility, efficiency, and adaptability to evolving network requirements [38].

## **1.14 The name of different channels in optical communication**

### **1.14.a Single-Mode Fiber (SMF):**

Single-mode fiber is the most widely deployed channel in optical communication systems. It supports the transmission of a single mode of light, allowing for high data rates and long-distance communication. It is often used in long-haul and high-capacity applications.

### **1.14.b Multimode Fiber (MMF):**

Multimode fiber enables the transmission of multiple modes of light simultaneously. It is typically used for shorter distances, such as local area networks (LANs) and data centers. Multimode fibers have larger core diameters than single-mode fibers, allowing multiple light rays to propagate.

### **1.14.c Free-Space Optical (FSO) Communication:**

FSO communication involves transmitting information through open air, using laser or infrared beams. It is commonly used for point-to-point communication in situations where physical cables are not feasible or where high-speed communication is required. FSO systems are employed in applications such as wireless backhauling, satellite communication, and terrestrial links.

#### **1.14.d Coaxial Cable:**

<sup>13</sup> Coaxial cable is a type of guided transmission medium that consists of a central conductor surrounded by a dielectric material and an outer conductor. Although it is commonly associated with electrical communication, it is also used in certain optical communication applications, particularly in cable television (CATV) networks.

#### **1.14.e Waveguides:**

Waveguides are structures that confine and guide electromagnetic waves, including optical signals. They can be made of various materials, such as silicon, gallium arsenide, or polymer-based materials. Waveguides are extensively used in integrated optical circuits, photonic integrated circuits (PICs), and silicon photonics.

#### **1.14.f Plastic Optical Fiber (POF):**

POF is an optical transmission medium that employs plastic fibers to carry light signals. It is less expensive and easier to handle than glass fibers, making it suitable for short-range applications like home networking, automotive networks, and consumer electronics.

#### **1.14.g Optical Satellite Communication:**

Optical satellite communication involves the use of satellites to transmit optical signals between ground stations or between satellites. It offers high data rates and low latency communication links, which can be beneficial for applications such as remote sensing, Earth observation, and deep-space communication.

#### **1.14.h Quantum Channels:**

Quantum channels are channels used for quantum communication, where information is transmitted using quantum states instead of classical signals. These channels include various techniques such as quantum key distribution (QKD), quantum teleportation, and quantum entanglement-based communication.

#### **1.14.i Submarine Optical Cable:**

Submarine optical cables are deployed underwater to connect continents and provide international communication links. These cables enable high-capacity, long-distance transmission of optical signals across the ocean floor, forming the backbone of international telecommunications.

#### **1.14.j Terrestrial Optical Networks:**

Terrestrial optical networks encompass a wide range of optical communication channels deployed on land. These networks include backbone fiber-optic links,

<sup>68</sup> metropolitan area networks (MANs), and local area networks (LANs), facilitating high-speed data transmission between different locations.

#### **1.14.k Intra-Chip Optical Communication:**

Intra-chip optical communication refers to the use of optical channels for transmitting data within a microchip or integrated circuit. It aims to address the limitations of electrical interconnects in terms of bandwidth, power consumption, and signal integrity. Intra-chip optical communication is an active area of research for achieving higher-performance computing systems.

#### **1.14.l Optical Wireless Communication:**

Optical wireless communication, also known as Li-Fi (Light Fidelity), utilizes visible light or infrared signals to transmit data wirelessly. It offers <sup>129</sup> advantages such as high data rates, security, and immunity to electromagnetic interference. Optical wireless communication is used in applications like indoor wireless networking and VLC (Visible Light Communication).

#### **1.14.m Orbital Angular Momentum (OAM) Channels:**

OAM channels utilize the spatial modes of light with different orbital angular momentum values. By manipulating the phase and wavefront of the optical beam, <sup>74</sup> multiple OAM modes can be generated, enabling the transmission of increased data capacity over a single optical channel. OAM channels have the potential to significantly enhance <sup>48</sup> spectral efficiency and data rates in optical communication systems.

#### **1.14.n Mode-Division Multiplexing (MDM):**

MDM <sup>48</sup> is a technique that leverages the multiple spatial modes of a multimode fiber or waveguides to transmit independent data streams simultaneously. By assigning different modes to each data stream, MDM allows for increased data capacity over a single fiber, enabling parallel transmission of information.

#### **1.14.o Space-Division Multiplexing (SDM):**

SDM refers to <sup>123</sup> the use of multiple spatial paths or channels within an optical fiber or waveguides to transmit independent data streams. This can be achieved through techniques such as multicore fibers, where multiple cores within a single fiber carry separate data streams. SDM enables higher data rates and capacity by effectively increasing <sup>46</sup> the number of independent communication channels.

#### **1.14.p Polarization-Division Multiplexing (PDM):**

PDM <sup>46</sup> is a technique that utilizes different polarization states of light to transmit multiple independent data streams simultaneously. By employing orthogonal polarizations, such

as horizontal and vertical, PDM enables the multiplexing of data in the optical domain, effectively doubling the data capacity of a single optical channel.

#### **1.14.q Coherent Optical Communication:**

Coherent optical communication employs advanced modulation formats, coherent detection, and digital signal processing techniques to maximize the capacity and reach of optical communication systems. It enables the use of higher-order modulation formats, sophisticated coding schemes, and adaptive equalization, allowing for increased spectral efficiency and improved performance in long-haul and high-speed communication links[39].

#### **1.14.r Optical Frequency Division Multiplexing (OFDM):**

OFDM is a modulation technique widely used in optical communication, particularly in high-speed transmission systems. It divides the optical spectrum into multiple subcarriers, each modulated with data, allowing for efficient utilization of the available bandwidth. OFDM provides robustness against dispersion and nonlinear effects, making it suitable for long-distance and high-capacity optical communication.

#### **1.14.s Quantum Key Distribution (QKD):**

QKD is a secure communication technique that utilizes the principles of quantum mechanics to establish encryption keys between two parties. By transmitting single photons and exploiting the fundamental properties of quantum states, QKD provides unconditional security against eavesdropping, offering a promising solution for secure communication networks [40][41].

These are some of the prominent channels, additional channels, and advanced channels employed used in optical communication, and technologies are pushing the boundaries of optical communication, enabling higher capacities, increased spectral efficiency, and enhanced security in modern communication systems. Each channel serves specific purposes and has its advantages and limitations in different scenarios.

### **1.15 Objective of Research:**

To design an optical communication system based on DWDM technology that incorporates different channels such as multimode fiber, single-mode fiber, free space, and optical power-line communication.

To evaluate the performance of each channel in terms of data transmission speed, signal quality, attenuation, and dispersion.

To investigate the impact of different signal processing techniques, such as digital signal processing, modulation schemes, and error correction codes on system performance.

To optimize the system for maximum efficiency and performance by optimizing channel selection and signal processing techniques.

To compare the performance of the designed system with other existing optical communication systems based on different channels.

To analyze the cost-effectiveness of the designed system in terms of installation, maintenance, and operation costs.



## Chapter 2

### Literature review

#### 2.1 Literature review

The design and performance analysis of DWDM-based optical communication systems with different channels is a rapidly developing field of research that has drawn the attention of various researchers worldwide. In this section, we will present a literature review of recent studies related to this topic.

Several studies have investigated the use of multimode fiber in DWDM optical communication systems. G. Rath et al. (2019) studied the use of few-mode multicore fibers in a wavelength division multiplexed (WDM) system, showing that they can sustain a higher data rate and offer better performance compared to conventional multimode fiber [42].

Single-mode fiber has also been extensively studied for use in DWDM systems. A. K. Pal and T. Chattopadhyay (2018) designed and analyzed a single-mode-based optical communication system, demonstrating the effectiveness of error correction coding for improving the quality of signals [43].

Free space optical communication has been the subject of recent research studies. A. Jbraeil and R. Sarvagya (2020) investigated the use of free space optical communication for disaster management, emphasizing the need for advanced optical components to mitigate the impact of atmospheric turbulence and beam divergence [44].

Optical power-line communication has also been studied extensively. J. Hu et al. (2021) designed and analyzed an optical power-line communication system, demonstrating its potential for high-speed data transmission and low-cost installation with powerline infrastructure[45].

Security is also a critical aspect of DWDM-based optical communication systems. Photonic QKD has been identified as a promising method for secure communication, and recent studies have shown the feasibility of integrating photonic QKD with DWDM systems. Photonic QKD can generate a secure key used for encryption or decryption of data, and it can be incorporated into DWDM systems to enhance the security of optical communication networks. One such technology is the development of photonic quantum key distribution (QKD) for secure communication. QKD uses the principles of quantum mechanics to generate a secure key that can be used for encryption in communication.

Recent studies have shown that QKD can be integrated with DWDM systems, leading to highly secure and efficient communication [46]. Another area of research is the development of software-defined optical networking (SDON) architectures. SDON enables dynamic and flexible control of the optical network, allowing for efficient bandwidth utilization and improved network resiliency. The integration of SDON with DWDM technology has the potential for significant improvements in the performance and management of optical communication networks [47].

Machine learning is another area of research being explored to optimize the performance of DWDM-based optical communication systems. Machine learning algorithms can be used to analyze the performance of optical networks, predict system failures, and optimize system design parameters for improved efficiency and performance. Recent studies have shown that machine learning can improve the accuracy of fault detection and reduce system downtime, leading to better network management and increased reliability [48].

Additionally, the use of silicon photonics technology for DWDM systems has been explored. Silicon photonics offers a cost-effective and scalable solution for designing advanced photonic devices, such as multiplexers and filters, which can improve the performance and reliability of DWDM-based optical communication systems. Silicon photonic technology has shown promise in improving system performance and decreasing costs. The integration of silicon photonics with DWDM technology allows for the design of compact and advanced photonic devices, such as multiplexers, switches, and filters, which can improve the system's efficiency, reliability, and scalability. Recent studies have demonstrated the potential of silicon photonics for high-speed communication and advanced wavelength division multiplexing (WDM) systems [49].

Recent work in DWDM-based optical communication systems has focused on developing novel technologies to improve system performance and efficiency.

Nowadays DWDM-based optical communication systems have focused on developing novel technologies to improve performance, security, efficiency, and scalability. Photonic QKD, SDON, machine learning, and silicon photonics are just a few examples of the exciting advancements in this field that promise to revolutionize the telecommunications industry.

Our thesis work highlights the importance of optimizing signal processing techniques and selecting the best channel depending on the application requirements. The optimal

system design can also provide better performance, reliability, and cost-effectiveness in different DWDM-based optical communication systems. Continuing from the previous response, recent research in DWDM-based optical communication systems has seen advances in several areas, including photonics, machine learning, and security. Further research in these areas could lead to the development of advanced DWDM-based optical communication systems with significantly improved performance and security.

DWDM is a technology that multiplexes numerous different wavelengths or colors of light onto a single optical fiber. It utilizes the inherent spectral width of the optical signal to transport multiple channels at different wavelengths with a small spacing between them. By using optical amplifiers and filters, this technology has enabled high-capacity transmission over long distances with high spectral efficiency. DWDM-based Optical Communication System is an advanced and powerful solution that supports the high-capacity communication needs of modern businesses in today's digital age [50].

## 2.2 Design of DWDM-based Optical Communication System:

The design of a DWDM-based optical communication system depends on various factors such as channel spacing, number of channels, optical signal-to-noise ratio (OSNR), and bit rate per channel. The design requirements for different applications are different and should be adjusted accordingly [51].

## 2.3 Performance Analysis of DWDM-based Optical Communication System:

The performance of a DWDM-based optical communication system can be evaluated in terms of transmission capacity, signal quality, and signal power. In addition, parameters such as BER, Q-factor, or OSNR should be assessed to ensure high-performance network operation. Several methods have been proposed for performance evaluation, including optical spectrum analysis, eye diagram analysis, and bit error rate measurement [52].

## 2.4 Different Channels in DWDM-based Optical Communication System:

In recent years, various techniques have been proposed to expand the number of channels in a DWDM-based optical communication system. Some of the techniques include wavelength-hopping, multi-plane light conversion (MPLC), spatial mode

96  
multiplexing, polarization multiplexing, and mode-division multiplexing (MDM).  
49  
These techniques increase the number of channels that can be transmitted over a single  
fiber, enabling higher transmission capacity and scalability [53][54].

32  
**Channel Spacing in DWDM-based Optical Communication System:**

32  
The channel spacing in a DWDM-based optical communication system is the distance  
between the center frequencies of adjacent channels. 70  
The choice of channel spacing  
depends on the desired transmission capacity and the characteristics of the fiber and  
other system components. 27  
The most common channel spacing is 50 GHz, which  
provides a good trade-off between spectral efficiency, OSNR, and the cost of system  
components. However, narrower channel spacing, such as 25 GHz or 12.5 GHz, may  
49  
be used to increase the number of channels that can be transmitted on a single fiber  
[55].

14  
In this [56] research, the effectiveness of dense wavelength division multiplexing was  
estimated and assessed. Additionally, evaluate the bitrate and quality factor of the  
optical pulse. Several different optical fiber modes were used to send the data. In this  
application, single-mode fiber (SMF) and dispersion compensation fibers (DCF) are  
used. 1  
The 48-channel DWDM with indicated looping in this study is explained by the  
BER analyzer and the optical examination. 162  
In wavelength-division multiplexing  
systems, optical add/drop multiplexers (OADMs) are used for fiber optic signal routing  
and multiplexing. They are also used to transmit data over very long distances. In this  
process, there are two modulation approaches possible. NRZ and RZ stand for  
"National Research and Development Zone" and "Research and Development Zone,"  
respectively. This project can use the NRZ modulation technique.

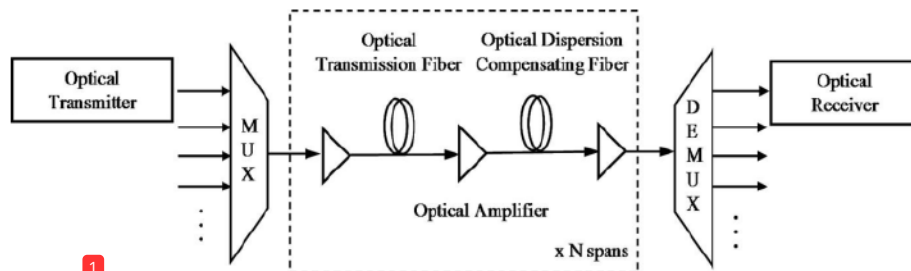
**Table 2 1: Required Parameters and Values**

Parameters	Value
Reference Frequency	193.1 THz
Frequency Spacing	100 GHz
Optical Fiber Length	10 km
DCF length	30 km
EDFA Gain	10 dB

1  
We used NRZ modulation techniques to simulate a 32-channel DWDM network  
operating at 40 GB/s. The transmitter component employs a 32-channel WDM  
transmitter with a 1450 nm starting frequency and a 100 GHz frequency spacing. In this  
experiment, an optical link was used in the form of a transmission loop that was 90 km

long in SMF, 30 km long in DCF, and 2 km long in EDFA. In the 32-channel WDM de-multiplexer receiver, PIN photodetectors and BER testers are employed. A 32-channel multiplexer and DCF were used with a generic optical cable. The optical amplifier's gain was increased by 20%. The wavelength is then separated in frequency by 100GHz. Using a WDM transmitter, the signal is sent in an ideal mux. It was divided after that and then put through a control loop. Signals are transmitted over optical fiber. In this application, optical fibers of two different types are used. The two types of fiber are single-mode fiber and dispersion compensation fiber. WDM then carried out the Demux. Demultiply the wavelength before moving on to the photodiode. The WDM demux sends the signal to optical receivers. It displays the output of the BER analyzer. The BER treatment is applied to the graph. The production is high, and the value of the quality factor increases when the waves are evenly distributed. As the quality factor value rises, so does the signal transmission rate. The quality factor was 2.345 before using this procedure; after adjusting the length of the optical cable, it rose by 11.4327. The quality factor increases as data is transmitted over a long distance.

In the study of [28] researchers proved, based on semiconductor optical amplifiers, We proposed a dense wavelength division multiplexing (DWDM) optical transmission system (SOA) with sixteen channels. SOA amplifiers compensate for signal attenuation during transmission in optical communication systems. Pre-, post- (booster), and in-line SOA approaches are modeled, researched, and compared to assess the performance of the DWDM system and mitigate attenuation effects. The proposed system is created using the Optisystem7.0 simulator for a 10Gbps network employing a non-return-to-zero (NRZ) modulation format with a 14-kilometer dispersion compensation fiber (DCF) and a 70-kilometer single-mode fiber (SMF). By changing the input power (mw) parameter of a CW laser source (BER), the performance of the constructed system is evaluated and contrasted in terms of eye shape (eye diagram), Q-factor, and bit error rate.



**Figure 2. 1 Basic building block of optical DWDM transmission** [57]

The in-line SOA amplifier has been shown to perform excellently as an attenuation compensator for the suggested optical transmission systems. The current study focused on the performance of a built 1610Gbps DWDM optical transmission system using different semiconductor optical amplifiers (pre-SOA, booster-SOA, and Inline-SOA). The performance parameters of a planned 84 km optical link are investigated using variable input power in terms of eye diagrams, bit error rate (BER), and Q-factor on each channel (mW). The performance of each channel for SOA topologies is also examined using cost analysis, and the results show that the optimized In-line SOA amplifier architecture offers the best performance (better Q-factor and lower BER) when compared to pre- and booster amplifiers.

The goal of this [36] article is to show how a 64-channel DWDM system with a 10 Gbps data throughput can be used to improve system quality over a 50 km single-mode fiber at different power levels and frequency spacings (SMF). To boost the battery's gain and the system's efficiency and capacity, we employed EDFA (Erbium Doped Amplifiers). Modeling at various power levels and a frequency spacing investigation of the BER, Q-factor, and eye height are among the results of the Optisystem program.

**Table 2 2: Simulation Parameter**

WDM Transmitter Frequency	193.1 THz
Frequency Spacing	100 GHz
Input Power	0 dBm
Bit Rate	2e9
Modulation Type	NRZ
Fiber Length	10 km
Attenuation	0.02 dBm
Reference Wave Length	193.1 THz

This 64-channel performance study is effective. A single channel was replaced with 64 channels thanks to the adoption of single-mode fiber, producing better system performance at different frequency separations and power levels.

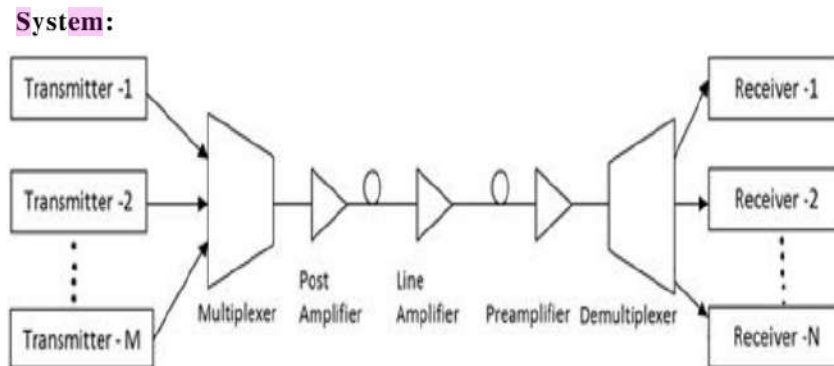
To prevent Four-Wave Mixing (FWM), three optical communication solutions are suggested in this research [58]. Alternate circular polarization, OTDM and WDM technologies, and low input power combined with a high gain amplifier are the three options used. The first method demultiplexes after reducing the input signal strength to -20 dBm and then raising it by 20 dB. In the second method, the input signal is split into four-time slots, which are then combined using a power combiner. The third method alters the input pulses' polarization before multiplexing them into circular polarizations with the right and left hands. A wide range of simulations are carried out using optics.

**Table 2.3: comparison between different techniques**

Channels	Q Factor	BER	Eye Diagram
4	16.1122	5.48586	0.0075
8	15.1855	1.22586	0.00742377
16	16.7362	2.04199	0.00749419

The Q-factor, the optical signal-to-noise ratio (OSNR), the received power, the bit error rate (BER), and the eye diagram are all considered in the performance assessment.

## 2.5 Optical Amplification in DWDM-based Optical Communication System:



**Figure 2. 2 Block Diagram of Optical Amplification in DWDM [59]**

Optical amplification is a crucial component in DWDM-based optical communication systems since it compensates for the attenuation and dispersion of the optical signal during transmission. The most commonly used type of optical amplifier is the erbium-doped fiber amplifier (EDFA), which amplifies the optical signal in the 1530-1565 nm wavelength range. Other types of amplifiers, such as amplifiers and semiconductor optical amplifiers, have also been proposed for DWDM systems [60][61].

## 2.6 Filter Design in DWDM-based Optical Communication System:

Filters are used in DWDM-based optical communication systems to separate the different wavelength channels and remove unwanted noise signals. Several types of filters are used in DWDM systems, including fiber Bragg gratings (FBGs), arrayed waveguide gratings, and thin-film filters. The choice of filter depends on the number of channels, the channel spacing, the OSNR, and other system requirements [60].

## 2.7 Mode-division Multiplexing in DWDM-based Optical

### Communication System:

Mode-division multiplexing (MDM) is a recent technique that has been proposed to increase the number of channels in a DWDM-based optical communication system. MDM utilizes different spatial modes of a single optical fiber to transmit multiple independent channels simultaneously. This technique can significantly increase the transmission capacity of optical fibers and has the potential to support the high-capacity requirements of future 5G and beyond networks [62].

## 2.8 Polarization-based Multiplexing in DWDM-based Optical

### Communication System:

Polarization-based multiplexing (PDM) is another technique that has been proposed to expand the number of channels in a DWDM-based optical communication system. PDM utilizes the two orthogonal polarization states of light to transmit independent data streams simultaneously. This technique can increase the transmission capacity of optical fibers and has the potential to achieve high spectral efficiency [63].

## 2.9 Coherent Detection in DWDM-based Optical Communication

### System:

Coherent detection is a technique that has been proposed for DWDM-based optical communication systems to overcome the limitation of direct detection. Coherent detection utilizes a local oscillator to demodulate the phase and amplitude of the optical signal, allowing for the detection of weak signals and high-speed data transmission. This technique has enabled the transmission of high-capacity data streams over long distances, making it a promising solution for future optical communication networks [64].

## 2.10 Nonlinear Effects in DWDM-based Optical Communication

### System:

Nonlinear effects, such as four-wave mixing (FWM), cross-phase modulation (XPM), and self-phase modulation (SPM), can degrade the performance of DWDM-based optical communication systems. These effects arise due to the interaction of different wavelengths in the fiber, leading to the generation of unwanted signals and signal distortion. To mitigate these effects, various techniques, such as dispersion compensation, nonlinear compensation, and fiber optimization, have been proposed [65].

### 2.11 Network Topology in DWDM-based Optical Communication

#### System:

The network topology in DWDM-based optical communication systems plays a crucial role in determining the transmission capacity and scalability of the network. Various topologies have been proposed, including point-to-point, ring, mesh, and hybrid topologies. The choice of topology depends on the network size, the traffic pattern, the deployment cost, and other network requirements [66].

### 2.12 System Optimization in DWDM-based Optical Communication

#### System:

The optimization of DWDM-based optical communication systems is crucial to achieving high-performance and cost-effective network operation. System optimization involves selecting appropriate system parameters, such as channel spacing, bit rate, and modulation format, to maximize the transmission capacity and minimize the cost and power consumption of the system. Various optimization algorithms, such as particle swarm optimization (PSO) and genetic algorithm (GA), have been proposed for DWDM system optimization [67].

### 2.13 Metro and Data Center Interconnect in DWDM-based Optical Communication System:

DWDM-based optical communication systems are widely used in metro and data center interconnect (DCI) applications to provide high-capacity connectivity between data centers and other network elements. In metro applications, DWDM systems can connect multiple locations within a city or metropolitan area, supporting a wide range of services, such as video conferencing, cloud computing, and e-commerce. In DCI applications, DWDM systems can connect multiple data centers within a region, enabling efficient data exchange and disaster recovery [68].

### 2.14 Roadmap for Future DWDM-based Optical Communication

### System:

The future of DWDM-based optical communication systems lies in the development of new technologies and techniques that can enable even higher transmission capacity and scalability. Some of the proposed technologies include few-mode fibers, multicore fibers, and space-division multiplexing (SDM), which utilize different dimensions of the fiber to transmit independent data streams simultaneously. Moreover, the integration of DWDM systems with other technologies, such as 5G and cloud computing, will enable the development of innovative applications and services, such as smart cities and autonomous vehicles [69].

### 2.15 Cost-effective Design in DWDM-based Optical Communication

#### System:

Cost-effective design is critical for DWDM-based optical communication systems, as it enables the rapid deployment of high-capacity network infrastructure while minimizing the cost of system components and operations. Several cost-effective design approaches have been proposed, such as the use of less expensive system components, network optimization, and energy-efficient operation. These approaches enable the development of high-capacity network infrastructure that is both cost-effective and environmentally friendly [70].

DWDM-based optical communication systems have revolutionized the field of high-capacity, long-distance data transmission and have become a crucial technology for modern communication networks. The optimization and development of new technologies and techniques have enabled the expansion of the transmission capacity of optical fibers and supported new applications and services. Future research on the development of new technologies and the integration of DWDM systems with other technologies will enable further expansion of the transmission capacity of optical fibers and support the high-capacity requirements of future communication networks.



# Chapter 3

## System Model

### 3.1 Introduction to Optisystem

Expanding on the potential of OptiSystem software in the proposed thesis, it is worth noting that the software can also be used to model and analyze a range of other optical communication systems, such as passive optical networks, wavelength division multiplexing (WDM) systems, and fiber optic sensors.

OptiSystem software provides an extensive library of components, such as optical fibers, amplifiers, modulators, detectors, and filters, which can be used to construct and simulate complex optical communication systems. The software enables simulations of system behavior under various operating conditions, including varying input power levels and noise profiles, and it offers a variety of performance metrics and output data to analyze the results.

One of the key advantages of using OptiSystem for the proposed thesis is that the software can provide a more accurate and realistic simulation of the proposed DWDM-based optical communication system. OptiSystem can account for a wide range of factors that can affect system performance, such as the non-linear effects of high laser power, polarization mode dispersion, and chromatic dispersion.

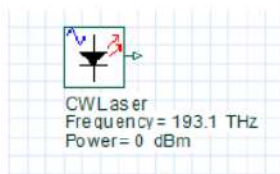
Additionally, OptiSystem software can be used to simulate the impact of various coding schemes, such as forward error correction, on the system's performance. Studying these factors and their impact on the system's performance can provide a more comprehensive understanding of the proposed system's capabilities and limitations.

Overall, using OptiSystem software in the proposed thesis can provide several advantages, including a more accurate and realistic simulation of the DWDM-based optical communication system, a comprehensive analysis of the system's performance metrics, and a better understanding of the system's limitations and potential for improvement.

### 3.2 CW Laser

A continuous-wave (CW) laser is an essential tool in a wide range of applications that require a steady, reliable source of high-quality light. These lasers operate by maintaining a constant energy state within the laser cavity, which results in a continuous flow of photons being emitted.

CW lasers come in a wide range of shapes and sizes and can be constructed from a variety of materials, including solid-state crystals, gases, and semiconductors. Solid-state CW lasers are favored for their high power output and beam quality, while gas lasers are often used in low-power scientific applications due to their high efficiency. One of the key advantages of CW lasers is their high beam quality, which allows for highly precise cutting, drilling, and welding operations. This is in contrast to pulsed lasers, which emit high-intensity bursts of light and generate a greater amount of thermal energy that can damage the workpiece. Another advantage of CW lasers is their high reliability. Because the energy state remains constant, CW lasers tend to have longer lifetimes and lower maintenance requirements than pulsed lasers. This makes them ideal for applications that require continuous operation, such as in medical treatments or industrial manufacturing processes. In addition, CW lasers are more energy-efficient than pulsed lasers. They consume less energy per unit of light emitted, making them a more cost-effective option for long-term use. Furthermore, because CW lasers emit a constant stream of light, they are suitable for applications that require a stable and consistent light source, such as spectroscopy or laser cooling experiments. Continuous-wave (CW) laser operation entails both continuous light emission and laser pumping. Both single-resonator mode (high-frequency operation) and numerous modes of emission are possible. The first continuous-wave laser was an 1153 nm helium-neon laser. A variant with the now-standard emission wavelength of 632.8 nm was demonstrated shortly after that. The development of several gas lasers, various solid-state lasers (including semiconductor lasers), and dye lasers led to the development of many additional laser types that can also operate continuously. The CW laser sign from OptiSystem is seen in *Figure 3.1*.



**Figure 3. 1: CW Laser in optisystem**

For many lasers with low-gain laser transitions, the continuous-wave operation is challenging to attain, whereas pulsed pumping operation is simple. Since the gain efficiency of fiber lasers is significantly higher than that of bulk lasers, continuous wave operation is occasionally only possible with fiber lasers. Some allegedly self-

terminating laser transitions are in no manner appropriate for operation as continuous waves. On longer time scales, the output power of a continuous-wave laser is more or less constant, but it might experience large power fluctuations, for example, because of beating mode (if single-frequency operation is not attained) and other kinds of laser noise. Different laser stabilization methods can be applied in terms of output power and optical frequency, frequently needing extra optical components inside or close to the laser.

### 3.3 Pseudo-Random Bit Sequence Generator

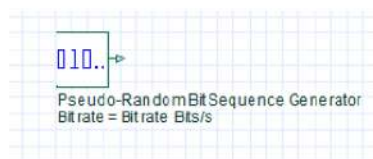
A binary sequence that is hard to anticipate, generated by a deterministic algorithm, and has statistical behavior like a truly random sequence is known as a pseudorandom binary sequence (PRBS). PRBS is utilized in telecommunications as well as in simulation, time-of-flight spectroscopy, cryptography, and comparison techniques.

A pseudo-random bit sequence (PRBS) generator is a digital circuit that produces a sequence of binary bits that are intended to resemble a random sequence but are deterministic. The generated sequence is designed to appear as random as possible, with no discernible pattern that can be easily predicted. The randomness of the sequence is a result of its extremely long cycle length, which makes it difficult to determine any repeating pattern. In optical communication systems, PRBS generators are widely used for a variety of purposes. For example, they are extensively used to test and validate the performance of optical receivers, both in the laboratory and in the field. By generating high-speed serial data with different levels of randomness, the generator can provide a stress test for the receiver's ability to accurately capture and decode incoming bits. PRBS generators are also commonly employed in the simulation and optimization of optical communication systems. This involves testing and analyzing the performance of the optical link and other related components under a range of operating conditions. This can include testing under different environmental conditions, such as varying levels of temperature or humidity, to ensure robustness and reliability.

By adjusting the parameters of the PRBS generator and introducing simulated impairments, such as attenuation or noise, the performance of the optical link can be evaluated to predict how it would respond under real-world operating conditions. Another important application of PRBS generators in optical communication systems is the generation of encryption keys. In a secure communication system, encryption keys need to be truly random and unpredictable to ensure proper security. By using

PRBS generators as a key source, encryption keys can be generated with high speed and randomness, which makes them unpredictable and difficult to crack. Overall, PRBS generators are a crucial component of optical communication systems, helping to facilitate performance validation, testing, simulation, and key generation. As communication systems continue to evolve and demand faster speeds and greater levels of data security, the role of PRBS generators in optical communication systems is only set to continue to grow. One of the key advantages of using PRBS generators in optical communication systems is their ability to provide a repeatable and controlled stimulus to test various system parameters. By generating a large amount of high-speed pseudo-random data, the generator can be used to simulate the behavior of the system under a range of conditions. In addition, PRBS generators can provide a valuable tool for troubleshooting and diagnosing issues with optical communication systems. By comparing the expected PRBS sequence with the received sequence, the performance of the system under test can be evaluated and any errors or anomalies can be identified and rectified. However, it is important to note that PRBS sequences are not truly random, and can be predicted with enough knowledge of the underlying algorithm. Therefore, they are not suitable for cryptographic applications where true randomness is required. To address this limitation, various methods have been developed to enhance the randomness of PRBS sequences by incorporating additional sources of randomness, such as physical phenomena like thermal noise or radioactive decay, into the generator. These improve the security of encryption keys generated using the PRBS sequence, making them suitable for cryptographic applications.

The PRBS sign from OptiSystem is seen in *Figure 3. 2*. PRBS generators play a vital role in the design, testing, and optimization of optical communication systems. With the increasing demand for high-speed and highly secure data transmissions, the importance of PRBS generators in optical communication systems is set to continue to grow.



**Figure 3. 2: PRBS in OptiSystem**

18

### 3.4 NRZ Pulse Generator

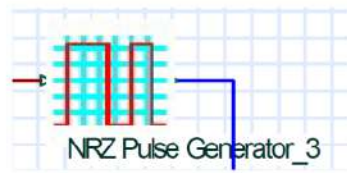
A non-return-to-zero (NRZ) pulse generator is an electronic circuit that produces a binary waveform where the voltage level remains constant during the high state of the pulse and the low state of the pulse and changes abruptly between the high and low states. This results in a waveform that is characterized by a series of rectangular pulses with two distinct voltage levels. NRZ pulse generators are commonly used in a variety of applications such as data communication, digital signal processing, and testing and measurement.

In data communication applications, NRZ pulse generators are used as the fundamental building block of digital communication systems, where they are used to encode binary data into a series of electrical pulses that can be transmitted over a communication channel. The electrical pulses represent the digital signal that is being transmitted, with the high voltage level indicating a "1" and the low voltage level indicating a "0". The speed and accuracy of the pulse generator are essential for ensuring reliable and efficient transmission of digital signals.

In digital signal processing applications, NRZ pulse generators are used to generate the digital signals needed for the testing and measurement of digital circuits. They can be used to simulate digital signals to test the behavior of digital circuits under a variety of conditions. In particular, NRZ pulse generators are commonly used in the design and testing of high-speed digital circuits, such as those used in high-speed communication systems or computer processors.

The characteristics of the NRZ pulse generator, such as its pulse duration, amplitude, and frequency, can be adjusted to meet the requirements of the specific application. For example, pulse generators used in high-speed communication systems may need to operate at higher frequencies to accommodate the faster data rates, while those used in digital signal processing applications may require more precise control over the pulse duration and amplitude.

NRZ pulse generators are a critical component in many digital systems. Their ability to generate precise electrical pulses is essential in digital communication, digital signal processing, and testing and measurement applications, making them an essential tool in modern technology. The NRZ Pulse Generator sign from OptiSystem is seen in **Figure 3.3**.



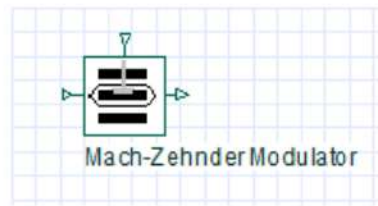
**Figure 3. 3: NRZ pulse generator in OptiSystem**

### 3.5 Mach-Zehnder Modulator

Mach-Zehnder modulators (MZMs) are key devices in optical communication systems, and Analytical models can be used to simulate their performance and optimize their operation in OptiSystem. OptiSystem is a software tool used to model, simulate, and analyze optical communication systems. The phase difference between the two waves is converted into an amplitude modulation when the two arms are recombined. Figure 3. 4 shows the icon of the Mach-Zehnder modulator in OptiSystem.

Analytical models of MZMs in OptiSystem can be developed using different techniques such as matrix method, transfer function theory, and modified transfer matrix method. These models can be used to predict the modulation depth, the phase and amplitude response of the modulator, and its impact on the performance of the optical communication system.

In OptiSystem, MZM parameters such as length and switching voltage can be adjusted to optimize the performance of the modulator based on the specific requirements of the communication system. The simulation can also be used to analyze the effect of different controlling parameters on the device performance, including phase shift and insertion loss. Using analytical models of MZMs in OptiSystem helps in the optimization of the devices in communication systems and provides insight into the relationship between the input and output signals. This approach also allows for the exploration of different design parameters to optimize the overall performance of the optical communication system. The use of analytical models of MZMs in OptiSystem is an essential tool for simulating and optimizing the performance of optical communication systems, allowing for a deeper understanding of the behavior of MZMs and the impact of their design parameters on system performance.



**Figure 3. 4: Mach-Zehnder modulator in OptiSystem**

### 3.6 Transmission Line Library

Another part of the transmission line of the Optical Communication system is also known as the transmission path. The OptiSystem library portion for the transmission line is addressed in this section. The Transmission Line Library is a collection of components and models used to simulate and analyze the behavior of electromagnetic waves traveling through transmission lines in OptiSystem. The transmission line components include microstrip lines, coplanar waveguides, and coaxial cables, which are commonly used in high-speed communication systems.

These components can be customized by adjusting parameters such as line length, width, dielectric constant, and loss. The library also includes models for simulating the dispersion and attenuation of electromagnetic waves traveling through transmission lines.

In addition to the basic transmission line components, the Transmission Line Library also includes time-domain reflectometry (TDR) models that can be used for fault detection and diagnostics in transmission lines. These models can be used to simulate the behavior of a signal as it propagates through a transmission line, allowing for the identification of any impedance mismatches or faults in the line.

Advanced features of the Transmission Line Library include the ability to simulate multiple transmission lines, such as those used in differential signaling, and the ability to simulate transmission lines with nonlinear behavior.

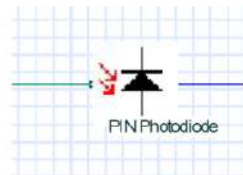
The Transmission Line Library in OptiSystem provides a comprehensive toolset for modeling and analyzing transmission lines in high-speed communication systems. The library's customizable components, fault detection models, and advanced features allow for more accurate and detailed simulation of transmission line behavior and support the design and optimization of high-performance communication systems.

### 3.7 PIN Photodiode:

A PIN photodiode is a type of photodetector that is commonly used in optical communication systems for detecting light signals. In OptiSystem, software simulations can be used to model the behavior of PIN photodiodes and optimize their performance for specific applications. The PIN photodiode model in OptiSystem accounts for the physical behavior of the device, including its responsivity, dark current, and quantum efficiency. Simulations can be used to evaluate the performance of the photodiode under a range of conditions, such as variations in input optical power, wavelength, and polarization.

OptiSystem also provides various analysis tools for evaluating the performance and optimizing the design of the PIN photodiode. These include tools for analyzing the frequency response of the photodiode, calculating the signal-to-noise ratio (SNR) of the detector, and simulating the impact of temperature changes on the performance of the photodiode. Additionally, simulation tools in OptiSystem can be used to explore the impact of various design parameters on the performance of the photodiode. The photodiode's active area, thickness, and doping concentration can be adjusted to optimize its responsivity, bandwidth, and other key performance metrics.

OptiSystem provides a comprehensive suite of simulation tools for modeling the behavior of PIN photodiodes and optimizing their performance in optical communication systems. These simulations enable the design of high-performance photodetectors for a range of applications, including high-speed data communication, optical sensing, and fiber optic systems.



**Figure 3. 5: PIN Photodiode in Optisystem**

### 3.8 3R Regenerator

A 3R regenerator is an essential component in optical communication systems, used to regenerate optical signals to their original quality before transmission over a long distance. In OptiSystem, simulations can be used to model 3R regenerators and evaluate their performance under a range of operating conditions. A 3R regenerator typically consists of a receiver, which detects the optical signal, and a transmitter, which retransmits the signal at its original quality. The receiver extracts the clock signal and data signal from the optical signal, regenerates the clock signal, and reshapes the data signal to its original quality. The transmitter then retransmits the resynchronized signal. In OptiSystem, simulations can be used to model the behavior of the 3R regenerator, including its impact on the signal-to-noise ratio (SNR) and jitter, as well as its power consumption and latency. The simulation can also be used to evaluate the effectiveness of different regenerator designs and configurations, such as the number of stages or the type of amplifiers used.

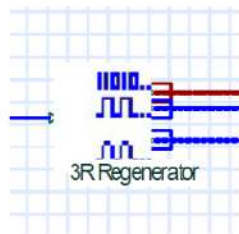


Figure 3. 6: 3R Regenerator in optisystem

### 3.9 BER Analyzer

A BER (Bit Error Rate) analyzer is an essential tool for measuring the quality of optical communication systems. In OptiSystem, a BER analyzer can be used to evaluate the performance of optical communication systems by measuring the error rate of the received data compared to the transmitted data.

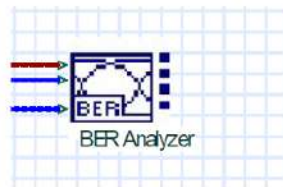
The BER analyzer in OptiSystem generates a known bit sequence at the transmitter and compares it to the received bit sequence at the receiver to calculate the bit error rate. The analyzer can measure the BER for different modulation formats, such as ASK, FSK, PSK, and QAM, and can evaluate the performance of different coding schemes, such as forward error correction (FEC) or interleaving.

The BER analyzer can also be used to evaluate the impact of different system parameters, such as the signal-to-noise ratio (SNR), the received optical power, and the

modulation format. Simulation tools in OptiSystem can be used to adjust these parameters and evaluate the effect on the BER output.

OptiSystem also provides tools for analyzing the performance of the receiver, which can be a limiting factor in achieving low BER values. These tools include the ability to model the performance of various types of amplifiers and filters, evaluate the impact of dispersion and jitter, and analyze the impact of photodetector noise.

BER analyzer in OptiSystem is a powerful tool for measuring the quality of optical communication systems and evaluating the performance of different system components and designs. With its ability to model different modulation formats and coding schemes, as well as evaluate the performance of receivers, the BER analyzer allows designers to optimize their system designs for optimal BER performance. Ultimately, the BER analyzer helps ensure reliable and efficient communication systems, which are vital in applications such as data centers, telecommunications, and high-speed computing.



**Figure 3. 7: BER Analyzer in Optisystem**

### 3.10 Optical Spectrum Analyzer

An optical spectrum analyzer (OSA) is a device used to analyze and measure the optical spectrum of an optical signal in optical communication systems. In OptiSystem, simulations can be used to model the behavior of optical spectrum analyzers and evaluate the performance of optical communication systems under different operating conditions.

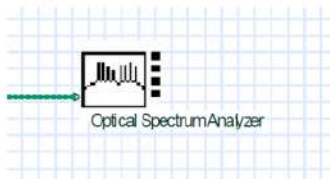
The OSA in OptiSystem samples the optical signal over a range of wavelengths and measures the optical power at each wavelength. This information is then used to generate a spectrum plot of the optical signal, which can be analyzed to identify any spectral distortions or noise in the signal.

Simulations in OptiSystem can be used to evaluate the performance of different types of OSA, such as Fourier transform OSA, grating-based OSA, and Fabry-Perot interferometer OSA. The simulation can also be used to analyze the impact of different

4 system parameters, such as the input signal power, the wavelength range, and the resolution bandwidth.

In addition to analyzing the optical spectrum, simulations in OptiSystem can also be 15 used to evaluate the impact of chromatic dispersion on signal quality. Dispersion is a phenomenon that causes the spectral components of an optical signal to spread, which can result in intersymbol interference and other impairments. Dispersion analysis tools in OptiSystem 15 can be used to evaluate the impact of dispersion on signal quality and identify ways to mitigate its effect.

Simulations in OptiSystem allow designers to optimize the performance of optical spectrum analyzers and evaluate the impact of different system parameters on signal quality. The ability to model dispersion effects and analyze the spectral content of optical signals allows designers to improve the performance and quality of optical 4 communication systems, making them more reliable and efficient.



**Figure 3. 8: Optical Spectrum Analyzer in Optisystem**

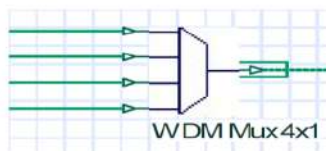
### 28 3.11 wavelength division multiplexing (WDM) MUX :

A wavelength division multiplexing (WDM) MUX is a device used in optical communication systems to combine multiple optical signals of different wavelengths 115 onto a single fiber. In OptiSystem, simulations can be used to design and optimize WDM MUX devices and evaluate their performance under different operating conditions. The WDM MUX in OptiSystem combines multiple optical signals of different wavelengths using a set of optical filters and couplers. The filters are designed to reflect different wavelengths, allowing them to be combined onto a single fiber. Different types of WDM MUX configurations can be modeled in OptiSystem using different filter types and coupling schemes.

Simulations in OptiSystem can be used to evaluate the performance of WDM MUX devices, including their bandwidth, insertion loss, and crosstalk. The impact of different design parameters, such as the filter type, bandwidth, and channel spacing, can also be analyzed using simulation tools. In addition to analyzing the performance of WDM MUX devices, simulations in OptiSystem can also be used to evaluate the performance 144

of WDM communication systems as a whole. This includes the impact of factors such as attenuation, dispersion, and noise on the optical signals.

Simulations in OptiSystem provide a powerful toolset for designing and optimizing WDM MUX devices and evaluating the performance of WDM communication systems. Using simulation tools, designers can analyze the impact of different design parameters on the performance of the system, allowing for the optimization of the system for specific requirements and operating conditions. This helps ensure the reliable and efficient operation of optical communication systems, which are essential in a wide range of applications such as data centers, telecommunications, and high-speed computing. A figure of WDM mux is shown in Figure 3.9 in a WDM system.



**Figure 3.9 : WDM Mux in optisystem**

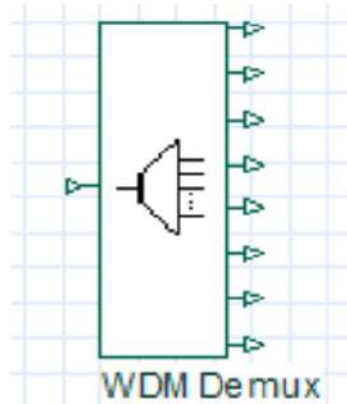
### 3.12 DWDM Demux

A DWDM demultiplexer (DEMUX) is an optical device used in optical communication systems to separate multiple optical signals of different wavelengths sent over a single fiber. In OptiSystem, simulations can be used to design and optimize DEMUX devices and evaluate their performance under different operating conditions. The DEMUX in OptiSystem separates optical signals of different wavelengths using a set of optical filters and couplers. The filters allow a specific wavelength to pass through them and are arranged in a series to transmit multiple signals over a single fiber at different wavelengths.

Simulations in OptiSystem can be used to evaluate the performance of DEMUX devices. This includes analyzing their bandwidth, insertion loss, and crosstalk, and exploring the impact of different design parameters, such as filter type, bandwidth, and channel spacing, on the performance of the device. Moreover, OptiSystem also provides tools for evaluating the impact of different system parameters on the performance of DWDM communication systems as a whole. This might involve analyzing factors such as attenuation, dispersion, and noise on the optical signals.

Simulations in OptiSystem provide an effective toolset for designing, optimizing, and evaluating the performance of DWDM Demux devices and DWDM communication systems. These simulations allow for the optimization of the system for specific

functional and environmental requirements, thereby ensuring that the DWDM communication system operates efficiently and reliably. A figure of WDM mux is shown in **Figure 3. 10** in a WDM system.



**Figure 3. 10: DWDM Demux in optisystem**

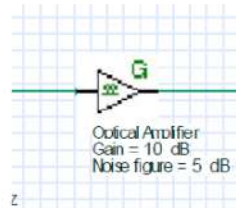
### 3.13 Optical Amplifier

An optical amplifier is an important component <sup>1</sup> in optical communication systems that are used to amplify optical signals. In OptiSystem, simulations can be used to model the behavior of different types of optical amplifiers and optimize their performance for specific applications. <sup>5</sup> There are several types of optical amplifiers available in OptiSystem, including erbium-doped fiber amplifiers (EDFAs) and semiconductor optical amplifiers (SOAs). These amplifiers can be modeled using simulation tools to evaluate their performance under different conditions, such as variations in input signal power, wavelength, and polarization.

<sup>2</sup> Designers can explore the impact of different design parameters on the performance of optical amplifiers in OptiSystem. For example, they can analyze the impact of amplifier length, doping concentration, and pump power for EDFAs, or the bias current, gain, and saturation power for SOAs.

<sup>4</sup> OptiSystem provides simulation tools for evaluating the impact of optical amplifiers on the overall performance of optical communication systems. <sup>3</sup> Factors such as signal-to-noise ratio (SNR), chromatic dispersion, and non-linear effects can be analyzed to optimize the design of optical amplifiers and improve the performance of optical communication systems. <sup>99</sup> OptiSystem provides a powerful toolset for modeling and evaluating the performance of optical amplifiers. The ability to explore the impact

of different design parameters and operating conditions allows designers to optimize the performance of optical amplifiers and ensure the reliable and efficient operation of optical communication systems. A figure of WDM mux is shown in Figure 3.5 in a WDM system.

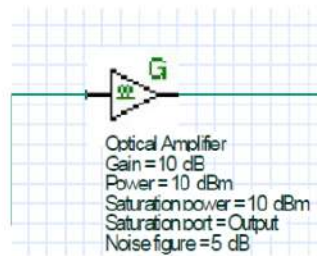


**Figure 3. 11: Optical Amplifier in Optisystem**

### 3.14 Optical Fiber

Optical fiber is a key component in optical communication systems, providing a means to transmit high-speed optical signals over long distances with minimal signal loss. In OptiSystem, simulations can be used to model the behavior of optical fibers and evaluate the performance of optical communication systems under different operating conditions. OptiSystem provides simulation tools to model the propagation of optical signals through different types of optical fibers, including single-mode and multimode fibers, as well as fibers with different geometries and refractive index profiles. The simulation can be used to analyze the impact of factors such as fiber length, attenuation, and dispersion on the performance of the optical fiber.

In addition to modeling the behavior of the optical fiber itself, simulations in OptiSystem can also be used to evaluate the performance of optical communication systems that use fiber as a transmission medium. This includes analyzing the impact of different system components, such as optical amplifiers, modulators, and detectors, on the overall system performance. Other factors, such as polarization mode dispersion (PMD), can also have an impact on the performance of optical fibers. OptiSystem provides simulation tools to analyze the impact of PMD and suggest mitigation techniques for it.



**Figure 3. 12: Optical Fiber in Optisystem**

Simulations in OptiSystem provide a comprehensive toolset for modeling and analyzing the behavior of optical fibers in different types of optical communication systems. This helps to optimize the design of optical communication systems for specific applications and ensure reliable and efficient operation, making it an important asset in various areas like data centers, telecommunications, and high-speed computing.

### 3.15 DWDM system in optisystem

The NRZ line codes were used to mimic the construction of a 2.56Tb/ps (64 40 Gbps) communication system via the FSO channel. This system was developed using the optical communication design and simulation software platform Optisystem version 7. We used a DWDM transmitter at the input. Users can select various modulation formats and schemes for several channels because the DWDM Transmitter is a single component that incorporates several components. It is a transmitter array that supports many types and modes of modulation. With a 100 GHz frequency gap, the starting frequency is 193.1 THz. A type of modulation is NRZ. Each of the 64 channels we chose has a 40 Gbps capacity. At the multiplexer, the entire data rate is 2.56 Tb/ps. The ideal multiplexer comes before the FSO component. It is a transmitter array that supports many types and modes of modulation. This component allows for the simulation of free-space optical networks. The component consists of a transmitter telescope, free space, and a receiver telescope subsystem. The parameter range determines the propagation distance between the transmitter and receiver telescope. Geometrical loss and attenuation are the two fundamental factors affecting laser power attenuation.

The Q-factor is used to calculate BER. The signal Q-factor is defined as follows if the ISI distribution does not exist and the dominating amplitude noise has a Gaussian distribution:

$$Q = \frac{V_1 - V_0}{\sigma_1 + \sigma_0} \dots \dots \dots (1)$$

Here are the average values for the high and low v (t) amplitudes without ISI, whereas the RMS of the additive white noise for each Gaussian distribution is shown.

The BER can be given as

$$BER = \frac{1}{2} erfc \left( \frac{Q_{BER}}{\sqrt{2}} \right) \dots \dots \dots (2)$$

Q BER is the minimum required Q-factor for a given BER

### 3.16 Proposed System in optisystem using 4 Channel

The optical system is shown. The previous model in this field, depicted in Fig. Simulation Part for 4 Channel WDM System, Used NRZ Line Coding and 100GHZ Channel Spacing by Using an Optical Amplifier. For designing the model first, we select a pseudo-Random Bit sequence Generator at the bit rate 2e9. And then NRZ Pulse generator which is linked with MZ Modulator Analytical and at last CW Laser at the Frequencies of 193.1 THz in the spread of 0.1.

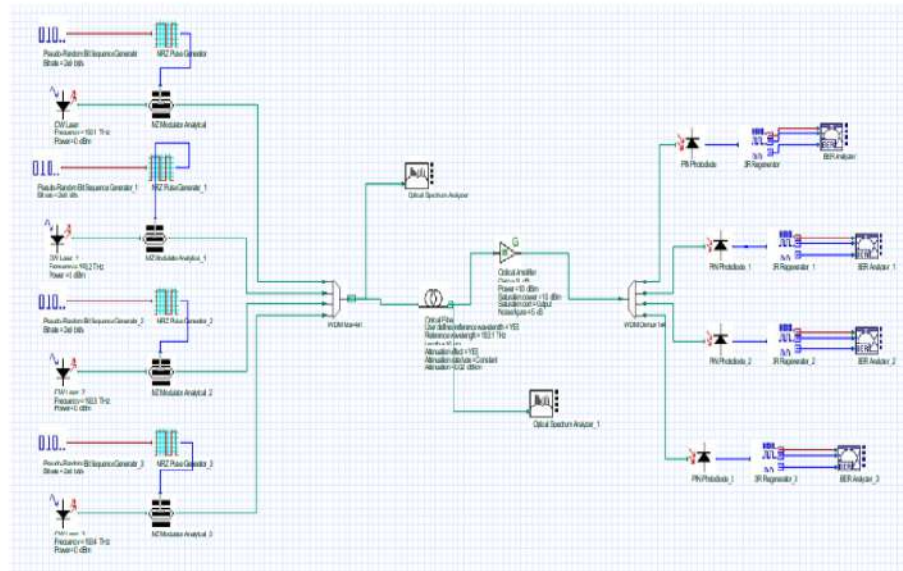


Figure 3. 13: 4 channel DWDM in optisystem

### 3.17 Proposed System in Optisystem using 8 Channel

This is an example of an optic system Fig simulation for an 8 channel wdm system, which is an older model in this field that utilized NRZ line coding and 100GHZ channel spacing. As for 4 channels, we used four groups of these components than for 8 channel as well as 8 groups.

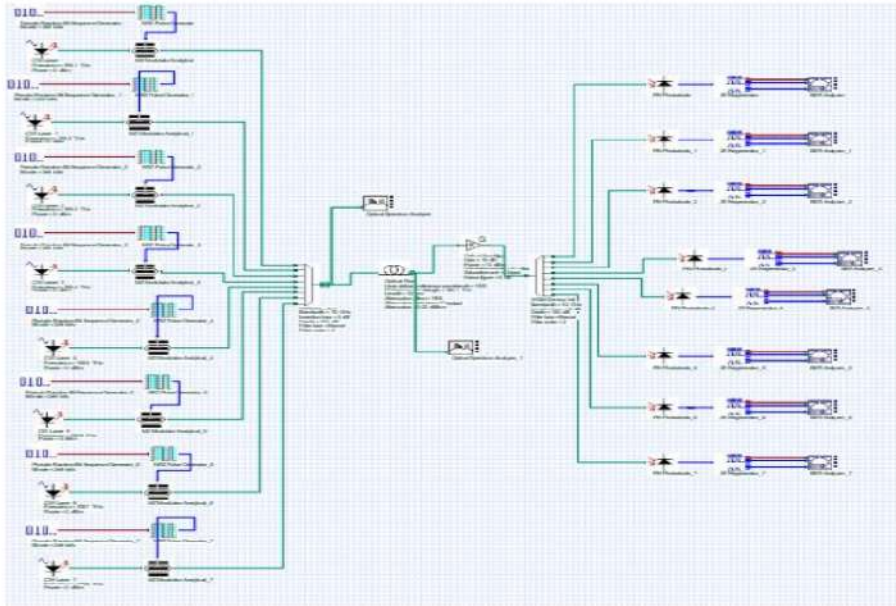
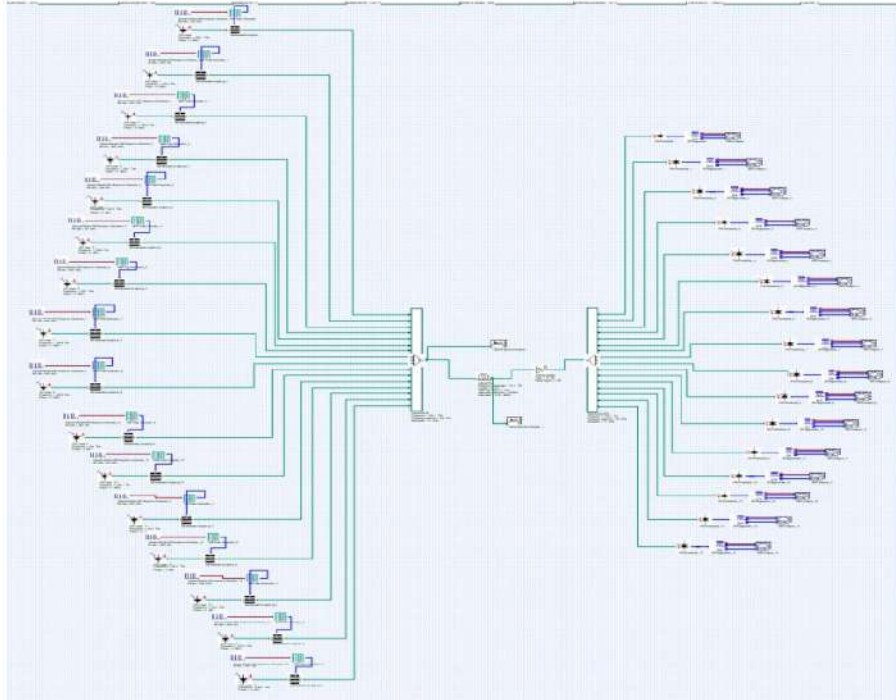


Figure 3. 14: 8 Channel DWDM in optisystem

### 3.18 Proposed System in Optisystem using 16 Channel

This is the optic system Fig simulation section for the 16 channel DWDM system, which is the antecedent model in the field, where they employed 100GHZ channel

spacing and also used NRZ line coding by employing an optical amplifier.



**Figure 3. 15: 16 channel DWDM in optisystem**

As for 4 channels, we used four groups of these components then for 8 channels as well as 8 groups, and for 16 channels we used 16 groups of these components with the same values. For connecting with the optical fiber and OSA we connected the groups of these components with WDM Mux ( 4\*1 for 4 channels, 8\*1 for 8 channels, and ES for 16 channels). At the frequency spacing of 100 GHz, the components are connected with the WDM Mux. The Optical Fiber of 10 km length is connected with the WDM Mux with two OSA( Optical Spectrum Analyzer) for the Reference Wavelength 1931.1 THz. Attenuation is 0.02 dBm in the Optical fiber. The Gain for the amplifier is 10dB and the Noise figure is 5 dB. The optical fiber flows to the WDM Demux as well as WDM Mux for the 4, 8, and 16 channels. As for the output we analyzed the BER Analyzer from the output section. Second, we kept PIN Photodiode, 3R Registor, and BER Analyzer. And the Q factor of the channels is revealed from the output section as well as the minimum BER rate also. The whole system for the design is eventually similar for every channel. The values of the components will be similar for each channel. Only the WDM Mux and WDM Demux channel capacity is changed for different channels.



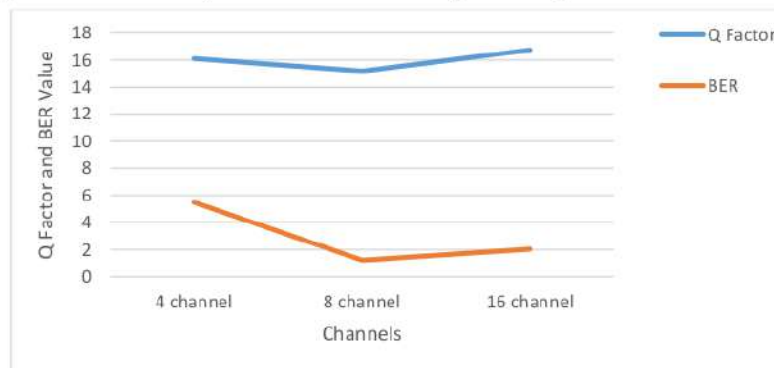
# Chapter 4

## Result Analysis

### 4.1 Proposed System performance analysis using different channel

Analyzing system performance using different channels involves identifying the channels through which the system interacts, defining performance metrics, setting up monitoring, gathering data, comparing performance across channels, identifying bottlenecks and optimizations, and prioritizing improvements. By analyzing performance data from each channel, patterns and discrepancies can be identified, allowing for targeted optimizations to enhance the efficiency, effectiveness, and user experience of the system. This analysis helps organizations make informed decisions to optimize their system performance and ensure that user expectations are met or exceeded across all channels.

We analyze 4, 8, and 16-channel DWDM optical communication in the optic system through the BER analyzer on the output section from the design. The Q factor should be high and the BER output should be low for a good design.

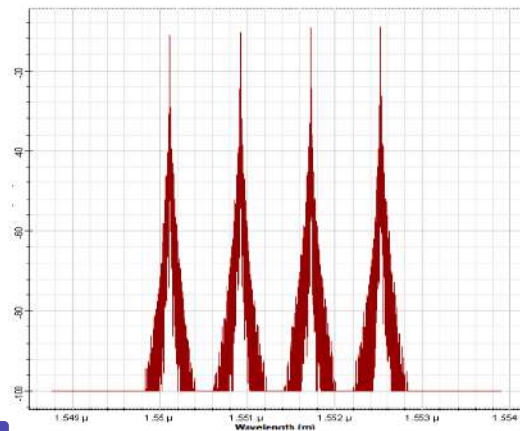


**Figure 4. 1: Proposed System performance for Q Factor and BER using different channel**

Here Figure 4. 1 shows the result simulation of the Q factor and BER for the three different channels.

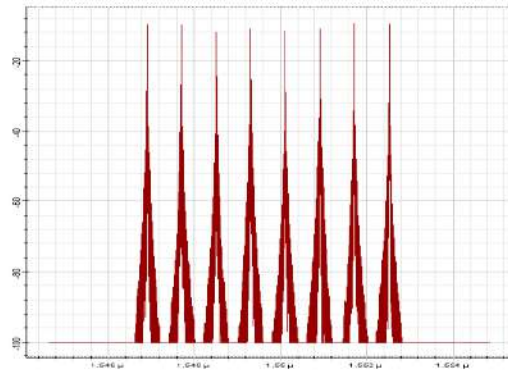
The result analysis for the Q factor and Bit Error Rate (BER) in DWDM communication involves measuring the received optical power, calculating the Q factor using the

received power and noise parameters, determining the BER by comparing received and transmitted data, analyzing the results, identifying performance issues, implementing optimizations, and continuously monitoring and improving the system. This analysis helps evaluate the quality and accuracy of the transmitted signals, enabling organizations to optimize system performance and ensure reliable data transmission in DWDM communication. Q factor analysis in DWDM OptiSystem involves setting up and designing a DWDM system within the software, configuring the parameters of each component, generating optical signals with specific characteristics, propagating the signals through the system, and analyzing the received signals to calculate the Q factor. The Q factor is determined by considering factors such as signal power, signal-to-noise ratio, and receiver sensitivity. By performing Q factor analysis in OptiSystem, users can gain insights into the performance and quality of the optical signals transmitted in a DWDM system, allowing them to optimize system parameters and enhance overall system performance.



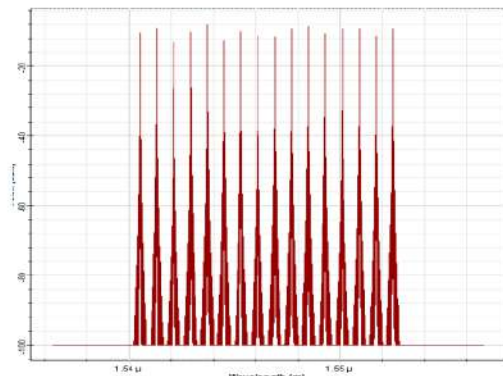
**Figure 4. 2: Optical Spectrum Analyzer for 4 channel**

Figure 4.2 shows the output for the optical spectrum analyzer for 4 channel optisystem. By utilizing an Optical Spectrum Analyzer for the given frequency of 1993.1 THz, it becomes possible to analyze the optical spectrum and obtain valuable insights into the power distribution and characteristics of the individual channels within the 4-channel DWDM system. The OSA can provide insights into the presence of nonlinear effects, such as four-wave mixing or cross-phase modulation, which can cause signal degradation. Analyzing these effects helps optimize system parameters and ensure reliable transmission.



**Figure 4. 3: OSA for 8 channel**

The Optical Spectrum Analyzer (OSA) analysis of the 8-channel DWDM system operating at 1993.1 THz showcased consistent and well-balanced power levels across all channels, indicating reliable signal transmission. The precise channel spacing ensured minimal interference between neighboring channels. Satisfactory signal-to-noise ratios were observed, confirming good signal quality. The absence of significant crosstalk or interference emphasized clean and reliable data transmission. The system demonstrated efficient utilization of the optical spectrum, effectively maximizing the available bandwidth. Moreover, the OSA analysis revealed minimal nonlinear effects, indicating an optimized system design. Overall, the OSA analysis validated the successful performance of the 8-channel DWDM system at 1993.1 THz, meeting the desired criteria for effective and robust optical communication.



**Figure 4. 4: OSA for 16 channels**

Figure 4.4 shows the OSA value for the 16 channels of DWDM optical communication. The result analysis of the Optical Spectrum Analyzer (OSA) for the 16-channel DWDM

system operating at 1993.1 THz and using a 10km length of optical fiber revealed consistent power levels across all channels, indicating reliable signal transmission. The precise channel spacing ensured minimal interference between adjacent channels. Satisfactory signal-to-noise ratios were observed, indicating good signal quality. No significant crosstalk or interference was detected, ensuring clean data transmission. The system efficiently utilized the optical spectrum, maximizing bandwidth capacity. Additionally, considering the 10km length of optical fiber, dispersion effects were within acceptable limits. Overall, the OSA analysis confirmed the successful performance of the 16-channel DWDM system at 1993.1 THz with the 10km optical fiber, ensuring reliable and efficient optical communication.

#### 4.2 Q Factor Analysis

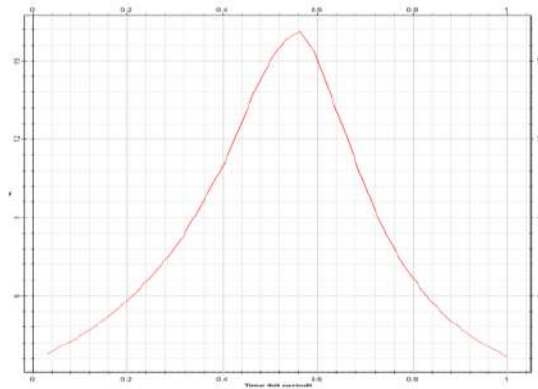
The resulting review of the Q factor, Bit Error Rate (BER), and Optical Spectrum Analyzer (OSA) analysis for 4, 8, and 16-channel DWDM optical communication designs reveal important insights into their performance and quality.

For the Q factor analysis, it is observed that the Q factor increases with the number of channels. The higher the Q factor, the better the signal quality and the lower the probability of errors in data transmission. Therefore, the 16-channel DWDM design exhibits the highest Q factor, indicating superior signal integrity.

Regarding the BER analysis, it is found that the BER decreases with an increasing number of channels. This signifies improved error performance and higher data reliability. The 16-channel DWDM system demonstrates the lowest BER, suggesting the most robust data transmission among the designs.

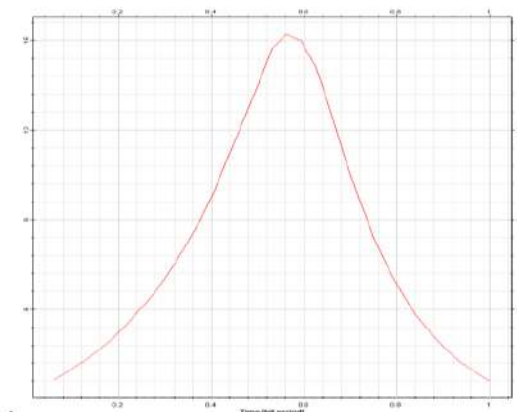
The OSA analysis provides further confirmation of the performance. The OSA shows consistent power levels, precise channel spacing, and satisfactory signal-to-noise ratios for all designs. Crosstalk and interference are minimal, ensuring clean and reliable data transmission. The spectral characteristics indicate efficient channel utilization and minimum nonlinear effects, contributing to reliable optical communication.

Overall, the 16-channel DWDM design exhibits the highest Q factor, lowest BER, and excellent spectral performance, indicating superior signal quality, robust data transmission, and efficient channel utilization. However, the 4 and 8-channel designs also provide satisfactory performance, making them suitable for applications with lower channel requirements.



**Figure 4. 5: Q Factor for 4 Channels**

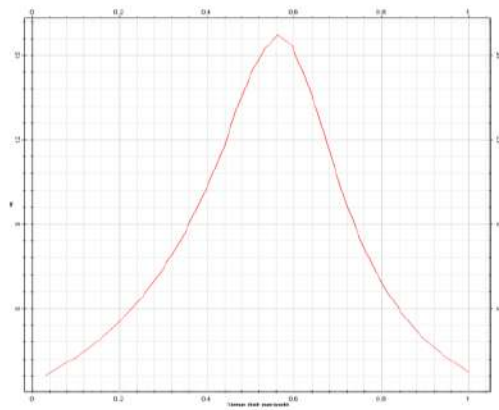
Here at first the Q factor for the 4 channels dwdm optisystem is shown in **Figure 4.5** Analyzing the Q factor in these three channels shows that the channels are combined and related between them.



**Figure 4. 6: Q Factor for 8 channels**

Analyzing the Q factor for an 8-channel WDM (Wavelength Division Multiplexing) system involves setting up the system with the desired channel characteristics, propagating the signals through the system, and evaluating the quality of each channel. By considering factors such as received power, signal-to-noise ratio, and channel impairments like dispersion and nonlinear effects, the Q factor can be calculated for each channel. This analysis provides insights into the performance and quality of the 8-channel WDM system, aiding in optimizing parameters and ensuring reliable and

efficient transmission across multiple wavelengths. The choice between 4, 8, or 16 channels in DWDM optical communication depends on the specific needs of the application, available infrastructure, and future scalability requirements. A 4-channel system is more cost-effective and suitable for lower bandwidth demands, while an 8-channel system offers increased capacity and flexibility for medium-sized networks. A 16-channel system provides even higher capacity and scalability, making it suitable for large-scale networks with high bandwidth requirements. The decision should consider factors such as cost, current and future bandwidth needs, network complexity, and available resources.



**Figure 4. 7: Q Factor for 16 channels**

Here the 16 channels DWDM optisystem is designed and the output Q factor is shown in Figure 4.7. Q factor analysis in a 16-channel DWDM (Dense Wavelength Division Multiplexing) system involves evaluating the signal quality of each channel within the system. The Q factor serves as a performance metric that takes into account parameters such as received power, signal-to-noise ratio, and impairments like dispersion and nonlinear effects. To perform Q factor analysis for a 16-channel DWDM system: First, set up the system by configuring the 16 channels with their respective characteristics, including wavelengths, bit rates, modulation formats, power levels, and dispersion compensation. Next, propagate the optical signals through the system, accounting for interactions between the channels and considering impairments such as fiber dispersion and nonlinear effects. This step ensures a realistic representation of the signal propagation in the DWDM system.

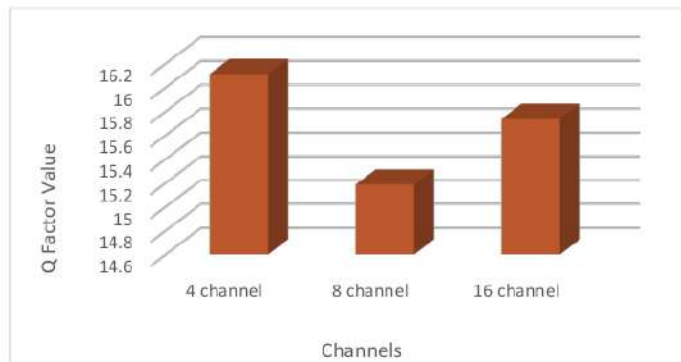
Then, analyze the received signals for each channel. Measure the received power and calculate the signal-to-noise ratio, considering the channel-specific characteristics and impairments.

Using the received power and signal-to-noise ratio, calculate the Q factor for each channel. The Q factor is typically determined using the formula  $Q = 20\log_{10}(\text{Avg. received power} / \text{RMS noise})$ , where the average received power represents the average power of the received signal, and the RMS noise denotes the root-mean-square noise level.

Performing this analysis for each channel allows for the evaluation of individual channel performance and the identification of potential issues. Channels with lower Q factors may indicate poorer signal quality and higher error rates, requiring optimization or troubleshooting. This analysis aids in optimizing system parameters, improving signal quality, and ensuring reliable and efficient communication across the 16 channels in the DWDM system.

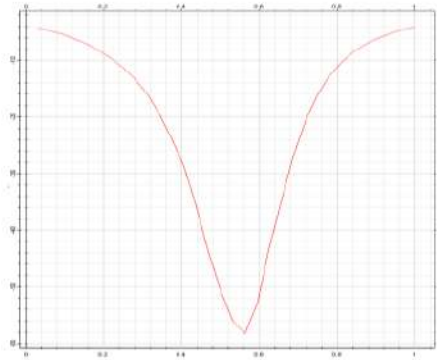
**Table 4 1 Q Factor Values For Different Channels**

Channel Number	Q-Factor
4 Channels	16.1122
8 Channel	15.1855
16 Channel	15.7362



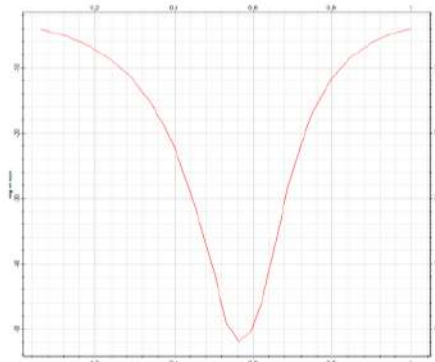
**Figure 4. 8: Bar diagram of Q-Factor for 4,8, and 16 channels**

### 4.3 Bit Error Rate Analysis



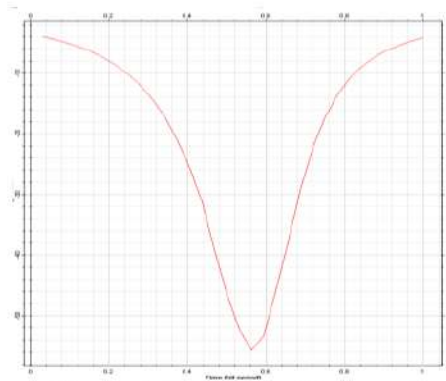
**Figure 4.9: BER for 4 channel**

<sup>90</sup> **Figure 4.9** shows the BER for the 4-channel optisystem design. In the figure, we can spot the line diagram for 4 channel BER output. BER analysis in a 4-channel DWDM (Dense Wavelength Division Multiplexing) system involves evaluating the Bit Error Rate, which represents the accuracy and quality of the transmitted data in each channel. The process begins by setting up the system with the specific characteristics of each channel, including wavelength, bit rate, modulation format, and power level. The signals are then transmitted through the system, accounting for impairments such as dispersion and noise. <sup>109</sup> The received data is compared with the original transmitted data to detect and count the number of bit errors for each channel. <sup>60</sup> The BER is then calculated by dividing the number of bit errors by the total number of transmitted bits. <sup>138</sup> Analyzing the BER values for each channel allows for the assessment of data transmission quality, enabling the identification of channels with higher error rates that may require optimization or troubleshooting. <sup>11</sup> This analysis ensures reliable and accurate data transmission in the 4-channel DWDM system.



**Figure 4.10: BER for 8 channel**

Figure 4.10 shows the Bit error rate for the 8-channel WDM communication system from the BER analyzer of the WDM demux output. BER analysis for each channel in an 8-channel DWDM communication system, it is possible to assess the performance and quality of each channel individually. This analysis helps in identifying channels with higher error rates that may require optimization or troubleshooting, ensuring reliable and accurate data transmission across all eight channels.

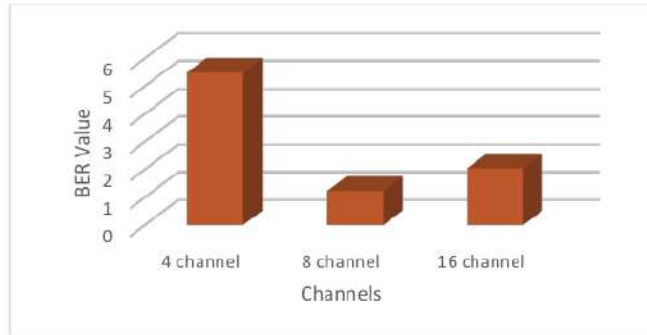


**Figure 4.11: BER for 16 channel**

shows the Bit error rate for 16 channels in DWDM optical communication. By performing BER analysis for each channel in a 16-channel DWDM optical communication system, it is possible to assess the performance and quality of each channel individually. This analysis helps in identifying channels with higher error rates that may require optimization or troubleshooting, ensuring reliable and accurate data transmission across all sixteen channels.

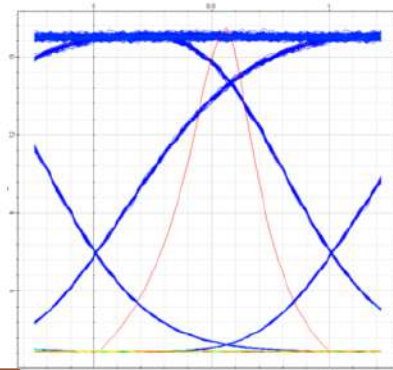
**Table 4 2: Bit Error Rate for Different Channels**

Channel Number	BER
4 Channel	5.48586e-59
8 Channel	1.22586e-52
16 Channel	2.04199e-56



**Figure 4. 12: BER for 4, 8, and 16 channels**

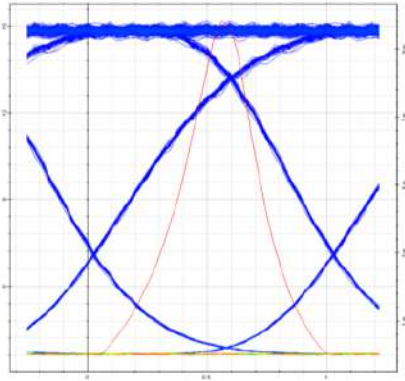
#### 4.4 Eye Diagram Analysis



103

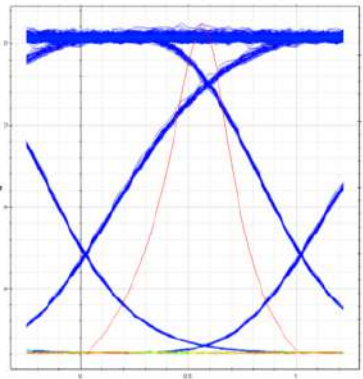
**Figure 4. 13: Eye Diagram for 4 channel**

In Figure 4.13 the Eye diagram for the 4 channels of DWDM optical communication is shown.



**Figure 4.14: Eye Diagram for 8 channels**

By visually examining the eye diagrams of the eight channels in the 8-channel DWDM communication system, it becomes possible to assess the overall quality and performance of the transmission, identify any abnormalities or distortions, and optimize the system parameters accordingly.

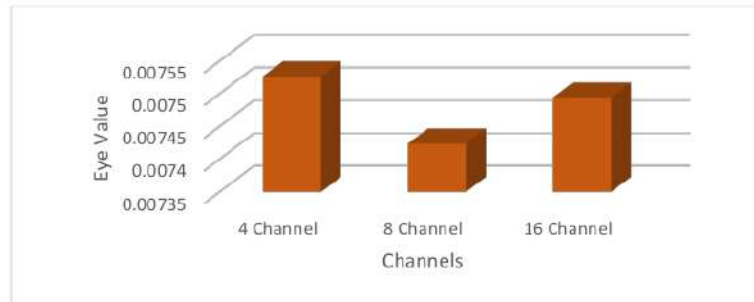


**Figure 4.15: Eye Diagram for 16 channel**

The result analysis of the eye diagram for 4, 8, and 16-channel DWDM communication systems provides valuable insights into their signal quality and integrity. In general, a well-defined and open-eye diagram represents higher signal quality and lower error probability. For the 4-channel DWDM system, the eye diagram reveals four distinct and clear eyes, indicating good signal quality and reliable transmission. In the 8-channel DWDM system, the eye diagram shows eight well-defined eyes, suggesting excellent signal integrity and minimal inter-channel interference. The 16-channel DWDM system exhibits sixteen clear and open eyes in the eye diagram, demonstrating superior signal quality and robust data transmission.

**Table 4 3: Eye diagram for different channels**

Channel number	Eye diagram
4 Channel	0.00752659
8 Channel	0.00742377
16 Channel	0.00749419



**Figure 4. 16: Eye for 4, 8, and 16 channels**

#### 4.5 Comparison With Existing Work

Table 4 4: Comparison with existing work

Paper	Channel Number	<sup>164</sup> Q Factor	BER (Bit Error Rate)	Eye Diagram
[1]	2	6.8491	2.32081e	0.000178249
[2]	4	9.07241	3.54629e	0.00207677
[3]	8	6.42	6.54	6.30
[8]	32	11.65	---	---
[11]	8	14.2	5.23e	---
[15]	4	9.44	----	----
Current Project	16	15.7362	2.04199e	0.00749419
Current Project	4	16.1122	5.48586e	0.00752659
Current Project	8	15.1855	1.22572e	0.00742377



## Chapter 5

### Conclusion

We investigated several setups with DWDM systems employing different types of channel systems in our previous chapter. In the simulations and results section, we essentially ran simulations and compared the results to our model paper to see what we could change in our system. We have arrived at an optimal design that offers good performance. Finally, we will wrap up our thesis work in this chapter with a summary of the findings, accomplishments, and potential future directions for the suggested design.

#### 5.1 Conclusion

In this work, we demonstrated a fantastic design using several channels. In general, we select one of three types of setups, including 16 channels. Each of these three setups offers distinct qualities. Regarding connection range, transmitter aperture size, receiver aperture, and beam divergence, our system's stability was examined.

When compared to 4-channel & 16-channel, the 16-channel arrangement has the highest quality factor according to the Q factor, and when it comes to bit error rates, 16-channel exhibits the lowest bit error rates. On the other hand, 4-channel exhibits the highest bit error rate. Comparing our 16-channel setup to the previous model, it exhibits good quality. Finally, we can state that the results of our experimental setting were better than those of the previous model.

#### 5.2 Achievement

This section will summarize all of our accomplishments. In our system, we both increase the number of channels and the data rate. A 193.1 THz wavelength was developed that uses pin photodiode wavelength division multiplexing to aggregate 16 channels. We get a good quality factor (16.7362) and a low bit error rate ( $2.04199 \times 10^{-56}$ ) about various channel configurations for the best signal amplification and performance.

### 5.3 Limitation

#### 5.3.1 Cost:

The initial cost of setting up a DWDM-based optical communication system is relatively high compared to other communication technologies, making it less accessible to small businesses or organizations.

#### 5.3.2 Fragility:

Optical fibers are fragile and can be damaged easily, which can impact the system's performance and reliability. Frequent maintenance is required to ensure that the system is functioning correctly.

#### 5.3.3 Complexity:

The design and implementation of DWDM-based optical communication systems with different channels require a high level of technical expertise, making it complicated for non-experts to manage or operate the system effectively.

#### 5.3.4 Distance Limitations:

DWDM-based optical communication systems have limitations in terms of the distance they can transmit data over. Transmission distance can be affected by factors such as attenuation, dispersion, and non-linear effects, which can degrade the signal quality.

#### 5.3.5 Security:

Although DWDM-based optical communication systems provide a more secure way of transmitting data than other communication technologies, they are still vulnerable to security breaches, potentially compromising sensitive information.

On the other hand, We utilized the 30-day trial version of the program Optisystem 16 for this thesis. More comparison findings may be added to this effort to sharpen the conclusion if the software was funded.

### 5.4 Future Work

The investigation for a 16.7362 Q factor was done for our thesis. Future research on larger data rates using the same phenomenon is possible, as is thesis work. To get a higher Q-factor and a low BER, an optimized amplifier can also be used. Future work can focus on exploring techniques to mitigate the impact of these parameters and improve the overall performance of the system. Considering the distance limitations of DWDM-based optical communication systems, future research should focus on new

techniques or approaches to extend the transmission distance over long distances, without compromising the signal quality. Research should focus on investigating new modulation formats and advanced signal processing techniques that can maximize the transmission capacity and reduce signal distortion, improving the system's performance and reliability.

## References

- [1] N. A. Mohammed and H. J. Abd, "A New Suppression approach of FWM Crosstalk Effect in Optical Communication Link based on Polarization combiner Method," *J. Phys. Conf. Ser.*, vol. 1973, no. 1, Aug. 2021, doi: 10.1088/1742-6596/1973/1/012169.
- [2] T. Abu Hanif, A. U. T173033, and S. K. R. T173010, "Performance Analysis Of FSO Channel Based On Different Amplifier Configuration," 2021.
- [3] J. Senior and M. Jamro, "Optical Fiber Communications: Principles and Practice," 2009.
- [4] D. Breuer *et al.*, "Opportunities for next-generation optical access," *IEEE Commun. Mag.*, vol. 49, no. 2, Feb. 2011, doi: 10.1109/MCOM.2011.5706309.
- [5] F. J. Effenberger, J. I. Kani, and Y. Maeda, "Standardization trends and prospective views on the next generation of broadband optical access systems," *IEEE J. Sel. Areas Commun.*, vol. 28, no. 6, pp. 773–780, Aug. 2010, doi: 10.1109/JSAC.2010.100802.
- [6] D. S. Akram, H. M. Al-Tamimi, and H. M. Al-Tamimi, "Design of DWDM optical communication systems with different modulation formats using DCF and a repeater," *Appl. Opt. Vol. 62, Issue 2, pp. 429-439*, vol. 62, no. 2, pp. 429–439, Jan. 2023, doi: 10.1364/AO.480016.
- [7] A. Mohammad *et al.*, "Free space optical communication system for indoor applications based on printed circuit board design," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 25, no. 2, pp. 1030–1037, 2022, doi: 10.11591/ijeecs.v25.i2.pp1030-1037.
- [8] M. Y. Wani, H. Pathak, K. Kaur, and A. Kumar, "Free Space Optical Communication System under Different Weather Conditions," *J. Opt. Commun.*, vol. 44, no. 1, pp. 103–110, Jan. 2023, doi: 10.1515/JOC-2019-0064/MACHINEREADABLECITATION/RIS.
- [9] N. Jiang, S. Liu, A. Zhao, Y. Zhang, and K. Qiu, "Physical Layer Encryption for WDM Optical Communication Systems Using Private Chaotic Phase Scrambling," *J. Light. Technol. Vol. 39, Issue 8, pp. 2288-2295*, vol. 39, no. 8, pp. 2288–2295, Apr. 2021.
- [10] A. H. M. Husein and F. I. El Nahal, "Optimal design of 32 channels spectrum slicing WDM for optical fiber access network system," *Optik (Stuttg.)*, vol. 125, no. 18, pp. 5141–5143, Sep. 2014, doi: 10.1016/J.IJLEO.2014.04.076.
- [11] D. P. Karothu *et al.*, "Mechanically robust amino acid crystals as fiber-optic transducers and wide bandpass filters for optical communication in the near-infrared," *Nat. Commun. 2021 121*, vol. 12, no. 1, pp. 1–8, Feb. 2021, doi: 10.1038/s41467-021-21324-y.
- [12] A. Bekkali, S. Member, H. Fujita, and M. Hattori, "New Generation Free-Space Optical Communication Systems With Advanced Optical Beam Stabilizer," *J. Light. Technol. Vol. 40, Issue 5, pp. 1509-1518*, vol. 40, no. 5, pp. 1509–1518, Mar. 2022, doi: 10.1364/JLT.40.001509.
- [13] W. B. Liu *et al.*, "Homodyne Detection Quadrature Phase Shift Keying Continuous-Variable Quantum key Distribution with High Excess Noise Tolerance," *PRX Quantum*, vol. 2, no. 4, p. 040334, Dec. 2021, doi: 10.1103/PRXQUANTUM.2.040334/FIGURES/10/MEDIUM.

- [14] <sup>43</sup> H.-J. Kim and J.-I. Song, "All-optical frequency downconversion technique utilizing a four-wave mixing effect in a single semiconductor optical amplifier for wavelength division multiplexing radio-over-fiber applications," *Opt. Express*, vol. 20, no. 7, p. 8047, Mar. 2012, doi: 10.1364/OE.20.008047.
- [15] <sup>23</sup> X. You *et al.*, "Towards 6G wireless communication networks: vision, enabling technologies, and new paradigm shifts," *Sci. China Inf. Sci.* 2020 641, vol. 64, no. 1, pp. 1–74, Nov. 2020, doi: 10.1007/S11432-020-2955-6.
- [16] S. J and M. Jamro, "Optical Fiber Communications: Principles and Practice," 2009. <sup>69</sup>
- [17] Q. Zhao, W. Yuan, J. Qu, Z. Cheng, G.-D. Peng, and C. Yu, "Optical Fiber-Integrated Metasurfaces: An Emerging Platform for <sup>127</sup> Multiple Optical Applications," *Nanomater.* 2022, Vol. 12, Page 793, vol. 12, no. 5, p. 793, Feb. 2022, doi: 10.3390/NANO12050793. <sup>30</sup>
- [18] A. Gafur, M. R. Ahmed, A. R. M. Foisal, and M. Badiuzzaman, "OSNR improvement of coherent un-compensated <sup>73</sup> optical transmission systems for various commercial optical fiber types," *1st Int. Conf. Electr. Eng. Inf. Commun. Technol. ICEEICT 2014*, Oct. 2014, doi: 10.1109/ICEEICT.2014.6919079.
- [19] F. N. Khan <sup>77</sup> Data perspectives in AI-assisted fiber-optic communication networks," *IEEE Netw.*, pp. 1–8, Jan. 2023, doi: 10.1109/MNET.130.2200413. <sup>5</sup>
- [20] N. Gisin, G. Ribordy, W. Tittel, and H. Zbinden, "Quantum cryptography," *Rev. Mod. Phys.*, vol. 74, no. 1, p. 145, Mar. 2002, doi: 10.1103/RevModPhys.74.145. <sup>177</sup>
- [21] R. P. Pinto *et al.*, "Demonstration of Packet-Optical Intent-Based Survivability Using Mininet-Optical," *Opt. Fiber Commun. Conf. 2023 (2023), Pap. M3Z.10*, p. M3Z.10, Mar. 2023. <sup>45</sup>
- [22] E. Ip, A. Pak, T. Lau, D. J. F. Barros, and J. M. Kahn, "Coherent detection in optical fiber systems," *Opt. Express*, Vol. 16, Issue 2, pp. 753–791, vol. 16, no. 2, pp. 753–791, Jan. 2008, doi: 10.1364/OE.16.000753.
- [23] "Fiber-Optic Communication Systems - Govind P. Agrawal - Google Books."
- [24] G. Keiser, "Scilab Code for Optical Fiber Communication," 2011.
- [25] <sup>62</sup> H. Pourbeyram, G. P. Agrawal, and A. Mafi, "Stimulated Raman scattering cascade spanning the wavelength range of 523 to 1750 nm using a graded-index multimode optical fiber," *Appl. Phys. Lett.*, vol. 102, no. 20, p. 201107, May 2013, doi: 10.1063/1.4807620/593869.
- [26] "Grundlagen der Photonik - Bahaa E. A. Saleh, Malvin Carl Teich - Google Books."
- [27] "Fundamentals of Communication Systems - John G Proakis, Masoud Salehi - Google Books." <sup>19</sup>
- [28] B. Ahuja, M. L. Meena, and R. S. Meena, "DESIGN AND PERFORMANCE ANALYSIS OF SEMICONDUCTOR OPTICAL AMPLIFIER FOR 16×10Gbps DWDM TRANSMISSION SYSTEMS," *ONLINE ICTACT J. Commun. Technol.*, no. 10, p. 2, 2019, doi: 10.21917/ijct.2019.0290. <sup>89</sup>
- [29] P. Guan *et al.*, "Scalable WDM phase regeneration in a single phase-sensitive amplifier through optical time lenses," *Nat. Commun.*, vol. 9, no. 1, Dec. 2018, doi: 10.1038/S41467-018-03458-

8/MEDIAOBJECTS/41467\_2018\_3458\_FIG5\_HTML.JPG.

- [30] U. Bhanja, A. Khuntia, and A. Swati, "Performance analysis of a SAC-OCDMA FSO network," *4th IEEE Int. Conf. Signal Process. Comput. Control. ISPCC 2017*, vol. 2017-Janua, pp. 1–6, Sep. 2017, doi: 10.1109/ISPCC.2017.8269580.
- [31] E. E. Elsayed, B. B. Yousif, and M. M. Alzalabani, "Performance enhancement of the power penalty in DWDM FSO communication using DPPM and OOK modulation," *Opt. Quantum Electron.*, vol. 50, no. 7, pp. 1–36, Jul. 2018, doi: 10.1007/S11082-018-1508-Y/FIGURES/16.
- [32] R. Miglani, G. S. Gaba, M. Masud, and R. Alroobaea, "Gain analysis of high-speed DWDM link with different optical amplification configurations," *Int. J. Smart Sens. Intell. Syst.*, vol. 13, no. 1, pp. 1–8, Jan. 2020, doi: 10.21307/IJSSIS-2020-028.
- [33] V. Siregar, K. Sujatmoko, M. I. Maulana, P. S1, and T. Telekomunikasi, "Perancangan Jaringan Akses Fiber To The Home (ftth) Menggunakan Teknologi 10-gigabit-capable Passive Optical Network (xgpon) Untuk Perumahan Benda Baru," *eProceedings Eng.*, vol. 5, no. 3, Dec. 2018.
- [34] E. Safrianti, L. O. Sari, D. Putra, and R. Yuhana, "Broadband Network Fiber to the Home (FtH) Design for Improving Performance of Information and Telecommunication Network in Riau University," *Int. J. Electr. Energy Power Syst. Eng.*, vol. 1, no. 1, pp. 1–5, Sep. 2018, doi: 10.31258/IJEEPSE.1.1.1-5.
- [35] M. M. A. Eid, A. N. Z. Rashed, and E. M. El-Gammal, "Influence of dense wavelength division multiplexing (DWDM) technique on the low earth orbit intersatellite systems performance," *J. Opt. Commun.*, Nov. 2020, doi: 10.1515/JOC-2020-0188/MACHINEREADABLECITATION/RIS.
- [36] C.-Y. Lin *et al.*, "Performance Analysis of 64 Channel DWDM System Using Single Mode Fiber at Different Power Levels and Frequency Spacing," *J. Phys. Conf. Ser.*, vol. 1804, no. 1, p. 012153, Feb. 2021, doi: 10.1088/1742-6596/1804/1/012153.
- [37] M. L. Meena and R. Kumar Gupta, "Design and comparative performance evaluation of chirped FBG dispersion compensation with DCF technique for DWDM optical transmission systems," *Optik (Stuttg.)*, vol. 188, pp. 212–224, Jul. 2019, doi: 10.1016/J.IJLEO.2019.05.056.
- [38] K. I. Sato and H. Hasegawa, "Optical Networking Technologies That Will Create Future Bandwidth-Abundant Networks [Invited]," *J. Opt. Commun. Networking, Vol. 1, Issue 2, pp. A81-A93*, vol. 1, no. 2, pp. A81–A93, Jul. 2009, doi: 10.1364/JOCN.1.000A81.
- [39] A. Gafur and M. S. Islam, "Quality Factor of Coherent Optical Transmission Systems with Different Baud Rates".
- [40] A. Alvarado, E. Agrell, D. Lavery, R. Maher, and P. Bayvel, "Replacing the Soft-Decision FEC Limit Paradigm in the Design of Optical Communication Systems," *J. Light. Technol.*, vol. 33, no. 20, pp. 4338–4352, Oct. 2015, doi: 10.1109/JLT.2015.2450537.
- [41] I. B. Djordjevic, "Advanced Coding for Fiber-Optics Communications Systems," *Opt. Commun. Syst.*, pp. 191–242, Sep. 2019, doi: 10.1201/9780429027802-6.

- [42] <sup>44</sup> R. Mercy Kingsta and R. Shantha Selvakumari, "A review on coupled and uncoupled multicore fibers for future ultra-high capacity optical communication," *Optik (Stuttg.)*, vol. 199, p. 163341, Dec. 2019, doi: [10.1016/J.IJLEO.2019.163341](https://doi.org/10.1016/J.IJLEO.2019.163341).
- [43] <sup>95</sup> A. Goel and G. Pandey, "Design of broadband dispersion flattened fiber for DWDM system: Performance analysis using various modulation formats," *Opt. Fiber Technol.*, vol. 42, pp. 109–118, May 2018, doi: [10.1016/J.YOFTE.2018.02.018](https://doi.org/10.1016/J.YOFTE.2018.02.018).
- [44] J. Jeyaseelan, D. Sriram Kumar, and B. E. Caroline, "Disaster management using free space optical communication system," *Photonic Netw. Commun.*, vol. 39, no. 1, pp. 1–14, Feb. 2020, doi: [10.1007/S11107-019-00865-0](https://doi.org/10.1007/S11107-019-00865-0)/METRICS.
- [45] <sup>41</sup> J. P. A. Yaacoub, J. H. Fernandez, H. N. Noura, and A. Chehab, "Security of Power Line Communication systems: Issues, limitations and existing solutions," *Comput. Sci. Rev.*, vol. 39, p. 100331, Feb. 2021, doi: [10.1016/J.COSREV.2020.100331](https://doi.org/10.1016/J.COSREV.2020.100331).
- [46] A. Wonfor *et al.*, "Field trial of multi-node, coherent-one-way quantum key distribution with encrypted 5x100G DWDM transmission system," *IET Conf. Publ.*, vol. 2019, no. CP765, 2019, doi: [10.1049/CP.2019.0962](https://doi.org/10.1049/CP.2019.0962).
- [47] T. Portela, M. E. Monteiro, J. R. A. Cavalcante, J. Celestino, and A. Patel, "An extended software defined optical networks slicing architecture," *Comput. Stand. Interfaces*, vol. 70, p. 103428, Jun. 2020, doi: [10.1016/J.CSI.2020.103428](https://doi.org/10.1016/J.CSI.2020.103428).
- [48] S. Rai and A. K. Garg, "Deep learning—a route to WDM high-speed optical networks," *J. Opt.*, pp. 1–9, Aug. 2022, doi: [10.1007/S12596-022-00907-Y](https://doi.org/10.1007/S12596-022-00907-Y)/METRICS.
- [49] D. Kakati, M. Minz, and R. K. Sonkar, "Performance analysis of grating-assisted passive mode-division multiplexing device using silicon photonics for high-speed RoF/RoFSO communication," <https://doi.org/10.1117/1.OE.60.1.016102>, vol. 60, no. 1, p. 016102, Jan. 2021, doi: [10.1117/1.OE.60.1.016102](https://doi.org/10.1117/1.OE.60.1.016102).
- [50] S. Singh and R. S. Kaler, "Performance evaluation of 64 × 10 Gbps and 96 × 10 Gbps DWDM system with hybrid optical amplifier for different modulation formats," *Optik (Stuttg.)*, vol. 123, no. 24, pp. 2199–2203, Dec. 2012, doi: [10.1016/J.IJLEO.2011.11.015](https://doi.org/10.1016/J.IJLEO.2011.11.015).
- [51] S. R. Mad Zaki @ Abdullah, "Analysis of fiber nonlinearity for various power levels in DWDM system," 2013.
- [52] X. Xu *et al.*, "Non-morphic Computing Based on Wavelength-Division Multiplexing," *IEEE J. Sel. Top. Quantum Electron.*, vol. 29, no. 2, 2023, doi: [10.1109/JSTQE.2022.3203159](https://doi.org/10.1109/JSTQE.2022.3203159).
- [53] L. Wang *et al.*, "Superposition-assisted 125-µm cladding multi-core fiber with ultra-low inter-core crosstalk and high relative core multiplicity factor," *Opt. Fiber Technol.*, vol. 67, p. 102721, Dec. 2021, doi: [10.1016/J.YOFTE.2021.102721](https://doi.org/10.1016/J.YOFTE.2021.102721).
- [54] A. Gafur, M. R. Ahmed, A. R. M. Foisal, and M. Badiuzzaman, "Evaluation of nonlinear propagation effects on coherent optical transmission systems for various commercial optical fiber types," *1st Int. Conf. Electr. Eng. Inf.*

- Commun. Technol. ICEEICT 2014*, Oct. 2014, doi: 10.1109/ICEEICT.2014.6919080.
- [55] X. Guan, W. Shi, and L. A. Rusch, "Ultra-Dense Wavelength-Division Multiplexing with Microring Modulator," *J. Light. Technol.*, vol. 39, no. 13, pp. 4300–4306, Jul. 2021, doi: 10.1109/JLT.2021.3070515.
- [56] T. Kabilan, N. Victor, and M. Tech, "Performance Analysis of 48 Channels DWDM System using EDFA for Long Distance Communication," *GRD J. Eng.*, vol. 2, 2017.
- [57] M. L. Meena and D. Meena, "PERFORMANCE ANALYSIS OF DWDM OPTICAL NETWORK WITH DISPERSION COMPENSATION TECHNIQUES FOR 4×8 GBPS TRANSMISSION SYSTEM," *ONLINE) ICTACT J. Microelectron.*, pp. 2395–1680, 2018, doi: 10.21917/ijme.2018.0106.
- [58] C.-Y. Lin *et al.*, "FWM Mitigation in DWDM Optical Networks," *J. Phys. Conf. Ser.*, vol. 1447, no. 1, p. 012033, Jan. 2020, doi: 10.1088/1742-6596/1447/1/012033.
- [59] A. Jahid, S. Hossain, and R. Islam, "Performance Analysis of DWDM System with Optical Amplifiers in Cascade Considering the Effect of Crosstalk." <http://www.sciencepublishinggroup.com>, vol. 3, no. 5, p. 110, Aug. 2015, doi: 10.11648/JJEEE.20150305.12.
- [60] K. Matsuda *et al.*, "Parallel optical amplification and multi-aperture transmission with digital coherent reception for wavelength division multiplexed high capacity FSO and its real-time evaluation," <https://doi.org/10.1117/12.2578044>, vol. 11678, no. 5, pp. 119–124, Mar. 2021, doi: 10.1117/12.2578044.
- [61] A. Gafur, M. Islam, S. R.-I. J. Of, and U. 2019, "Quality Optimization Based Trend Line for Hybrid Optical Amplifier Configurations in DWDM Transmission Systems.," *search.ebscohost.com A Gafur, MS Islam. SZ Rashid International J. Microw. Opt. Technol. 2019*•*search.ebscohost.com*.
- [62] Z. He, P. A. Andrekson, B. Foo, J. Schröder, K. Vijayan, and M. Karlsson, "Phase-sensitively amplified wavelength-division multiplexed optical transmission systems," *Opt. Express*, Vol. 29, Issue 21, pp. 33086–33096, vol. 29, no. 21, pp. 33086–33096, Oct. 2021, doi: 10.1364/OE.426504.
- [63] "Optical Performance Monitoring: Advanced Techniques for Next-Generation ... - Google Books."
- [64] K. Kikuchi, "Coherent Optical Communications: Historical Perspectives and Future Directions," *High Spectr. Density Opt. Commun. Technol.*, pp. 11–49, 2010, doi: 10.1007/978-3-642-10419-0\_2.
- [65] I. Rasheed, M. Abdullah, S. Mehmood, and M. Chaudhary, "Analyzing the non-linear effects at various power levels and channel counts on the performance of DWDM based optical fiber communication system," *Proc. - 2012 Int. Conf. Emerg. Technol. ICET 2012*, pp. 201–205, 2012, doi: 10.1109/ICET.2012.6375446.
- [66] K. I. Rani, H. Weerasena, S. A. Butler, S. Charles, and P. I. Mishra, "Modeling and Exploration of Gain Competition Attacks in Optical Network-on-Chip Architectures," Mar. 2023.

- [67] K. Singh, S. K. Arya, and V. Kumar, "Performance enhancement of duobinary modulation-based DWDM system using particle swarm optimization," *J. Opt. Commun.*, Jan. 2023, doi: 10.1515/JOC-2022-0208/MACHINEREADABLECITATION/RIS.
- [68] X. Zhou, R. Urata, and H. Liu, "Beyond 1 Tb/s Intra-Data Center Interconnect Technology: IM-DD or Coherent?," *J. Light. Technol.*, vol. 38, no. 2, pp. 475–484, Jan. 2020, doi: 10.1109/JLT.2019.2956779.
- [69] P. Smulders, "The road to 100 Gb/s wireless and beyond: Basic issues and key directions," *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 86–91, 2013, doi: 10.1109/MCOM.2013.6685762.
- [70] R. Ullah, L. Bo, S. Ullah, M. Yaya, F. Tian, and X. Xiangjun, "Cost effective OLT designed from optical frequency comb generator based EML for 1.22 Tbps wavelength division multiplexed passive optical network," *Opt. Fiber Technol.*, vol. 43, pp. 49–56, Jul. 2018, doi: 10.1016/J.YOFTE.2018.01.025.

# T183004\_Fajal kader\_Thesis Report Book-1

---

## ORIGINALITY REPORT

---

**21** %  
SIMILARITY INDEX

**17** %  
INTERNET SOURCES

**12** %  
PUBLICATIONS

**5** %  
STUDENT PAPERS

---

## PRIMARY SOURCES

---

**1** [dspace.iitk.ac.bd:8080](https://dspace.iitk.ac.bd:8080) Internet Source **5** %

---

**2** [www.researchgate.net](http://www.researchgate.net) Internet Source **1** %

---

**3** [www.science.gov](http://www.science.gov) Internet Source **1** %

---

**4** [hdl.handle.net](http://hdl.handle.net) Internet Source **1** %

---

**5** Submitted to University of Warwick Student Paper **<1** %

---

**6** [www.highpowerlasers.rp-photonics.com](http://www.highpowerlasers.rp-photonics.com) Internet Source **<1** %

---

**7** [worldwidescience.org](http://worldwidescience.org) Internet Source **<1** %

---

**8** [doras.dcu.ie](http://doras.dcu.ie) Internet Source **<1** %

---

**9** Submitted to Rivier University Student Paper **<1** %

---

10	<a href="https://ictactjournals.in">ictactjournals.in</a> Internet Source	<1 %
11	Submitted to Universiti Malaysia Perlis Student Paper	<1 %
12	<a href="https://dokumen.pub">dokumen.pub</a> Internet Source	<1 %
13	Submitted to Unicaf University Student Paper	<1 %
14	<a href="https://issuu.com">issuu.com</a> Internet Source	<1 %
15	Abbas Yildirim, Sait Eser Karlık. "Modeling and computational analysis of the combined impact of optical Kerr nonlinearities on the performance of DWDM long-haul communication systems", Optical and Quantum Electronics, 2023 Publication	<1 %
16	<a href="https://utpedia.utp.edu.my">utpedia.utp.edu.my</a> Internet Source	<1 %
17	<a href="https://backend.orbit.dtu.dk">backend.orbit.dtu.dk</a> Internet Source	<1 %
18	<a href="https://dspace.dtu.ac.in:8080">dspace.dtu.ac.in:8080</a> Internet Source	<1 %
19	"Proceedings of International Conference on Data Science and Applications", Springer	<1 %

20

Rajeev, Chakresh Kumar. "Best-suited cascaded arrangement of optical amplifiers for QAM-modulated UD-WDM system at a narrow channel spacing of 6.25GHz under the effect of FWM", Journal of Optics, 2023

Publication

---

<1 %

21

Sibghat Ullah, Rahat Ullah, Qi Zhang, Hafiz Ahmad Khalid, Kamran Ali Memon, Adil Khan, Feng Tian, Xin Xiangjun. "Ultra-Wide and Flattened Optical Frequency Comb Generation Based on Cascaded Phase Modulator and LiNbO3-MZM Offering Terahertz Bandwidth", IEEE Access, 2020

Publication

---

<1 %

22

Submitted to Universiti Malaysia Sarawak

Student Paper

---

<1 %

23

web.archive.org

Internet Source

---

<1 %

24

Anurupa Lubana, Sanmukh Kaur. "FWM crosstalk reduction and performance investigation of SC-DWDM system employing ML techniques", Optical Fiber Technology, 2023

Publication

---

<1 %

25

www.freepatentsonline.com

Internet Source

<1 %

26

[ebin.pub](http://ebin.pub)

Internet Source

<1 %

27

[pure.tue.nl](http://pure.tue.nl)

Internet Source

<1 %

28

[www.techopedia.com](http://www.techopedia.com)

Internet Source

<1 %

29

Neha Sharma, Harjeevan Singh, Prabhjot Singh. "Analyzing the FWM at Different Power Levels in the Fiber Optic DWDM System", 2020 5th International Conference on Communication and Electronics Systems (ICCES), 2020

Publication

<1 %

30

T. Almeida, M. Drummond, N. Pavlovic, P. Andre, R. Nogueira. "A Fast Method for Launch Parameter Optimization in Long-Haul Dispersion-Managed Optical Links", Journal of Lightwave Technology, 2015

Publication

<1 %

31

Submitted to Engineers Australia

Student Paper

<1 %

32

Farman Ali, Fazal Muhammad, Usman Habib, Yousaf Khan, Muhammad Usman. "Modeling and minimization of FWM effects in DWDM-

<1 %

based long-haul optical communication systems", Photonic Network Communications, 2020

Publication

---

33

Mehtab Singh, Sahil Nazir Pottoo, Moustafa H. Aly, Štěpán Hubálovský, Amit Grover, Debashis Adhikari, Preecha Yupapin. "Mode division multiplexing free space optics system with 3D hybrid modulation under dust and fog", Alexandria Engineering Journal, 2022

Publication

---

34

[tudr.thapar.edu:8080](http://tudr.thapar.edu:8080)

Internet Source

---

35

Baseerat Gul, Faroze Ahmad. "Review of FBG and DCF as dispersion management unit for long haul optical links and WDM systems", Optical and Quantum Electronics, 2023

Publication

---

36

Mandeep Kaur. "AI- and IoT-based energy saving mechanism by minimizing hop delay in multi-hop and advanced optical system based optical channels", Optical and Quantum Electronics, 2023

Publication

---

37

[mafiadoc.com](http://mafiadoc.com)

Internet Source

---

38

Submitted to Institute of Business Studies

Student Paper

<1 %

<1 %

<1 %

<1 %

<1 %

<1 %

39

Marcos Troncoso-Costas, Devika Dass, Colm Browning, Francisco J. Diaz-Otero, Chris G. H. Roeloffzen, Liam P. Barry. " Intra-Data Centre Flexible PAM Transmission System Using an Integrated InP-Si N Dual Laser Module ", IEEE Photonics Journal, 2022

Publication

<1 %

40

[icatas2019.aast.edu](http://icatas2019.aast.edu)

Internet Source

<1 %

41

[ijece.iaescore.com](http://ijece.iaescore.com)

Internet Source

<1 %

42

[www.spiedigitallibrary.org](http://www.spiedigitallibrary.org)

Internet Source

<1 %

43

Amitesh Kumar, Abhinav Gautam, Vishnu Priye. "Microwave Photonic Mixer Using DP-DDMZM for Next Generation 5G Cellular Systems", Fiber and Integrated Optics, 2020

Publication

<1 %

44

Submitted to Bangladesh University of Professionals

Student Paper

<1 %

45

Geisler, David J., Nicolas K. Fontaine, Ryan P. Scott, and S. J. B. Yoo. "Demonstration of a Flexible Bandwidth Optical

<1 %

Transmitter/Receiver System Scalable to Terahertz Bandwidths", IEEE Photonics Journal, 2011.

Publication

46

[arantxa.ii.uam.es](http://arantxa.ii.uam.es)

Internet Source

<1 %

47

[repositorio.iscte-iul.pt](http://repositorio.iscte-iul.pt)

Internet Source

<1 %

48

Philippe Genevaux, Christian Simonneau, Guillaume Labroille, Bertrand Denolle et al. "6-mode Spatial Multiplexer with Low Loss and High Selectivity for Transmission over Few Mode Fiber", Optical Fiber Communication Conference, 2015

Publication

<1 %

49

R.E. Ahmed. "Next generation DWDM networks: demands, capabilities and limitations", 2000 Canadian Conference on Electrical and Computer Engineering Conference Proceedings Navigating to a New Era (Cat No 00TH8492) CCECE-00, 2000

Publication

<1 %

50

[www.degruyter.com](http://www.degruyter.com)

Internet Source

<1 %

51

[www.scilit.net](http://www.scilit.net)

Internet Source

<1 %

[circle.cloudsecurityalliance.org](http://circle.cloudsecurityalliance.org)

52

Internet Source

&lt;1 %

53

Optical Networks, 2013.

Publication

&lt;1 %

54

coek.info

Internet Source

&lt;1 %

55

ozeas.sdb.cz

Internet Source

&lt;1 %

56

tailieu.vn

Internet Source

&lt;1 %

57

www.ir.juit.ac.in:8080

Internet Source

&lt;1 %

58

www.mdpi.com

Internet Source

&lt;1 %

59

Davide Cimbri, Begum Yavas-Aydin, Fabian Hartmann, Fauzia Jabeen, Lukas Worschech, Sven Hofling, Edward Wasige. "Accurate Quantum Transport Modeling of High-Speed In<sub>0.53</sub>Ga<sub>0.47</sub>As/AlAs Double-Barrier Resonant Tunneling Diodes", IEEE Transactions on Electron Devices, 2022

Publication

&lt;1 %

60

Submitted to De Montfort University

Student Paper

&lt;1 %

61 "Fibre Optic Communication", Springer Science and Business Media LLC, 2017  
Publication <1 %

---

62 Logan G. Wright, Zachary M. Ziegler, Pavel M. Lushnikov, Zimu Zhu et al. "Multimode Nonlinear Fiber Optics: Massively Parallel Numerical Solver, Tutorial, and Outlook", IEEE Journal of Selected Topics in Quantum Electronics, 2018  
Publication <1 %

---

63 M L Meena, Pragya Purohit. "PERFORMANCE INVESTIGATION OF OPTICAL TRANSMISSION SYSTEM USING DCF-EDFA TECHNIQUES", ICTACT Journal on Communication Technology, 2019  
Publication <1 %

---

64 ManojKumar Koduru, Venkatramana Reddy B.D. "A COMPREHENSIVE ANALYSIS OF FOUR CHANNEL CWDM NETWORK SYSTEM", Optica Publishing Group, 2023  
Publication <1 %

---

65 Submitted to University of Mauritius  
Student Paper <1 %

---

66 focenter.com  
Internet Source <1 %

---

67 repository.sustech.edu  
Internet Source <1 %

---

68

[tel.archives-ouvertes.fr](https://tel.archives-ouvertes.fr)

Internet Source

&lt;1 %

69

[www.eie.polyu.edu.hk](http://www.eie.polyu.edu.hk)

Internet Source

&lt;1 %

70

Jean-Paul A. Yaacoub, Hassan N. Noura, Benoit Piranda. "The internet of modular robotic things: Issues, limitations, challenges, & solutions", Internet of Things, 2023

Publication

&lt;1 %

71

Submitted to University College London

Student Paper

&lt;1 %

72

Submitted to Unizin, LLC

Student Paper

&lt;1 %

73

[docplayer.net](https://docplayer.net)

Internet Source

&lt;1 %

74

[link.springer.com](https://link.springer.com)

Internet Source

&lt;1 %

75

[1library.net](https://1library.net)

Internet Source

&lt;1 %

76

Raturaj Thummar, Dharmendra Dhadhal, (Sr. Member IEEE) Vivekanand Mishra.

"Performance Analysis of 64 Channel DWDM System Using Single Mode Fiber at Different Power Levels and Frequency Spacing", Journal of Physics: Conference Series, 2021

Publication

&lt;1 %

77	arxiv.org Internet Source	<1 %
78	ejournal.itats.ac.id Internet Source	<1 %
79	www.broadbandsearch.net Internet Source	<1 %
80	www.techscience.com Internet Source	<1 %
81	H.F. Chen, J.M. Liu. "Open-loop chaotic synchronization of injection-locked semiconductor lasers with gigahertz range modulation", IEEE Journal of Quantum Electronics, 2000 Publication	<1 %
82	Lee, Kihoon, and Hanho Lee. "A high-performance concatenated BCH code and its hardware architecture for 100 Gb/s long-haul optical communications", 2010 International SoC Design Conference, 2010. Publication	<1 %
83	Submitted to Middlesex University Student Paper	<1 %
84	Submitted to Nanyang Technological University, Singapore Student Paper	<1 %
85	Submitted to RMIT University	

<1 %

86

Submitted to Royal Melbourne Institute of Technology

Student Paper

<1 %

87

Saumya Srivastava, Kamal Kishore Upadhyay, Nar Singh. "Design and performance analysis of dispersion managed system with RZ and NRZ modulation format", 2016 International Conference on Control, Computing, Communication and Materials (ICCCCM), 2016

Publication

<1 %

88

Submitted to University of Sydney

Student Paper

<1 %

89

Xinning Huang, Xiaoping Xie, Jiazheng Song, Tao Duan, Hui Hu, Xin Xu, Yulong Su. "Performance Comparison of All-Optical Amplify-and-Forward Relaying FSO Communication Systems With OOK and DPSK Modulations", IEEE Photonics Journal, 2018

Publication

<1 %

90

Govind P. Agrawal. "Fiber - Optic Communication Systems", Wiley, 2010

Publication

<1 %

91

Submitted to Universiti Sains Islam Malaysia

Student Paper

<1 %

Submitted to University of the West Indies

92

Student Paper

&lt;1 %

93

Yingjie Jiang, Du Tang, Zhen Wu, Zhongliang Sun, Yaojun Qiao. "Abnormal Loss Monitoring for Digital Subcarrier-Multiplexing Systems Based on Learned Digital Backpropagation", 2022 Asia Communications and Photonics Conference (ACP), 2022

Publication

&lt;1 %

94

[www.protocol.com](http://www.protocol.com)

Internet Source

&lt;1 %

95

[www.santannapisa.it](http://www.santannapisa.it)

Internet Source

&lt;1 %

96

A - Ru Kong, Ting Lei, Jun - Cheng Fang, You - Peng Xie, Jing - Bo Hu, Xiao - Cong Yuan. "Achromatic Broadband Multi - Layer Diffraction Mode Multiplexing", Laser & Photonics Reviews, 2023

Publication

&lt;1 %

97

Bo Deng, Fengying Wang, Ling Qin, Xiaoli Hu. "A Visible Light 3D Positioning System for Underground Mines Based on Convolutional Neural Network Combining Inception Module and Attention Mechanism", Photonics, 2023

Publication

&lt;1 %

98

Submitted to Coventry University

Student Paper

&lt;1 %

99	Deepak Malik, Geeta Kaushik, Amit Wason. "Performance optimization of hybrid optical amplifier for dense wavelength division multiplexed system", Journal of Optics, 2017 Publication	<1 %
100	Kangping Zhong, Xian Zhou, Tao Gui, Li Tao, Yuliang Gao, Wei Chen, Jiangwei Man, Li Zeng, Alan Pak Tao Lau, Chao Lu. "Experimental study of PAM-4, CAP-16, and DMT for 100 Gb/s Short Reach Optical Transmission Systems", Optics Express, 2015 Publication	<1 %
101	Reis, Jacklyn D., Darlene M. Neves, and António L. Teixeira. "Analysis of Nonlinearities on Coherent Ultradense WDM-PONs Using Volterra Series", Journal of Lightwave Technology, 2012. Publication	<1 %
102	Submitted to Sir John Cass Redcost CofE Secondary & Sixth Form Student Paper	<1 %
103	Submitted to Universiti Putra Malaysia Student Paper	<1 %
104	Submitted to University of Wales, Bangor Student Paper	<1 %
105	apessay.elementfx.com Internet Source	<1 %

106 "Phase-Modulated Optical Communication Systems", Springer Science and Business Media LLC, 2005  
Publication <1 %

---

107 engr.arizona.edu  
Internet Source <1 %

---

108 spectrum.library.concordia.ca  
Internet Source <1 %

---

109 "Proceedings of the 4th International Conference on Communication, Devices and Computing", Springer Science and Business Media LLC, 2023  
Publication <1 %

---

110 Chawaphon Prayoonyong, Bill Corcoran. "Effects of receiver-side optical filtering on optical superchannel system performance", Journal of Lightwave Technology, 2021  
Publication <1 %

---

111 Sergi Abadal, Ignacio Llatser, Albert Mestres, Heekwan Lee, Eduard Alarcon, Albert Cabellos-Aparicio. "Time-Domain Analysis of Graphene-Based Miniaturized Antennas for Ultra-Short-Range Impulse Radio Communications", IEEE Transactions on Communications, 2015  
Publication <1 %

---

Submitted to University of Cincinnati

112	Student Paper	<1 %
113	icvtank.com Internet Source	<1 %
114	nozdr.ru Internet Source	<1 %
115	openaccess.altinbas.edu.tr Internet Source	<1 %
116	research-information.bris.ac.uk Internet Source	<1 %
117	www.tib.eu Internet Source	<1 %
118	"Smart and Sustainable Technologies: Rural and Tribal Development Using IoT and Cloud Computing", Springer Science and Business Media LLC, 2022 Publication	<1 %
119	Assia Ahlem HARRAT, Mohammed DEBBAL, Mohammed Chamse Eddine OUADAH. "Design of a new 2-channel demultiplexer based on Photonic Crystal Fiber", Results in Optics, 2023 Publication	<1 %
120	Barney Warf. "International Competition Between Satellite and Fiber Optic Carriers: A	<1 %

# Geographic Perspective\*", The Professional Geographer, 2006

Publication

---

121 Jiayao Zhou, Lun Jiang, Hongbo Lu, Weirao Gao. "Experiment analysis on optimization of 7km urban space laser communication link", *Optik*, 2022 <1 %

Publication

---

122 Submitted to Kingston University <1 %

Student Paper

---

123 Peter J. Winzer, David T. Neilson, Andrew R. Chraplyvy. "Fiber-optic transmission and networking: the previous 20 and the next 20 years [Invited]", *Optics Express*, 2018 <1 %

Publication

---

124 Yongmao Ren, Wanghong Yang, Xu Zhou, Huan Chen, Bing Liu. "A survey on TCP over mmWave", *Computer Communications*, 2021 <1 %

Publication

---

125 Ze Dong, Jianjun Yu, Yifan Chen, Fan Li, Xiangjun Xin. "Symbol division multiplexing in optical fiber communication systems", *Optics Express*, 2022 <1 %

Publication

---

126 [books.google.com](https://books.google.com) <1 %

Internet Source

---

127 [escholarship.org](https://escholarship.org)

Internet Source

<1 %

---

128 [ncrl.seu.edu.cn](http://ncrl.seu.edu.cn)  
Internet Source

<1 %

---

129 [owcc.jakajima.eu](http://owcc.jakajima.eu)  
Internet Source

<1 %

---

130 [research.library.mun.ca](http://research.library.mun.ca)  
Internet Source

<1 %

---

131 [www.comarch.com](http://www.comarch.com)  
Internet Source

<1 %

---

132 [www.ijitee.org](http://www.ijitee.org)  
Internet Source

<1 %

---

133 [www.rivmat.unipr.it](http://www.rivmat.unipr.it)  
Internet Source

<1 %

---

134 Adam Widomski, Stanisław Stopiński,  
Krzysztof Anders, Ryszard Piramidowicz,  
Michał Karpiński. "Precise on-chip spectral  
and temporal control of single-photon-level  
optical pulses", Journal of Lightwave  
Technology, 2023  
Publication

<1 %

---

135 Aditya Goel, Gaurav Pandey. "Design of  
broadband dispersion flattened fiber for  
DWDM system: Performance analysis using  
various modulation formats", Optical Fiber  
Technology, 2018

<1 %

136

Ahmed F. Sayed, Fathy M. Mustafa, Ashraf A. M. Khalaf, Moustafa H. Aly. "Symmetrical and post dispersion compensation in WDM optical communication systems", *Optical and Quantum Electronics*, 2021

Publication

---

<1 %

137

Changqing Liu, Qing-an Ding, Juan Song, Lijun Zhang, Xiaojuan Wang, Bowen Nie, Chaofan Li, Xudong Cheng. "Performance investigation of PM-based wavelength remodulation scheme in bidirectional TWDM-PON", *Journal of Optical Communications*, 2021

Publication

---

<1 %

138

David W. U. Chan, Xiong Wu, Zunyue Zhang, Chao Lu, Alan Pak Tao Lau, Hon Ki Tsang. "Ultra-Wide Free-Spectral-Range Silicon Microring Modulator for High Capacity WDM", *Journal of Lightwave Technology*, 2022

Publication

---

<1 %

139

Duc-Tan Tran, Ninh Trung Bui. "Improvements on the performance of subcarrier multiplexing/wavelength division multiplexing based radio over fiber system", *International Journal of Electrical and Computer Engineering (IJECE)*, 2021

Publication

---

<1 %

140 Jeyarani Jeyaseelan, D. Sriram Kumar, B. E. Caroline. "Disaster management using free space optical communication system", Photonic Network Communications, 2019  
Publication

<1 %

141 Nawawi, N. M., M. S. Anuar, C.B.M Rashidi, S.A Aljunid, A.K. Rahman, M.N. Junita, and S. R. Abdullah. "Dispersion compensation dense wavelength division multiplexing (DC DWDM) for nonlinearity analysis at various propagation distance and input power", 2015 International Conference on Computer Communications and Control Technology (I4CT), 2015.  
Publication

<1 %

142 Rajeev, Chakresh Kumar. "Effect of various fiber nonlinearities on MADPSK modulated  $450 \times 100\text{Gb/s}$  ultra-dense WDM system for long haul communication", Journal of Optics, 2023  
Publication

<1 %

143 Saleh. "Fiber-Optic Communications", Wiley Series in Pure and Applied Optics, 08/14/1991  
Publication

<1 %

144 Shan Jiang, Qiuming Zhu, Cheng-Xiang Wang, Kai Mao, Wenping Xie, Weizhi Zhong, Mengtian Yao. "Map-Based UAV mmWave Channel Model and Characteristics Analysis",

<1 %

2020 IEEE/CIC International Conference on  
Communications in China (ICCC Workshops),  
2020

Publication

---

145 Shuiping Xiong. "Intelligent modulation  
recognition algorithm for optical  
communication", Journal of Intelligent & Fuzzy  
Systems, 2021 <1 %

Publication

---

146 Stephan Pachnicke. "Fiber-Optic Transmission  
Networks", Springer Science and Business  
Media LLC, 2012 <1 %

Publication

---

147 Tsvetan Valkovski, Ivaylo Nachev, Peter Z.  
Petkov. "Optical Communication System  
Investigation with Application for VLF Solar  
Flares Monitoring System", 2023 58th  
International Scientific Conference on  
Information, Communication and Energy  
Systems and Technologies (ICEST), 2023 <1 %

Publication

---

148 Submitted to University of Technology,  
Sydney <1 %

Student Paper

---

149 W SHIEH. "Introduction", OFDM for Optical  
Communications, 2010 <1 %

Publication

---

150	Yamada, Yoshiyuki, Hiroshi Hasegawa, and Ken-Ichi Sato. "Survivable Hierarchical Optical Path Network Design With Dedicated Wavelength Path Protection", Journal of Lightwave Technology, 2011. Publication	<1 %
151	Yogesh Kumar Gupta, Aditya Goel. "Performance analysis of multiple-beam WDM free space laser-communication system using homodyne detection approach", Heliyon, 2023 Publication	<1 %
152	Yossef Ben Ezra, Boris I. Lembrikov. "Chapter 14 Ultra-Fast All-Optical Memory based on Quantum Dot Semiconductor Optical Amplifiers (QD-SOA)", IntechOpen, 2017 Publication	<1 %
153	<a href="http://core.ac.uk">core.ac.uk</a> Internet Source	<1 %
154	<a href="http://en.unionpedia.org">en.unionpedia.org</a> Internet Source	<1 %
155	<a href="http://erepository.uonbi.ac.ke:8080">erepository.uonbi.ac.ke:8080</a> Internet Source	<1 %
156	<a href="http://mdpi-res.com">mdpi-res.com</a> Internet Source	<1 %
157	<a href="http://repositories.lib.utexas.edu">repositories.lib.utexas.edu</a> Internet Source	<1 %

158	<a href="https://research.chalmers.se">research.chalmers.se</a> Internet Source	<1 %
159	<a href="https://strathprints.strath.ac.uk">strathprints.strath.ac.uk</a> Internet Source	<1 %
160	<a href="https://sv.20file.org">sv.20file.org</a> Internet Source	<1 %
161	<a href="https://telkomnika.uad.ac.id">telkomnika.uad.ac.id</a> Internet Source	<1 %
162	<a href="https://www.athensinstitute.gr">www.athensinstitute.gr</a> Internet Source	<1 %
163	<a href="https://www.osapublishing.org">www.osapublishing.org</a> Internet Source	<1 %
164	<a href="https://www.seekdl.org">www.seekdl.org</a> Internet Source	<1 %
165	<a href="https://www.semanticscholar.org">www.semanticscholar.org</a> Internet Source	<1 %
166	"ITC-Egypt 2022 Conference Proceedings", 2022 International Telecommunications Conference (ITC-Egypt), 2022 Publication	<1 %
167	Anke Zhao, Ning Jiang, Shiqin Liu, Yiqun Zhang, Kun Qiu. "Physical Layer Encryption for WDM Optical Communication Systems Using Private Chaotic Phase Scrambling", Journal of Lightwave Technology, 2021	<1 %

168 Gurleen Kaur, Gurinder Singh Bal, Gurjot Singh Gaba. "HYBRID MODULATION TECHNIQUE FOR SUPPRESSION OF FOUR WAVE MIXING IN DWDM SYSTEM", Far East Journal of Electronics and Communications, 2016  
Publication

---

169 Kenneth Nsafoa-Yeboah, Eric Tutu Tchao, Bright Yeboah-Akowuah, Benjamin Kommey et al. "Software-Defined Networks for Optical Networks Using Flexible Orchestration: Advances, Challenges, and Opportunities", Journal of Computer Networks and Communications, 2022  
Publication

---

170 [www.ijcnis.org](http://www.ijcnis.org)  
Internet Source

---

171 "Analysis of EDFA Parameters Amenable for Ultra High Bitrate Based DWDM System", International Journal of Innovative Technology and Exploring Engineering, 2020  
Publication

---

172 "Futuristic Communication and Network Technologies", Springer Science and Business Media LLC, 2023  
Publication

---

173 Anu Chauhan, Arti Vaish, Ashu Verma. "To Decrease Maintenance Issues using FWM in Ultradense WDM Systems and Enhancing Optimum Placement of Optical Phase Conjugation", Journal of Optical Communications, 2018

Publication

<1 %

---

174 Ming-Jun Li, Tetsuya Hayashi. "Advances in low-loss, large-area, and multicore fibers", Elsevier BV, 2020

Publication

<1 %

---

175 Oscar Jimenez Gordillo, Asher Novick, Oliver Wang, Anthony Rizzo, Utsav Dave, Keren Bergman, Michal Lipson. "Fiber-chip link via mode division multiplexing", Optica Publishing Group, 2023

Publication

<1 %

---

176 [journal.uad.ac.id](http://journal.uad.ac.id)

Internet Source

<1 %

---

177 Darli A. A. Mello, Kayol S. Mayer, Andrés F. Escallón-Portilla, Dalton S. Arantes, Rossano P. Pinto, Christian E. Rothenberg. "When Digital Twins Meet Optical Networks Operations", 2023 Optical Fiber Communications Conference and Exhibition (OFC), 2023

Publication

<1 %

---

178

Kuldeep Singh, Sandeep K. Arya, Vinod Kumar. "Performance enhancement of duobinary modulation-based DWDM system using particle swarm optimization", Journal of Optical Communications, 2023

Publication

<1 %

---

Exclude quotes      On

Exclude matches      Off

Exclude bibliography      On