Performance Analysis of Fiber Optic Communication Systems Using Space Division Multiplexing

Gammachu Namara Goshu

A Thesis Submitted to the Department of Electronics and Communication Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Communication Engineering

Office of Graduate Studies

Adama Science and Technology University

June, 2022

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Advisor: Dr. Demissie Jobir

Co-Advisor: Mr. Tadesse Hailu

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Declaration

I hereby declare that this Master Thesis entitled "Performance Analysis of Fiber Optic Communication Systems Using Space Division Multiplexing" is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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List of Acronyms and Abbreviations

APD	Avalanche Photodiode
BER	Bit Error Rate
BPSK	Binary Phase shift Keying
C-band	Conventional band
CD	Chromatic Dispersion
CDM	Code Division Multiplexing
Demux	Demultiplexing
DGD	Differential Group Delay
DSP	Digital Signal Processing
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-Doped Fiber Amplifier
EOC	Electrical To Optical Converter
EON	Elastic Optical Network
FDM	Frequency Division Multiplexing
FMF	Few Mode Fibers
FO	Fiber Optics
FOC	Fiber Optics Communication
FOC	Fiber Optics Communication
GVD	Group Velocity Delay
L- Band	Long band
LED	Light-Emitting Diode
MCF	Multicore Fiber
MD	Modal Dispersion
MDL	Mode Dependent Loss
MEF	Multi-Element Fiber
MIMO	Multiple Input Multiple Outputs
MMF	Multimode Fiber
Mux	Multiplexing
NLS	Nonlinear Schrödinger
ODWDM	Optical Dense Wavelength Division Multiplexing
OEC	Optical To Electrical Converter
OFA	Optical Fiber Amplifier

OFDM	Optical Frequency Division Multiplexing
OTDM	Optical Time Division Multiplexing
OTDR	Optical Time Domain Reflectometer
OWDM	Optical Wavelength Division Multiplexing
PDM	Polarization Division Multiplexing
PIN	Positive Intrinsic Negative
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation.
S-band	Short band
SCF	Single Core Fiber
SDM	Space Division Multiplexing
SI	Step Index
SMF	Single-Mode Fiber
SNR	Signal-to-Noise Ratio
SOA	Semiconductor Optical Amplifier
SPM	Self Phase Modulation
TDM	Time-Division Multiplexing
WC-MCF	Weakly Coupled Multicore Fiber
WDM	Wavelength Division Multiplexing
XT	Cross Talk

Abstract

Space division multiplexing is a multiplexing technique used for guided and unguided media, to transmit large amounts of data and highly improve the data-carrying capacity. Space-division multiplexing in fiber optic is used to enhance high-capacity information transmission. The capacity of fiber-optic communication technology has increased highly and optical communication technology has been mostly advancing. The current multiplexing techniques like time-division multiplexing, and dense wavelength division multiplexing by using a single-mode fiber /Single core fiber. Using these techniques did not overcome over 100 terabits per second per fiber because of the linearity and nonlinearities of fiber optics. To transmit a high capacity over 100 Tbps /fiber and long-haul transmission, the multiplexing techniques that are needed to break the bottleneck of the capacity limit are termed space-division multiplexing. In this thesis work, the materials we used are Matlab and optisystem software. The methods used for doing this work are studying the basic theory, architectures, and related areas of the research, revising this to add the literature, related to fiber optic communication systems with Space division multiplexing, and identifying parameters. The capacity enhancement in fiber space-division multiplexing is 14.75 Pb/s/fiber and thus the haul of transmission is 250km with usable wavelength-band C+L band. The signal/noise ratio is 35 dB with the number of mode one and the number core is four. In fiber-optic communication systems, the fiber loss is 0.2 dB/km with a power consumption reduction is 20 dBm and cross-talk, loss, and distortion reduction in fiber optic using multimode fiber and multicore fiber. The space division multiplexing includes a great role in fiber optics just in case of effective information transmission by enhancing capacity, reduction of unwanted signal, and power during information transmission; space-division multiplexing in fiber optic is incredibly essential for effective communication with extremely high capacity and long haul transmission. Using mode/core or division multiplexing in fiber optic communication to provide a good communication system for future work.

Keywords: *Space Division Multiplexing, Single-mode fiber, Multicore fiber, capacity enhancement, long-haul transmission, loss reduction, optical communication system*

CHAPTER ONE

Introduction

1.1. Background of the study

In fiber optic communication (FOC) systems capacity enhancement is the measure issue and employed for increasing high data-carrying capacity and long-haul data transmission (Xavier & Lima, 2020). This capacity enhancement had reached its capacity crunch due to linearity and nonlinearity. There is different multiplexing technology that enhances capacity in optical fiber communication (OFC) transmission such as frequency division multiplexing (FDM), time-division multiplexing (TDM) wavelength division multiplexing (WDM), code division multiplexing (CDM), and capacity limited 100Tb/s/fiber. The FOC scheme has three basic elements those are, transmitter, receiver, and optical fiber channel, which is shown in figure 1.1. The fiber optic beam emitted from the apiece of the transmitter remains spatially enclosed (J. Zhao, Liu, & Xu, 2019). In the communication system, the most necessary things are power used in the transmission of information in communication, and the optical channel that carries information from transmitter to receiver.

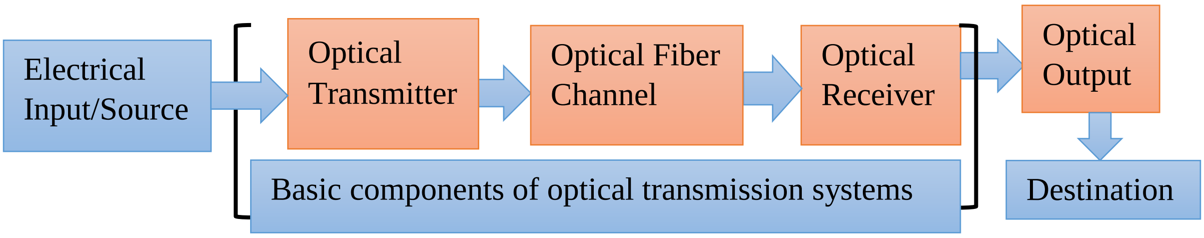

Figure 1.1.The general block diagram of FOC systems (Gupta, 2018)

The information source is generated and by using an electrical to the optical converter (EOC), it's converted and passed via an optical channel and reached the optical receiver, finally converted from optical to electrical (OEC) and reaches the destination (Kaushik, Singh, & Rajpoot, 2020). The light transmitted through fiber encompasses a vital role when we need extreme bandwidth, most secure, and long-haul transmission. In fiber optic, the link allows the transmission of various wavelengths of light together over a definite fiber (Keiser, 2021). The program is comprehensive from research elements, orders, and networks, as well as from technical gatherings to showing (Z. Liu et al., 2022). In current FOC systems using SMF is located transmission schemes are arriving at their capacity limit (Rademacher, Puttnam, Luís, Klaus, et al., 2021). The optical links contain components of FOC systems and to be effective communication, the links should be connected perfectly, which is shown in figure 1.2.

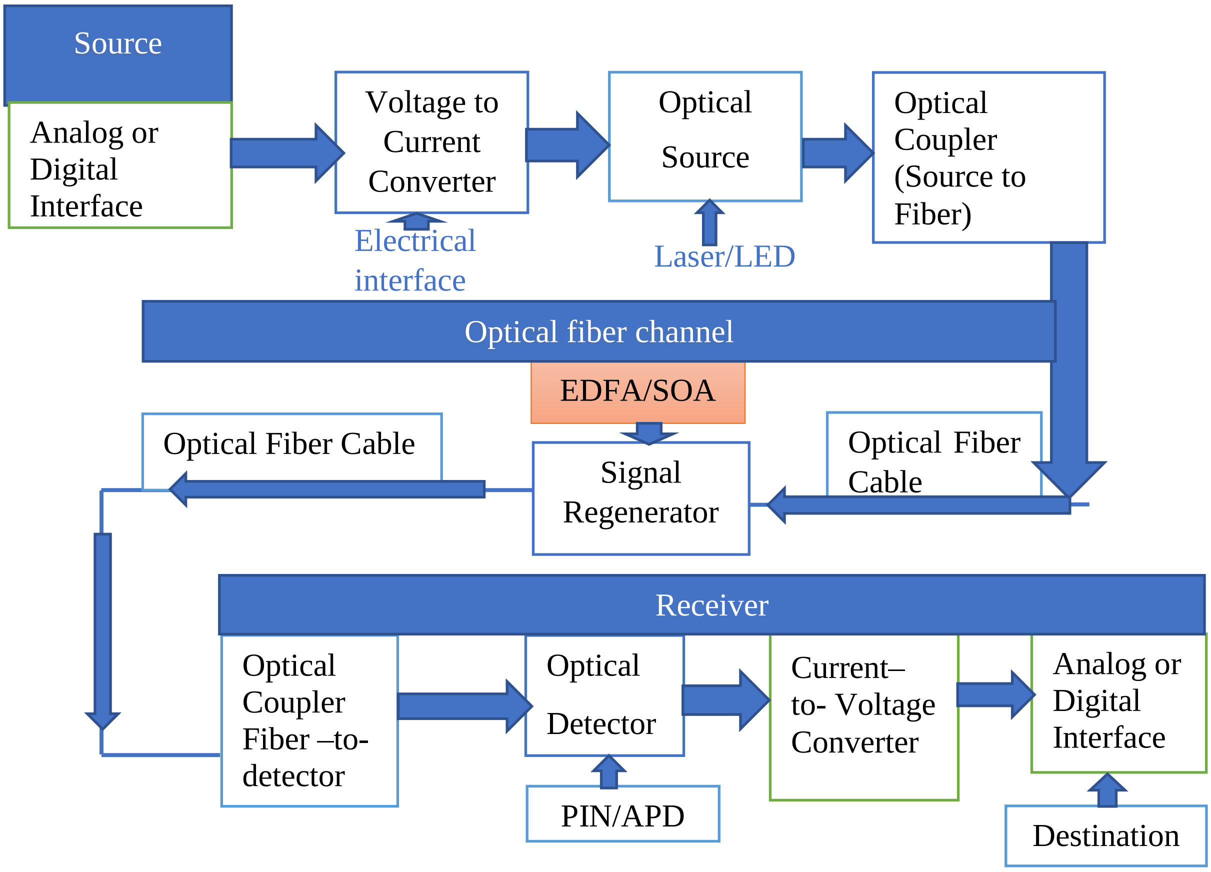

Figure 1.2. The block diagram of the OFC links (Elion & Elion, 2020)

Figure 1.2, contains all the main components and their role in FOC systems. The first one is the electrical input/source that is introduced at the start of being attended to transmit. The second one is the optical transmitter. It has passed the converted electrical signal into the optical channel. The optical transmitter contains the subsequent elements, optical input, electrical interface, and an optical modulator. The most factors of an optical transmitter carry with it energy connected to an information encoder/modulator, a ray of light, and an optical connector to an optical channel. The third one is the optical fiber channel. It is consistent with a fiber media arrangement that supports a data link between two ends. The fourth one is the optical receiver. It component a fiber-optic network, which is employed to receive the signals. In the FOC scheme, photodetectors are employed as a recipient. The optical receiver receives the data that has been transmitted from the transmitter and passed the received information. In fiber optic, the evaluation of the fiber networks forever presents opportunities and challenges which means distribution, and specific algorithms are essential to handle the talent distribution problems and to produce new specifications, that's SDM (Yang, 2020).

The development and technologies are increasing; human needs increase as technology increases in the same manner. In this era, the capacity of data transmitted has been increased linearly; with the evolution of fiber optic communication. These evolutions aim to suit human needs by producing large capacity and long-haul transmission.

Electrical TDM	Optical TDM	Optical WDM/DWD	Digital coherent	EON	SDM-EON
-1980	1980-1995	1995-2010	2010-2015	2015-2020	2020-

Figure 1. 3. Long haul fiber optic terrestrial transmission system evolution (Yang, 2020)

An ultimate important concern in periodically dependent fiber optics link is expounded to the nonlinear belongings happening inside all OFC systems (Longo et al., 2020). Regenerators are used, the self-phase modulation (SPM) belongings to extend only a single device that tells the time to arrange, and the repeater spacing in SPM is (< 100 km) capacity which can be given as,

$$P_{in} < \frac{0.1\alpha}{\gamma N_A} \tag{1.1}$$

where N_A is numerical aperture, N_A =1 or the condition $P_{in} << 22\,mW$. The repeater spacing when optoelectronic used regenerator in nonlinear effect is 0.1, where α and γ are loss and nonlinearity respectively and P_{in} is input power (Rademacher et al.). The condition of the average capacity depends on the shape (broadening /narrowing) of optical light pulses. It is nevertheless that the average capacity endures $1\,mW$ for SPM belongings to wait insignificant for a light wave order designed to conduct over a distance in addition to 1000 km. The restricting worth of the average capacity likewise depends on the type of fiber at which point light is reproducing through the productive center extent effective area (A_{eff}). The SPM belongings are the main inside dispersal-compensating fibers for that A_{eff} is usually nearly 20 μm^2 . The effect of SPM on pulses spreading inside a light transmitted through fibers may be included by utilizing the nonlinear Schrödinger (NLS) equating as, (Rademacher et al., 2018)

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} - \beta_2 i \frac{\partial^2 A}{\partial t^2} + \beta_3 \frac{\partial^3 A}{\partial t^3} + \frac{\alpha}{2} A = i\gamma(|A|^2 \ A) \ , \tag{1.2}$$

where $\beta_1, \beta_2 \, and \, \beta_3$ represent first, second, and third-order dispersions, α and γ indicate fiber losses and nonlinearity effect respectively, and A is the amplitude of the pulse propagating along z. In a FOC system, there are major effects, which are linearity, nonlinearity effects, and maximum input power that affect the information transmission in FOC systems. The first one is the linear effects of the FOC systems. Linear effect in fiber optics depends on some parameters, like loss, and dispersion. The reason why linear effects depend upon that parameter is if more loss with large wavelength and dispersion, the fiber cannot transmit by carrying high capacity, this suggests that these parameters have a great effect on OFC system. The loss is the linear effect that depends upon the wavelength of the signal, and factors within the most loss of fiber optics transmission. The key parameter for the optical signal loss is shown below and can be defined as,

$$P_r = P_t \exp(-\alpha L) \tag{1.3}$$

$$\alpha dB = -\frac{10\log(\frac{P_r}{P_t})}{L} \tag{1.4}$$

where, P_r and P_t are signal received power, and the signal transmitted power respectively, as well as L and α are the distance of transmission and loss respectively, the minus(-) sign shows that the loss. It is known that as the length of the fiber increases the loss also increases and when the received power increase, the loss will be decreased; the minimum loss of optical fiber is around 0.2dB/km at a wavelength of 1550nm. The light transmitted through fibers dispersal limits the bandwidth and haul of fiber optics transport. The reason for light transmitted through fiber dispersion contains fiber material, waveguide, mode, and optical signal. Various causes, dispersal is especially detached into material dispersion; waveguide dispersal is for most material dispersal and polarization mode dispersal. The second one is nonlinear effects that are different from the linear effect caused due to refractive index intensity-dependent.

1.1.1. Space Division Multiplexing for FOC systems.

Space division multiplexing is a multiplexing technology that allows multiple spatial channels to pass information via fiber cable. In this it divides space, however, where is this space, and the way it is possible, this space is that cross-sectional area of optical fiber, which can explain during this section. The key good thing about SDM is that it creates multiple paths for each signal (Gadalla, 2016). The more cores incorporated in an MCF, the more modes it can maintain at the same time (Jung et al., 2017). SMD uses multiple spatial channels to extend the capacity for FOC (Huang et al., 2022). The capacity different multiplexing techniques will be used across different physical dimensions (Pauwels, Van der Sande, & Verschaffelt, 2019), which can be shown in the figure 1.4.

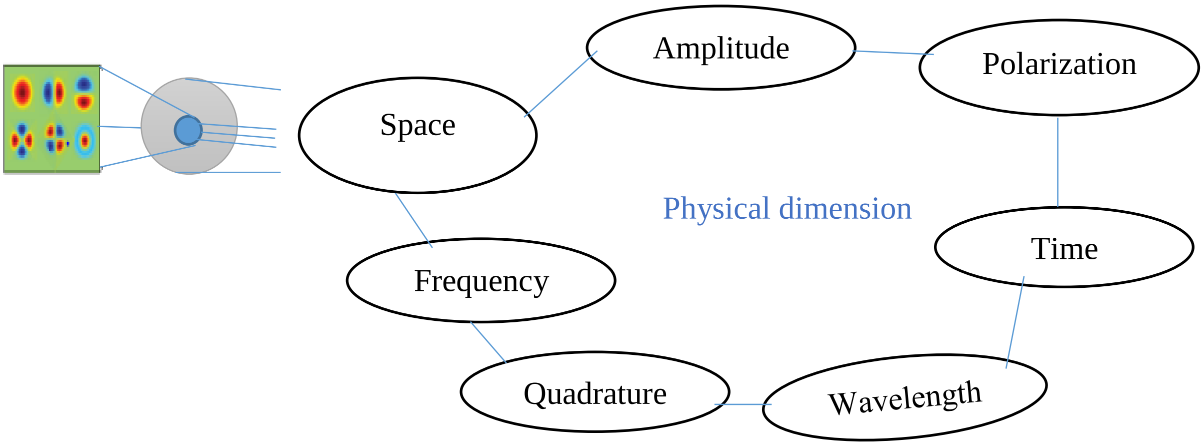

Figure 1.4. Different spatial mux exploits Physical dimensions (Winzer & Foschini, 2011)

In FOC space, positon modulation is very important for MMF transmission (JJA Van Weerdenburg et al., 2017). The SDM uses MCF, MMF, FMF, and SMF to increase the capacity of fiber optic communication.

Figure 1.5. SDM using MMF in OFC systems (Puttnam, Rademacher, & Luís, 2021)

The dedicated channels are allocated for each signal that can carry a large amount of data. Increasing the bandwidth of MCFs. The most effective and practical dispersion reduction in MCF is a trench-assisted (TA) construction, placing each core among specific MCFs is called TA (Ye, 2015). The signal transmission is following by spacing each of signal carriers, which is shown in figure 1.6.

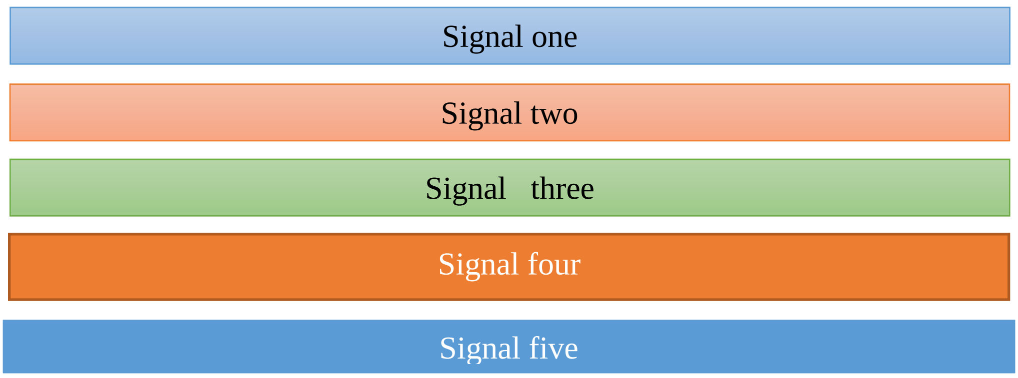

Figure 1.6. SDM in FOC Systems (Winzer, 2014)

SDM in fiber optics is to enhance the capacity of fiber cables for short and long-haul enabling vast increases in transmission capacity by using space channels and is connected by M- link in communication systems.

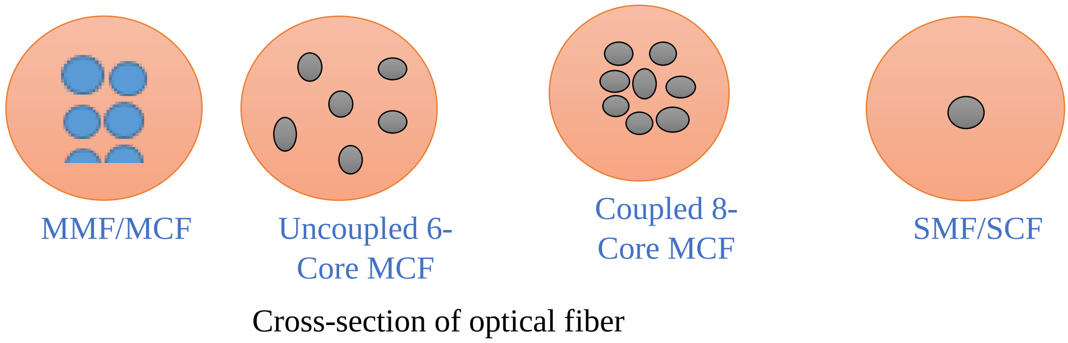

Figure1.7. Schematic diagram of cross-sections of SDM in OFC (Hayashi et al., 2013)

In SDM technology, d/t modes of transmission are distributed on various spatial paths within the MMF/MCF with crosstalk and mode coupling. MCF transmits one mode on one core and the more cores incorporated in an MCF, the more modes. However, under restrictions of the crosstalk between different modes and thus the dimensions of traditional fiber, the MCF cannot accommodate it. The MMF and MCF in optical fiber are to reduce nonlinear signal distortions and temporal signal spread making CC-MCFs attractive for long-haul transmission. The seven-core CC-MCF transmission is shown to outperform both a four-core CC-MCF and SMF with matching core properties. The results of that experiment are shown in figure 9, for recirculating transmission up to a 6600 km distance. Similar performance between the fiber types was observed at low launch powers, but the CC-MCFs enabled greater signal quality and reach because the launch power is increased (Puttnam, Rademacher, et al., 2021).

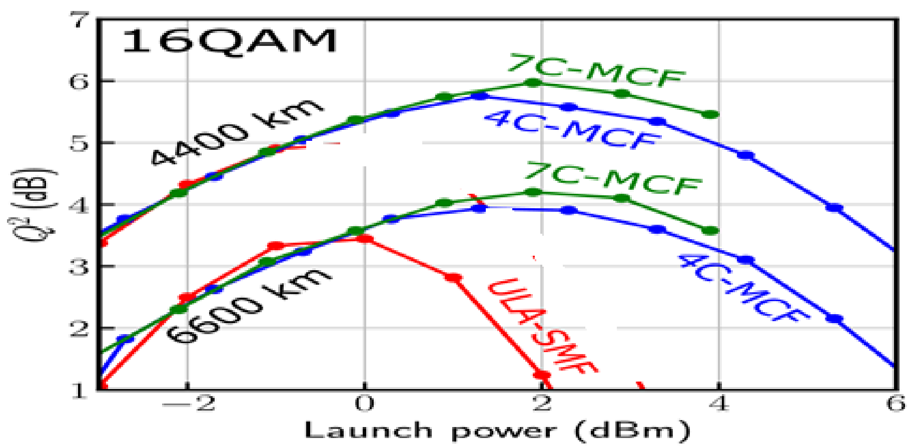

Figure 1.8. Transmission using SMF and CC-MCF (Puttnam, Rademacher, et al., 2021)

In addition, the mux methods within, which there's a physical separation of the cross-section area of fiber optics, are employed to deliver simultaneously different data streams that are the role of SDM is to create multiple spatial paths of light pulse in OFC systems.

1.1.2. The why SDM in FOC systems

There are several ways to increase capacity and long-haul OFC transmission and the SDM contains MMFs, MCFs, the combinations of them, and coupled and uncoupled modes, over one/more amplifiers, which is to break the capacity limit of OFC that's 100Tbps/fiber using SCF/ SMF and produce an exchange of data at a distance with high capacity. SDM in OFC is to increase the no. of obtainable data channels inside the fiber (Rjeb, Fathallah, & Machhout, 2021). The reason why SDM is that it can handle ultra-high capacity and long-distance information transmission quite other mux technology. The bandwidth of this light transmitted through fibers communication structures established TDM, digital coherent and WDM using SMFs is arriving capacity crunch of around 100Tb/s /fiber. However, SDM can break this capacity limit. The most purpose of the SDM is to overcome/beat the capacity limit and break the bottleneck of data transmission, increasing carrying capacity, to transmit long haul in FOC systems. It transmits and handles high capacity transmission the optical fiber amplifiers (OFA) and SDM fiber incorporate excellent roles to be transmitted and carrying the amount of information transmission in fiber. SDM fiber achieved the subsequent conditions like transmitting SDM fiber in ultra-long-haul transmission systems, ultra-low transmission loss, and dispersion for improving optical SNR. The higher spatial-mode density for increasing the spatial channel count within standard 125-µm cladding, and low differential group delay (DGD) between spatial modes dispersion (SMD) for suppressing digital signal processing (Hayashi, TAMURA, HASEGAWA, NAKANISHI, & TARU, 2017).

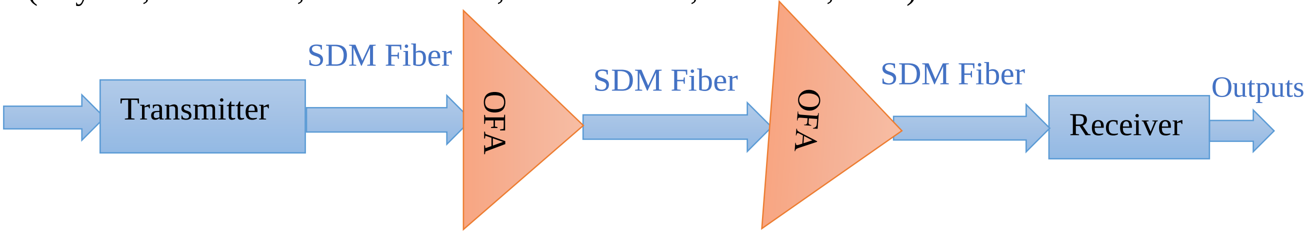

Figure 1.9.The block diagram high capacity and long haul transmission using SDM (Rademacher, Luís, et al., 2021)

This SDM has existed two main purposes the one is the ability to break the capacity limit, as shown in figure1.11. The gap had been generated between network capacity and the traffic that endures handling, the capacity limit of SMF core fiber is 100Tbps despite utilizing the available multiplexing in the way that WDM and high spectral cannot resolve this obstacle, We need the essential multiplexing method namely SDM that increase network capacity (Gadalla, 2016).

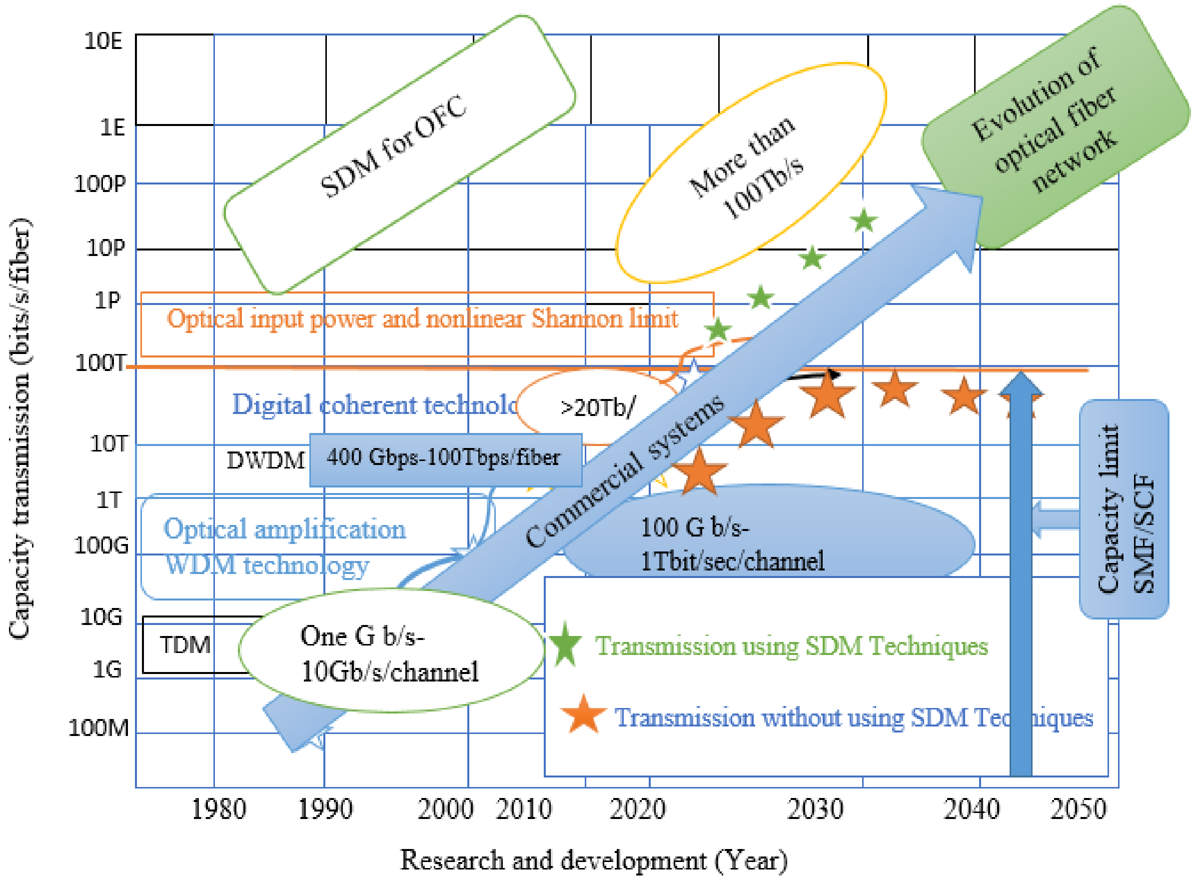

Figure 1.10. Progress in optical transmission capacity (Mizuno & Miyamoto, 2017).

The 2^{nd} purpose of the SDM is that it has the high ability to interconnect density and increase the capacity of optical fiber why because if seven cores of MMF represent the seven SMF the density will increase and reduce cost and cable number and pave the direction towards ultra-dense optical interconnects. Figure 1.10, shows how information is transmitted from optical source to destination using SDM by handling high capacity of data and OFC system (Gadalla, 2016). For example, the suitability of chip to chip in investigating MCF implies the optimization of MCF applications (François & Laramée, 2013). In this, thesis work we understand that SDM can reduce the number and enable large reductions in cost-per-bit Peta fiber cable (Richardson, Fini, & Nelson, 2013) to be used as well as save that and enhance the capacity for which it is used. The MCFs, FMF, and their hybrid consolidation, FM-MCFs are hopeful broadcast media for future extreme-capacity, SDM light transmitted through fibers transmission methods (Rademacher, Puttnam, Luís, Klaus, et al., 2021).

1.2. Statement of the problem

In fiber-optic communication systems, capacity has a great role in the current world. Currently, data rates in fiber optic communication technology have increased and advanced highly for several decades, supporting our increasingly information-driven society and economical aspects. In fiber-optic communication systems, different multiplexing techniques are used to enhance the capacity of fiber optic; such as frequency division multiplexing, time-division multiplexing, wavelength division multiplexing, and dense wavelength division multiplexing. However, they did not produce high capacity transmission over 100Tb/s using Single-mode fiber /Single core fiber. There is still a need to break through the limitation and overcome the bottleneck of devices for high-capacity data transmission of information. To overcome the limitation, space division multiplexing can breaks the Shannon nonlinear limit and can solve the problem. Space division multiplexing for fiber optic communication increases the data-carrying capacity and long-haul transmission in fiber optic communication systems. In addition, space division multiplexing technique can extremely enhances the capacity of fiber optic communication system.

1.3. Objectives

1.3.1. General Objective

The general objective of this thesis is to analysis the performance of fiber optic communication systems using space-division multiplexing.

1.3.2. Specific Objectives

The specific objectives of this thesis are as follows:-

1 Analysis of the performance of FDM, TDM, CDM, WDM, DWDM, Digital coherent, and SDM.
2 To enhance high capacity and reduce cross-talk, using MMF, and MCF as SDM.
3 To reduce fiber loss and distortion in optical fiber communication systems using MMF and MCF with SM techniques as SDM.
4 To reduce energy (Power) consumption and improve efficiency in optical fiber using MMF as SDM.
5 Comparing the performance of different types of multiplexing techniques with SDM.

1.4. Significance of the study

The focus of this thesis is to extend/increase capacity, and haul to reduce energy/power consumption, cost, cross talk, loss, and distortion, and to produce high-performance OFC systems consistent with input signals by breaking the capacity crunch using SDM techniques. Supported the optical and electrical, signal-processing algorithms, system-level design, and, most significant. SDM produces an extremely high data rate, and long-distance transmission with high performance. Additionally, it will provide an understanding of actual bottlenecks and breakthroughs in terms of energy consumption and data transmission with high-performance effectiveness is most significant) long-haul interconnects. SDM techniques break through enhance high capacity and long haul FOC systems.

1.5. Scope of the Study

The scope of the thesis is using the SDM technique for FOC to enhance extremely high capacity and long-distance that had been limited. It breaks the capacity crunch using SMF/SCF as well as in FOC networks at reduced energy, and cost per transmitted bit per fiber and space. In addition to this to produce the most effective performance in OFC systems, and reduction of loss using MMF, and MCF. The essential idea is to use MMFs such as several WDM bit streams that may be transmitted over different modes of the same fiber. The energy advantage comes from integrating the functionalities of key optical components into a smaller number of devices. As an example, if one multimode optical amplifier is employed to amplify all spatially multiplexed bit stream, power consumption is probably going to be lower compared to using separate amplifiers using SDM for fiber optics transmission.

1.6. Contribution of the thesis

In this, thesis we contribute the capacity enhanced with distance in an optical fiber by using wavelength band C+L- band and one MMF to transmit information in Peta term. The other one is cost-effective and energy/power efficiency with high SNR. The loss and dispersion are reduced. By comparing different multiplexing with SDM with great difference in capacity, the distance of transmission, cost, and power consumption reduction. In OFC, using SDM is very important especially to enhance capacity and transmit information long haul. Studying in this area has a great novelty and is essential in fiber optic to transmit information.

CHAPTER TWO

Literature Review

2.1. Introduction

(Richardson et al., 2013), “In fiber-optic communication, capacity enhancement has been highly advancing rapidly for several decades, supporting our increasingly information-driven society and economic aspects.” **(Jiang & Tsubokawa, 2020)** “The progress has been to find innovative ways to increase the capacity of fiber optic and to achieve this, and many researchers and scholars have explored and attempted to optimize different multiplexing techniques such as, time, wavelength, polarization, and phase.” Fiber optic has a vital role for communication infrastructure and the capacity enhancement of OFC systems. In OFC, data traffic is growing exponentially because of the emergence of assorted network services. **(Shi, Tian, & Gervais, 2020)** “The transmission capacity of fiber optic has dramatically increased to advanced communication technologies like WDM and multi-level modulation within their paths.” **(Giles, Chen, & Garcia-Munoz, 2014)** “In OFC we need low complexity at the receiver and the paths of those optical signals traverse through the network may be selected by using reconfigurable optical add-drop multiplexers at network nodes.” **(Shi et al., 2020)** “The capacity of manipulating electrons and photons on the same platform has great advantages like producing a single chip with high capacity, low cost, small size, and magnitude reduction with low power consumption in OFC systems.” **(Temprana et al., 2015)** “The nonlinear optical response of silica imposes a fundamental limit on the data transfer capacity in fiber optic.”

(Amphawan, Fazea, & Elshaikh, 2016) “The capacity is rapidly approaching its capacity limit because of the amplification bandwidth, which has been worn-out and drastic improvements in SNR cannot be expected anymore.” **(X. Liu, 2019)** “ The capacity enhancement in fiber optic uses detection and modulation.” **(Rademacher, Puttnam, Luís, Eriksson, et al., 2021)** “The SMF is widely used for data, transmission and it is the light transmitted through a fiber transmission that has a capacity limit of up to 100Tb/s.” **(Klaus et al., 2017)** “These fibers has a finite capacity that we are approaching.” **(Winzer, 2015)** “The recent major advancement in fiber technology is SDM. It is the only long-haul viable path for high capacity in fiber optics networks, as well as ultra-long-distance transport. SDM-supported MCFs have emerged as an answer to the matter of saturation of the capacity of optical transmission systems.” **(Li, 2014)** “This text presents the recent progress on the MCFs for future large-capacity and long-distance transmission. Using this SDM, it is possible to mitigate dispersion and cross-talk in fiber optics." **(Saitoh & Matsuo, 2013)** "In MCFs, there's a tradeoff relationship between low crosstalk and high multiplicity of the number of cores, and also the core arrangement must be carefully determined and supported by the desired cross-talk level." **Z. Zhao, Tang, & Lu, (2020)** "The core size is possible to handle with one MMF." **(Ospina et al., 2020)** "In addition to this in fiber optics, there is mode-dependent loss." **(Willner et al., 2021)** "By using advancing technology we can reduce the cross talk and modal coupling and where new fiber designs and components establish multiple co-existing data channels that supported light propagation over distinct transverse optical modes." **(Sun et al., 2013)** "The existence of high capacity with power" and **(Sinkin et al., 2017)** "An optimal spectral efficiency crunched by EDFA-based SDM transmission systems." **(Xavier & Lima, 2020)** "It is the most promising solution to enhance the capacity of fiber optics, where several spatial paths during an SMF are used to enable simultaneous data transmission of several independent data streams for every carrier wavelength in communication systems and decrease the price in optical fiber is very essential." **(Horvath, Munster, Vojtech, & Smotlacha, 2019)** "SDM technology required the development of the latest kinds of fibers and new components like spatial multiplexers and optical amplifiers capable of amplifying all spatial channels simultaneously and therefore the coupled multimode that are used for understanding the impact of the dispersive and nonlinear effects in SDM systems within the spatial channel." **(Feng et al., 2017)** "The high capacity fiber optic networks, and WDM technology incorporates SDM and is low in cost spectrally efficient is advanced. The spatial degrees of freedom are already being employed within the optical switches to enable WDM demultiplexing and switching to multiple ports. This suggests that adding SDM compromises some aspects of the switching performance. To manage increased numbers of spatial channels, it should be necessary to compromise on the spectral resolution and thus the channel count. It also seems likely that because the number of those spatial channels increases, there'll be a corresponding reduction within the number of wavelength channels to be switched, ultimately leading us to a purely spatial switching network." **(Pauwels et al., 2019)** "It's a pretty technique to extend the per-fiber data rate optical transmission systems by transmitting independent data channels at the identical wavelength over different spatial channels a significant" and **(Jiang & Tsubokawa, 2020)** "advance for increasing transmission capacity was achieved when multiple data channels were multiplexed using different wavelengths over one fiber." **(Zhou & Xie, 2016)** "The foremost important issue for the viability of the SDM technique concerns the crosstalk among the signals propagating in numerous modes of a fiber link." **(Z. Zhao & Tang, 2021)** "The novel perceiving applications accompanying unprecedented accomplishment improvement will come together, for instance, distributed turning and shape sensing, multi-limit sensing, extreme-long-distance vibration sensing, and interference fading suppression." **(J. J. A. van Weerdenburg, 2019)** "The reduced loss and modal dispersion led to the endless deployment of optical connections based on SMFs." **(Saitoh & Matsuo, 2016)** "The essence of optical signals, the physical multiplexing ranges involve six aspects, that are time, polarization, frequency, amplitude, phase, and space." **(Rjeb et al., 2021)** "In the OFC system, SDM can intensely increase the chance of frequency range and channel capacity, which is called nonlinear Shannon's limit, and TDM, PDM, WDM, and multilevel modulation, had been working. SDM in light transmitted through fibers find out increases the number of data channels expected to be transmitted.' However, Multi-element fibers (MEFs) are bestowed as an alternative SDM technology that can address a few of the disadvantages that current implementations exhibit." **Rancaño et al., (2014)** "The benefits got from the fiber arithmetic show that MEF may be cost-effective for SDM use in monetary (commercial) optical networks." **(Van Uden et al., 2014)** "The system acting was evaluated by measuring BERs at three various wavelengths, 1550 nm, 1556 nm, and 1562 nm, and matched into the comb's shortest, core, and most wavelength, individually. All measurements acted accompanying all 60 wavelengths and 12 modes present in optical fiber and a brand new 1 that increases the bandwidth of fiber optics is important to stop an area crunch." Here, by engaging few-trend MMF, compact three-spatial waveguide multiplexers, strength-efficient repetitiveness, diversified-recommendation diversified-productivity equalization, we display the animation of referring to space multiplexing to achieve an information rate of 5.1Tb/s /fiber on distinct intuitiveness over a single fiber. Furthermore, by joining this approach accompanying intuitiveness SDM 50 intuitiveness carriers on a frequency 50 GHz transmission throughput of 255 Tb/ s over a 1 km fiber link is worked out.

2.2. Related work

(Rademacher, Luís, et al., 2021) 'At the wavelength of 1550 nm, the loss was measured as 0.181dB/km loss for the space of 60Km that was measured by launching light into one core and receiving the output power of all cores. However, the designed cutoff wavelength was 1350nm and the dispersion slope and chromatic dispersion were designed to be approximately 0.06ps/nm/km and 21 ps/nm/km respectively at a wavelength of 1550nm. This resulted in an exceeding distance between the cores of 29.4 µm. The diameter of the core was 125µm and thus the gap between the core and equidistant core is 17 µm, After 60 km distance of fiber, the crosstalk is so large that when sending light into one core, the flexibility is equally distributed across all cores at the simplest of the fiber. The depolarized broadbills and accustomed measure the crosstalk between cores to avoid the strong multi-path interference present within the fiber. we have got demonstrated a record transmission distance of 4200 km and a record spatial spatial-spectrally employing a three-core microstructure fiber and six-space- and polarization- and 5-WDM 40-Gbit/s channels, resulting in an aggregate capacity of 1.2 Tb/s over a 250-GHz bandwidth. Further reducing the core spacing and core diameter within the 3C-MSF is required to balance the comparison between the two fiber types. The report on recent wideband, high-capacity transmission experiments using either FM or CC -MCFs. We show its overall favorable transmission properties at the worth of a lower spatial channel density.' **(Savović et al., 2022)** "Mode coupling considerably reduces the length of these fibers, which SDM may achieve with minimal crosstalk between neighboring optical channels, in line with the findings and up to 120 m and 30 m, respectively. The two and three spatially multiplexed channels within the investigated MMF step-index silica optical fibers are used with low crosstalk. When building an SDM-based OFC transmission, such characterization of optical fibers should be taken into consideration." (John van Weerdenburg et al., 2018) "The mux of polarization channels and 12 spatial with 120 wavelength band C-band in which each carry 16QAM symbols at 30 GB over graded-index FMF."

2.2.1 Capacity enhancement in OFC using 38 core-3 modes with a capacity of 10.Peta-bit/s

(Rademacher, Puttnam, et al., 2020) "As reported the transmission capacity using 368-WDM and the number of core and mores are 38 and 3 respectively. The distance and spectral efficiency of transmission is 13 km and 58.7 bps/Hz respectively and that has low DMD with high uniformity amongst the core." **Rademacher, Puttnam, Luís, Klaus, et al., (2021)** "The modulation used in this case is 256-QAM in SDM for FOC systems using various methods and in SDM light transmitted through fibers transmission schemes and producing extremely capacity record-breaking 10.66 Pb/s transmissions in a 38-core, three-mode fiber, and 172 Tb/s over more than 2000 km. Coupled with three core fibers, utilizing the bandwidth is more than 75 nm in C- and L-bands wavelength." However, it consumes cost and energy and in our thesis is cost and energy effective in OFC systems.

2.2.2 Capacity enhanced 1-Pb/s using SMF heterogeneous MMF

(Kobayashi et al., 2017) "The capacity enhanced in this case is 1.0 Pb /second by using SMF with heterogeneous MMF and the distance of transmission is 205.6 km. The usable wavelength band is c- the band with modulation PDM- 16 QAM. The amplification technique used in this one is the unidirectional inline amplified transmission with spectral efficiency 217.6b/s/Hz. The no. of SMF with MMF used is 32 core." When compared with the thesis it consumes much cost and energy.

2.2.3 High transmission of 0.715 Peta b/s/fiber over 19-core

(Rademacher, Puttnam, Luís, Eriksson, et al., 2021) 'In light transmitted through fibers networks, the data rate to be sent is well raised during earlier times. Core and mode networks are necessary to communicate.' **(Puttnam et al., 2019)** "The capacity is in Peta bits per second per fiber manifest 0.715 Peta b/s recirculating transmission through 19 cores of 31.4 km MCF amplified accompanying C+L-band, cladding-pumped, multi-core EDFA and transmitting 345×24.5 GB PDM-16QAM signals over 2009.6 km for 1.44 Exb/s×km throughput-distance amount."

2.2.4. Capacity enhancement over multi-core fiber link with a 19-core optical amplifier with a capacity of 715 Tb/s

(Awaji et al., 2017) "As reported that a record on the SDM transmission trial employed an MCF amplifier. Fully decoded optical data transmission of 715 Tb/s realized over the distance of 2,009 km in a 19-core and cladding-pumped EDFA amplified MCF link utilizing systematize PDM 16-QAM of 345 carriers that carry over the C and L band." Here the number of the usable core is more this not more capacity enhanced more than 100Tb /s /fiber because the no. of the core is 19 which is less and cost-effective and energy efficiency and as well as DMD and loss are more. However, in our case, the loss is minimum, cost-effective with high capacity within the distance.

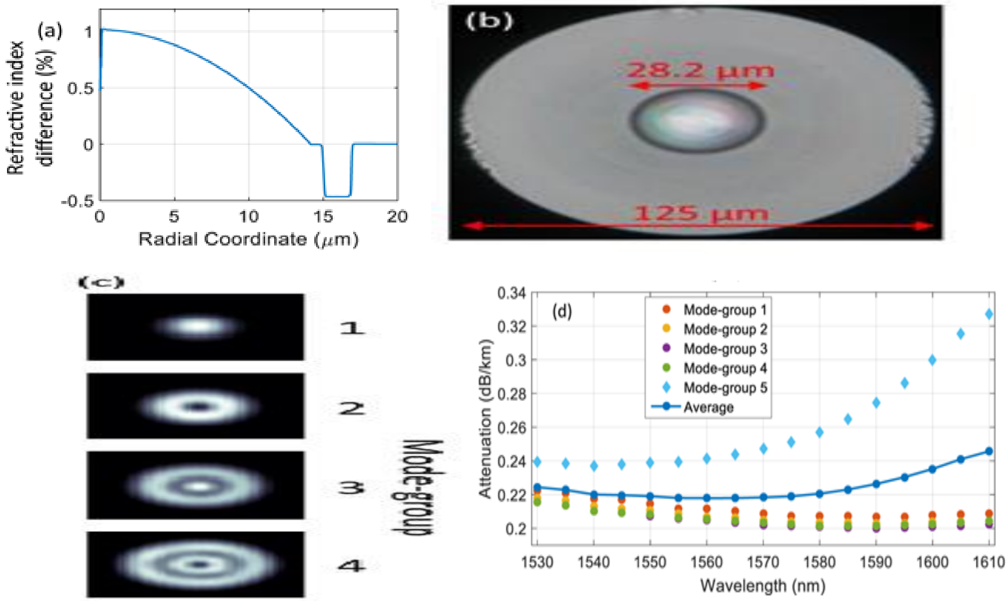

Figure 2.1.Different mode transmission of optical fiber (Rademacher, Puttnam, Luís, Eriksson, et al., 2021).

a) The index of refraction profile of the ditch-assisted, sorted-index (graded index) 15-mode fiber. b) Photograph of the fiber is also a drawing of individual parts of the mechanism (cross-section). c) Camera recording of the output mode intensity sketches later 7.6 km 15-modes fiber when inspired accompanying ASE noise of 40 nm frequency range. Just one is shown per mode group, as all modes within the individual mode group have equal intensity patterns. Different numbers of branching force maxima validate a powerful way of group discrimination of mode-multiplexer and fiber. d) intuitiveness-dependent loss calculations of the 23 km long 15-mode fiber. The requirement model group encompasses a better loss, assigned to increased processing machine-turning sensitivity. Here it's cost-consuming thanks to using many components much use of MCF furthermore as time-consuming and capacity isn't much. We modified this to fewer components and time use. Increase capacity up to 14.75 Pb/s/fiber and fewer losses around 0.2 dB/Km

2.2.5. Optical Core Fiber in SDM for Optical Fiber

(Saitoh & Matsuo, 2016) "The basic technologies for an extreme-speedy optical device for transmitting and receiving are required for 1Tbps/fiber transmission. After the swift incident during the last decades, there are various types of MCF for various applications" as shown in figure 2.2. MIMO depends on the idea of variety gain to increase the capacity through the channel. In particular, it takes advantage of relating to space difference, that is to say, diversified independent paths through the channel.

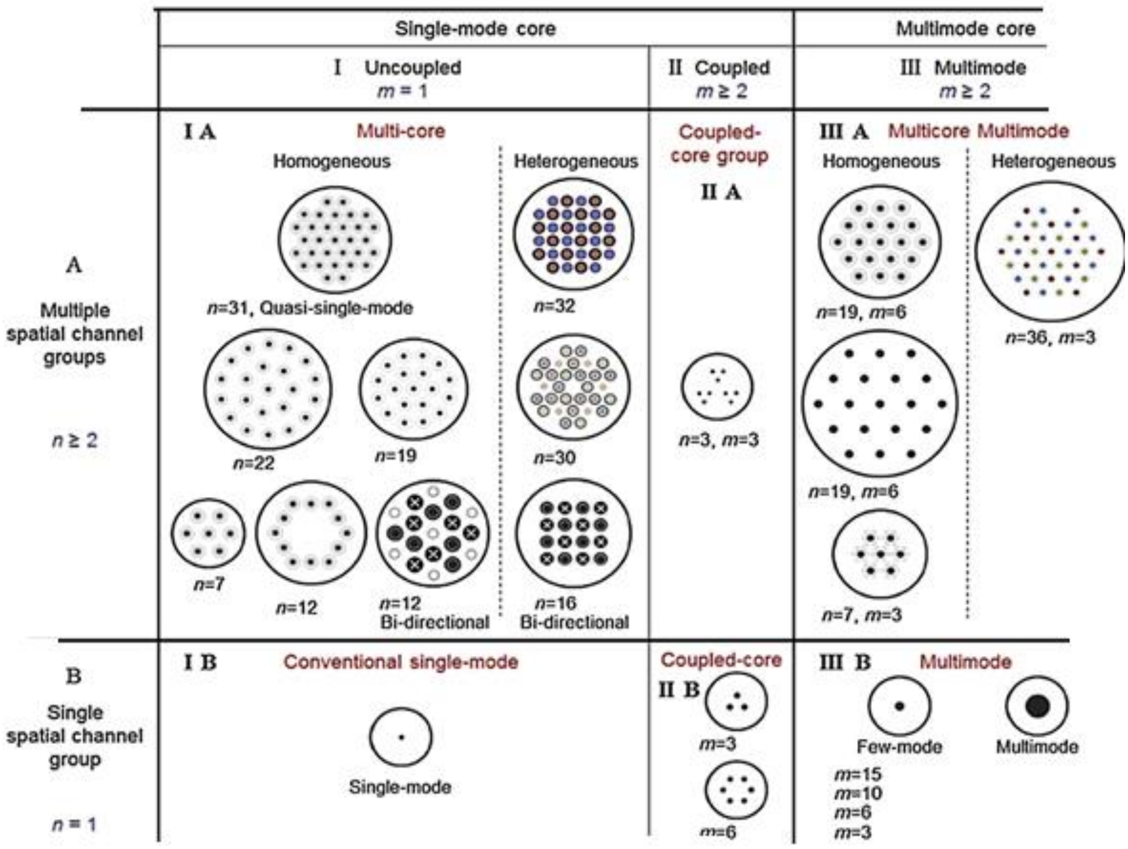

Figure 2.2. Different Types of optical mode and core fiber ' (Saitoh & Matsuo, 2016)

(Rademacher et al., 2018) "The transmission demonstrations over SM-MCFs have demonstrated with up to 32 cores and FM or MMF with up to 45 modes. Combining few-mode cores in MCFs has enabled single optical fibers with over 100 spatial channels and total transmission throughputs of over 10 Pb/s and with significantly enlarged cladding diameter similarly as in an exceedingly 2018 published paper the transmission capacity is around 10.16Pb/S/ fiber." In this case, more amount of cores and modes are used which consumes cost, and time in addition to this the capacity enhanced is only up to 10.16 pb/second/fiber. When components are more lost and dispersion would happen. Our work capacity is enhanced more than this and uses less number of components, less cost, less loss, and dispersion.

Table 2.1.Comparison of this thesis and the latest published papers

Transmission demonstrations in 125 (cladding)and 62.5micrometer(core)diameters fiber					
Parameters	This Thesis	Recently published paper			
	Year	Year	Year		Year
	2022	(Puttnam, Luís, Rademacher, Awaji, & Furukawa, 2021)	(Puttnam et al., 2020)	(Rademacher, Luís, et al., 2020)	(Rademacher et al., 2018)
No. of cores	4	4	4	3	1
No. of modes	1	1	1	1	3
Data rate	14.75Pb/s/fiber	319Tera	610Tera	172Tera	159Tera
MIMO Required	Yes	No	No	Yes	Yes
Transmission. dis(km)	250	3001	54	2,040	1,045
Wave. Band	C+L	S+C+L	S+C+L	C+L	S+C+L
Data rate*distance (km)	14.75Pb/s*250 =3687.5pb/s *km	957Pbps *km	33Pbps *km	351Pbps *km	166Pbps *km
Cost(ETB)	857,625	10,294,930.5	185,247	6,998,220	3,584,872.5
Energy/power (dBm)	-13	19.543	20.16	18.26	22.13
Q-factor	120	96	84	75	77
SNR(dB)	35	30	20	25	20
Gaps	-	-Not cost-effective. -Not power effective. - Q-factor is not effective.	- Not cost effective. -Not power effective. -No more SNR. -Q-factor is not effective.	- Not cost-effective -Not power effective -No more SNR - Q-factor is not effective	- Not cost effective. - Not power effective. - No more SNR. - Q-factor is not effective.

CHAPTER THREE

System Model Design

3.1 Introduction

The systems model design for the performance analysis of fiber optic communication systems using SDM methods is appropriate. In this case, it allows multiple spatial channels to pass information regarding space courses together to pass different data streams and admit multiple spatial channels like SMF, MMF, MCF, MMF- MCF, FMF, etc. It is trusted for long-haul transmission, high-speed data rates, and extreme data-carrying capacity accompanying extreme density and this may be attainable only by SDM. In addition to this, the SDM enhance the high ability of transmission through raised spatial channels and improve as well as break transmission limit. It is individual high-quality electronics to spice up the competency of optical fiber-located transmission. Different methods are demonstrated in fiber optics to increase capacity; however, SDM is the favored individual in optical fibers to boost the capacity of fiber optic transmission. SDM in FOC supports networks that extremely enhance high-capacity optical transport networks because it is popular that it has many benefits in the communications area. The most important purpose of the SDM is to break the capacity limit in space multiplexing. Each scope cross-section extent of the fiber each user acted not ISI accompanying each. In OFC schemes, MMF and FMF do not have any difference. Because MMF has to transfer a much amount of data than FMF in communication systems, especially in fiber i.e. more amount of modes are incorporated in it. In the case of SCF with MCF, there is the largest difference between them why because in OFC systems SCF can carry information up to 100 Tb/s/fiber.

3.2. Methods/ Flow of the Study

The research has been conducted as follows:-

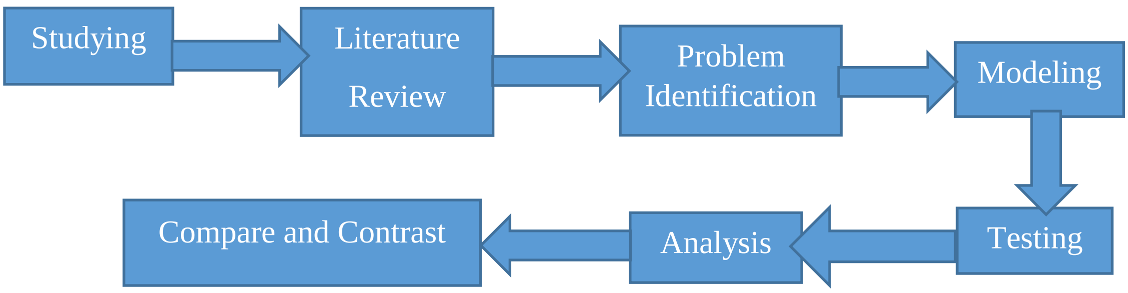

Figure 3.1 Block diagram of Methodology

i. Studying the basic theory, architectures, and related areas of the research.
ii. Revising this add the literature, associated with fiber communication, SDM for fiber communication systems, and different multiplexing techniques.
iii. Identifying the parameters that are necessary for this thesis work.
iv. Modeling our system by using optisystem software.
v. Testing of the proposed system that is simulated.
vi. Compare and contrast our results by using different parameters and classify them into main categories depending on their performance.

3.3. The proposed block diagram of FOC systems using SDM

In OFC, systems capacity and haul are the most issues during information exchange. As it is known, when capacity increases the transmission distance is decreasing and vice versa. Therefore, the technology extremely enhances high capacity and long-haul transmission and that technology is SDM. In fiber optic, SDM is the technique that enhances the capacity of fiber of more than 100Tb/s/fiber. The following diagram shows that OFC by using SDM to enhance high capacity and long haul transmission. In this case, the way to boost high capacity and long-haul transmission using SDM techniques with SMF and MCF technology.

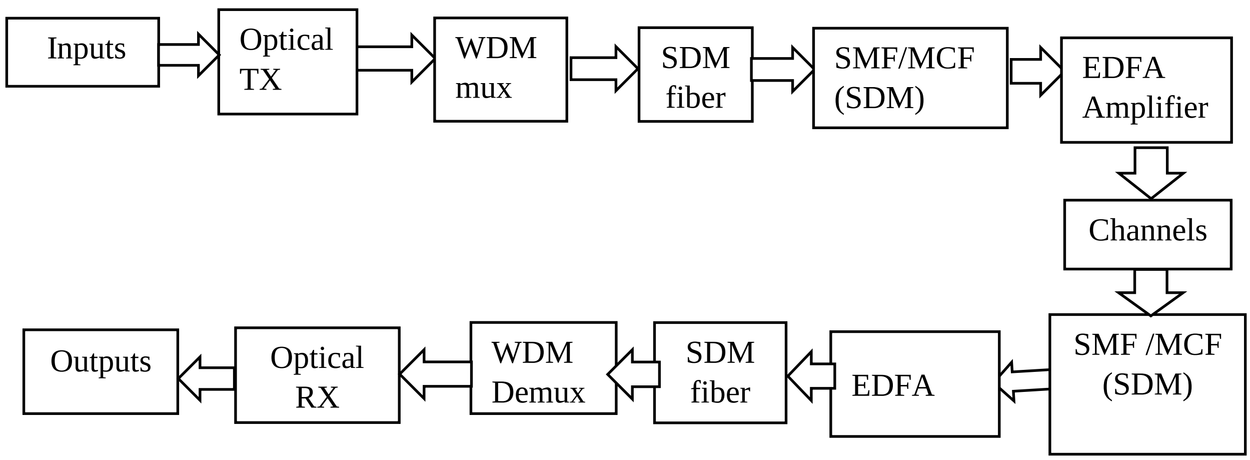

Figure 3.2. The block diagram of SDM in OFC systems

The capacity enhancement and long-haul transmission in fiber optics are possible by using d/t-mux techniques. However, some mux techniques have capacity limits. Nevertheless, SDM technology breakthrough this scalability limit. In figure 3.2, there is a capacity enhancement and long-haul transmission. It is known that when the haul increases the capacity and Q-factor is decreasing, so we would rather have a high carrying capacity also as an amplifier that amplifies the signal or information. In the above figure the data carried by optical fiber cable and transmitter by the optical transmitter, passes to SDM fiber, by using MMF/MCF it follows, amplified by EDFA reach the receiver side. Mathematical Model for the this systems.

3.4. Modeling of SDM in OFC systems

In SDM, handling a large amount of information to transmit information with high data-carrying capacity is deployed. SDM technology is used to avoid the capacity crunch of current mux used such as SMF/SMF-based OFC systems and to satisfy the exponentially increasing capacity demands by transmitting different data streams over spatially diverse transmission paths or multiple spatial channels for each user. As shown in figure 3.3, within the schematic, diagram with many transmitters connected with different spacing (cross-sectional area) and spending through N- no of the channels connected with M-link and demultiplexed yet again and produce a large amount of output at the receiver side as shown. There are d/t inputs that are connected to SDM and it handles a large amount of data and might transmit to realize the destinations.

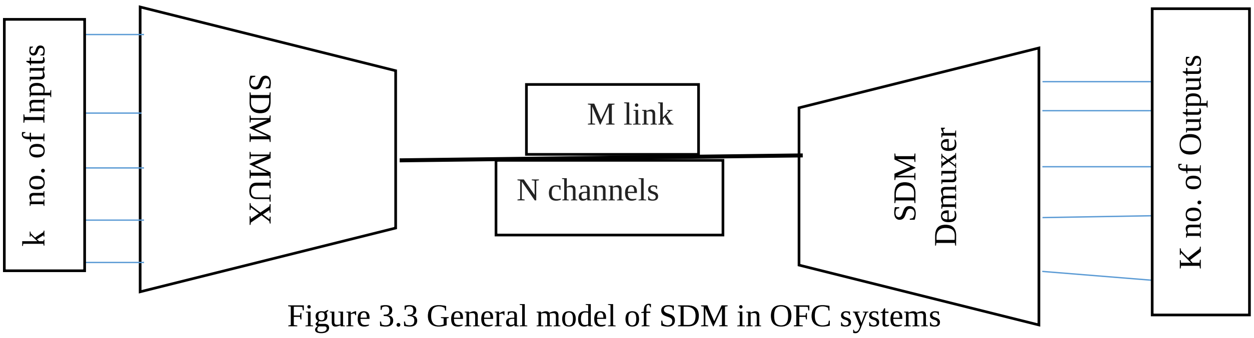

Figure 3.3 General model of SDM in OFC systems

In figure 3.3, it is drawn that there's a k-no of inputs, multiplexed by using SDM, and transmitted by N- no of channels through M-Link and demuxer and producing K-no of outputs. There is a k-no of inputs and a K-no of outputs.

3.5. Modeling of FDM, TDM, CDM, Digital coherent, WDM, and DWDM in FOC systems

Modeling of every the multiplexing is the one that shows the difference between them diagrammatically. Each of them is incredibly important in OFC systems and modeling of those is utilized in OFC systems. However, there is a d/c in capacity and speed similarly because of the distance of the transmission and components used.

3.5.1. FDM in OFC Systems

The FDM in optical communication systems supports high rate transmission over the frequency with subcarriers and simultaneously removes signal dispersion thanks to multipath frequency for every user and propagation with different delays within the channel on the receiver side.

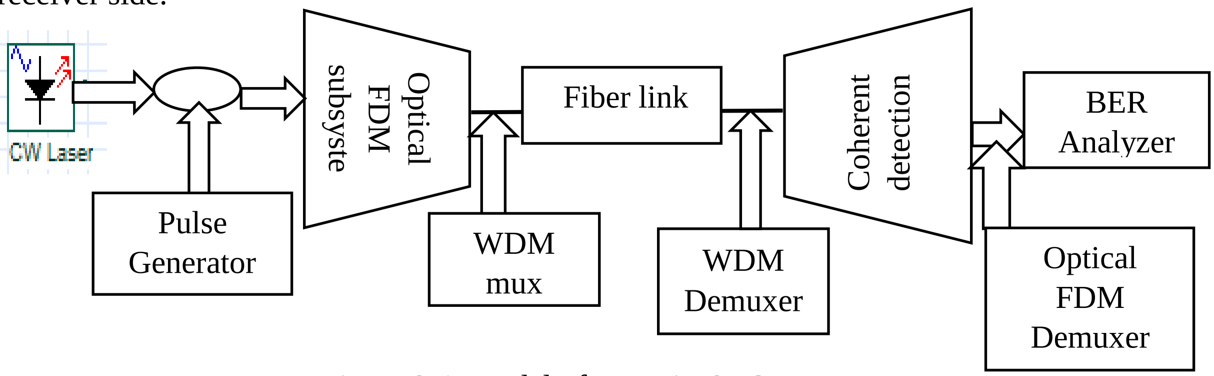

Figure 3.4. Model of FDM in OFC systems

In the figure above it is known that optical FDM is one of the techniques during which the frequency is varying for each coming signal and the optical FDM when implemented in fiber channels comes, is easily dispersed using SMF. The optical FDM model is with an SMF and each CW laser source pairs with a special frequency to transmit information. The pulse generator generates and transmits data and sends it to optical FDM subsystems, then with the same wavelength, and uses fiber to pass information to the receiver side. After it, reach the receiver side and demux, pass to coherent detection, after detection pass to the optical FDM subsystem, and reach the BER analyzer.

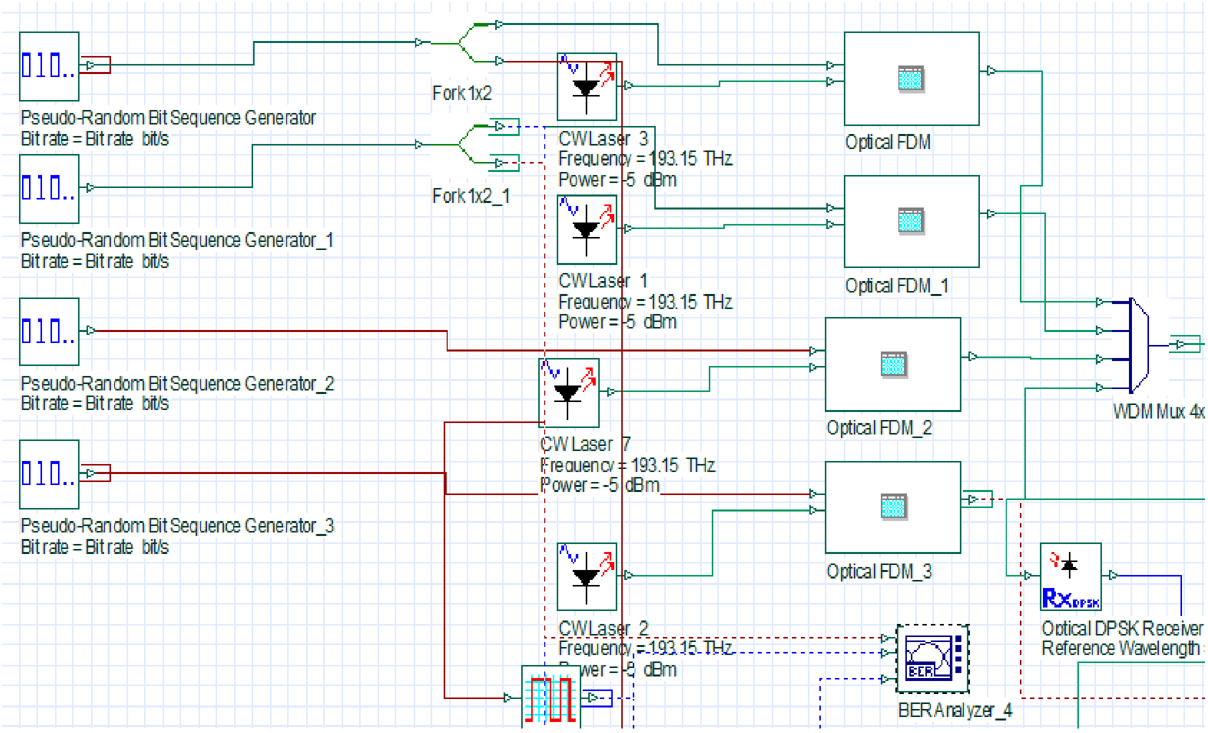

Figure 3.5. The circuit diagram of the OFC transmitter side

The transmitter side of optical FDM is the one that transmits information in OFC systems and contains many components as displayed in the circuit diagram. The data is transmitted using PRBSG passed to optical FDM with the same wavelength and passed to the receiver part.

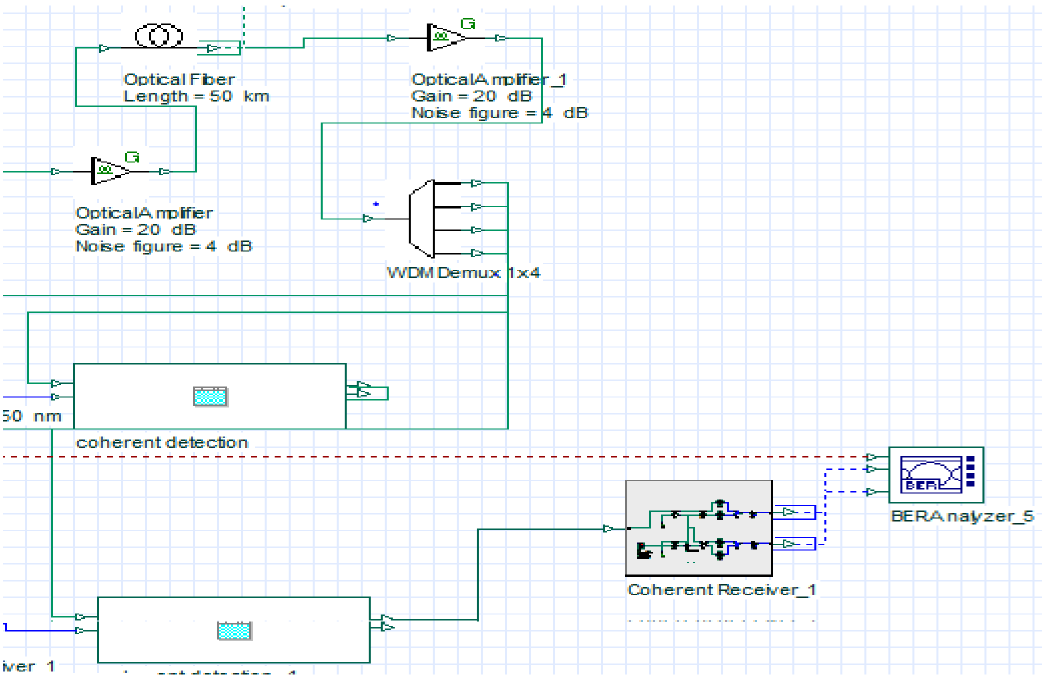

Figure 3.6. The circuit diagram of the OFC receiver side

The receiver part of optical FDM is the one that receives information in optical communication and contains many components as displayed in the circuit diagram. The data rate is received through detectors passed to the destination and with the same wavelength.

3.5.2 TDM in OFC Systems

In OFC, using TDM is preferable in comparison to FDM this suggests that the transmission concerning capacity is for FDM mega term, however for TDM Giga terms. In OTDM, the signal is carried by their unique time slot for every signal with the same frequency and wavelength. In OTDM, high capacity and better speed are required, which includes a vital role and transmissions over thousands of km. optical TDM could be multiplexed that achieves a high data rate in FOC systems and a limited capacity 100 Tbps/fiber using SMF and this bottleneck has been broken by optical SDM.

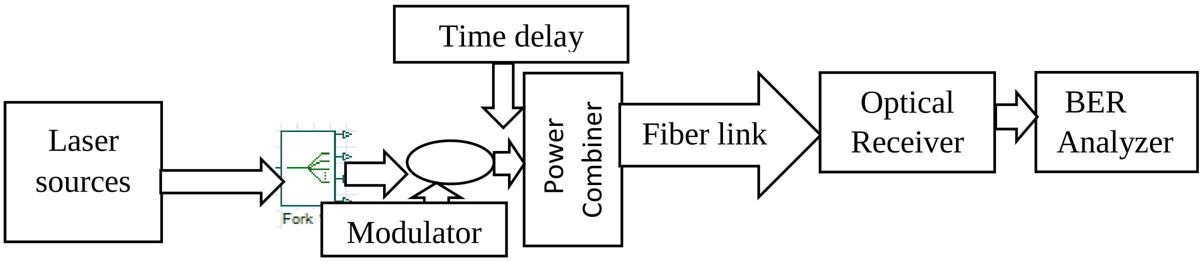

Figure 3.7. Model of TDM in optical fiber

In figure 3.7 the optical FDM; the laser source is connected to fork 1x4, and therefore the signal is passed to the optical modulator, then through power combiner, it will be combined and passed through fiber optics; reach receiver parts

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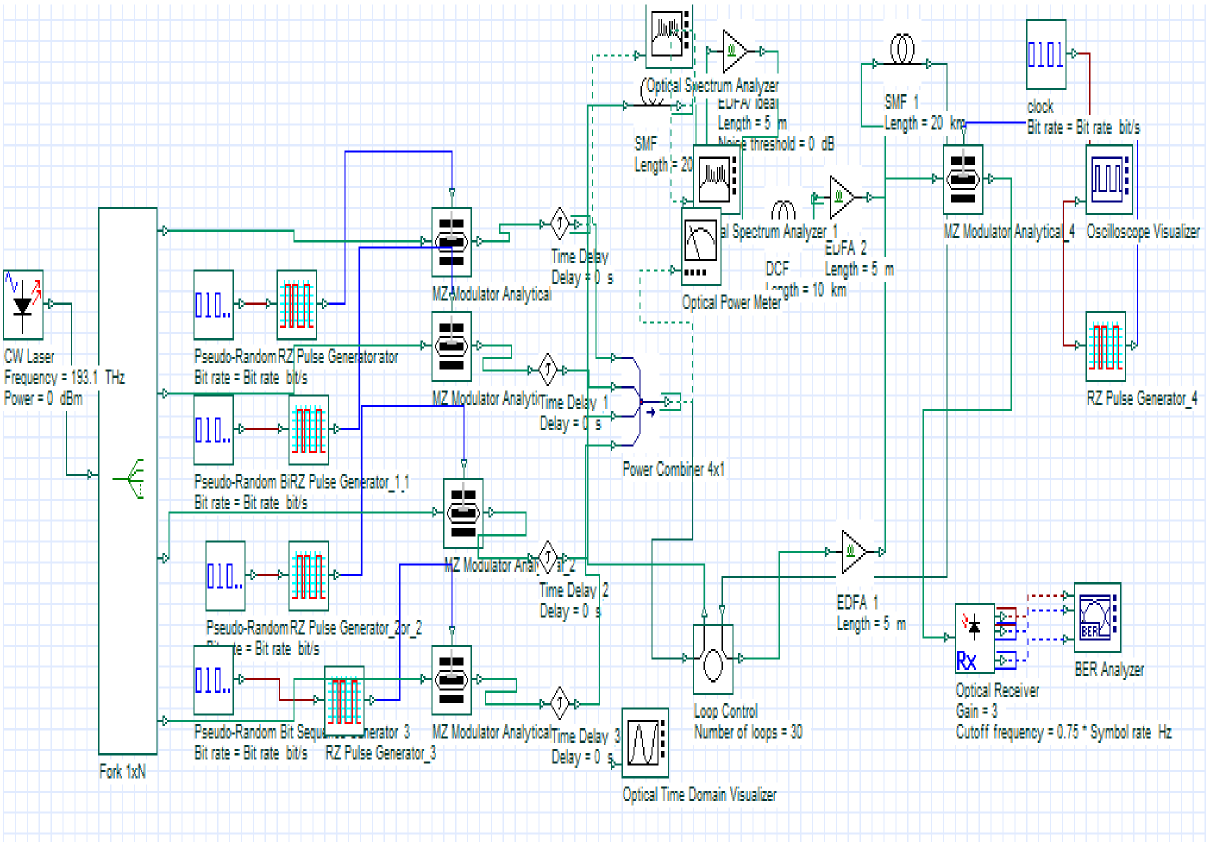


Figure 3.8. The circuit diagram of optical TDM

Figure 3.8, shows the circuit diagram of how OTDM is connected and working. The optical TDM technology, transmit the signal through fiber optic cable by varying timeslot during communication systems with the same frequency and others for each user. This circuit diagram contains different components to transmit with high speed and rate in OFC transmission.

3.5.3 CDM in OFC system

CDM is a mux technology that is used to enhance the capacity transmission OFC in which the parallel SMF and cores are carrying data and integrated into the same cladding of the fiber.

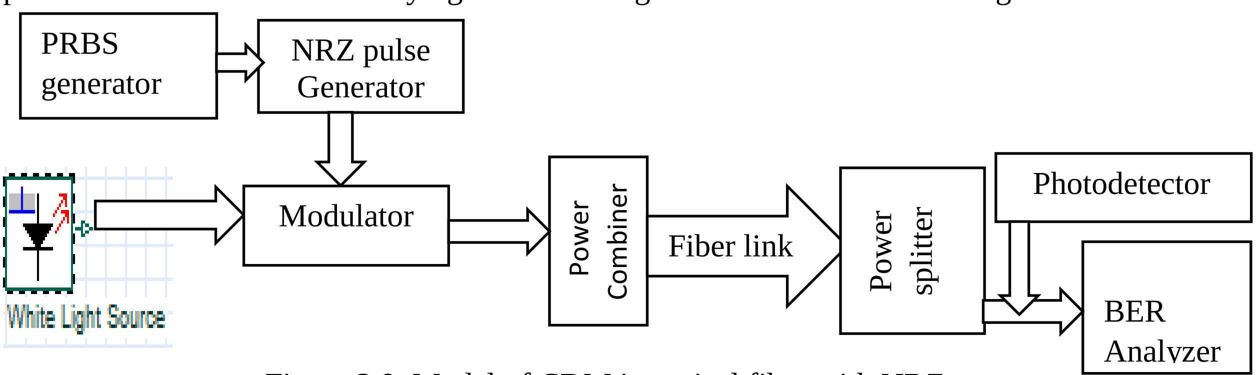


Figure 3.9. Model of CDM in optical fiber with NRZ

CDM in OFC allows many different users to access with the same wavelength, frequency, and time. However, different code of transmission. It is reliable because it doesn't influence others. It is shown in the above model white light sources can carry light pulse and pass to PRBS and modulator. The modulator is connected to a power combiner, connected to a power splitter via a fiber link. The data could be passed to the receiver side and this optical CDM is combined with other multiplexing techniques to increase the efficiency of OFC.

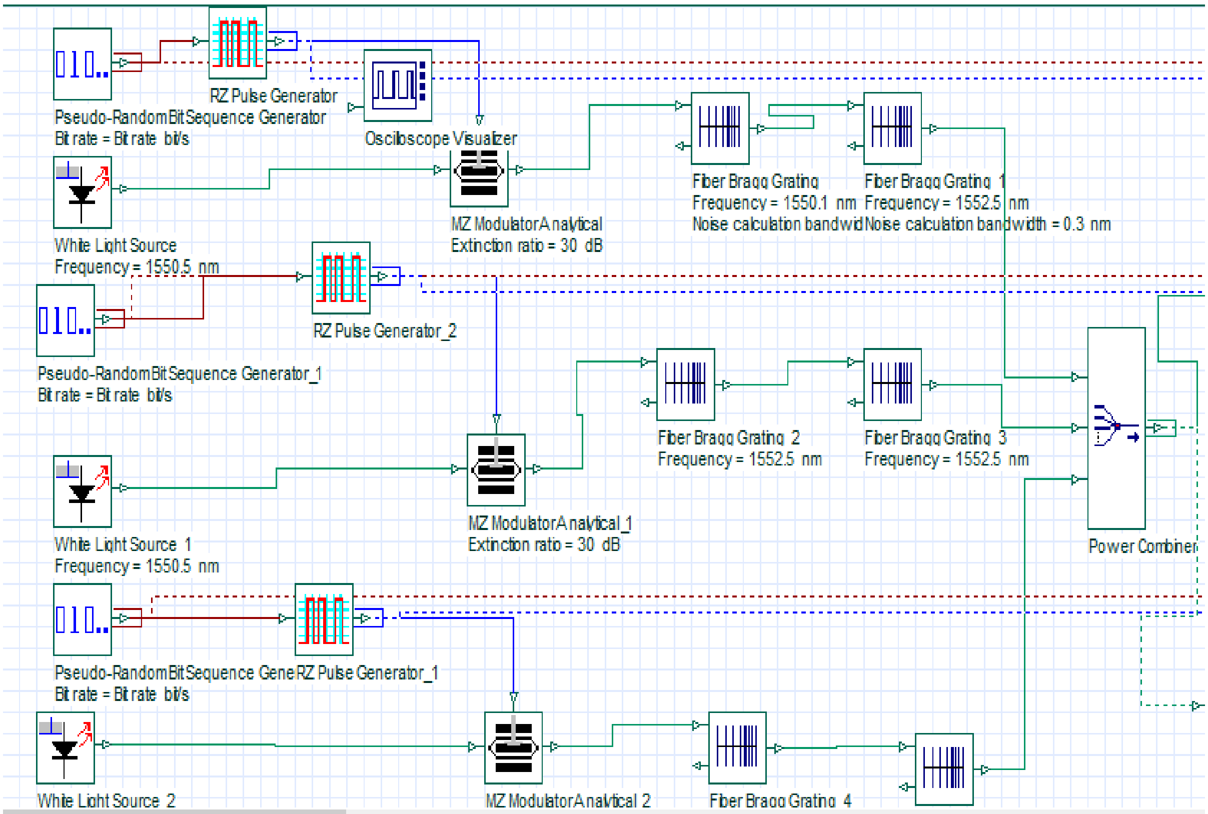


Figure 3.10. The circuit diagram of the optical CDM transmitter side

In figure 3.10, the transmitter side has many components from the source to the power combiner and each of them has its function. When comparing the circuit and functionality it is poor for communication. This implies that it is used for wireless communication (unguided) rather than wire (guided) communication systems.

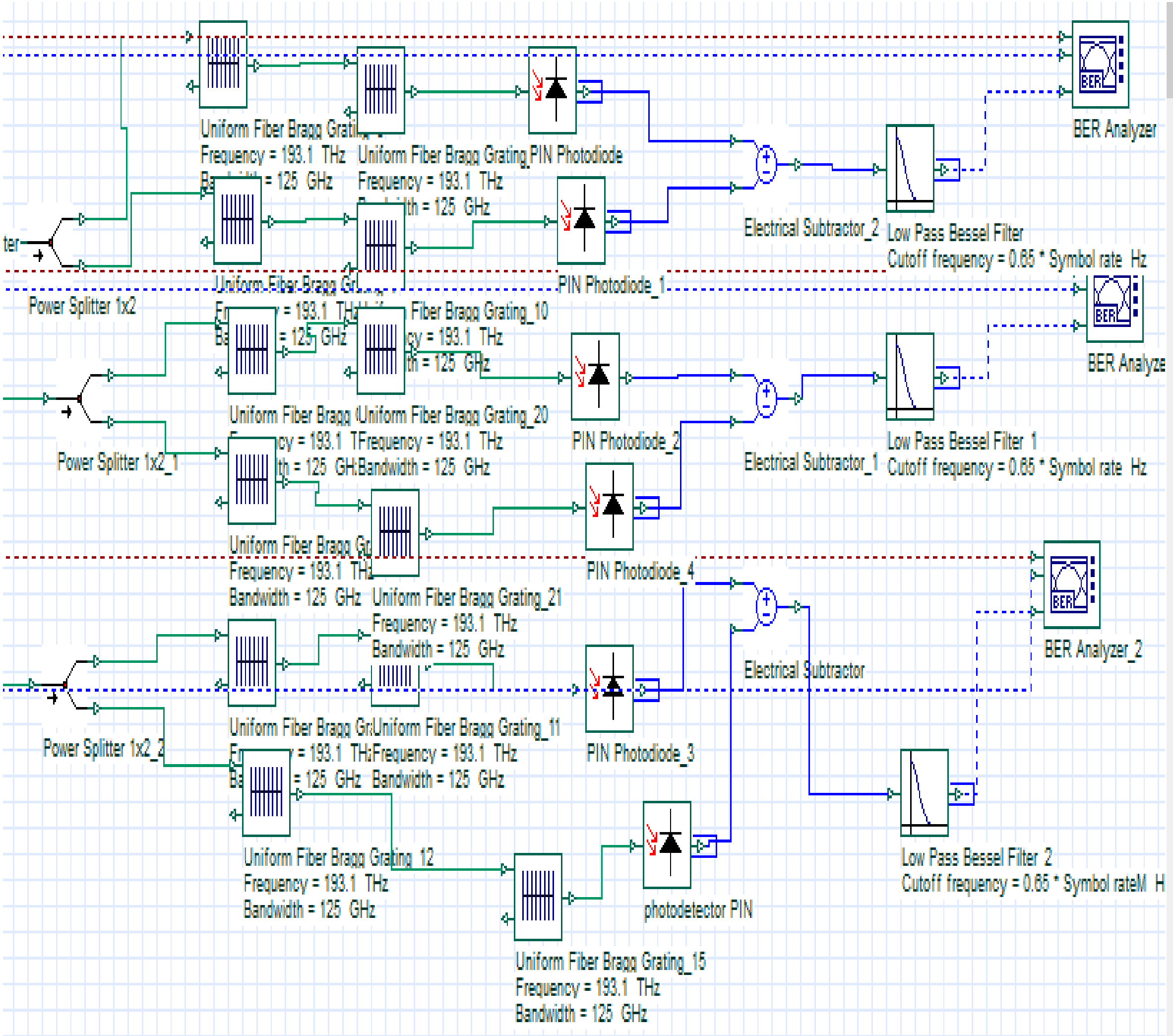


Figure 3.11. The circuit diagram of the optical CDM receiver side

In optical CDM, there are the transmitter and receiver parts to perform the effective transmission in FOC systems. The result produced by optical CDM is displayed in chapter four.

3.5.4. WDM in OFC Systems

In WDM, the user has their unique wavelength and every channel includes a different carrier frequency; channel spacing is around 50GHZ. In OFC, the WDM can carry capacity in terms of Tbp/s per fiber. WDM could be a technology, which allows multiple optical carrier signals via one link of fiber optics channel but has unique wavelengths of CW laser lights. Optical WDM combines multiple optical signals on one fiber by using different wavelengths for every user. In FOC, optical WDM allows multiple signals from different transponders, is combined by a WDM multiplexer and passes the data through an optical fiber wire and their wavelengths are different with the same timeslot and frequency.

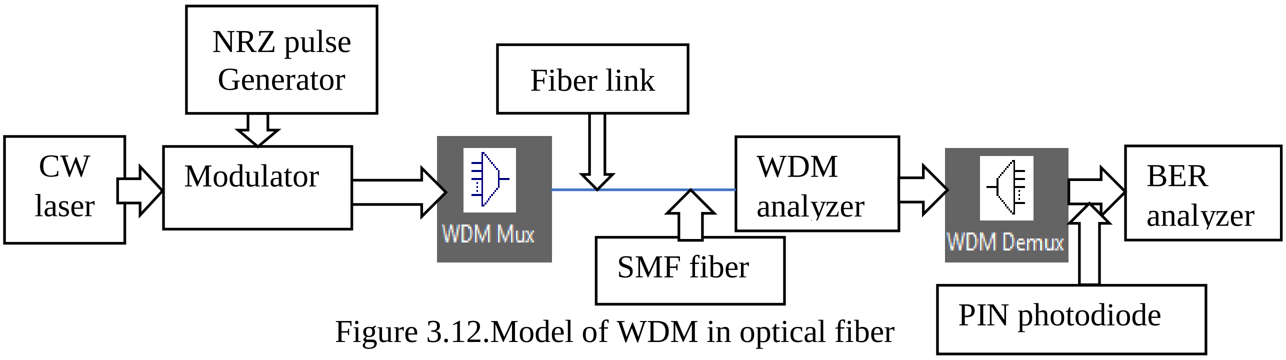


Figure 3.12.Model of WDM in optical fiber

In WDM, there are two main components these are coarse WDM (CWDM) and dense WDM (DWDM) available. However, CWDM differs from DWDM channel spacing and DWDM with a channel spacing of 20nm, which is number spacing, which allows more signal, because of this, many more wavelengths, are supported. The WDM is preferable to the other multiplexing techniques except for SDM in optical communication systems.

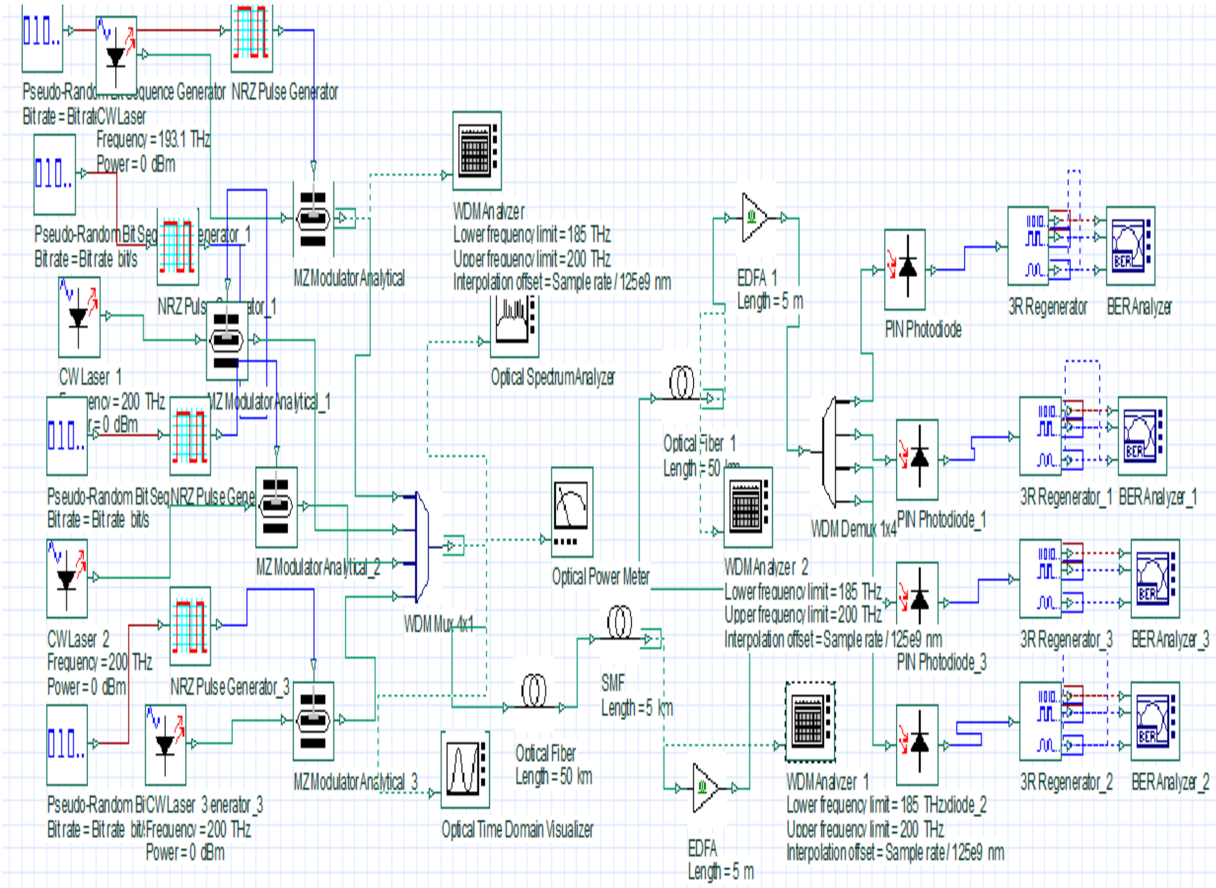


Figure 3.13. The circuit diagram of WDM in OFC systems

From the above circuit diagram, we understand how the components (laser source, pulse generators, and modulators) at the transmitter side and (PIN photodiode, regenerators, and BER analyzers) at the receiver side are connected to the module and produce results.

3.5.5. DWDM in OFC Systems

As it is known, DWDM is preferable compared to mux including CWDM except for SDM in case quality, capacity, and haul transmission. However, each of them has its wavelength band, the ability to carry data, and BER and SNR. DWDM can cover wavelength -band C- and L-band in OFC systems.

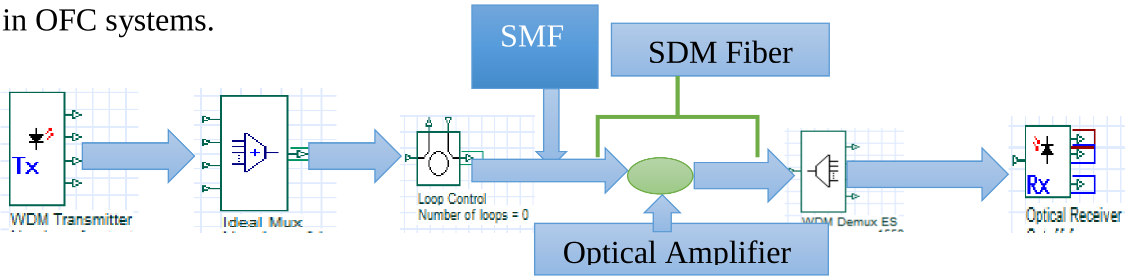


Figure 3.14. Model of DWDM in OFC systems

The optical DWDM is the most effective to transmit high-capacity and long-haul transmission systems. The signal is transmitted from the transmitter, passed to the ideal mux, controlled in loop control, connected to the fiber mode, amplified, and demuxed.

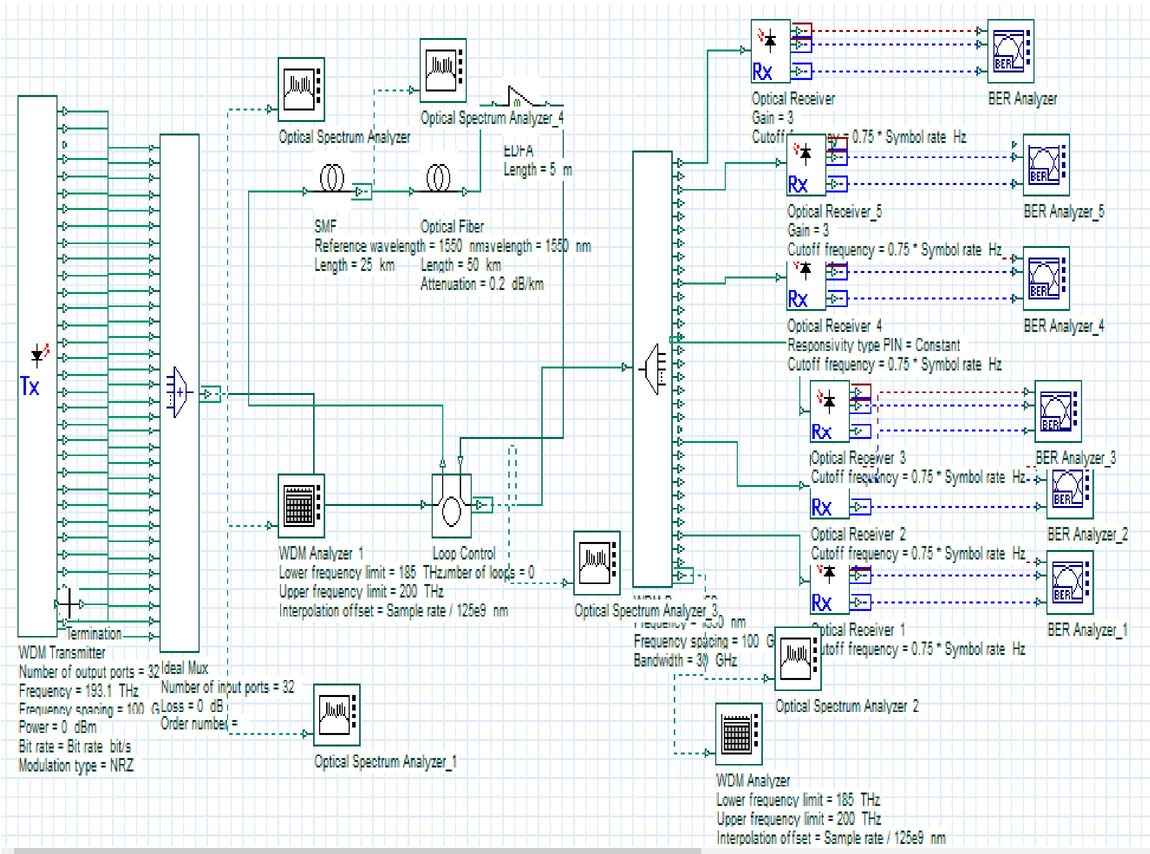


Figure 3.15. The circuit diagram of ODWM

The above circuit shows the optical DWDM that is the most effective and the current technology used today. The interconnection of all components in the above ckt diagram is used for an effective and better way of optical communication systems.

3.5.6. Digital coherent in OFC Systems

The digital coherent optical communication is the digital (quantized) and used to transmit information over fiber optics cable. The coherent FOC combined with other mux techniques and modulations

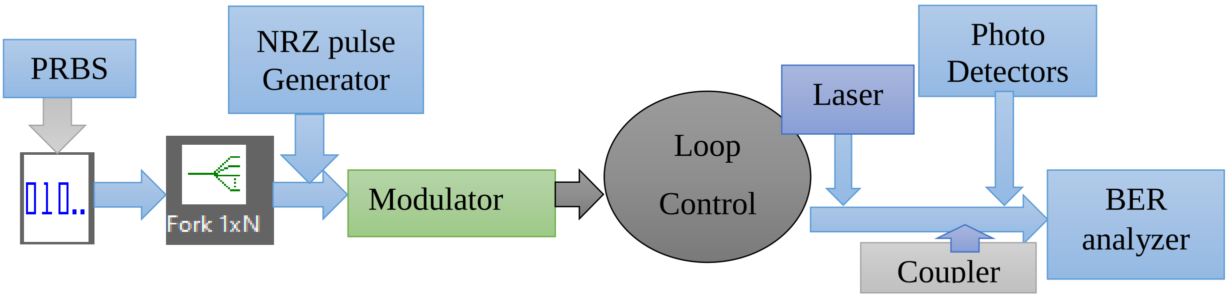


Figure 3.16. Model of Coherent optical communication link

It has great advantages in OFC systems. Digital coherence in fiber optics offers high sensitivity and bandwidth. The Digital coherent uses 4-QAM with a 210 km distance of transmission and have huge applications in future work in FOC systems. From figure 3.16, the bit is transmitted by using NRZ, passes to the modulator by a control loop, and reaches the receiver side.

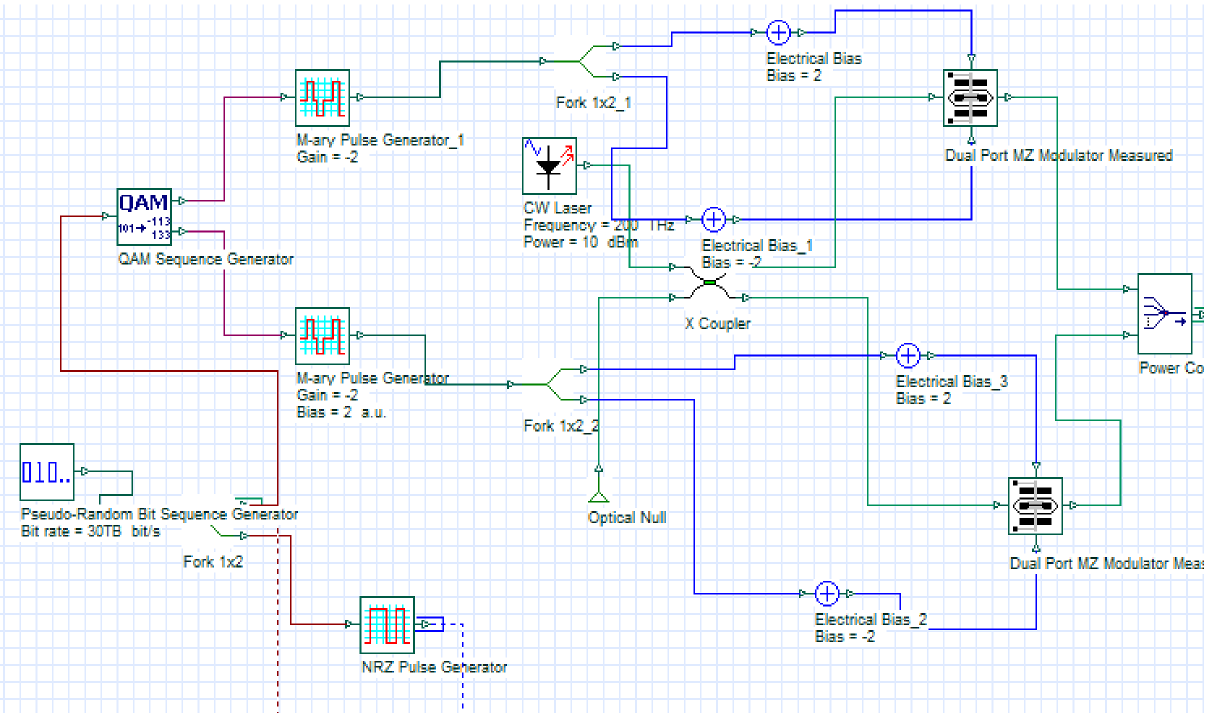


Figure 3.17.The circuit diagram of the optical coherent transmitter side

Figure 3.17 shows the transmitter side of the circuit diagram of coherent OFC systems. They are used to transmit signals as well as send them to the optical channels. This circuit is constructed from different components of such as PRBS, fork, pulse generator, CW laser, electrical bias, etc.

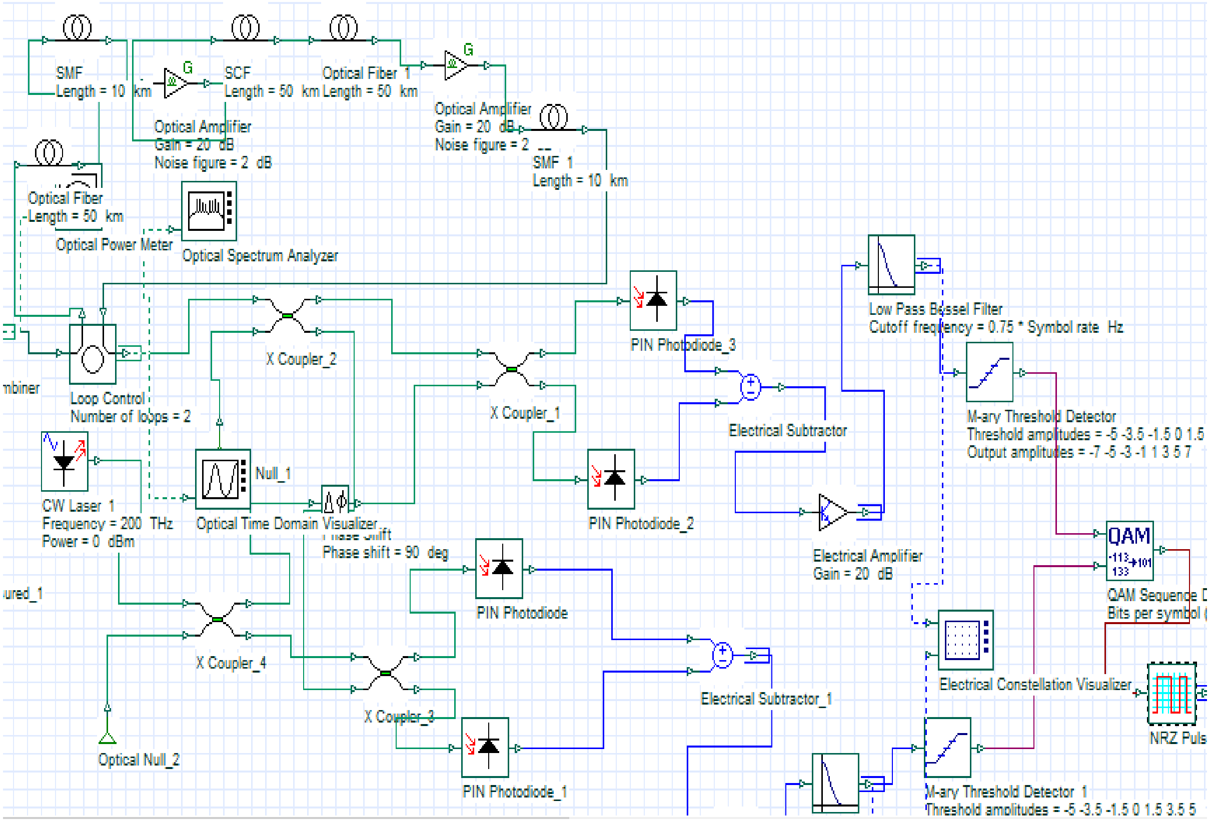


Figure 3.18. The circuit diagram of the optical Coherent receiver side

This one indicates the receiver part of coherent optical fiber communication systems, which contains loop control, photodetector electrical amplifiers, low pass filters, threshold detector, and BER analyzer.

3.6. Capacity enhancement in optical fiber using SDM

SDM in OFC is to enhance high capacity, which means it enhances OFC more than capacity limit of fiber optics and for long-haul transmission by using MMF and MCF. It is essential for many things.

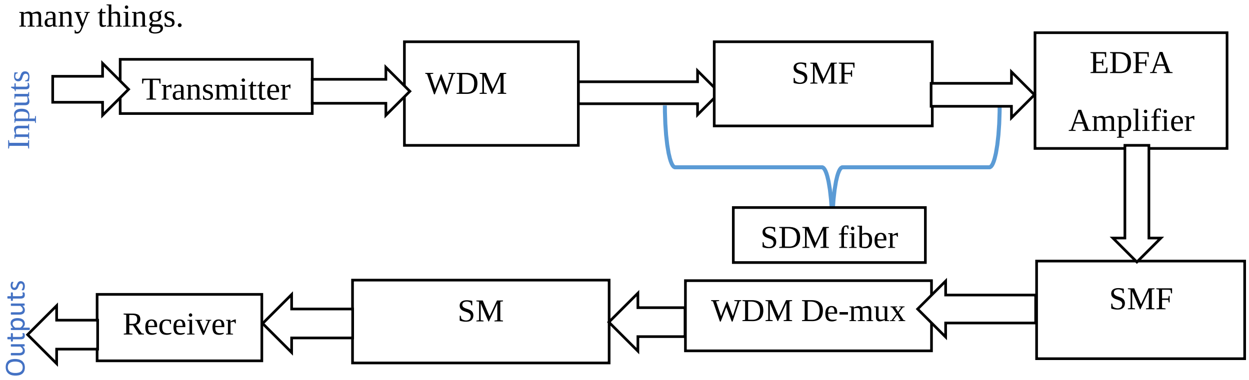


Figure 3.19. Block diagram of SDM that enhances the capacity of fiber optic

In FOC using SDM can break the capacity crunch and transmit high-capacity information by using different techniques of space multiplexing and allowing spatial paths through a cross-section of the optical fiber. The effects of optical fiber will be reduced. The capacity can be expressed as,

$$C = \frac{B \log_2 \left(1 + SNR\right)}{M} \tag{3.1}$$

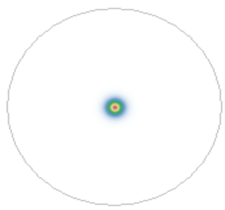
where C, M, and B, are capacity, mode, and bandwidth, respectively. However, the usable mode for high capacity (14.75petabit per second per fiber); the equation can be written as,

$$C = B \log 2(1 + SNR) \tag{3.2}$$

Table 3.1 Guided modes of fiber at a wavelength of 1625nm and diameter of core and cladding 62.5/125

	1	mode	core	beta	n. eff	A eff	Pin core	Cut off
1.	0	1	4	5.59/ μm	1.446 μm	114.3 μm^2	100.0%	-
2.	1	1	4	5.58/ μm	1.443 μm	193.8 μm^2	100.0%	2008.07

In table 3.1 the usable parameters to enhance the capacity of fiber optics using SDM. The number of modes used is one (m=1) and the number of cores is four (c=4) for this the effective areas are 114.3 μm^2 and 193.8 μm^2. The mode profile is shown below.



$LP_{0,1}$

Figure 3.20. Mode profile at a wavelength of 1625nm

3.7. Reduction of cross-talk in OFC systems

The reduction of crosstalk/receiver complexity should have to be reduced especially when data /information is transmitted at a high capacity with the long-haul transmission.

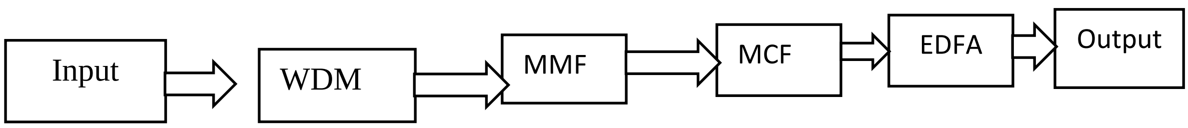


Figure 3.21. Block diagram of Cross talk reduction in OFC using MMF with d/t modulation

From figure 3.20, we understand that cross-talk sometimes-called receiver complexity is one factor that is created at the receiver side and that should be reduced. Crosstalk is a disturbance caused by the electric or magnetic fields of one telecommunication signal that affects the signal of adjacent circuits; This phenomenon that causes this is called electromagnetic interference. In MCF crosstalk becomes a crucial factor to have in consideration because having multiple cores so tightly packaged inside a single cladding will inevitably cause that the signals being transmitted inside them will be severely limited due to the degradation caused by the crosstalk. Crosstalk (XT) can be defined and P' (Z) is the power at the output of the reference core and P (Z) is the power at the output of the interference core(s). Mathematically expressed as,

$$XT(Z) = 10\log_{10}\frac{P'(Z)}{P(Z)} \tag{3.3}$$

3.8. Reducing losses and distortion/dispersion in OFC systems

Reducing the linear effects has vital advantages in optical fiber communication, especially in the case of capacity and long-haul transmission systems. As the linear effects in OFC are reduced the capacity increase and it is known that loss is the reduction of the power of light during data transmission. Therefore, these losses and distortions will be reduced in SDM using MMF by using different modulation techniques. These techniques with amplifier and produces better communication. The block diagram of loss reduction is as shown in figure 3.21.

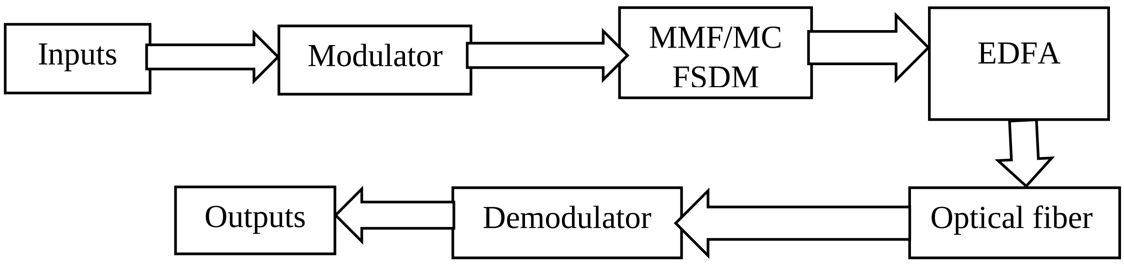


Figure 3.22. The block diagram of loss and distortion reduction

The loss and distortions are the main issues in FOC systems when the signal is transmitted the weakness/ power reduction will happen due to losses so our signal never travels along with the long-distance we need modulation and amplifier. By using modulation techniques our signal will reach the place where we need it. From the above block, diagrams the signal is followed and modulated by a modulator and passed by SDM fiber cable and connected with MMF, and reached the destinations. The dispersion/ distortion has a great effect in communication transmission is calculated as,

$$D = \frac{-\lambda}{c} \frac{d^2}{d} \frac{n.eff}{\lambda^2} \quad (3.4)$$

where D is dispersion, λ is the wavelength, c is the speed, d is the distance, $n.eff$ effective refractive index. There are many ways to calculate the fiber loss in the transmission information and to determine the power needed for a particular fiber link. This gives the actual fiber loss values for all events (count such as connectors, splices, and fiber loss) and other communication links. There are two very essential things to calculate fiber loss in transmission and estimate the power requirements. The optical fiber link length and loss variables are to be known to estimate the most distance of the fiber optic budget and loss. In OFC, estimating fiber haul is incredibly important. This calculation will estimate the most distance for the selected fiber link given the fiber optics budget and therefore the number of connectors, splices, et al contained within the link and which is given as,

$$Fiberlength = \frac{([opticalbudget]-[linkloss])}{loss/km} \quad (3.5)$$

The actual maximum distance of transmission will vary depending on the actual fiber optic loss/km, design of fiber optics, quality of connectors and actual loss per pair, quality of splices and actual loss per splices, quality of splices, and connectors in the optical fiber link.

Table 3.2 Factors that evaluate SDM in FOC systems.

System factors	Considerations/ Choices
Types of fiber	MCF/SMF
Dispersions/Attenuations	Signal regenerators
Fiber nonlinearities	The wavelength, and transmission power
Operating Wavelength	1550 and 1625 nm
Transmitter power	Expressed in dBm
Fiber loss	Expressed in dB/km
Source type	LED and Laser diode
Receiver sensitivity	Expressed in dBm
Receiver types	PIN/APD

3.9. Reduce Power Consumption and improve efficiency in OFC Systems

In OFC, system power is the major issue for the transmission of data and everyone knows that in fiber optic, data is transmitted within the modes of digital data, which implies we transmit digital data within the type of a lightweight pulse with two levels. The two levels are logic 0’s and logic 1’s and the digital logic is represented by 0V and 5V respectively. In FOC systems logic one represents photons/light intensity and logic 0 represents no intensity level. In this case, to transmit a 5V level or several photons from one end to a different end, the system requires some amount of power, which is more compared to transmitting a 0v level or no light. Here, we've got made an algorithm to transmit a sequence of binary streams within which if several set bits or logic 1 is quite 0’s then we are going to invert that sequence of binary and generate modulating carrier pulse only if the bit is 1.

In OFC, the data transmit sequences of bits of various lengths. In every sequence, the probability of 0’s and 1’s is additionally different. Each bit within the binary sequence is either ‘0’ or ‘1’ that features a different representation. Similarly, in optical we represent it within the kind of photons. If photons of a selected wavelength are present meaning logic is ‘1’ else it's logic ‘0’. However, here we noticed that to represent logic ‘1’, we'd like more power. We mean that if the probability of logic ‘1’ in any sequence is over logic ‘0’ then the transmitter wants more power to transmit. Design an algorithm to cut back the ability that's consumed by the transmitter to transmit that sequence during which several 1’s are more. The direct transmitter in our algorithm, firstly, within the transmitter block, we read any block of information in binary form and build its frame where the frame size is 32 bits/frame. At starting of the frame, we add a small amount which is employed at the receiver to spot that the new frame is started which is by default set as logic ‘0’. The subsequent step is to count the quantity of logic ‘1’ bits of every frame. If logic ‘1’ bits are quite half the dimensions of the frame rate invert the entire frame including the beginning bit which we've added at the start of the frame so we get a brand new sequence of ‘0’ and ‘1’ within the transmitter block. If bits during a frame are but 32 and therefore the count of 1’s is additionally but 1/2 the frame then we will transmit that frame normally means without inverting.

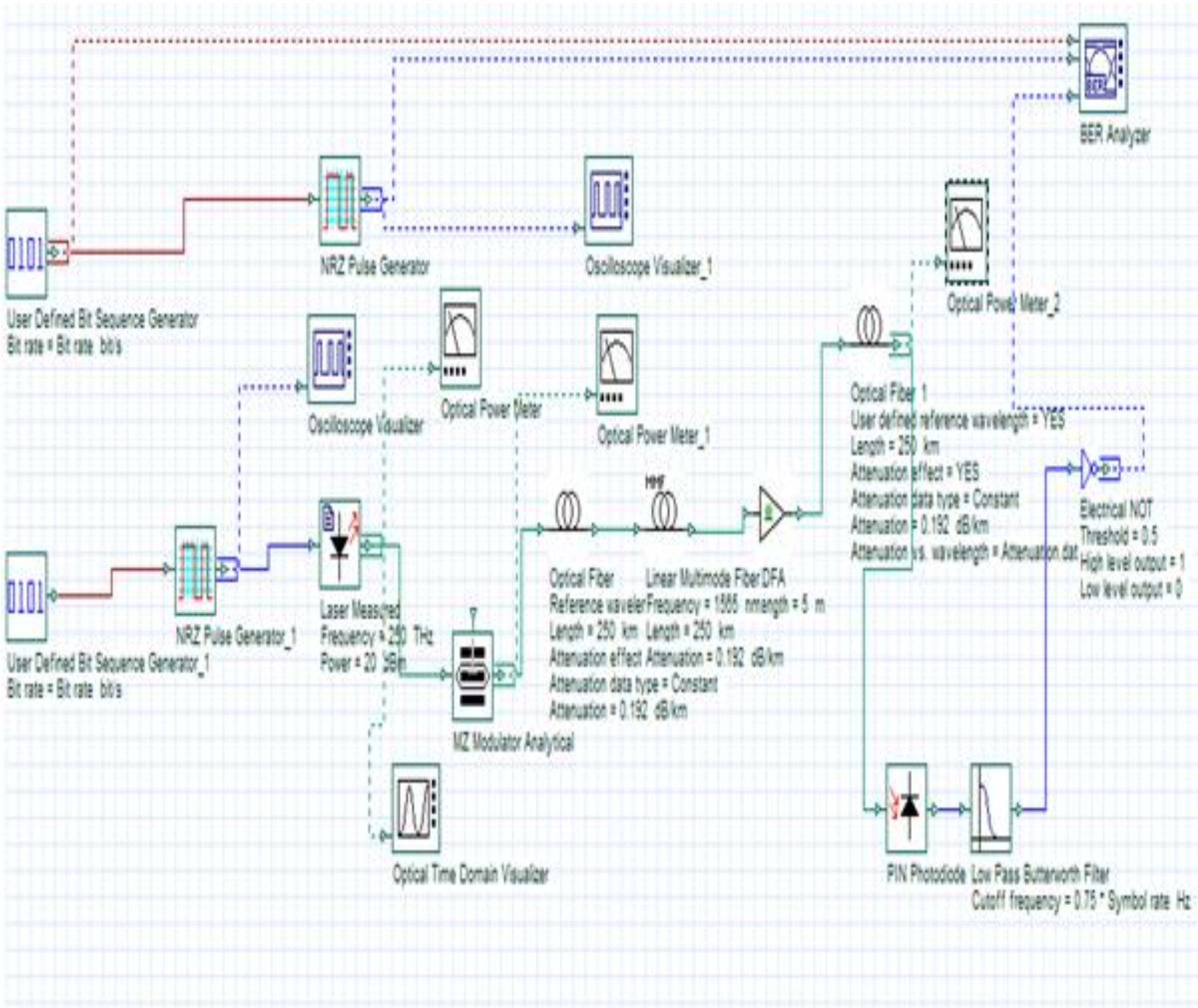


Figure 3. 23. Direct transmitter

Now, at the receiver block, if starting a bit of the frame is set or logic ‘1’ then inverts the other bits of the frame and sends it to the decoder block, else if starting bit is logic ’0’. Directly send it to the decoder block to decode and convert back into the form of worthy information or original data, which is transmitted by the transmitter. In our algorithm, firstly, in the transmitter, we read any block of data in binary form and create its frame where the frame size is 32 bits/frame.

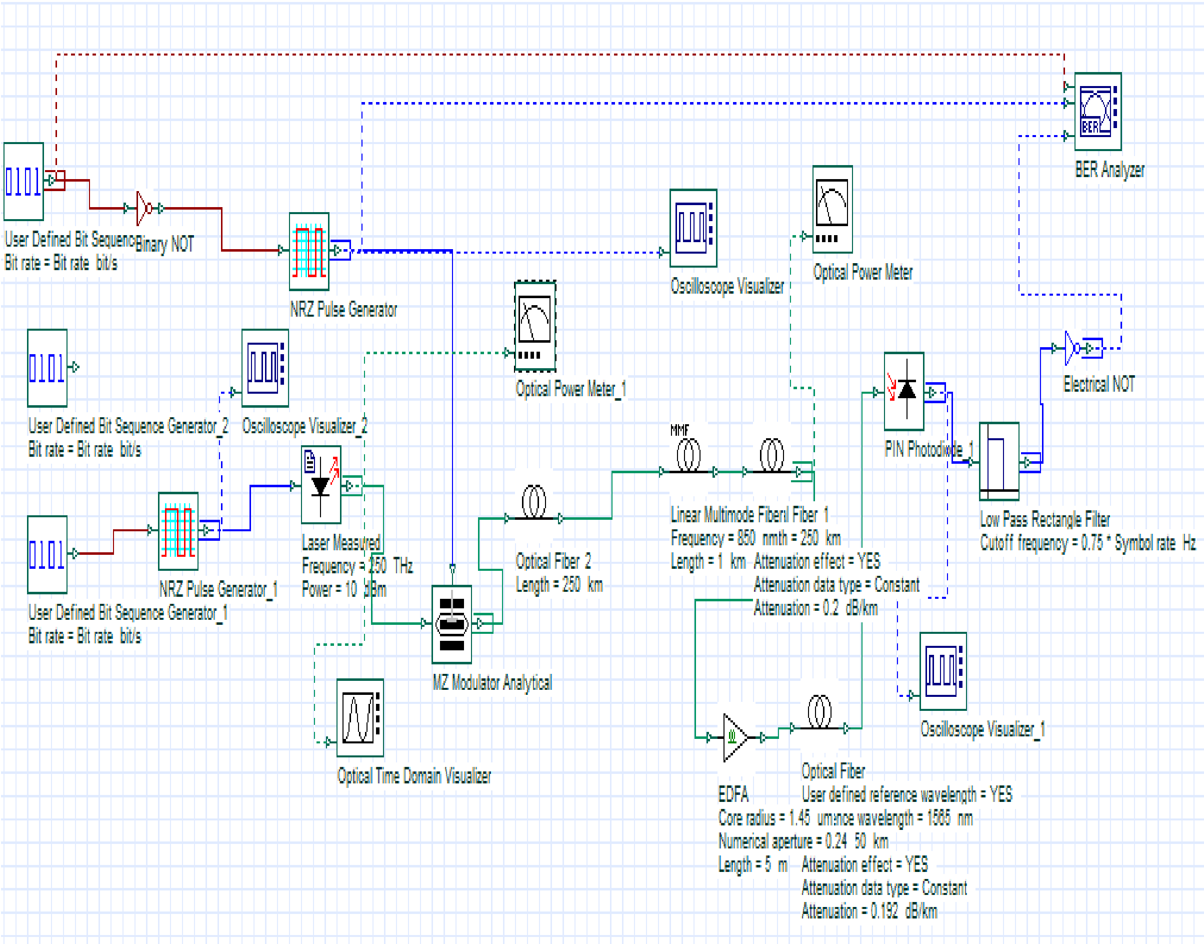


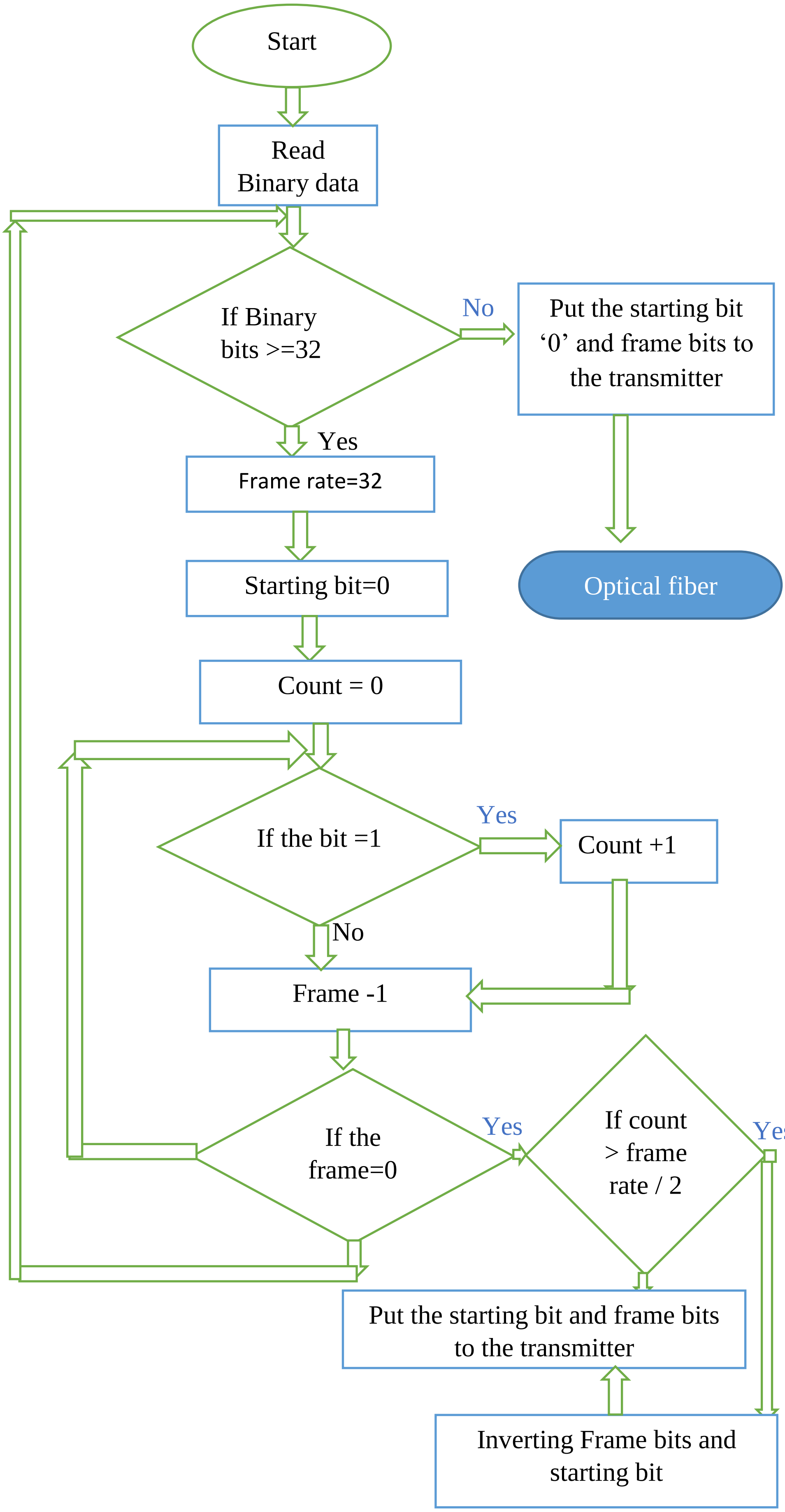
Figure 3. 24. Inverted transmitter Circuit

The inverted transmitter circuit will first invert the whole sequence of binary stream, switch the laser according to the binary stream and after that transmits to the optical cable and observe the power consumption of the laser for the inverted transmitter. In optical fiber communication systems optical power budget calculation is the major issue in reduction of power consumption reduction and transmission of power. The optical power budget is measured by dB that can be calculated by subtracting the minimum receiver sensitivity from the minimum transmit power. The mathematical model/ expression of optical power budget is as follows,

$$P_B(dB) = P_{TX}(dBm) - P_{RX}(dBm) \tag{3.6}$$

where P_B is optical power budget, P_{TX} is transmit power, P_{RX} is Received power.

The purpose of power budgeting is to ensure that the optical power from the transmission side to receiver is adequate under all circumstances.


Start
Read
Binary data
If Binary
bits >=32
No
Put the starting bit
‘0’ and frame bits to
the transmitter
Optical fiber
Yes
Frame rate=32
Starting bit=0
Count = 0
If the bit =1
Yes
Count +1
No
Frame -1
If the
frame=0
Yes
If count
> frame
rate / 2
Yes
Put the starting bit and frame bits
to the transmitter
Inverting Frame bits and
starting bit

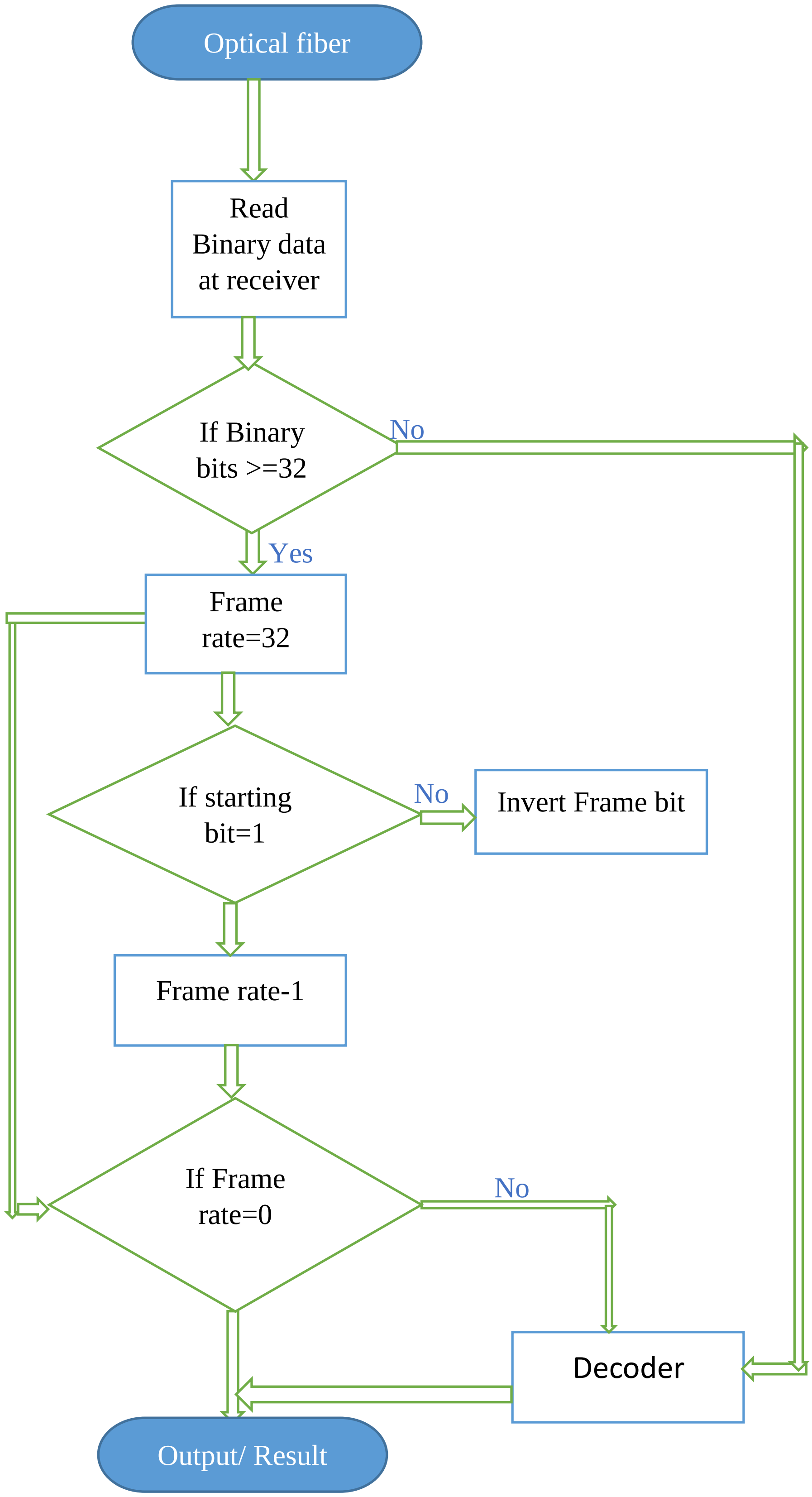


Figure 3.25. Flow chart algorithms of energy/power reduce consumption.

In OFC, system power is the major issue for the transmission of data and everyone knows that in fiber optic, data is transmitted within the sort of digital data, which suggests we transmit digital data within the kind of a light-weight pulse with two levels. The two levels are logic 0’s and logic 1’s and therefore the digital logic is represented by 0V and 5V respectively. In FOC systems logic one represents photons/light intensity and logic 0 represents no strength. In this case, to transmit a 5V level or several photons from one end to a different end, the system requires some amount of power, which is more as compared to transmitting a 0v level or no light. Here, we've made an algorithm to transmit a sequence of binary streams during which if several set bits or logic 1 is quite 0’s then we are going to invert that sequence of binary and generate modulating carrier pulse only if the bit is 1. In OFC, we transmit sequences of bits of various lengths. In every sequence, the probability of 0’s and 1’s is additionally different. Each bit within the binary sequence is either ‘0’ or ‘1’ that features a different representation. Similarly, in optical we represent it within the type of photons. If photons of a selected wavelength are present meaning logic is ‘1’ else, it's logic ‘0’. However, here we noticed that to represent logic ‘1’, we want more power. We mean that if the probability of logic ‘1’ in any sequence is over logic ‘0’ then the transmitter wants more power to transmit. Therefore, we design an algorithm to scale back the ability that is consumed by the transmitter to transmit that sequence during which several 1’s are more. The direct transmitter in our algorithm, firstly, within the transmitter block, we read any block of information in binary form and make its frame where the frame size is 32 bits/frame. At starting of the frame, we add a touch which is employed at the receiver to spot that the new frame is started which is by default set as logic ‘0’. The following step is to count the quantity of logic ‘1’ bits of every frame. If logic ‘1’ bits are over half the dimensions of the frame rate invert the full frame including the beginning bit which we've added at the start of the frame and so we get a brand new sequence of ‘0’ and ‘1’ within the transmitter block. If bits in an exceeding frame are but 32 and also the count of 1’s is additionally but half the frame then we are going to transmit that frame normally means without inverting.

CHAPTER FOUR

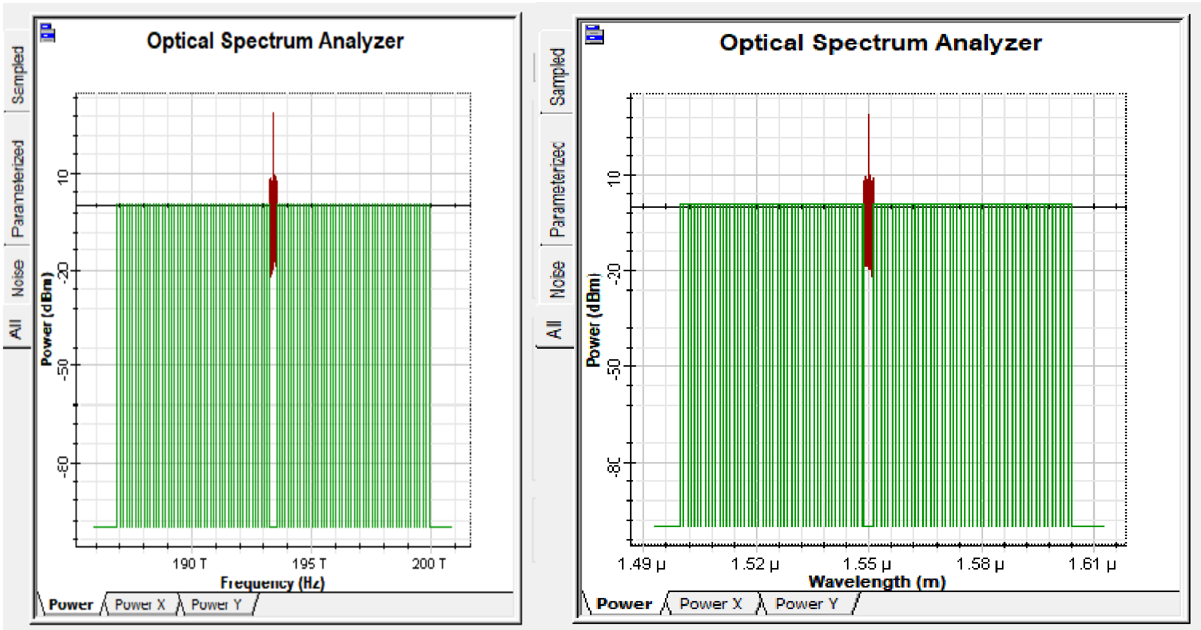
4. Results and Discussions

4.1 Introduction

In, fiber optic communication systems there are different multiplexing techniques, which are used to transmit data with high capacity and long haul transmission. Capacity enhancements in OFC systems using SDM techniques have a vital role in information exchanges. Many techniques are available however; it is impossible to extremely produce high-capacity and long haul FOC systems. In this chapter, we obtained the results of, FDM, TDM, CDM, WDM, DWDM, Digital coherent, and SDM as well as cross-talk, loss, distortion, and power consumption reduction in OFC systems. Comparing and analyzing the performance, different multiplexing techniques in fiber optic to produce effective communication systems.

4.2. Result for FDM in OFC systems

The optical FDM is one of the optical multiplexing techniques, which allows multiple optical signals through multiple channels.



(a) (b)

Figure 4.1. Optical spectrum analyzer. (a) Power vs Frequency, and (b) power vs wavelength

In figure 4.1, the power used is around 9dBm and the maximum frequency used is 200THz as shown in figure 4.1 (a). In figure 4.1(b), the power we used is the same but the maximum wavelength used is around 1610nm, which is used in OFC systems and the wavelength band used is C+L- band. Even if it transmits the quality of the signal, reaching the receiver is not as much.

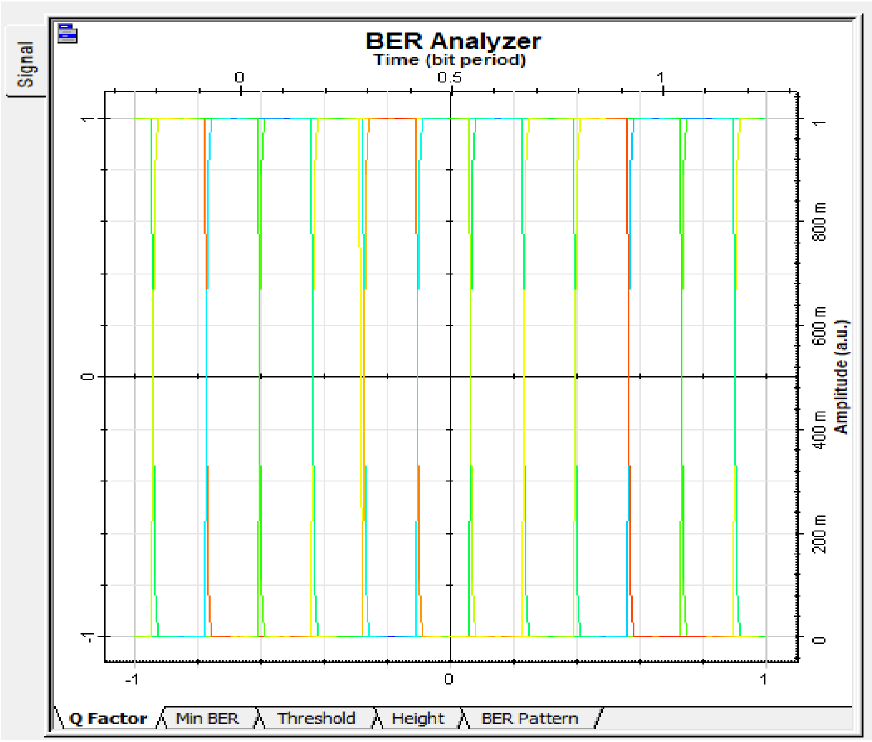
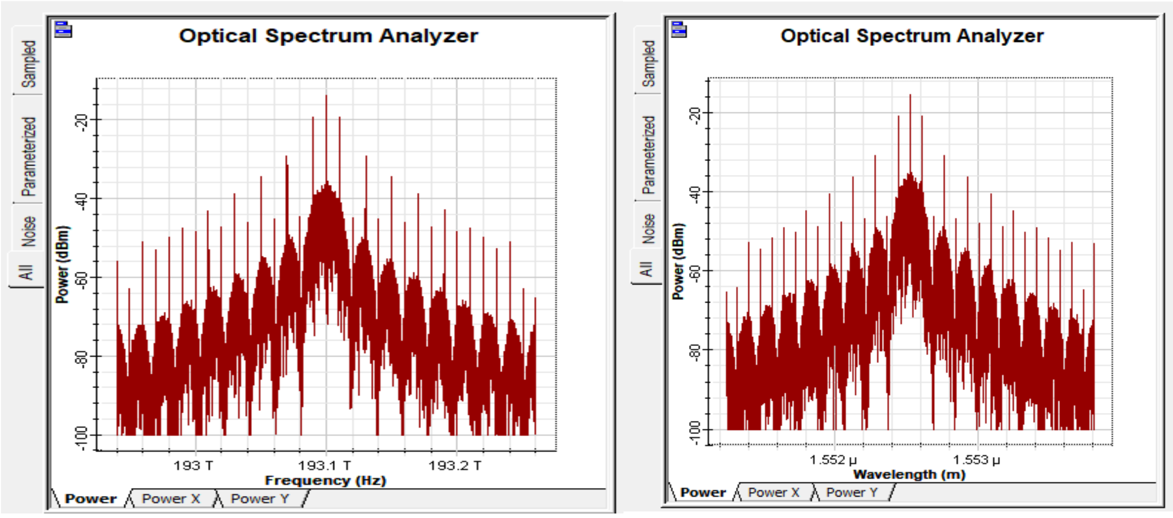


Figure 4.2. BER analyzer

In the above figure, the value for Q-Factor is one, and the threshold, height, and BER pattern is zero. This implies that the pattern of the eye diagram is very poor and it is not much used in OFC systems to transmit information. The BER used in this case is 10^{-9} in optical communication systems.

4.3. Result for TDM in OFC systems

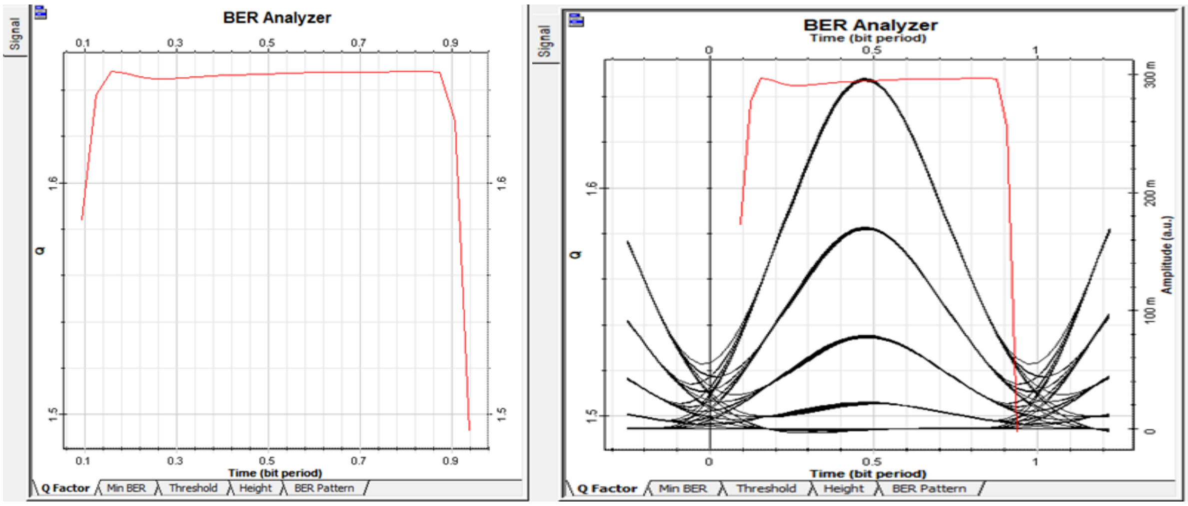
In OTDM, the optical signal has a different time slot for each incoming signal. It is shown in figure 4.3 below; an optical spectrum analyzer is used to analyze frequency and wavelength with their respective power but also analysis the other parameters. The optical spectrum determines the power with frequency and wavelength. The values is simulated using optisystem software (Power, Q-factor, BER, distance, capacity, SNR, loss and etc.).



(a) *(b)*

Figure 4.3. Optical Spectrum Analyzer. (a) Power vs Frequency, (b) Power vs Wavelength

An optical spectrum analyzer that is used to analyze/evaluates the power with the frequency needed and wavelength determines the OTDM here. Let us compare figure 4.3 (a) and (b). In figure 4.3(a), the maximum power needed is -25dBm and the max frequency range used is frequency range is 193THZ-193.4THZ. In figure 4.3 (b), the power is the same (-25dBm,) and the wavelength used is 1553nm/1.553 μm . The wavelength band used is a C- band.

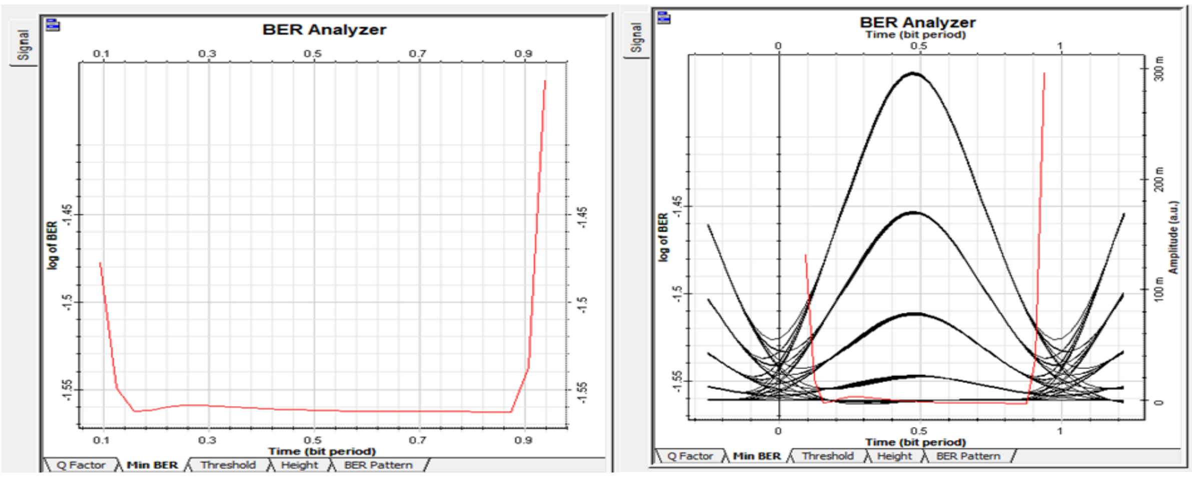


(a) (b)

Figure 4.4. BER analyzer. (a) Q-Factor vs Time. (b) Q-Factor with Eye diagram

Here we compare Q-factor with the time and explain the eye diagram with the Q-factor. When Q-factor increases the SNR also increases the time bit period may increase or decrease it depends but the Q-factor and the SNR have linear relations. Figure 4.4 (a), shows the minimum SNR. As we know, the SNR is 20dB and the Q-factor value is 1.69. In figure 4.4 (b) when the

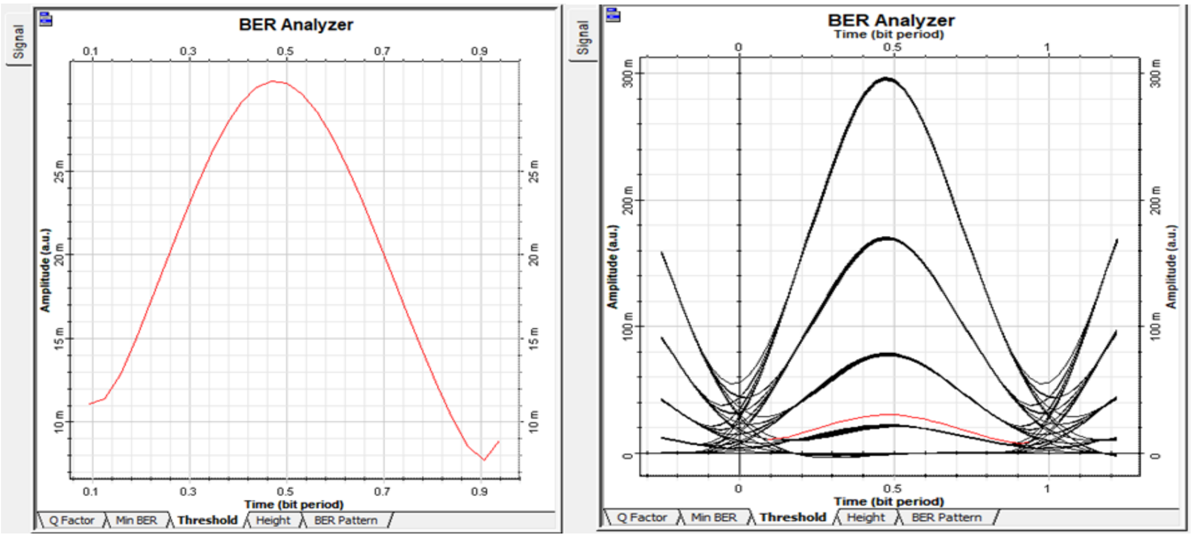
Q- factor is wide eye diagram quality is better unless not. The BER is 10^{-9} the haul transmission of fiber optic communication is 350km.



(a) (b)

Figure 4.5. BER analyzer (a) BER vs Time and (b) Min BER with Eye diagram

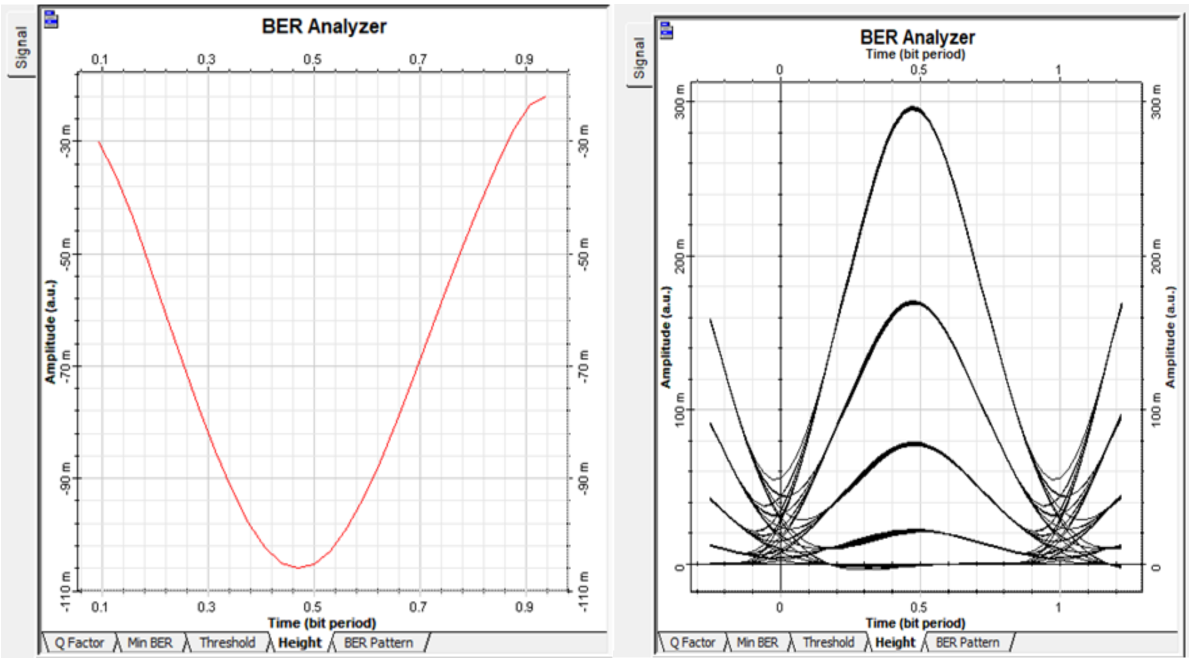
In the above figure, it is decided as the min BER and the eye diagram with when the BER is at the minimum. The minimum BER is -1.56. At the min-BER, the signal quality is good, but if the BER is high, the quality of the signal is decreasing. The no. of mode and core used for this haul transmission is one (SMF/SCF =1) and the number of loss is 0.2dB/km. In this optical TDM, the diameter core /cladding is 9000/125000nm



(a) (b)

Figure 4.6. BER analyzer. (a) Threshold vs time bit period (b) Threshold vs eye diagram

Figure 4.6 (a) and (b) shows the threshold and the eye diagram with the threshold, which show the threshold value and the eye diagram together. The reason why we set a threshold of eye diagram is that the plot of eye diagram and choose measurement tab that is threshold is the measurement tab in optical spectrum analyzer. Figure 4.6(a) show the threshold of the BER analyzer is 25.5m and figure 4.6(b) simply shows the eye diagram with a threshold. The threshold is the y-axis and is generally half of the signal range. The level zero and level one areas can be annotated by checking the Annotate check box. As observed in figure 4.6 (b) threshold with eye diagram the threshold is minimum compared to the maximum and a little bit greater than the minimum eye diagram.



(a) (b)

Figure 4.7.BER analyzer. (a) Height vs amplitude and (b) height vs Eye diagram

Here we discuss height, eye diagram, and BER pattern of the optical signal using OTDM in communication systems. Figure 4.7 (a) shows the height of the signal on the y-axis and the height is around -30.25m, where the minus (-) shows the direction, and figure 4.7 (b) is an eye diagram with height. As we have said in figure 4.7 (a) the height is more minimum and it is not displayed on the eye diagram. We can understand in figures 4.7 (a) and (b) the height.

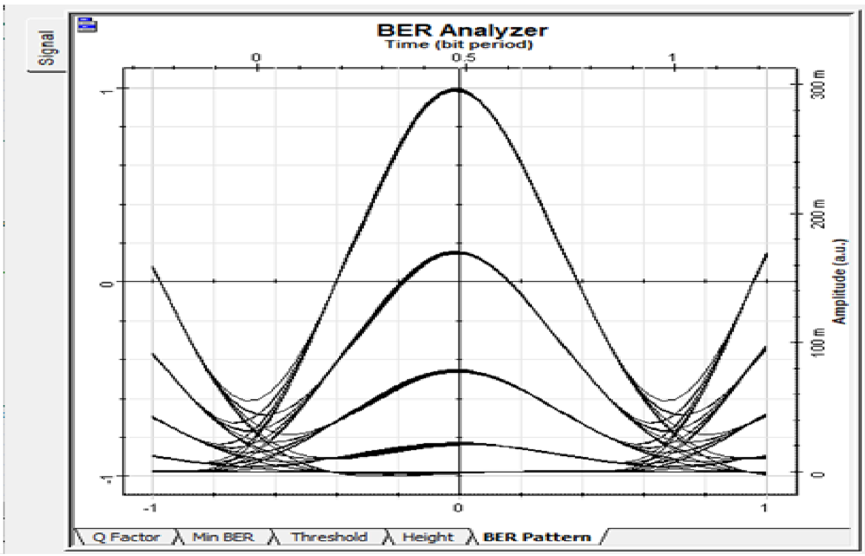
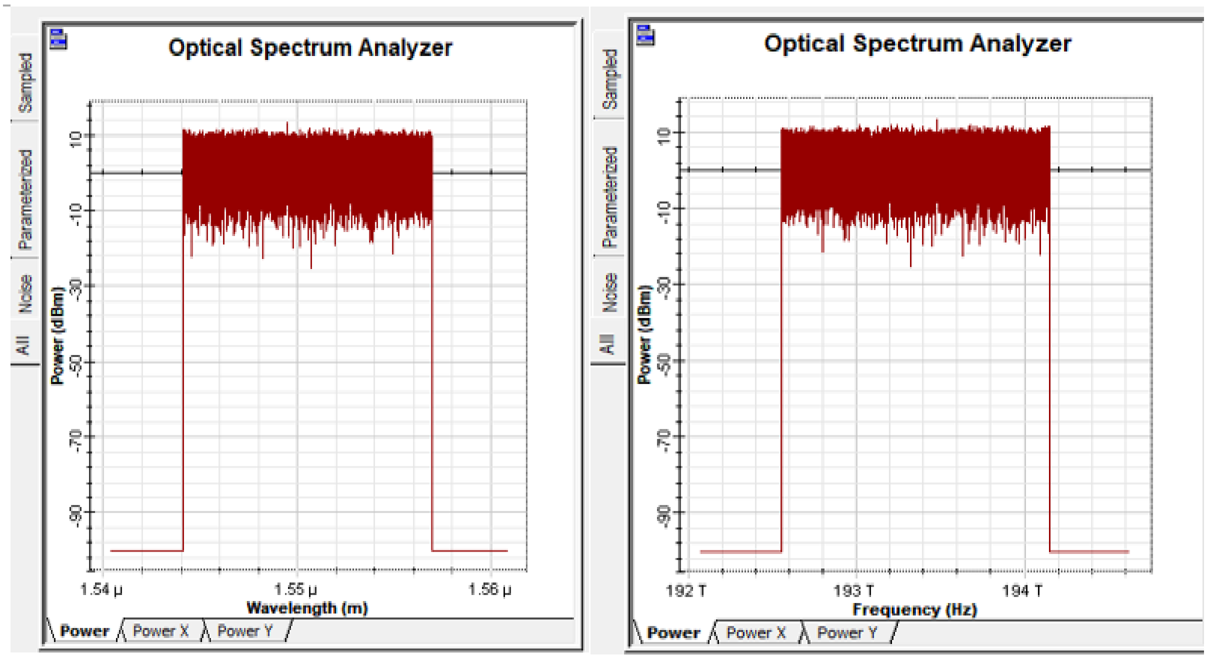


Figure 4.8. BER analyzer.

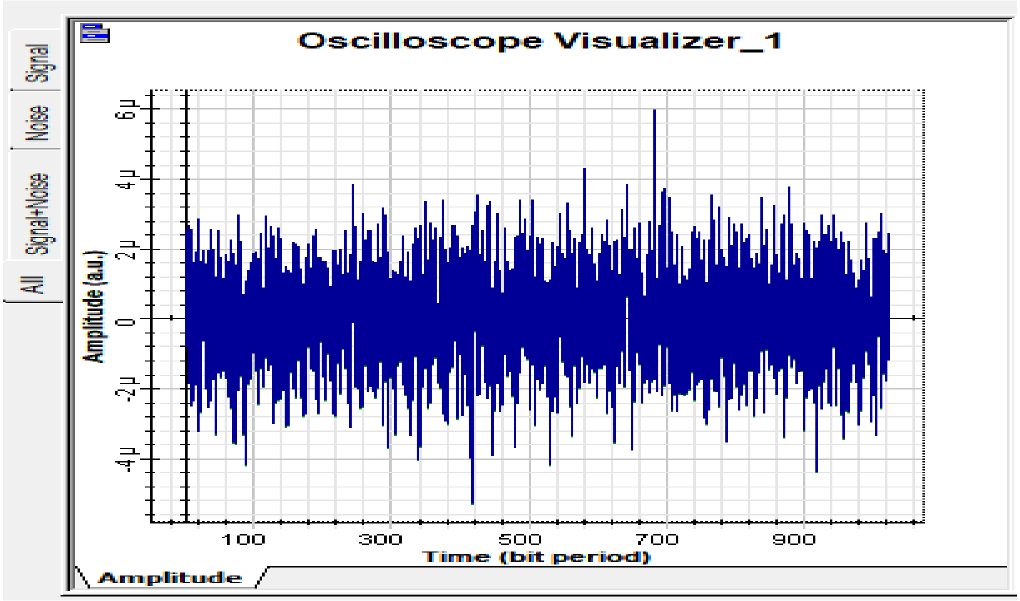
In figure 4.8, the BER analyzer analysis the pattern of the eye diagram to determine the BER pattern. The bit error pattern is the measurement tabs and the maximum pattern displayed is around one. The bit error pattern is good to compare to the bit error pattern of optical FDM.

4.4. The result for CDM in OFC systems

OCDM is one of the optical multiplexing techniques in which each optical signal carrier has its code to pass information. The OCDM allows multiple signals and passes information through a single/ same optical channel (optical link).



(a) (b)



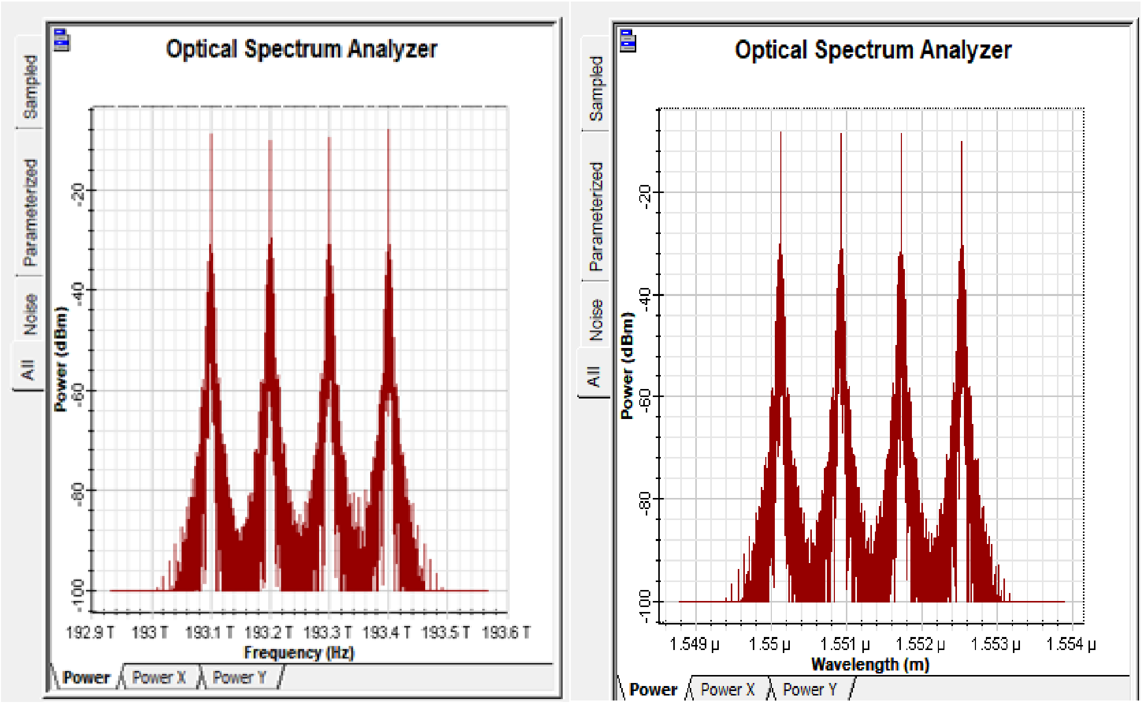
(c)

Figure 4.9. Optical spectrum analyzer (a) wavelength vs power and (b) Frequency vs power, (c) oscilloscope visualizer

The optical spectrum analyzer analysis and determine the frequency as well as the wavelength, which expresses the range of frequency and the range wavelength. As observed in figure (a) the wavelength is represented by the x-axis and frequency is represented the same in figure (b). The maximum frequency used here is 194 THz whereas the maximum wavelength used is 1.56 μm. This implies the wavelength used in C-band. The capacity of Gbps/fiber with a haul of 450km. The oscilloscope visualizer determines the amplitude of the optical signal as shown in figure 4.9 (c). The maximum power used in this OCDM is around 10dBm for both figure 4.9 (a) and (b). The SNR is 15dB BER10^{-9}. The mode and core used in this case are SMF with the no. of loss 0.4dB/km. The signal quality of OCDM is not good, as observed above in figures (a) and (b). In figure4.9 (c) the oscilloscope visualizer measure amplitude.

4. 5. The results for WDM in OFC systems

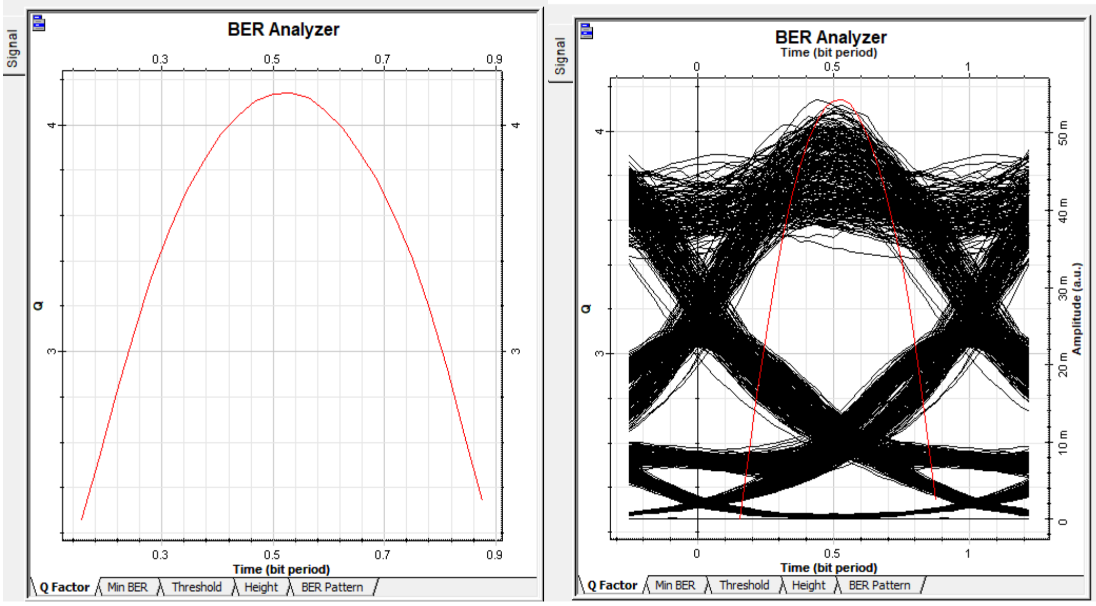
We know that WDM in optical communication systems can carry a large amount of information/ high capacity in terms of Giga and Tbps /Hz. This implies different multiplexing techniques using WDM for high capacity and hauls spatial transmission. The below one shows the circuit diagram of WDM in optical communication by using SMF or SCF with EDFA. However, here we used SMF.



(a) (b)

Figure 4.10. Optical Spectrum Analyzer. (a) Power vs Frequency, (b) Power wavelength

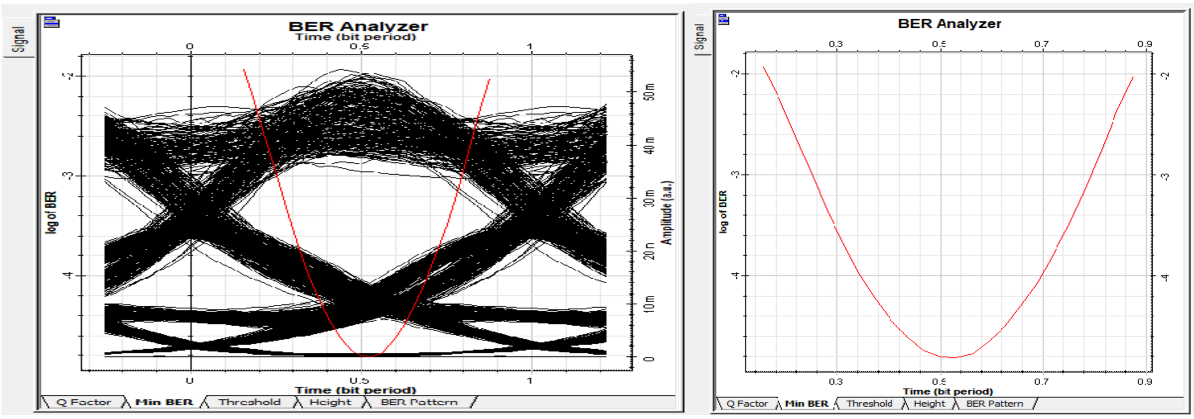
In figure 4.10 the frequency and wavelength of WDM in an OFC system. Each of the is displayed in figure 4.10 (a) and (b) and the frequency range and wavelength range is determined. The optical spectrum analyzer is used to analyze/evaluates the power with the frequency needed and wavelength to determine the OWDM here. Let us compare figure 4.10 (a) and figure 4.10 (b). In figure (a) the maximum power needed is -20.25dBm and the maximum wavelength is up to 1.554 μm in the figure 4.10 (b) the power is the same (-20.25dBm) and the maximum frequency is 193.6THZ, this implies that by using the same power the optical signal is transmitted across the transmission. The wavelength range (band) used is a conventional band (C- band) and the frequency range 192.9THZ-193.6THZ, and the wavelength range 1.549 μm -1554 μm with power -15dBm. The result is from the simulated software.



(a) (b)

Figure 4.11. BER analyzer. (a) Q -factor vs Time (b) Q-factor vs time with Eye diagram

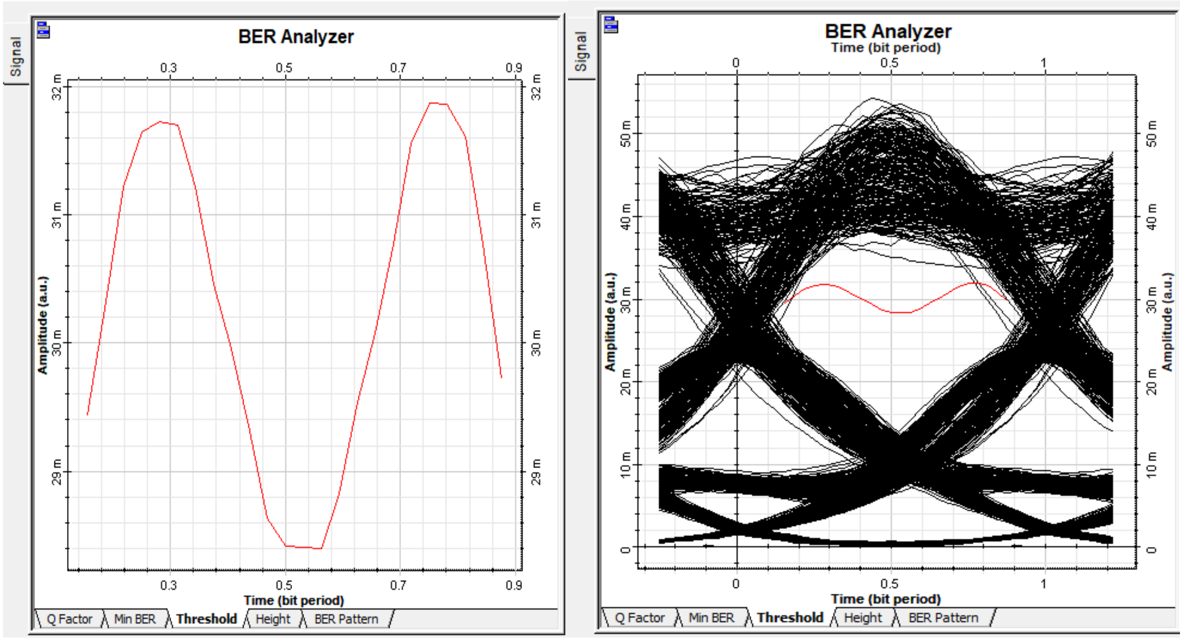
In above figure 4.11(a) and (b) shows Q-factor and Q-factor with the eye diagram and the BER analyzer calculates the performance of Q-factor. All parameters are the most important to measure the OWDM by using the BER analyzer in FOC transmission. When Q-factor increases the BER rate decrease, the capacity, and when the Q-factor decreases the BER increases, the loss will increase, and the capacity will be decreased. The BER 10^{-12} and the SNR are 30dB in fiber optic. As well as the capacity and haul, transmission signal in optical fiber communication is 35Tbps/fiber and 210km respectively.



(a) (b)

Figure 4. 12. BER analyzer. (a) Min BER vs Time and (b) Min BER with eye diagram

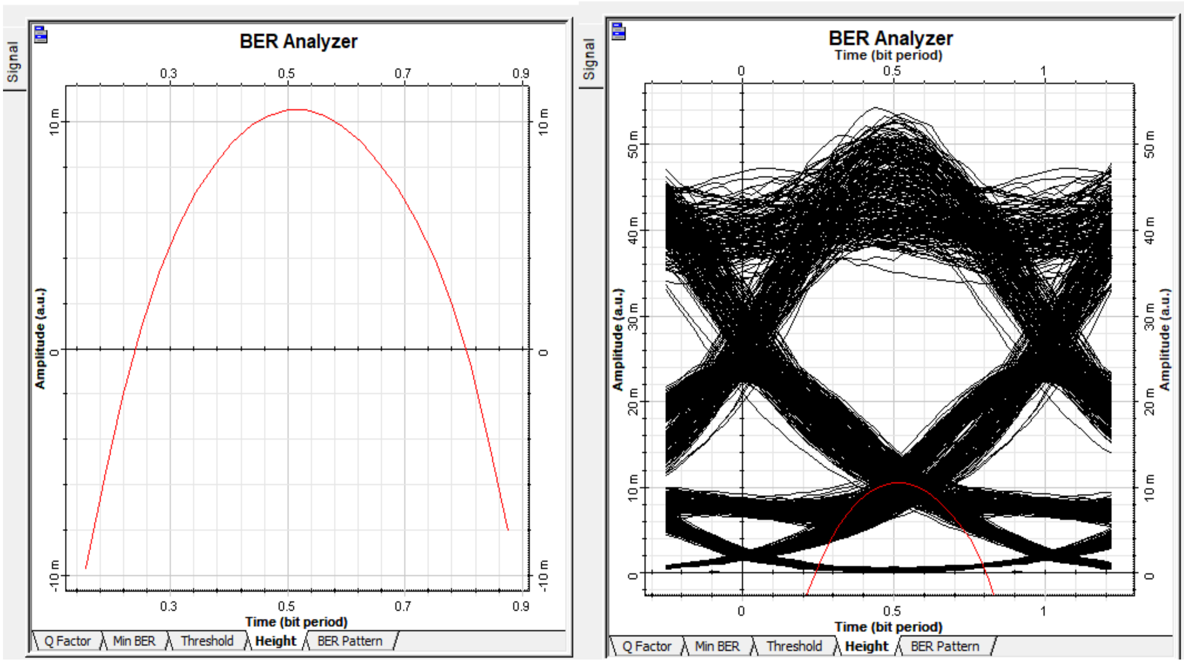
As we know that min-, BER is one of the parameters measured by using the BER analyzer. Here BER is decreasing SNR is increasing; capacity is also increasing as well as efficiency is increasing. In the above figure, the min BER is at -5.25, and at this, it has high SNR. However, log BER is -2.2. Here the signal quality is very good when we compare it to the other ones that the eye diagram (the measure of the signal quality) as shown in figure 4.12 (b).



(a) (b)

Figure 4.13. BER analyzer. (a)Threshold vs period and (b) Amplitude vs time

In this case, the BER analyzer determines the height and eye diagram with a height that is BER analyzer analysis and determines the height of the optical signal as well as the eye diagram with the height. This threshold is a measured tab that expressed amplitude (y-axis) and time (x-axis). Here from the above figure 4.13, we understand the relationship of height concerning amplitude as well as the threshold with the eye diagram. In figure 4.13 (a), the maximum threshold height is around 31.65m and the minimum one is 28.75m in figure 4.13 (b), the maximum amplitude of the eye is around 50.3m and the minimum one is 0m.



(a) (b)

Figure 4. 14. BER analyzer. (a) Height vs time. (b) Height of the eye and eye diagram

Here the maximum height is 10.25m and the bit period is around 0.9-bit period. Whereas the maximum eye diagram amplitude is around 50.5m and the minimum is 0m. From figure 4.14, the signal quality is good.

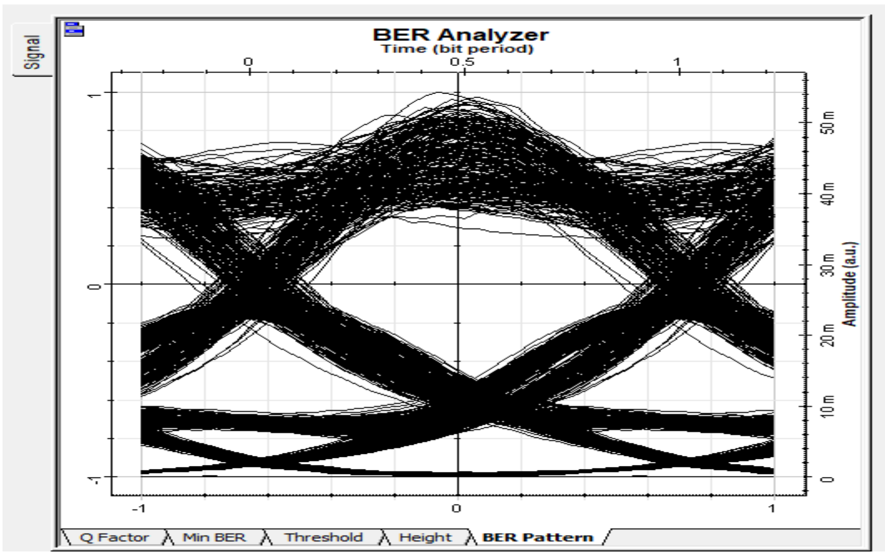


Figure 4. 15. BER pattern

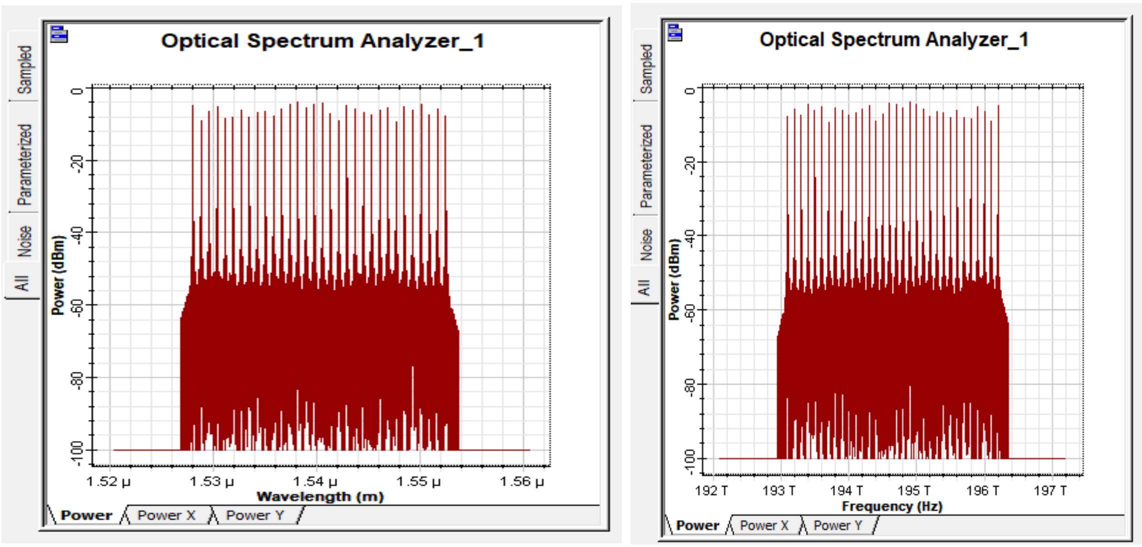
As we know, the BER analyzer analysis an eye diagram, the eye diagram is most important for dealing with the quality and stability of optical signals, and it contains height width, amplitude, etc.

Table 4. 1. WDM analyzer for WDM

Frequency (THz)	Signal power(dBm)	Noise power(dBm)	SNR(dB)	Noise Power: 0.1nm (W)	OSNR (dB)
193.1	-14.924732	-51.356881	36.43215	-53.393462	38.517899
193.2	-14.88221	-90.466549	75.584339	-92.912946	78.069243
193.3	-14.885009	-89.920414	75.035404	-92.404226	77.485818
193.4	-14.889557	-51.421506	36.53195	-53.480617	38.69911

5.6. Results for DWDM in OFC systems

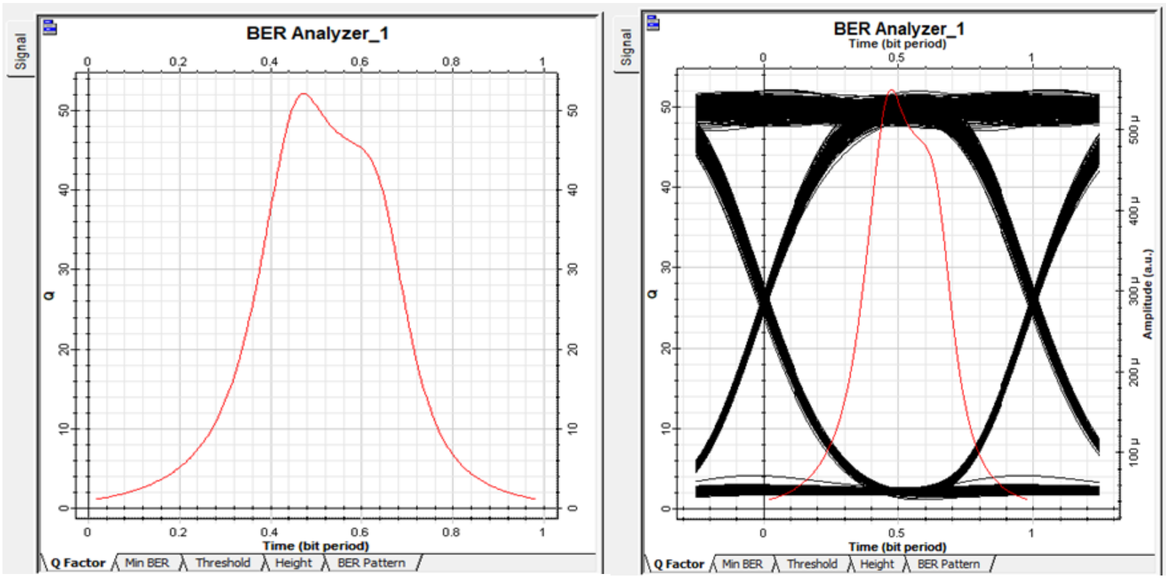
Here BER analyzer analysis the performance of the Q-factor, min- BER, threshold, height, and BER pattern with the Eye diagram, which is shown below. As we know from the background knowledge about DWDM it allows multiple optical signals and increases the bandwidth of existing OFC that transmits it by differing and separate data stream wavelengths each, transmitting each through a single link, and passing information.



(a) (b)

Figure 4.16. Optical spectrum analyzer. (a) Power vs wavelength and (b) power vs frequency

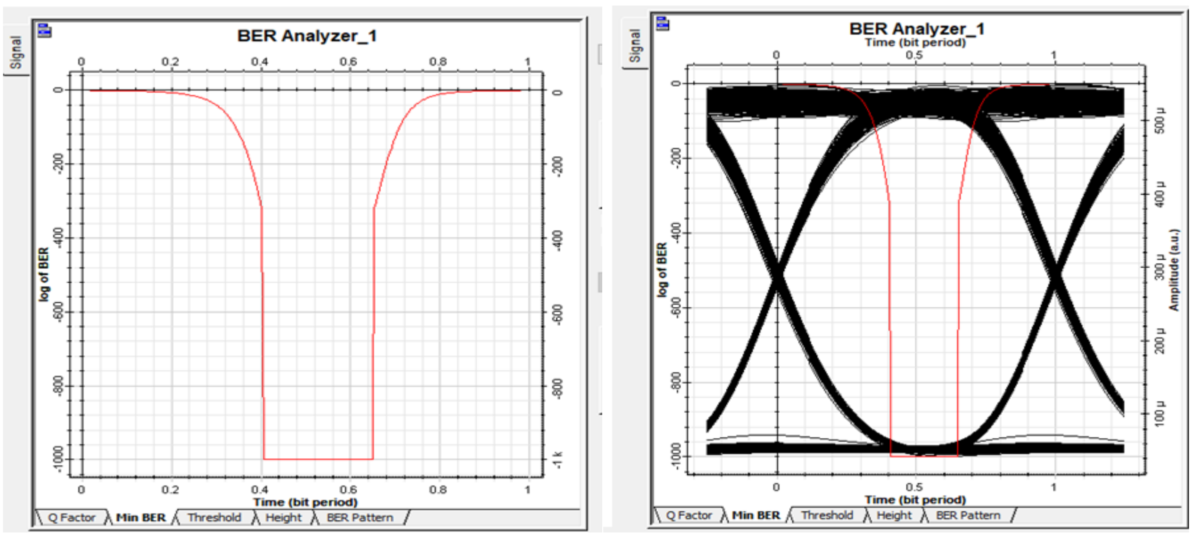
The main thing that we have to know is that there are two components in WDM these are the CDWM and DWDM. However, the information-carrying capacity is much greater (many multiple channels) than CWDM, and the DWDM. Here is the figure of wavelength and frequency with power in both figures, which shows that the maximum wavelength is 1.56 μm and the maximum frequency used is 197THz.The power that is used for DWDM is -20.5dBm.



(a) (b)

Figure 4.17. BER analyzer (a) Q- Factor vs time and (b) Q-factor with eye diagram

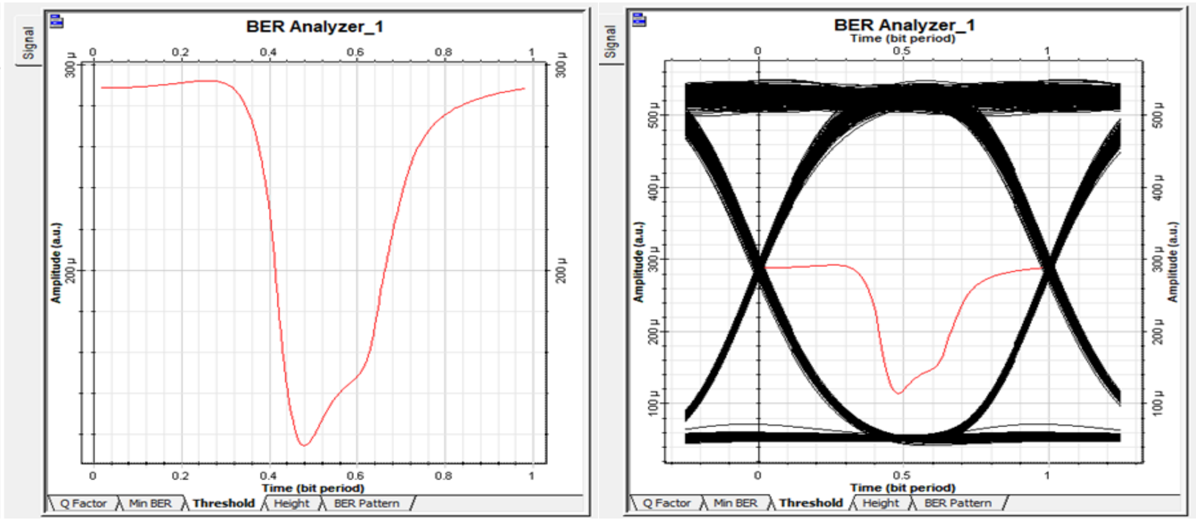
In the figure 4.17, (a) the maximum Q-factor is around 51 and the time is a bit period and the signal quality is good because when Q-factor is increasing the SNR also increases, and the capacity increases. When the Q-factor is high, the eye diagram is better, the bandwidth is increasing concerning the existed fiber. Here the Q- factor is high the signal to noise also high and better eye diagram when compare to the others.



(a) (b)

Figure 4.18. BER analyzer. In- BER vs Time and (b) Min –BER with eye diagram

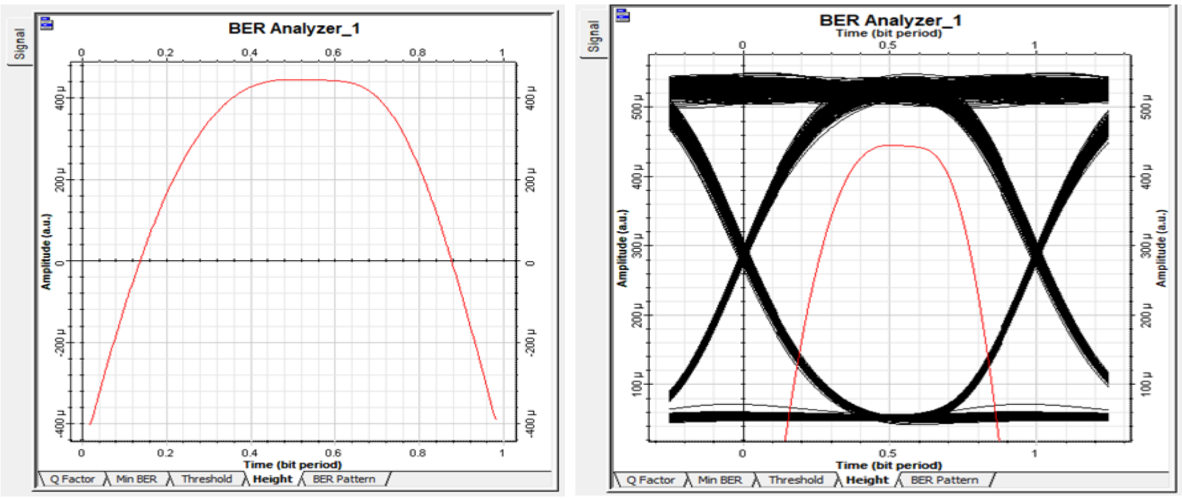
Here we deal with the Min BER and min BER- eye diagram. In figure (a) the min –BER is around 0 and the eye diagram has good quality and better, as well as the width of the eye, is wide the SNR is high and produces high-performance optical signal quality transmission systems.



(a) (b)

Figure 4.19. BER analyzer. (a) threshold vs time and (b) threshold vs eye diagram

From the above figures 4.19 (a) and (b) we know that threshold concerning time and with the eye diagram. The eye diagram has a good Q- factor and it is essential in OFC transmission.



(a) (b)

Figure 4.20. BER analyzer (a) Height vs amplitude, (b) height with the eye diagram.

In figure 4.20, the height is high so the quality is high also high. The SNR is 30dB, which is high as well as the optical SNR (OSNR) is also high the capacity is high it is 80Tbps/fiber. The haul transmission is 330km.

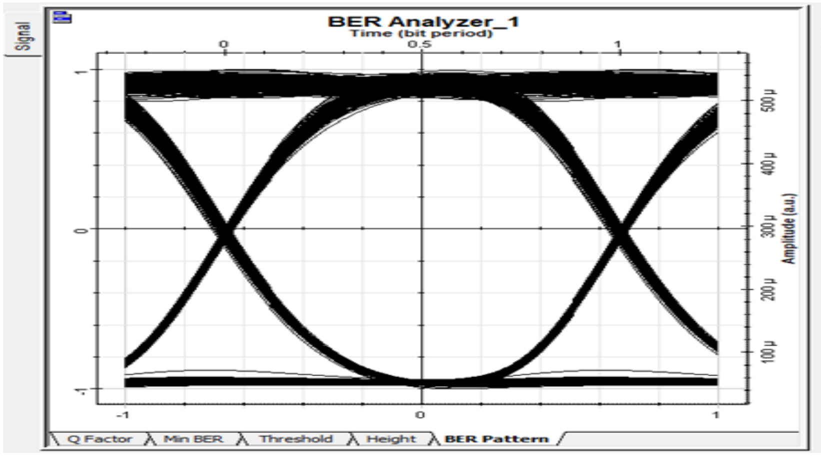


Figure 4.21. BER pattern

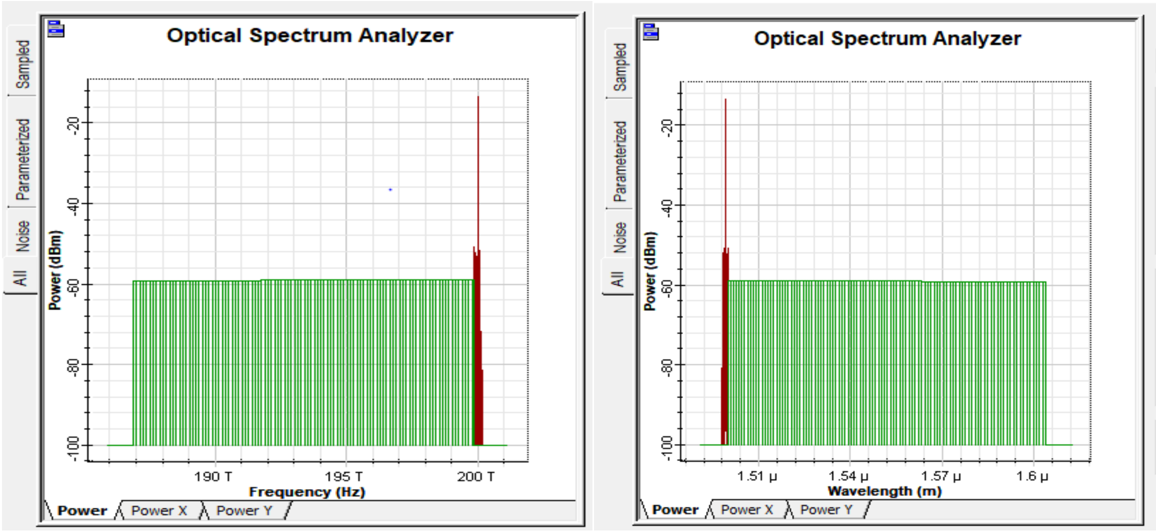
The eye diagram of the BER pattern is good as well a better quality of the signal is produced using the BER analyzer to test DWDM for fiber optics is very important. From all the above the DWDM is very important in the current issue.

Table 4. 2. WDM analyzer for DWDM

Frequency(THz)	Signal Power (dBm)	Noise power (dBm)	SNR(dB)	Noise power:0.1nm (dBm)	OSNR(dB)
193.4	-91.65	-100	8.77	-100	8.77
193.9	-88.83	-100	11.814	-100	11.81
194.4	-84.49	-100	15.5	-100	15.5
194.9	-79.82	-99.8	19.8	-100	20.17
195.4	-79.4	-91.78	18.38	-93.8	20.42
195.9	-63.27	-75.08	11.81	-77.12	13.85
196.1	-56.14	-90.68	34.53	-92.72	36.57
196.2	-51.36	-88.20	36.83	-90.24	38.87

4.7. Result for Digital Coherent OFC systems

The coherent optical fiber communication is analyzer using an optical spectrum analyzer and this analyzer analysis the frequency with power and wavelength the same.



(a) (b)

Figure 4.22. Optical spectrum analyzer (a) Frequency vs Power and (b) Wavelength vs Power

Figure 4.22 shows the frequency and wavelength concerning power in OFC. In figure re, (a) the maximum frequency used is 200THz with maximum power -18dBm. In figure (b), the maximum wavelength used is 1600nm, and the used wavelength band is the c- band.

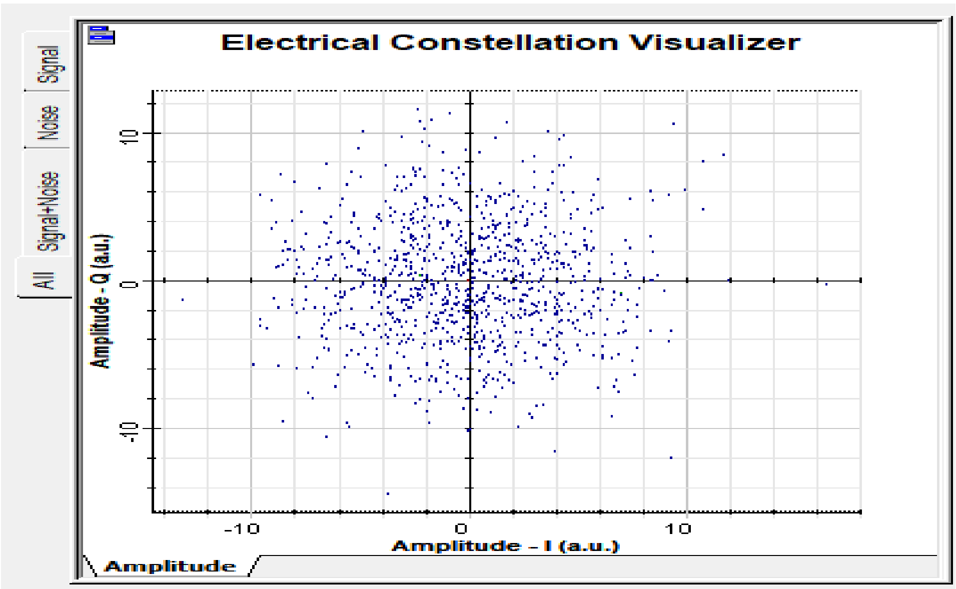
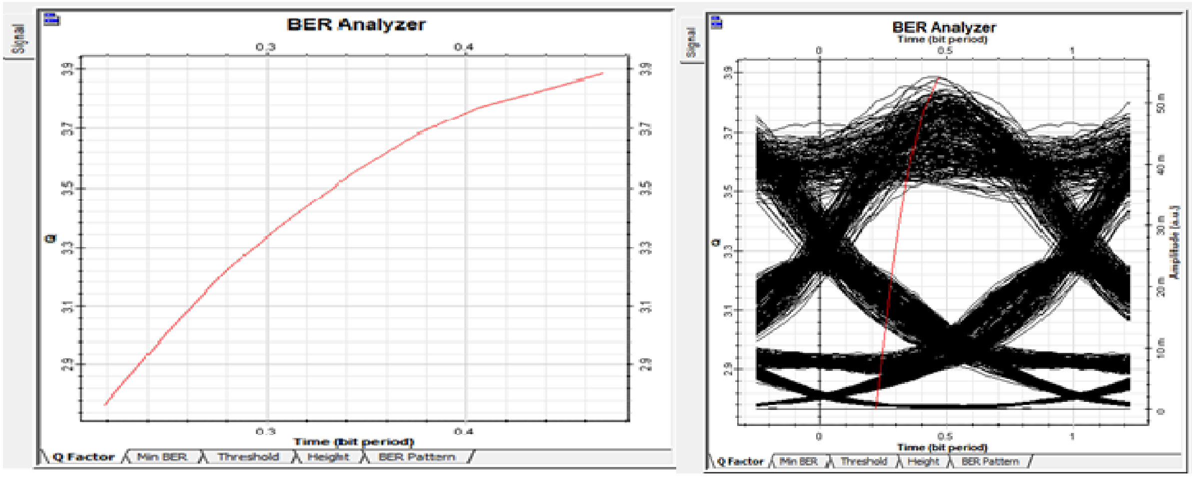


Figure 4.23. Electrical constellation visualizer

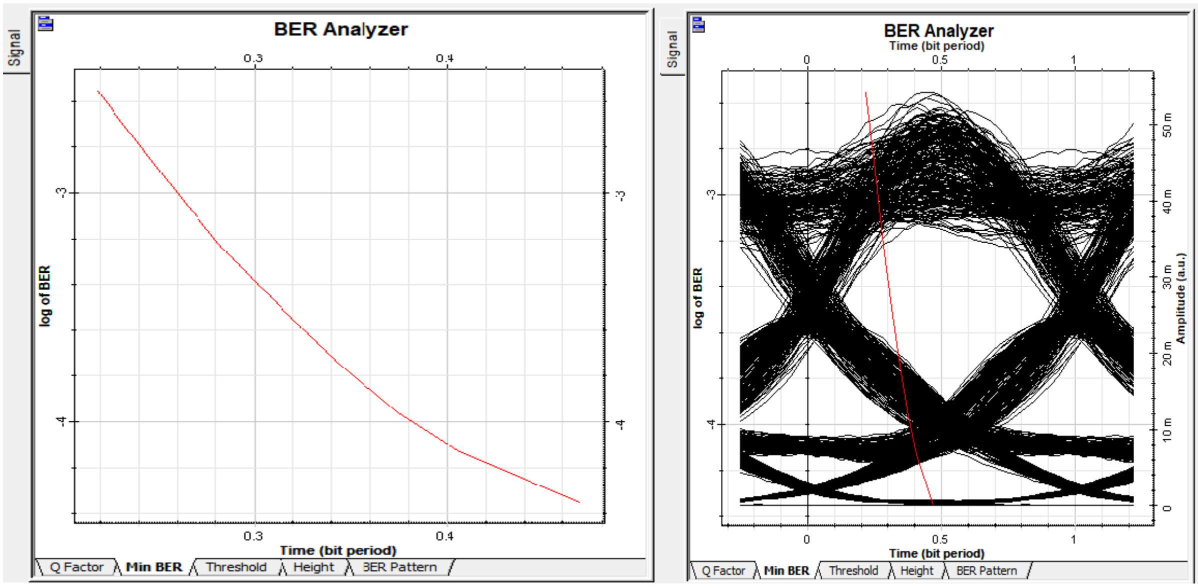
The above figure 4.23, shows the amplitude in phase (Amplitude -I) on the x-axis and amplitude –Quadrature (Amplitude -Q) on the y-axis. The maximum amplitude-Q and I are 10a.u.



(a) (b)

Figure 4.24. BER analyzer (a) Q-factor vs Time and (b) Q-factor vs Time with Eye diagram

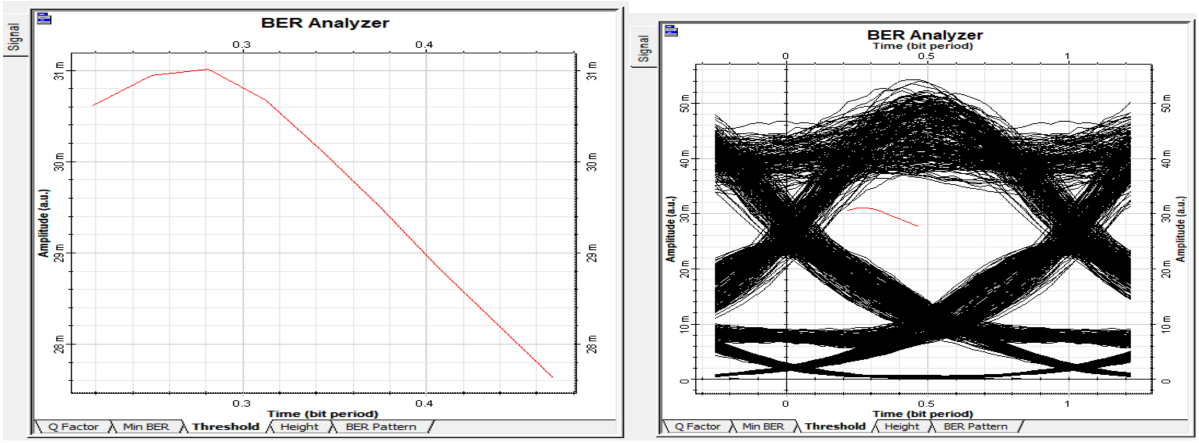
Here the quality factor is 3.9 good compared to optical FDM, TDM, and CDM and the SNR is 25dB. The BER is 10^{-11} with a good eye diagram. Figure 4.24 (a) shows the Q-factor of digital coherence in optical fiber communication transmission and figure 4.24 (b) shows the Q-factor with an eye diagram.



(a) (b)

Figure 4.25. BER analyzer (a) Min BER vs Time and (b) Min BER with Eye diagram

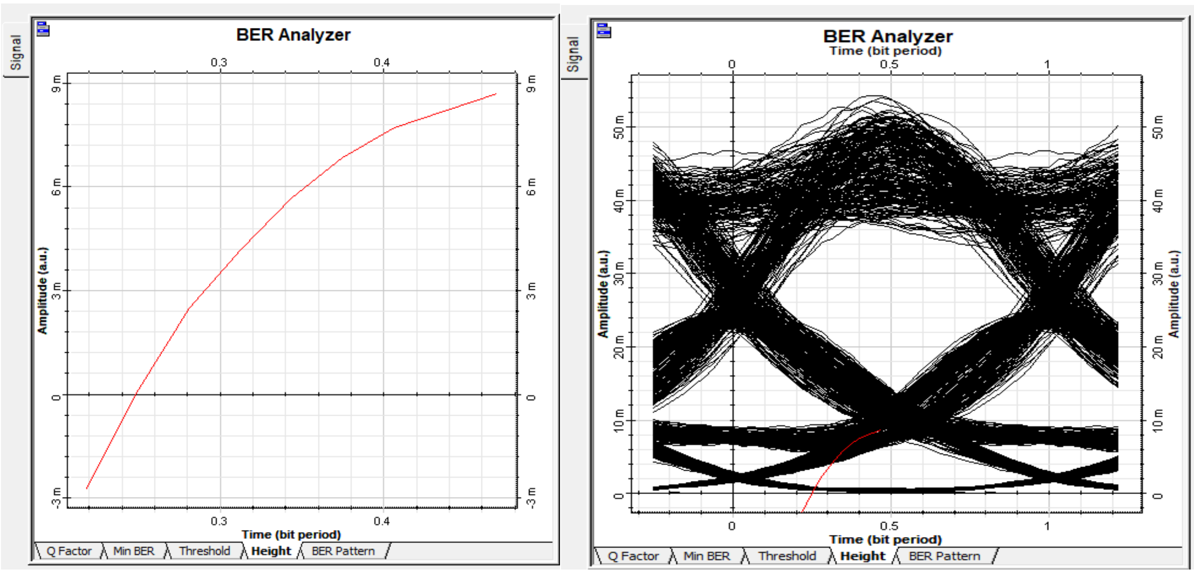
Here in figure 4.25 (a) the min BER is -0.003 and figure 4.25 (b) the min BER with an eye diagram concerning time (bit period) in communication systems.



(a) (b)

Figure 4.26. BER analyzer (a) Threshold vs Time and (b) Threshold vs Time with Eye diagram

Figure 4.26 shows the threshold with time (bit period) as well as this eye diagram. As it is observed, the amplitude of the threshold falls from 30.5m and stops at 27.5m. Figure 4.26 (a) shows, the y-axis amplitude of the signal and x-axis is time (bit period) and figure 4.26 (b) shows the threshold with an eye diagram.



(a) (b)

Figure 4.27. BER analyzer. (a) Height vs Time and (b) Height vs Time with Eye diagram

Here we observed that in figure 4.27(a) it is the parameter used is the height and its height is around max 8.9m with time in period 0.49-bit period. In figure 4.27 the eye diagram with high quality of signal in information transmission.

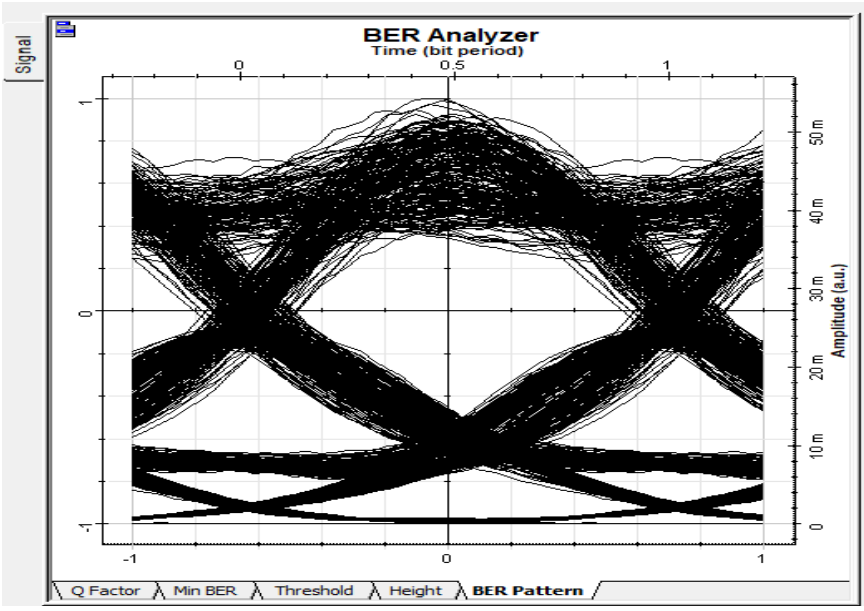


Figure 4.28. BER pattern using BER analyzer

The haul transmission and capacity are 1500km and 30Tbps/ fiber respectively and the loss during transmission is 0.2dB/km as well as SNR is 25dB. The quality of the eye diagram is also good. In optical communication, DWDM is very essential.

4.8. Capacity enhancement in OFC systems by using SDM

The enhanced capacity of fiber optics using the SDM technique for this thesis is about 14.75e+15(14.75 Peta) bit per second per fiber. The reason why we need high capacity (enhanced high capacity) is that humankind needs more and more (development and commercial) is highly increasing. Therefore, capacity enhancement is very important. Using M=2 and above reduce the capacity so that it is not needed to use at this time. For example M=2 the capacity is 7.74e+15 bit per second per fiber, so the previously reviewed paper reached 10.66 petabits per second per fiber. Because of this M=2 and more than that are not used .this is because of loss and modal dispersion in communication systems. This implies that when the number of modes is increasing the cross talk, loss and modal dispersion between strands of MMF in OFC increases, which means using the number of modes is not necessary here so we used one mode of propagating the signal pulse of light in OFC systems.

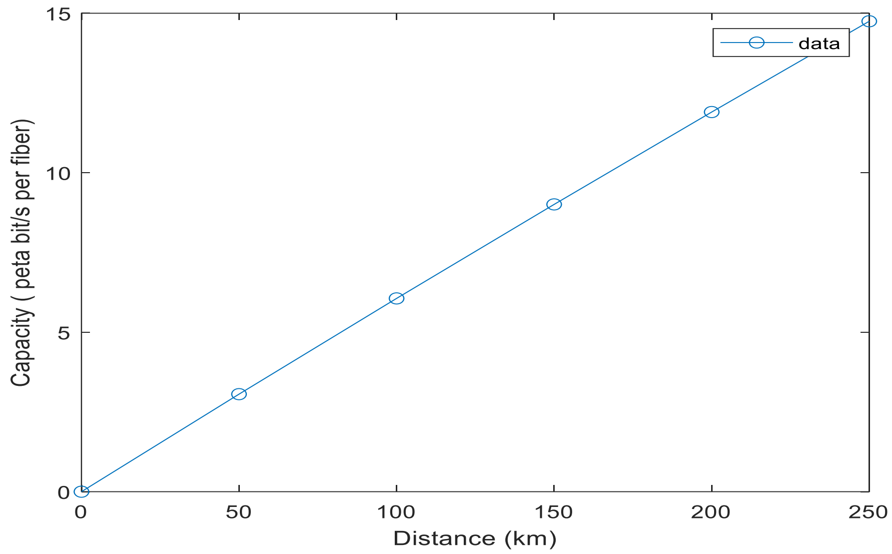


Figure 4.29. Capacity vs Distance

It is difficult to avoid modal dispersion in MMFs used commonly for SDM systems. In the above figure, we understand the r/sh between capacity and long transmission. As observed the capacity is increasing up to 14.75peta bit per second per fiber and the distance is 250Km. the fiber loss is 0.2dB/km and the power used is -13dBm.The biased current is 23mA, as well as the power at the biased current, is 0dBm. In fact, when capacity increase distance is decreasing, in this case the capacity increasing up to 14.75P/S/ fiber with distance 250km and when the number of modes is two the capacity is decreasing the distance is increasing.

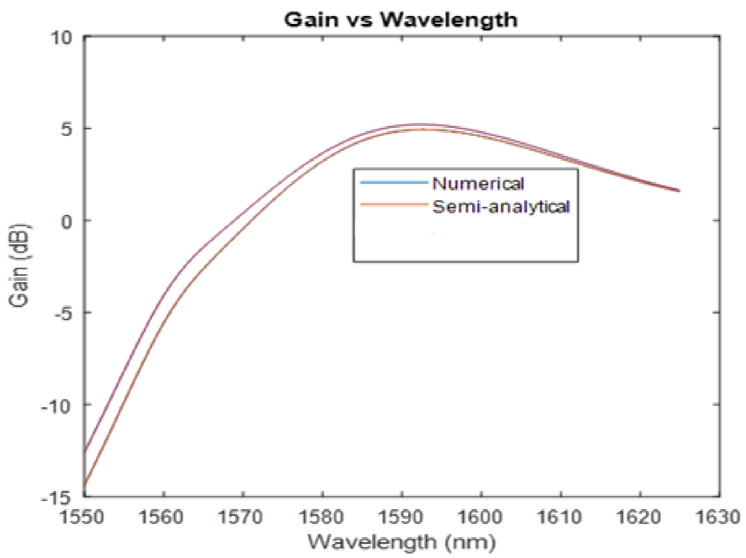


Figure 4.30. The Gain vs wavelength

Here the gain is around 5.5dBm.As the wavelength increase, the gain also increases up to 1595nm and after the gain is decreasing, the wavelength is increasing. This shows that the gain is fixed /constant it is access able for each wavelength. Therefore, the power to be transmitted from the transmitter is very important to proceed/ move the data rate with its capacity handled and the long haul transmission in OFC systems with the bandwidth, wavelength, BER, SNR, and amplification needed for this case.

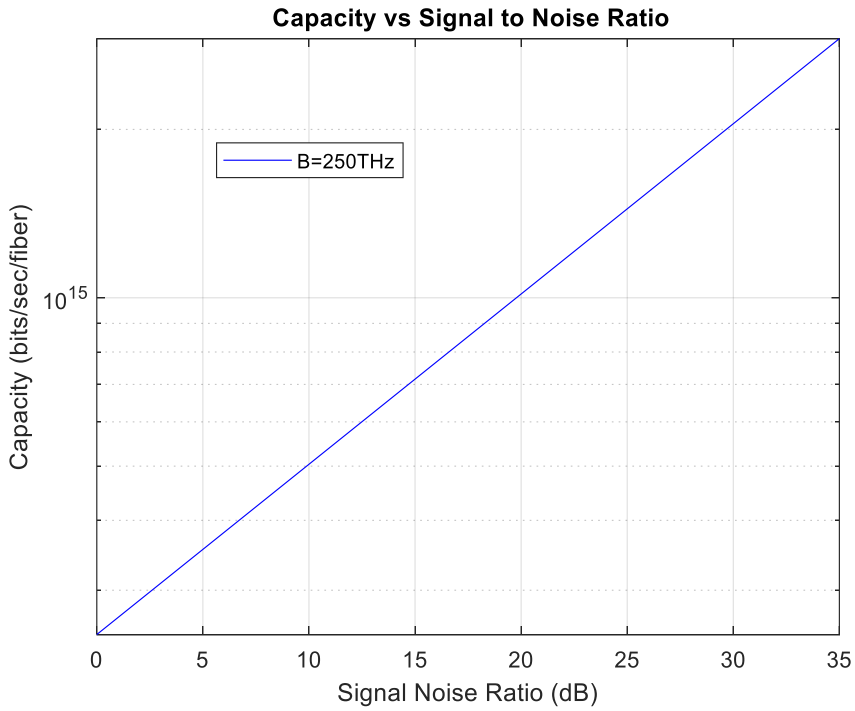


Figure 4.31. Capacity vs Signal to Noise Ratio

Here the usable bandwidth is 250THz for the capacity-enhanced 14.75-Pbs/fiber. The SNR is 35dB and the BER is 10^{-12} to transmit with the long- haul of transmission in OFC. Therefore 35dB for the transmission for 250Km.

4.9. Reduction of cross-talk in OFC by using MMF

The reduction of receiver complexity or cross-talk is very important in communication systems. In OFC systems, cross-talk is reduced by using MMF as SDM. Figure 4.32, shows the reduction of cross-talk in the OFC system and it is the main factor that affects the flow of information in communication systems, which should be reduced.

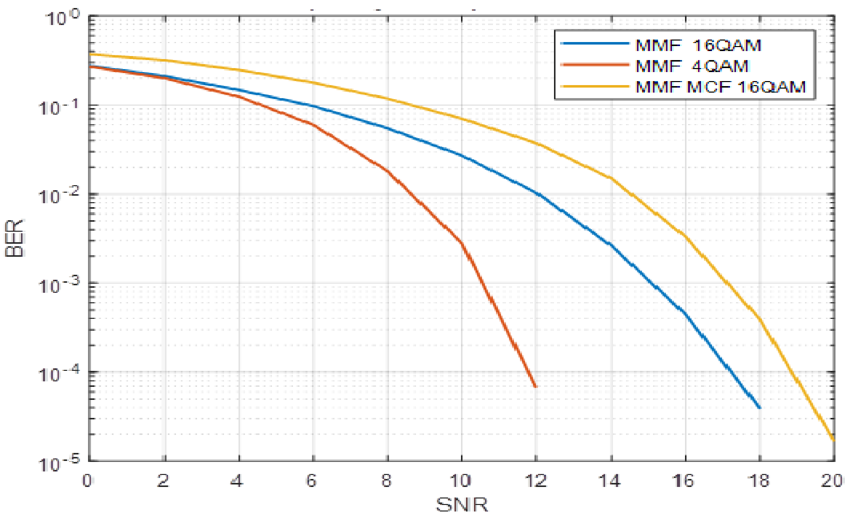


Figure 4.32. The cross-talk reduction in fiber optics using MMF With QAM and MCF

From the above figure, the BER is reduced, SNR is increased, and this will be possible with MMF with 16QAM, 4QAM, and MMF-MCF 16QAM. Here MMF 4- QAM is the most preferable to the other things. The above figure shows the reduction of cross-talk/receiver complexity on the receiver side. The reduction of BER and increase in SNR using MMF with QAM as SDM increase the capacity of OFC systems and the most SNR is 18dB and 10^{-9} BER.

4.10. Reduction of loss in OFC systems using SDM

The light pulse is transmitted through the cores at an angle and the angle of incidence hits the cladding, where lost. The attenuation, cladding, core, angle of incidence, macro bend, micro bend, and optical fiber. The reduction of the loss in OFC systems is one factor that limits the capacity enhancements and long-haul transmission of information. The reduction of loss in fiber optics is the one thing that has gotten to be reduced in an exceeding transmission communication system. Here loss reduction using MMF spatial modulation in fiber optics transmission systems. As observed in figure 4.33 loss in optical fiber will be reduced with the help of MMF in the SDM technique. The BER in this case 10^-12 and the SNR is 30dB as is shown in the figure above the BER is decreasing the SNR is increasing and vice versa. The performance is increasing with capacity also. Therefore, FOC loss is the main issue that interrupts communication during information transmission.

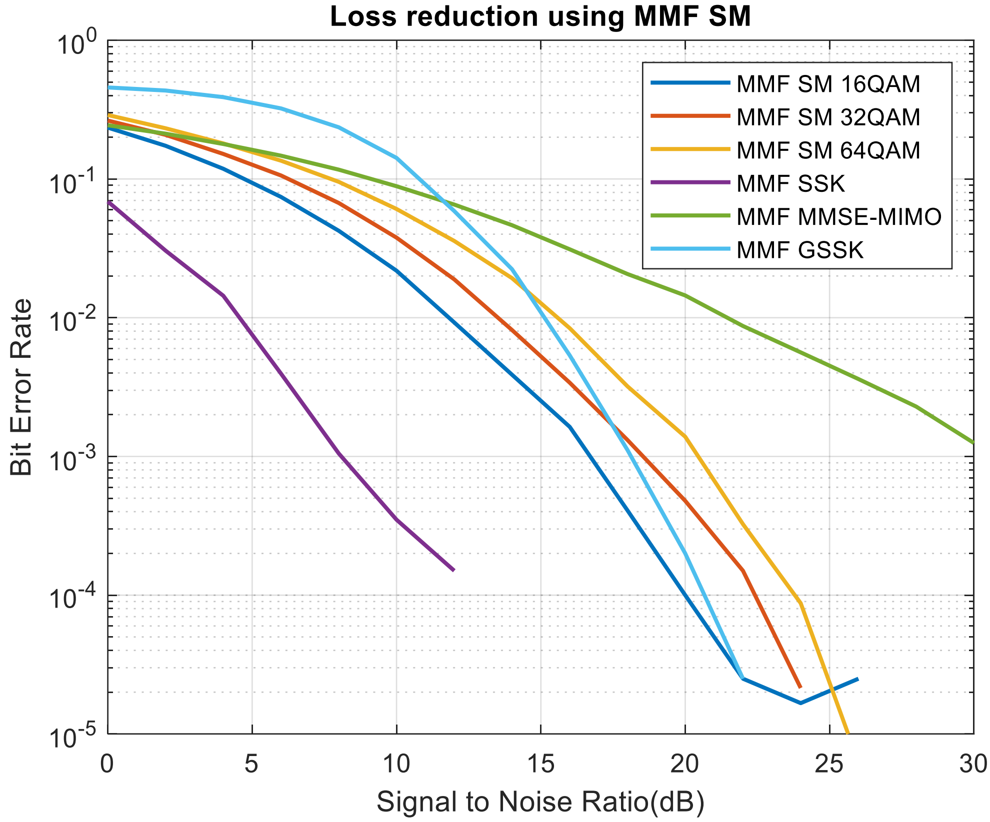


Figure 4.33. Reduction of loss in optical communication systems

The above figure shows the reduction of loss in FOC systems using spatial modulation with the 16QAM, 32QAM, 64 QAM, Spatial shift keying (SSK), General spatial shift keying (GSSK), and Minimum mean Square Error (MMSE) with MIMO. In this case, using all the items the loss will reduce due to the MMF with spatial modulation used as SDM; as we all know that SDM uses multiple signals with spatial/space modulation. In this paper space modulation and spatial modulation has no difference additionally as space multiplexing and spatial multiplexing. On the graph, the loss is generally reduced with MMF SSK. In this case, compared with another thing when the range increased from 16-to 32 more loss will happen so using MMF SM-64QAM is preferable.

4.11. Reduction of distortion/dispersion in OFC systems using SDM

The following figure shows the figure of distortion reduction in fiber optics using SDM, which is shown below. In OFC systems distortion reduction is the main issue because if more distortion is available the signal flow is difficult to transmit information. Here the MMF and MCF are used by 2:4 respectively.

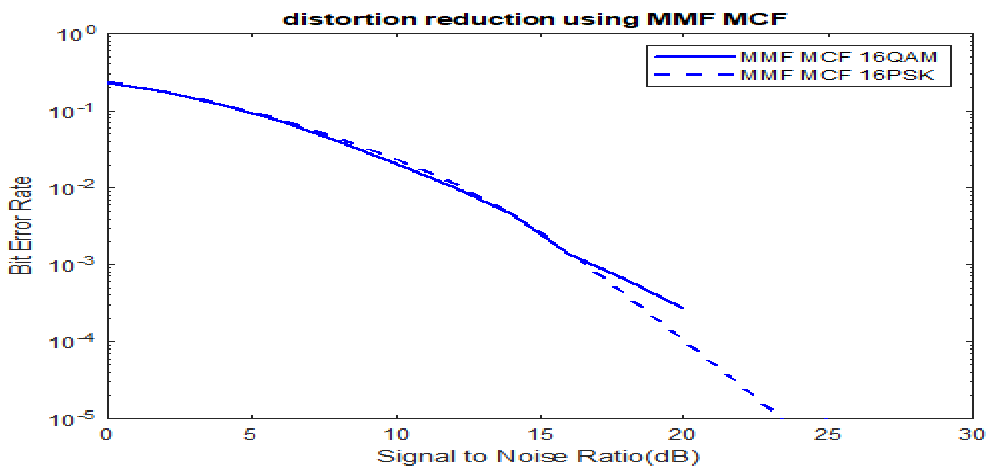


Figure 4.34. Distortion reduction in FOC using MMF-MCF in SDM

Here we have to understand that using SDM for optical fiber has a very important issue by using MMF with MCF and the BER is 10^-11 and the SNR is around 30dB for long haul transmission of information and the wavelength transmission with L- band.

4.12. Reduction of energy/power consumption in using MMF in SDM

The reduction of power consumption is the main issue in all OFC systems. It is shown below.

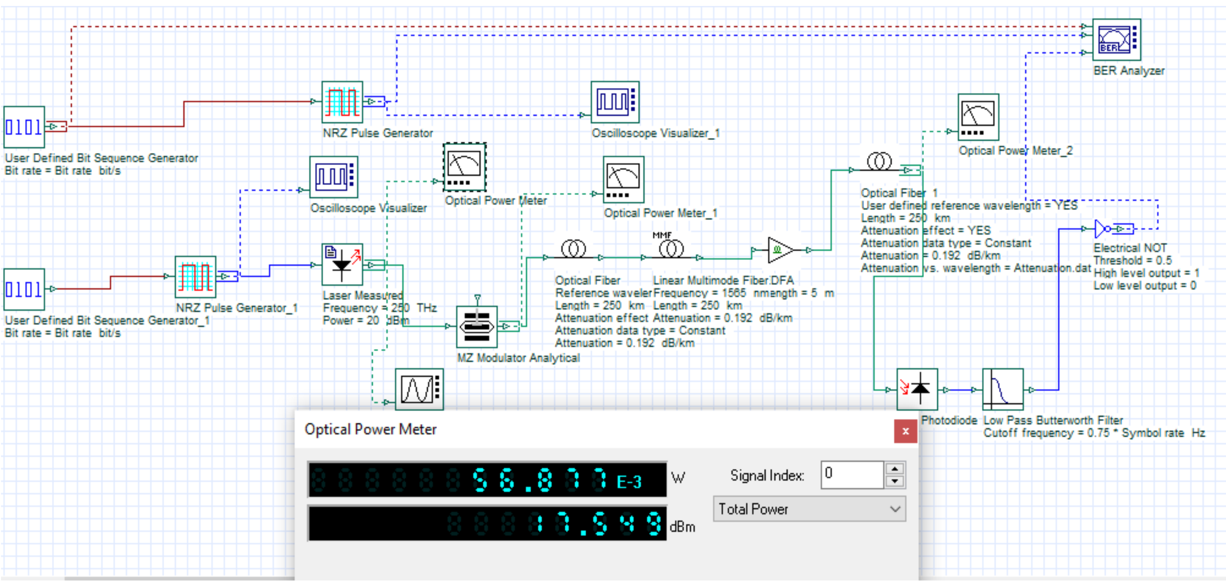


Figure 4.35. Result of power consumption of laser of direct transmitter

We design a Direct Transmitter diagram/ Circuit to reduce power/energy using Opt system Software that is use a laser for radiating 20dB power for any type of binary data stream. Therefore, power consumption for the direct transmitter is the same 17.550 dB for each sequence of logic 0's and 1's and transmits via the optical fiber wire, for communication systems as shown in the figure below. We use a laser with the frequency 250 THz and power supplying 20dBm for each binary data stream. The power consumption for this direct transmitter is the same 17.549dBm for a different binary sequence.

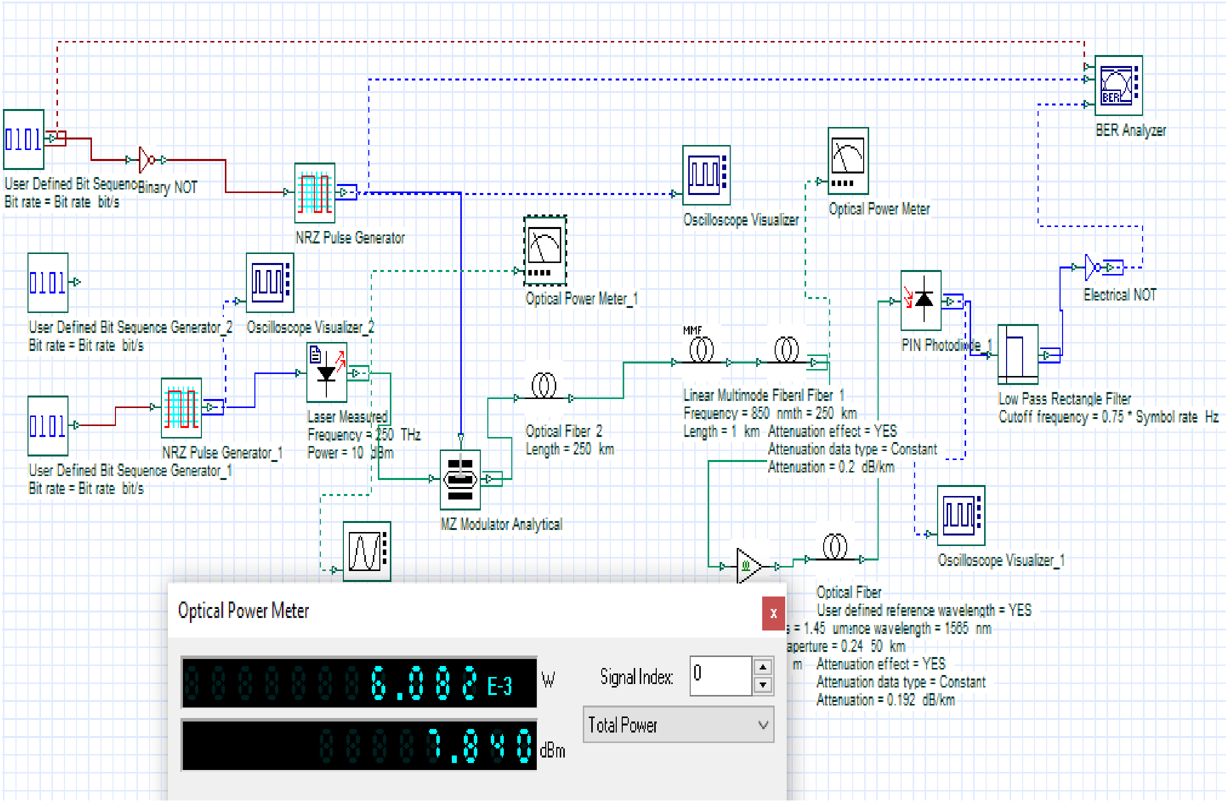


Figure 4. 36. Result of Power Consumption of Laser Inverted Transmitter

First, we transmit a binary stream of 1's up to 10^{15} bits through both direct transmitter and inverted transmitter to observe the power consumption of the laser respectively.

Table 4.3. Parameters to be considered for reduction of power consumption

Name	Value	Unit	Mode
Capacity	14.75e+15	b/se/Hz	Normal
Usable frequency	250	THz	Normal
Power	20	dBm	Normal
Fiber length	250	km	Normal
Attenuation/loss	0.2	dB/km	Normal
Power at a biased current	0	dBm	Normal
Bias current	23	mA	Normal

Table 4.4 Compare the performance of various types of multiplexing techniques

	Parameters in optical fiber communication systems							
S.no		FDM	TDM	CDM	Coherent technology	WDM	DWDM	SDM
1.	Max freq.	200THz	193.2 THz	194 THz	201.6 THz	193.6 THz	197 THz	250 THz
2.	Wav.Band	S+C	C+L	C	S+C+L	C	S+C	C+L
3.	BER	10^{-9}	10^{-9}	10^{-9}	10^{-11}	10^{-12}	10^{-12}	10^{-12}
4.	SNR(dB)	20	20	15	25	30	30	35
5.	Capacity	40Gbps/ fiber	200Gb/s/ fiber	60Gb/s/ fiber	30Tbs/ fiber	35Tb/se/ fiber	80Tb/s/ fiber	14.75Pb/s/ fiber
6.	Distance (km)	250	350	450	1500	210	330	250
6.	Power(dBm)	15	-25	10	18	-15.25	-20.25	20
7.	Mode type	SMF	SMF	SMF	SMF	SMF	SMF	SMF
8.	No of mode	1	1	1	1	1	1	1
9.	Core type	SCF	SCF	SCF	SCF	SCF	SCF	MCF
10.	No of core	1	1	1	1	1	1	4
11.	Core/ cladding diameter	9/125 μm	9/125 μm	9/125 μm	9/125 μm	9/125 μm	9/125 μm	9/125 μm
12.	Loss (dB/km)	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Conclusions and Recommendations

Conclusions

According to the results and discussion, the SDM in FOC systems has an important role to increase high-capacity data rates and long-haul transmission systems**.** SDM techniques enable a vast increase in transmission capacity by using space. We have demonstrated the capacity enhancement in fiber optics communication systems using SDM techniques since it is the focus of the thesis. The capacity enhanced to14.75peta bit per second per fiber with a distance transmission of 250km. The wavelength band S+C+L with SNR 35dB and the spatial channels with the frequency range of 250THz using MMF with the number of modes is one. The no. of core used in this case is four with the help of Matlab software. Compare and contrast the multiplexing techniques like FDM, TDM, CDM, WDM, DWDM, and Digital coherent technology with SDM by using optical fiber parameters. There is a huge difference between other multiplexing techniques and SDM in the case of FOC systems. Reducing the loss and its SNR 30dB, cross talk/receiver complexity with its SNR 30dB, and distortion/ dispersion in transmission systems. Finally, energy/power consumption reduction using MMF with the help of optical wave software and reduced power consumption 17.549dBm for direct transmitter and 7.840dBm for inverted one. Generally, we conclude as for extremely high capacity data and long-distance transmission SDM techniques for optical fiber are very essential to other multiplexing technologies.

Recommendations

Here we recommend the capacity enhancement for fiber optics communication systems using the SDM technique. As we know that in SDM for OFC systems using MMF, MCF, as well as a combination of them, is very important. For the future work:-

- Core division multiplexing by using FMF- MCF fiber for fiber optic transmission.
- Combination of mode and core division multiplexing with one MMF and limited no of MCF in fiber optic transmission.

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Appendix: Matlab Code

```
clc;
clear;
D=250000 ;% distance in m
lamda=1.625; % wavelength in microns
c=14.75 e15 ;   % capacity in peta bit per second per fiber
M =1; % no of mode
C =4; % no of core
B=250000000000000;    % Bandwidth B in Hz
color=['b'];
snr_db=(Z. Liu et al.); % in dB
snr=10.^(snr_db/10); % in linear scale
for i=1:1:4
 C=B(i)*log2(1+snr)/M;        % Capacity calculation
semilogy(snr_db,C,color(i));
 hold on;
 title(' Capacity vs Signal to Noise Ratio');
xlabel('Signal Noise Ratio (dB)');
ylabel('Capacity (bits/sec/fiber)');
grid on;
legend('show');
legend( 'B=250THz','Location','northwest');
end
clc,
close all
E = EDF(15.5, 'principles_type2');
m=1; % no of mmf
C= 4; % no mcf
B=250000000000000 ; %  band width in Hz
p=20; % power in dBm
df = 50e9;
dlamb = df2dlamb(df);
lamb = 1530e-9:dlamb:1625e-9;
```

```
L = 5e10; % total link distance in m
MMF = fiber(50e3, @(lamb) 0.18, @(lamb) 0);
 Pon = 1e-4;
Signal = Channels(lamb, Pon, 'forward');
Pump = Channels(1480e-9, 30e-3, 'forward');
problem.Pon = Pon;
problem.df = df;
TotalPump = 8:10;
% Ppump = (15:5:60)*1e-3;
Lspan = 0:50:250;
for p = 1:length(TotalPump)
 for l = 1:length(Lspan)
 MMF.L = Lspan(l)*1e3;
N = L/MMF.L; % number of amplifiers in chain
 [~, spanAttdB] = MMF.link_attenuation(Signal.wavelength);
   problem.spanAttdB = spanAttdB;
   problem.Namp = N;
  % Pump power for each span
   Pump.P = TotalPump(p)/N;
    fprintf('Lspan = %d km, Pump.P = %.2f mW\n', Lspan(l), Pump.P*1e3)
   % [E, Signal] = optimize_power_load_and_edf_length('particle swarm', E,
Pump, Signal, problem, true);
      Lopt(p, l) = E.L;
        % Capacity calculation using numerical model
        E.L = Lopt(p, l);
        SignalOn = Channels(Signal.wavelength(Signal.P ~= 0),
Signal.P(Signal.P ~= 0), 'forward');
        ASEf = Channels(SignalOn.wavelength, 0, 'forward');
        ASEb = Channels(SignalOn.wavelength, 0, 'backward');
        GaindB_semi_analytical = E.semi_analytical_gain(Pump, SignalOn);
        [GaindB, ~, ~, Pase, sol] = E.two_level_system(Pump, SignalOn, ASEf,
ASEb, df, ceil(Lopt(p, l)/0.05));
        figure(100), hold on, box on
        plot(SignalOn.wavelength*1e9, GaindB, 'DisplayName', 'Numerical')
```

```
plot(SignalOn.wavelength*1e9, GaindB_semi_analytical, 'DisplayName',
'Semi-analytical')
        xlabel('Wavelength (nm)')
        ylabel('Gain (dB)')
        legend('-DynamicLegend', 'Location', 'SouthEast')
        drawnow
            % Pase is ASE power in a bandwidth df
        Gain = 10.^(GaindB/10);
        C(p, l) = sum(log2(1 + SignalOn.P.*Gain./(Pase*(N-1))));
    end
        figure(10), hold on, box on
    plot(Lspan, Lopt(p, :), '-o', 'DisplayName', sprintf('Total pump = %d W',
TotalPump(p)))
    xlabel(' Distance (km)')
    ylabel('Optimal EDF length (m)')
    plot(Lspan, C(p, :), '-o', 'DisplayName', sprintf('Total pump power = %d W',
TotalPump(p)))
    xlabel('Distance (km)')
    ylabel ('Capacity ( peta bit/s per fiber)')
```