PERFORMANCE DEMONSTRATION OF OPTICAL FIBER AND LORA WIRELESS COMMUNICATION TECHNOLOGY FOR SMART POWER GRID METER READING APPLICATIONS

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DECLARATION AND APPROVAL

Declaration

This thesis is my original work and has not been presented for the conferment of a degree or award of a diploma in this or any other institution.

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ABSTRACT

The current electric grid is faced with the problem of slow and ineffective communication between the utility and the end users. Therefore, there was an urgent need for a communication system with automation capabilities and high-speed data transfer. This study sought to demonstrate a communication system performance of a power grid for real-time communication between the utility and the end users using the LoRa and optical fiber technology. The purpose of the study was to characterize and analyze the transmission performance of the Vertical Cavity Surface Emitting Laser (VCSEL) and Distributed Feedback Laser (DFB) on a G.655 non-zero dispersion shifted fiber transmitting at 1550 nm window. The set-up was evaluated using bit error rates (BER) analysis and eye diagrams for the VCSEL and DFB laser. There results showed successful transmission of 10 Gbps in 25 km and 50 km for VCSEL and DFB respectively. Simultaneous data and clock transmission at 0.4 GHz and 10 Gb/s over 25 km was successfully achieved using a VCSEL. The study utilized the all-optical wavelength reuse for the realization of a cheaper meter reading approach for smart grid application. This technique was demonstrated through the exploitation of the holding beam and the gain saturation of the EDFA. A 10 Gbps data was used to modulate a DFB laser and transmitted downstream over 50 km. The saturated EDFA lowered the downstream data's extinction ratio from 9.678 dB to 0.702 dB which was significant for both wavelength reuse and data rewrite for upstream transmission. The performance analysis for upstream and downstream transmission was done and the receiver sensitivity at back-to-back (B2B) determined at BER telecommunication threshold of 10^{-9}. The various eye diagrams were also analyzed for upstream and downstream transmissions. The wireless TTGO Long Range Radio (LoRa) ESP 32 Dev module was characterized. The experiment used a low-frequency clock drive to characterize LoRa. Using a Rohde and Schwarz signal generator and spectrum analyzer, the LoRa input power was set to -8.13 dBm and the frequency range between 600 MHz to 800 MHz. The implication of this was to provide a broadband frequency spectrum from which to select the frequency that would provide the optimum output power for transmitting the signal with the required strength. The strongest signal for transmission and the actuation of gates required for the gathering of meter reading results could be pushed at the low frequency of 730 MHz. The study has demonstrated a pervasive communication system for smart power grid meter reading technology. Further, the study characterised the optical sources necessary for signal generation, data erasure and wavelength reuse. This is crucial for offering an all-optical wavelength reuse option for electrical meter reading applications. The maximization of the available bandwidth (10Gbps) was also demonstrated in the study. Finally, the experiment demonstrated that it is possible to utilize both wireless and wired communication system for upstream and downstream communication for meter reading. The obtained results on data erasure, LoRa (Long Range) technology, and signal transmission using Vertical-Cavity Surface-Emitting Lasers (VCSEL) have multiple potential applications across various fields including high-speed data communication, Internet of Things (IoT) and smart metering. The implication to the current system is that aside from communication enhancement, utilities can also be able to use this technology for overall smart metering of electricity, gas and water to provide real-time consumption data to enable better management of the available resources.

DEDICATION

Dedicated to my dear parents Mr. Peter A. Anemba and Mrs Rose S. Aradi. May God bless you abundantly for giving me this lifetime opportunity.

"The only dreams impossible to reach are the ones you never pursue."

-Michael Deckman

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LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
AMR	Automatic meter reading
BER	Bit error rate
BPSK	Binary phase shift keying
CPP	Critical peak pricing
CSP	Communications service providers
DEMUX	De-multiplexer
DC	Direct current
DFB	Distributed feedback
DWDM	Dense wavelength division multiplexing
EA	Electrical amplifier
EDFA	Erbium-Doped fiber amplifier
EMI	Electromagnetic interference
ER	Extinction ratio
EV	Electric vehicle
FTTH	Fiber to the home
FTTx	Fiber to the x

GPRS	General Packet radio service
HD	High definition
IoT	Internet of Things
IP	Internet protocol
IRED	InfraRed Emitting Diode
IT	Information Technology
KETRACO	Kenya Electricity Transmission Company Limited
KPLC	Kenya Power and Lighting Company
LF	Low frequency
LoRa	Long range radio
MDMS	Meter data management system
MMF	Multimode fiber
MUX	Multiplexer
NAN	Neighboring area network
NRZ	Non return zero
NZDSF	Non zero dispersion shifted fiber
OFDM	Orthogonal frequency division multiplexing
OLT	Optical line terminal

ONUs	Optical network units
PBRS	Pseudo random binary sequence
PDs	Photo diodes
PEV	Plug in electric vehicle
PLC	Power Line Communication
PMD	Polarization mode dispersion
PON	Passive optical Network
Q-Factor	Quality factor
RF	Radio frequency
RTP	Real time pricing
RZ	Return-to-zero
SDN	Software defined network
SG	Smart grid
SMF	Single mode fiber
SMS	Short Message Service
SNR	Signal to noise ratio
TVWS	TV-white space
VCSEL	Vertical- cavity surface emitting laser
VOA	Variable optical attenuator

CHAPTER ONE

INTRODUCTION

1.1 Overview

This chapter discusses the study's background information, statement of the problem, justification, research objectives and significance of the study.

1.2 Background of the Study

A smart grid (SG) is a modernized electrical system in which new and more suitable models of energy production usage and distribution is made possible. The incorporation of a pervasive communication system, monitoring capabilities and autonomous management and control functionalities into the power system make the SG efficient. Electric power is among the most crucial that led to globalization and rapid industrialization in the 20^{th} century (Butt et al.,2021). The current electric grid was built in 1890s and since then, there have been technological improvements which have shaped their performance and power generation. The electric grid is regarded by scientists as one of the largest and most complex interconnected physical systems on earth. Because of its complexity, vastness and linkage to human involvement and development, it is termed as being an "*ecosystem*" in itself (Smartgrid.gov, 2021). It is anticipated that the future electricity industry will be much better informed than it is now. As such, it is expected that the business model would move from selling electricity to controlling a dynamic energy market that provides spot prices for consumers at relatively static prices (Smartgrid.gov, 2021). This will lead to a more competitive world and the need for timely and reliable voice and data communications will increase significantly.

Today, the electric grid worldwide is made up of more than 9200 units that generate electricity with more than a million megawatts of generating capacity linked to more than 300,000 miles of transmission lines (Smartgrid.gov, 2021). Despite the fact that the electric grid is an engineering marvel, the current engineering works are stretching the electric grid patch work nature to its capacity. In order to move forward, there is a requirement of a new form of electric grid that is constructed from the bottom up to withstand the computerized, digital equipment and technology groundswell that are dependent on it (Butt et al.,2021). In the recent years, there has been a radical transformation in the electric power system on a global scale. The decarbonised electricity supply acts to replace the rapidly aging assets and take charge of the natural resources with newer forms of information and communication technologies (Elprocus, 2013). Although these technological applications are an initial milestone for the smart grid structure, they are not fully complete in many African countries.

There are distinct differences between the traditional grid and the smart grid. The distinction is based on several characteristics ranging from technology, distribution, generation, sensors, restoration, monitoring, equipment, control and customer choices (Faizan, 2017). For example, with regards to technology, the traditional or conventional power grids utilize electromechanical technology while the smart grids utilize the digital technology. The application of digital technology on the smart grids allows for enhanced communication between individual devices which in turn facilitates self-regulation and remote control (Faizan, 2017). The electromechanical technology on the other hand is limited in the sense that it lacks the means of ensuring communication between devices as well as ascertaining internal regulation.

Table 1.1 provides more distinctions. Long-term economic gains will result from the initial association of SG application definition of the requirements for each application, which will enable the coordination of all subsequent SG applications under the authority's associations' management.

Table 1.1

A Comparison Between the Current Traditional Grid and the Smart Grid

Characteristics	Traditional Grid	Smart Grid
Restoration	**Manual:** Traditional energy infrastructure repairs need technicians to make their way to the site of the failure.	**Self-Healing:** Sensors can easily detect problems on the line and respond to do simple troubleshooting and repairs without intervention
Equipment	**Failure & Blackout:** Traditional energy infrastructure is susceptible to failures. Failure of infrastructure can result in blackouts.	**Adaptive & Islanding:** Using a SG system, power can be rerouted to go around any problem areas.
Control	**Limited:** Using traditional power infrastructure, energy is rather difficult to control.	**Pervasive:** With the increased amount of sensors energy companies have more control than ever over power distribution.

Source: Faizan (2017)

The traditional power grid with regards to the mode of distribution employs the one-way distribution method whereby the distribution of power can only be from the main plant with the utilization of traditional energy infrastructure. The SG in contrast uses the two-way distribution system. The generation of power in the traditional power grid is centralized whereby all power has to be centrally generated. When this happens, it eliminates the possibility of easily integrating alternative sources of energy into the grid. In the case of the SG, the generation is distributed (Faizan, 2017). This means that with the use of a SG infrastructure, the distribution of power can be from several substations and plants to assist in load balancing, peak time strains reduction and the overall limitation of power outages. Because this infrastructure is not set up and designed to handle several sensors on the lines, the conventional power grid uses few sensors. As a result, it is challenging to identify and localize an error, which might result in protracted downtimes. The sensors are spread out in the instance of the SG (Faizan, 2017). The various sensors installed on the lines in the SG help to identify the location of a problem and may thus be used to reroute power to the necessary spot while limiting the areas affected by the downtime.

1.2.1 Smart Grid Dispatching

Grid dispatch is a crucial part of the smart grid. It refers to the manifestation of both the technical and application level of the smart grid. It is the key to rapidly improve the ability of the power grid to accept clean energy. The dispatching of power grid is a crucial factor for stable and safe operation of a power system (Zhou et al., 2013). In the construction of a SG, the dispatching of power grid is faced with increasing opportunities and challenges with the access of large-scale intermittent sources of renewable energy, alternating current/ direct current hybrid systems, computer and information technology development and demand side management implementation (Zhou et al., 2013). Table 1.2 illustrates the SG dispatching special characteristics in comparison with smart grid dispatching.

Table 1.2

Smart Grid Dispatching Special Characteristics Compared with Smart Grid Dispatching

Characteristics of SG Dispatching	Smart Grid Dispatching
Interruptible load management	Electrical vehicle dispatching Certain non-rigid load dispatching Energy storage equipment dispatching
Bulk power grid dispatching	Large scale intermittent resources dispatching Scheduling and control of AC/DC hybrid power grid
Supporting technology for power grid dispatching	Integrated control and scheduling real time data base cloud computing New intelligent algorithms of optimization
Small and micro grid power dispatching	Distributed network dispatching with DG intelligent micro grid dispatching

Source: Zhou et al. (2013)

1.2.2 Global Consumption of Electricity

The global consumption of electricity is an important factor especially in coming up with alternative power sources. The use of electricity is necessary in human operations. Figure 1.1 is a representation of the current global consumption of electricity.

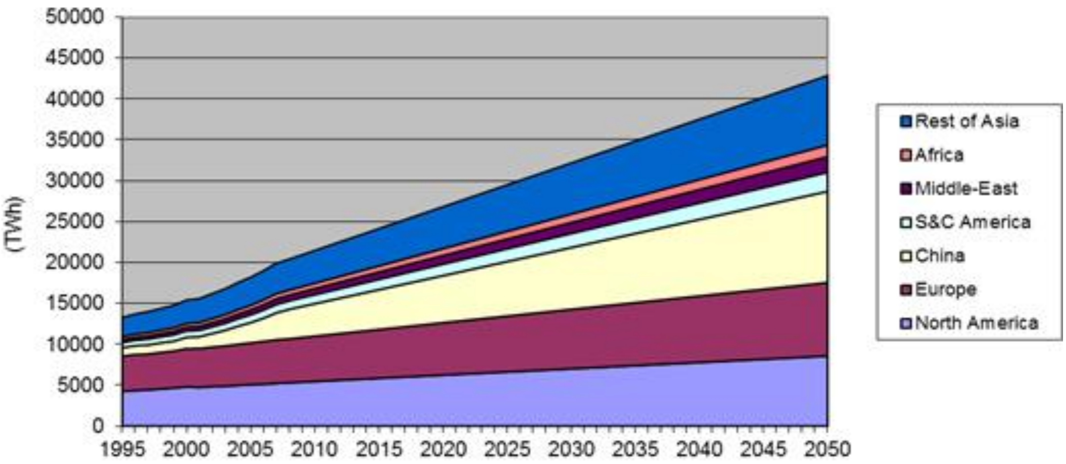

Figure 1.1: Global consumption of electricity (Sophie, 2016)

In the figure, it is projected that by the year 2050, the electric consumption levels would have increased significantly in all the continents (Sophie, 2016). However, the consumption in Asia, Africa, Middle East and South and Central America seem to be rapidly increasing, which is an indication of high electricity demands. As such, the consumption level of electricity needs to be accompanied by a safe, reliable and cost-effective grid that will ensure efficient and sufficient power delivery for all, thus the need for having a SG becomes necessary.

1.3 The Statement of the Problem

Developing nations are currently the epicentre of the transition of energy and the national electricity supply has been able to grow. However, there are still certain energy related problems that both public and private firms are facing while working towards providing quality services that are reliable and cost effective. There is the recurring experience of outages and voltage fluctuation that puts household electrical appliances and equipment at risk. The major problem lies in the fact that communication between the utility and the individual households is slow and manually monitored and therefore power outages are not reported on time.

Traditional power grids developed long time ago when there was minimal electricity requirement are still in operation. In this traditional power grid system, there is the establishment of power generation systems in localized areas that supply electricity to households and nearby communities. These grids are designed in such a way as to supply electricity to the homes of the consumers and once a month there is the billing of the electricity based on consumption. This manual meter reading system which is linked to the communication infrastructure is a slow activity especially consumers' convenience. With the growing demands for electricity, there is the need to have an automated distribution system and metering system that is efficient and reliable and will make meter reading easier. All these challenges narrow down to the primary problem of the absence of an efficient communication infrastructure between the utility and the end users. There is therefore, the need to develop a modern infrastructure that will improve communication and power supply service delivery to electric power consumers.

1.4 Objectives of the Study

1.4.1 General Objective

To demonstrate the performance of optical fiber and LoRa wireless communication technology for smart power grid meter reading applications.

1.4.2 Specific Objectives

i. To characterize the vertical cavity surface emitting laser (VCSEL) and the DFB Laser

ii. To evaluate the performance of VCSEL and DFB sources in transmitting data at 10 Gbps over 25 km and 50 km optical fiber.

iii. To demonstrate the all-optical wavelength reuse data erasure for application in smart meter reading.

iv. To characterize the long-range radio (LoRa) sender and receiver devices

1.5 Research Questions

i. What is the significance of characterizing the light sources (VCSEL and DFB)?

ii. What is the essence of evaluating DFB and VCSEL transmission performance using the optical fiber?

iii. What is all optical data erasing techniques and why is it significant in wavelength re-use?

iv. What is the significance of characterizing the LoRa transmitter before transmission?

1.6 Justification

The Kenyan government has an ambitious development agenda, which has a goal of transforming Kenya into a new growing, industrializing, middle income country by 2030. The vision 2030 was as a method of accelerating the country's transformation into a middle-income nation that is rapidly industrialized by the year 2030. Over 2 million houses are targeted for construction in Kenya, and this number is expected to rise by about 200,000 per annum. Over 90% of Kenya's urban houses are rental homes, and an estimated 61% of the country's 50 million citizens reside in slums. Establishing a SG means that Kenya will be in a better position to ascertain reliability, efficiency and modernization of communication between the end user and the utility. The current study aimed at bridging the gap of prompt power restoration for the case of recurring power outages by ensuring timely communication thereby between the utility and the end users whenever they occur.

The SG communication network through the utilization of the optical fiber technology has the potential to provide reliable services to consumers in developing nations through the integration of an effective communication system. Including an efficient and automated communication system in the current power supply system will be an attribute to achieving the targeted housing agenda, millennium development goals (MDGs) and the vision 2030 goal.

1.7 Significance of the Study

This study will ascertain communication efficiency in the grid through solving the issue of delayed power outage reports whenever they occur. It will give an idea to utilities on how to enhance communication between the power distribution company (KPLC) and the consumers without necessarily being on-site. The research will ease communication and ensure real-time monitoring of the grid thereby making the communication system efficient

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter provides information on the reported smart grids and optical fiber technology. It also describes various technological components and techniques that can be integrated into the optical fiber network. These include the VCSEL, DFB, data and clock transmission, all optical wavelength re-use and LoRa.

2.2 Internet of Things (IOT)

The Internet of Things (IoT) as an upcoming technology has caught the public attention and has aroused huge interests (Ghassemi et al., 2014). In essence, the potential of its deployment is dependent on wireless connectivity and therefore several attempts aimed at adapting the IoT application to the already existing wireless solutions have been made. The convergence of optical fiber systems and wireless communications like the LoRa example in the study has come up as a promising solution to aid support to the growth rate of data traffic demand in wireless applications (Ghassemi et al., 2014). As it stands now, IoT has an objective of delivering an electric grid that is smarter to enable more connectivity and information to different energy system components (Yang, 2019). It basically deals with the analysis of the application of the wireless technology in the SG which is why the current study made use of the LoRa technology as a wireless communication technology. Kenya cannot achieve an energy economy of the 21st century with an electricity system of the 20th century and therefore, a modern and automated SG technology would be necessary.

2.3 The Kenyan Electric Grid

In Kenya currently, there is a low electrification ratio with only 20% of the entire population having access to electricity and a 130-kWh per capita consumption against 550 kWh on average for Sub-Saharan Africa (African Development Fund, 2010). Access to electricity is much lower outside the urban areas with most rural areas experiencing a low reliability. Reinforcing the power supply in areas that are already electrified is also an additional challenge (African Development Fund, 2010). Developing nations particularly in Africa have translated their vision for the energy sector into a program of Energy Access Scale Up under which these nations will invest in the power transmission infrastructure project (African Development Fund, 2010). In Kenya, this project which was established in 2011 is set to deal with the construction of transmission lines, substation bays and new substations which will result in increased supply of power particularly in the eastern and western parts of Kenya and contribute towards enhancing new connections in rural areas.

Kenya Electricity Transmission Company Limited (KETRACO) is the project implementing agency. This agency in April 2010 signed a mutual co-operation with KPLC for the provision of both qualified and trained personnel in its functioning when it is not able to meet the requirements of staff (African Development Fund, 2010). In the implementation of transmission lines and substation contracts, KPLC has sufficient experience as well as adequate skill in financial management that will be of benefit to KETRACO staff through offering training on the job. Additionally, the contract to be signed into with the consultant and contractors responsible for the supervision and construction project will be inclusive of provisions to ensure that there is sufficient training for both KPLC/KETRACO engineers. This component technology transfer is essential for the project to improve the KPLC/KETRACO'S implementation on similar projects capacity (African Development Fund, 2010). However, this project would be better if at all there would be a consideration of the smart grid technology incorporation which can ensure communication efficiency and reliability of power transmission and distribution to consumers in the current traditional grid.

2.4 Smart Grid Legacy Technologies

To ensure the transformation of the current grid into a resilient, adaptable and dynamic one, SG will be among the biggest technological challenges of this time. However, the reward may be dramatic in that it will be in a better position to enable consumers to control their usage of electricity in a better way, incorporating the next plug-in electrical vehicles generation, enhancing efficiency and harnessing renewable energy in a better way (Energy.gov, 2010). Once the SG technology is embraced, there will be a notable revolution in the nations' generation, usage and delivery of electricity across the country through the combination of a two-way electricity flow with the two-way information flow. This will leverage the modern computing capabilities benefits to ensure information processing concerning the usage of electricity in a more dynamic way and enable some adjustments in the usage of electricity to make our utilization of electricity more efficient and reliable (Energy.gov, 2010). The foundation to achieving these potential benefits is through ensuring that the basic technological demands and needs of the SG are in position.

Mekkaoui et al.'s (2017) study found that the complexity of the power grid and the ongoing rise in electricity consumption create a need for effective power system control and analysis. The primary component of the SG is an intelligent and highly flexible infrastructure of communication that offers utilities with remote control and access components. These are inclusive of measurement and real-time sensing (Mekkaoui et al., 2017). The current distribution of grid for electric distribution is facing fundamental and rapid changes (Seifu, 2014). This indicates that various grid components, including cutting-edge devices like smart meters and intelligent sensors, are compatible with SG wireless networks. These components play a vital role in supporting a diverse array of applications like distribution automation and demand response. Demand response is the change in the consumption of power of an electric utility client to match the power demand with the supply better. A lot of smart devices may transmit data simultaneously for example in responding to an outage in power. This may lead to a severe congestion in network which is a major setback in ensuring timeliness and reliability of the transmitted data over these networks (Hein, 2019). The components and diversity of some networks such as the resources of renewable energy can build a time-varying traffic while there may also be a dense or sparse placement of smart devices and closely to other grid devices. This results in spatially varying demands in traffic with differing areas of coverage. Based on these challenges, advanced techniques must be put in action to maximize SG wireless networks efficiency.

According to Kimani (2020), cognitive machine-to-machine networking was used to design a smart power grid communication network via TV white space (TVWS), as illustrated in Table 2.1. The research was able to investigate how well the planned communication network performed. Throughput, route loss, and power consumption were the performance metrics examined. Based on the research, it was discovered that the built smart grid communication network was able to more fully satisfy an SG's latency requirements. Therefore, it was determined that the SG communication network as built is capable of utilizing TVWS for real-time communication.

Khan & Khan (2012) examined the performance of a WiMAX SG final mile network in a different study. The network serves the customers energy service interfaces (ESI).

The traffic model composed of alarm commands, metering data, network joining, telemetry signals, pricing signals, firmware updates, information broadcast and ESI information reports (Khan & Khan, 2012). The applications experienced different average delays from less than 200ms to more than 1,000ms.

Table 2.1

Comparison of Different Smart Grid Communication Technologies

Technology	Media	Operation	Merits	Demerits
Zigbee	Wireless	Unlicensed	Low power usage Short range Low complexity Low deployment cost	limited range data rate is low limited processing power WiFi, Bluetooth, and microwave interference
Bluetooth	Wireless	Unlicensed	Low power usage	limited range data rate is low
Wi-Fi	Wireless	Unlicensed	High power usage	Short range
WiMAX	Wireless	Licensed	High data rate Long range	Network speeds decrease as distance increases. Expensive license fees High frequencies cannot get past barriers.
Cellular Communication	Wireless	Licensed	High data rate High mobility Limited latency	high cost of deployment Insufficient spectrum
Power-Line Communication (PLC)	Power Line		High Speed Low cost due to already available infrastructure Low latency Widespread availability	Noisy and harsh medium Limited bandwidth Network topology has an impact on signal quality.
Optical Networks	Wired	Licensed	High speed Large bandwidth High degree of reliability Long range	High deployment cost
TV White Space	Wired	Unlicensed	High data rate Long range Adaptive power levels	Vulnerable to disturbances brought on by the re-emergence of PU

Source: Kimani (2020)

Another study by Rengaraju, Lung, & Srinivasan (2012) on communication requirements and analysis on distribution networks using WiMAX technology for SG presented a report on simulation model for the Distribution Area Network (DAN). The DAN was an integration of the Advanced Metering Infrastructures (AMIs) payload from the areas of the consumers (Rengaraju et al., 2012). There was a consideration of different smart grid applications in the simulation, i.e., Plug in Hybrid Electrical Vehicles (PHEV), substation automation, video surveillance voice and metering data. There was an experienced difference in the average delays by the applications from less than 50 mS to more than 400 Ms.

From Table 2.1 it can be concluded that communication through optical networks has several features which are appealing and which will enhance communication in the grid compared to the other wireless and wired communication technologies. Again, it has only a single demerit of high cost of deployment which in essence is not a primary problem as it is very cost effective in terms of maintenance. This makes this form of technology an ideal candidate for communication network deployment.

2.5 A Review on the Current Smart Grid

The SG is a digital technology that gives an allowance for two-way communication between electric utility or power providers and its clients. The sensing infrastructure along the lines of transmission is what contributes to the smartness of the grid. Zhang R, (2013) describes an SG as an innovative power supply system embedded in communication and IT. The SG has six fundamental functionalities which include demand response, advanced metering infrastructure, electric vehicles, distributed energy storage, distribution grid management and wide area situational awareness (Energy.gov, 2010). The SG is also defined as an automated, globally dispersed energy distribution network that provides two-way energy flow and information flow and which is able to track everything from power stations to consumer desires and even to individual devices (Zhang, 2013). Through the incorporation of control, analysis, monitoring and communication facilities, it is currently possible to undertake the optimization of power systems performance, thereby allowing the delivery of electricity in a more effective and efficient manner (Zhang, 2013). In the sector that relates to transmission and distribution, online transmission lines and primary equipment monitoring is crucial and can effectively improve power systems reliability. The advantages of distributed information and communications are embedded in the grid to supply in real time data and to provide the almost immediate supply and demand equilibrium at the system level.

SG requires advanced metering system, a demand response, a distributed output and much more to allow conventional utility functions and flexibility to respond to new needs. The power system can be optimized by providing tracking, measuring, control and communications facilities so that energy can be supplied more effectively. According to Yarali and Rahman (2012), the SG is designed to operate power distributors and generator networks with automatic control in response to power availability and user needs. Online monitoring of transmission lines and primary networks is critical in the transmission and distribution sector and can help increase the efficiency of power systems. The SG is composed of computer systems, automated smart meters, monitoring systems, sensors, and data control systems. In this case, these technologies will operate with the electrical grid to digitally respond to the electrical demand that is rapidly changing (Yarali & Rahman, 2012). SGs share multiple characteristics compared to the traditional grid primarily related to increased information and automated control system use and incorporation of advanced infrastructure and user products, complex grid operation and resource management, smart metering technology implementation, grid operations and state contact and monitoring.

SG is a representation of an opportunity that is unprecedented to move the energy industry into a modern era of efficiency, reliability and availability. In the phase of the transition period, carrying out improvements in technology, testing, standards and regulations development and the sharing of information between projects will be difficult (Smartgrid.gov, 2021). In most instances sharing between projects is essential in ensuring that the envisioned benefits from smart grid actualizes and becomes a reality. According to a report by the International Renewable Energy Agency (IRENA), as more and more developing countries globally intend to enhance their utilization of renewable sources of energy, the SG technology offers means to incorporate these renewable alternatives in an efficient and cost-effective way. The evaluation and justification of SG projects is often done on an economic basis (IRENA, 2015). It is possible to apply intelligent of flexible manufacturing research systems to control an electric power grid model utilizing technology and sensors. This will be made possible through the introduction of the SG. The automated equipment can be utilized to implement the SG and establish a controller that can be in a position to avoid power outages.

The SG communication technology assists in ensuring that there is a timely electricity recovery and in a more strategic manner after an emergency, thereby routing and connecting electricity first to emergency services. Additionally, it is a means of addressing the energy infrastructure that is aging and needs replacement or upgrading. It is a method of bringing increased national security to the energy system. SG is a promising power supply infrastructure integrated with communication and IT (Gonzalez, 2013). The power system is optimized to provide more efficient electricity through the inclusion of monitoring, analysis, control and communication facilities. The automation of the SG system is represented in Figure 2.1.

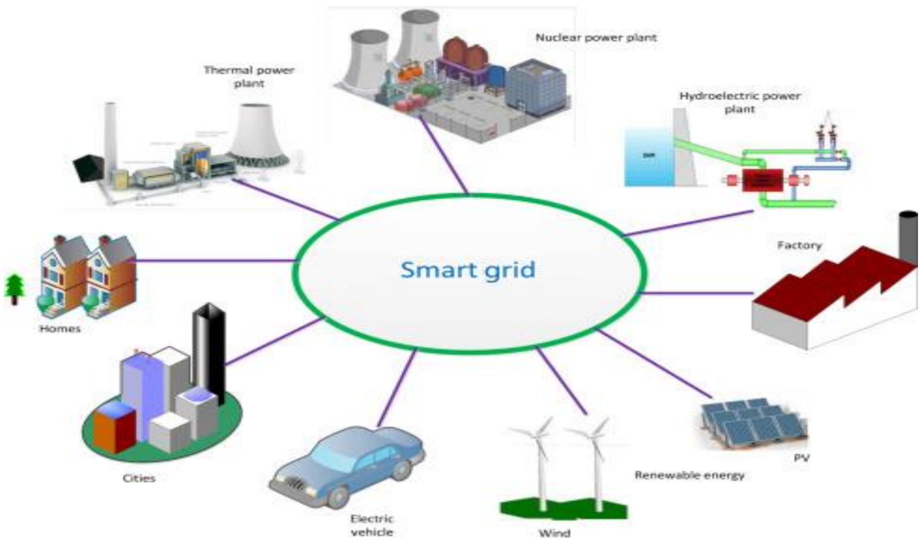

Figure 2.1: Smart grid conceptual model (Sayed & Gabbar, 2017)

From Figure 2.1, it can be seen that power supply is entirely dependent on the stability of the grid. Automation capabilities in the communication infrastructure would suffice the overall grid operation. Some SGs are made up of significantly high number of sensors. These sensors are deployed at all grid components levels including substation equipment, power plants, transformers, generators and home users (Baimel et al., 2016). The primary use of these sensors is for the acquisition of data as well as the exchange of information between data centres and equipment. Additionally, the SG utilizes actuators and clock systems to ensure that all grid components are under optimal control (Baimel et al., 2016).

2.5.1 Benefits of the Smart Grid

To guarantee a high rate of information flow, the SG in the communication infrastructure should have a large bandwidth and be automatically adaptable to any changes. Even though, there is still the evolution of a clear and concise SG definition, several characteristics still remain in control to the architectures of the SG (Sayed & Gabbar, 2017). These characteristics define the potential benefits of the SG to the overall electric power system. They include:

1. The incorporation of information and communication into every electrical generation, consumption and delivery aspect so to minimize impacts on the environment, improve reliability and service, enhance markets, and improve efficiency and lower costs.
2. Responds to the disturbance of the system in a manner that is self-healing.
3. It further employs distribution automation, digital information and an array of control strategies for the facilitation and integration of renewable energy generation, distributed resources of energy, energy storage systems, automated systems and also peak shaving technologies.
4. It accommodates all types of energy storage options and generation techniques.
5. It offers a higher quality of power needed for the digital economy of the 21st century.

A study by Pehlivanoğlu (2019) explains that the SG technology is further categorized based on its advantages on customers, the power grid and operating and social advantages:

i. Customers

- There is a reduction in the consumer bill thereby ensuring an optimization in the generation capacity investments, decreasing service cost and reducing the cost of congestion.
  - Enhancing reliability (power interruptions bettering the response).
  - Ensures a bidirectional communication energy storage which provides better customer service.
  - Monitoring improvements as a result of the deployment of more sensors which promotes networking display.

ii. Power Grid

- Minimizing losses because of a dispersed network.
- Ensures an extensive control system.

iii. Operating

- Optimizes the maintenance cost of equipment which decreases operation costs and enhances meter reading.
- Load forecasting- reduces the peak load and ascertains load predictions and planning.

The SG infrastructure is currently faced with several difficulties in its establishment. These problems range from lack of standards, transition, data privacy and data management (Folly, 2013). As it currently stands, most African nations lack SG policies. In Africa, there is the problem of having an outdated and aging infrastructure which is currently inadequate and needs primary augmentation and overhaul to support the SG technology growth. There is also a challenge of compatibility of the older equipment with the SG applications (Folly, 2013). SG cyber security is also a challenge for the SG technologies implementation. Due to the use of the internet to connect data flow between consumers and utilities, cyber security needs to be addressed.

The current grids are susceptible to a number of issues, including frequent outages, overloading, particularly during peak hours, service interruptions that typically are not reported on time, and human inefficiencies including meter transactions (taking meter readings from analogue meters and entering prepaid generation codes into digital meters) (Baimel et al., 2016). The lack of a dependable communication infrastructure between network devices, service providers, or utilities, and users is the main issue with these problems (Al-Omar et al., 2015). Water outages and power outages happen frequently, but because the utility providers lack a trustworthy communication system to quickly respond to grid faults, they are compelled to wait for customer complaints before acting. This results in losses increased before fixing the problem, which inconveniences many customers.

There is also the problem of limited availability of radio spectrum due to high cost of acquisition. This is a primary setback when it comes to the deployment of applications for wireless backhaul in SG. This is true especially for SG systems that are WiMAX based whereby the utility organizations are forced to acquire spectrum that is licensed as suggested by Al-Omar et al.(2015). The adoption of smart meters uses 2G/3G cellular technologies as the forms of communication architecture in the current grid networks. The implanted subscriber identification module (SIM) cards in smart meters allow the grid to communicate with the cellular network autonomously, just like a typical consumer device. The 2G, 3G, or 4G cellular core networks can transport traffic to utility servers or other grid devices (Gonzalez, 2013). A large number of machine-to-machine devices can result in a significant overload problem in the cellular networks, even though cellular networks can guarantee improved communication performance due to exclusive rights to use the cellular band and cellular network elaborate management (Lee et al., 2013). The service provider should spend both in communication infrastructure and bandwidth to serve a large number of grid gadgets in cellular networks.

However, this technology also has many drawbacks such as insufficient coverage in some regions. This is due to the fact that smart meters are buried underground and therefore, very heavy shadowing effects brought on by structures like buildings and walls. Furthermore, cellular bands have a history of being heavily utilized in crowded regions, making them potentially unsuitable for supporting the widespread deployment of grid networks (Lee et al., 2013). Human inefficiency is the other problem that has plagued current grids. In many places more so in the rural areas, analogue utility meters still exist where utility companies need to send personnel to manually read meters. Even in places where digital utility meters are supposedly present, there can be issues connecting to the utility provided data, which means that prepaid tokens may need to be acquired (Lee et al., 2013). This results in frequent complaints from customers, majority of whom either insert incorrect digits or leave out a single digit. The utility providers are locking important data about their customer usage patterns, which is crucial for planning and maintaining their networks and grids. This is due to inadequate infrastructure.

2.5.2 Smart Metering

The smart meter unlike the prepaid meter has its difference clear in the term "smart". The word smart is an indication of programmable capabilities. The "What", "How" among other factors of this will have a variation depending on the smartness of the system. Prepaid simply means paying for electricity in advance after which the service may be reduced or stopped after using the amount paid. This depends on the agreements of payment with the service provider.

According to Budka et al. (2010), smart metering is inclusive of a lot more than just the periodic measuring of energy. Power quality such as frequency, voltage and frequent power that is both reactive and active is a requirement in many new smart grid applications. Such measurements that the smart meter provides may be often needed to support the applications of energy management. Usually, the measurements may be once every 15 minutes (Budka et al., 2010). Smart meters provide measurements that can be utilized to support real time pricing (RTP), Critical peak pricing (CPP), time of use (TOU) features for demand and billing application response. The number of smart meters can vary depending on the utility size. Lack of timely smart metering standards, regulatory requirements and consideration of cost have resulted in the deployment vendor- proprietary solutions for smart metering based on neighbourhood area network (NAN) (Baimel et al., 2016). With the use of a wireless technologies deployed in unlicensed spectrum, there can be a ready deployment of these solutions.

Similarly, the solutions can be deployed using PLC technologies (Budka et al., 2010). A meter concentrator links to the meters over the NAN and takes part in the aggregation of data collection from the various meters it provides service. The number of served meters by the concentrator may vary from a few for a NAN that is PLC based to several for a radio frequency (RF) mesh-based solution. The meter concentrator links to the system of meter data management (MDMS) over an internet protocol (IP) network. There exist some smart meter products that have a direct interface to Ethernet or wireless service interfaces to link to services that are wire line (Budka et al., 2010). For such a deployment case, a meter concentrator is absent and therefore, there is a direct communication of the meter with the MDMS over an IP network.

The connections of smart meters to home area networks are vital to building or residential management of energy. Such a connection for instance allows pricing signal responses by appliances or other triggers transmitted over the smart grid. In normal conditions of operation, the response times that are acceptable for the completion of meter transaction can high and therefore, one-way packet latency allowance can also be high (Budka et al., 2010). The presence of an individual meter may not be critically considered to the operations of network which therefore means that a 99.95% objective availability should be more reasonable. Some smart grid applications may however require the transfer of data from all connected meters over a relatively short time. This requires a low latency for every individual's meter even if there may be the acceptability of a high latency for the purposes of billing. In SG security, smart meters are perhaps the weakest connection (Budka et al., 2010). In addition to the security threat of unauthorized physical access to the meter and usage of electricity data, threats related to wireless connectivity should also be considered in the network design.

2.5.3 Proposed Kenya Power Company Smart Metering System

Smart metering is among the newest SG application forms that most utilities have been able to deploy. Kenya power has recently introduced a smart metering project which in the long run will be able to benefit approximately fifty-five thousand clients both in medium and small enterprise sectors across the nation (Kenya Power, 2021). The World Bank is the key funder to this project, and has channelled Kshs.1.25 billion as funding to the project. This project is part of Kenya Electricity Modernization Project which is set to be completed soon. As part of the automated metering infrastructure (AMI), smart meters will facilitate two-way communication i.e., both supply into and from the national grid, between customers and the control station.

In case there is an occurrence of a power outage, the smart meters will be able to ensure a direct communication with National Contact Center of the power company. This will enhance efficiency through the facilitation of the immediate resolution as the Kenya power teams are timely alerted (Kenya Power, 2021). These smart meters will also be able to send signal notifications to clients through an SMS. However, there is need to design a more effective communication system test bed in the lab that can be implemented to perform and verify this two-way communication between the utility and the end users using an optical fiber cable which is where the study comes in.

2.6 The Optical Fiber Technology

A typical optical fiber network comprises of optical sources (transmitters), fiber, modulators, amplifiers, and photodiodes (receivers) all which play a role in a communication system (Alladi et al., 2019). Within an optical fiber, an optical light may move at a speed of 126,000 miles per second, giving it an advantage over copper wire for communication (Ezeh & Okwe., 2013). It also has an advantage of having no interference and low attenuation for long transmissions and with a very high bandwidth suitable for SG transmission and communication technologies. Optical fiber is commonly used by utilities around the globe as a key component of their SG programs. This helps to enhance the intelligence of their transport and delivery in communication networks

An optical fiber cable is a dielectric medium designed for the transportation of data over at the speed of light. The three main parts of the optical fiber are the core, cladding, and buffer coating. The buffer which is basically the outer coating is responsible for providing support and strength to the cable which prevents it from breaking. The core and cladding are designed in such a way that they enhance optical signals transmission (Wang, 2021). The second fiber section is designed for the terrestrial environment. The majority of cables made today have a Kevlar element that helps to give the cable more strength. The optical fibers inside the cable are supported by an outer sheath covering composed of hard plastic material, which increases the cable's bending radius and offers extra support over its lifetime. The operation of optical fiber cables can be in the 850 nm, 1300 nm or 1550 nm range of wavelength for the transmission of data. Figure 2.2 below shows the basic structure of the optical fiber cable. Each of these components are essential for the effective operation of the optical fiber cable.

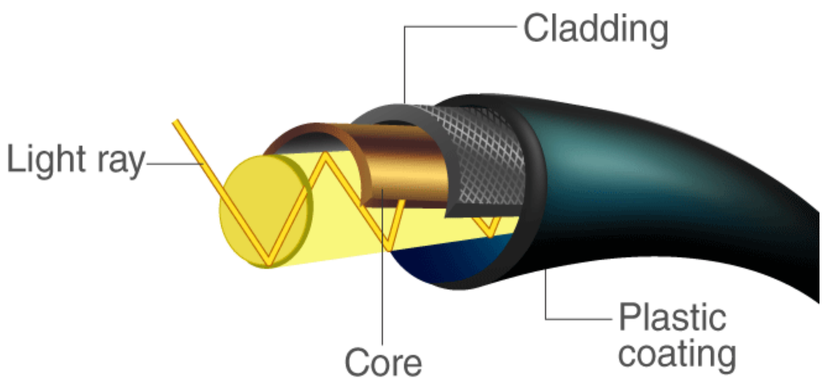

Figure 2.2: Components of the optical fiber cable (Wang, 2021)

2.6.1 Types of Optical Fibers

The optical fiber cable is the medium through which communication signals are transmitted. There are different types of optical fibers which are dependent on the material used, refractive index and the mode of light propagation. In the classification based on materials used, there are plastic and glass optical fibers (Byjus, 2021). Step index and graded index fibers are a classification based on the refractive index. Finally, in the classification of the mode of light propagation there are single mode fibers (SMF) and multimode fibers (MMF). The core's refractive index and the mode of propagation is utilized to form four types of combinations of optic fiber as graded index-single mode fibers, step index-single mode fibers, graded index-multimode fibers and step index-multimode fibers. The working of an optical fiber is guided by the principle of Total Internal Reflection (TIR). Light ray is used in the transmission of huge data amounts.

The G-655 standard also known as the nonzero dispersion-shifted fiber (NZDSF) has the dispersion at the 1550 nm wavelength close to zero but not zero (Liu, 2018). The positive dispersion of the G-655 is able to overcome the effects in wavelength division multiplexing (WDM) system like the four-wave mixing (FWM) because of high effective area. This fiber has its specification at 1550 nm and 1620 nm and at the same time has a low chromatic dispersion value at the conduction band in which Erbium Doped Fiber Amplifier (EDFA) will be able to boost the optical signals which is a match that gives the G-655 an edge over G-652 (Liu, 2018). The G-655 standard fiber used in the research is suitable for dense wavelength division multiplexing (DWDM) system in meeting the increasing capacity of transmission as well as the high capacity of long-haul WDM transmission system. The utilization of optical fiber technology supports the fast and timely transmission of electrical meter data from the consumer to the utility and from the utility to the consumer (Gaggero et al., 2021).

The designing of optical fibers is such that all the light is confined in the core as it propagates from the source to the receiver end using TIR (Wang 2021). The propagation of light rays is continuous and as they do that, they bounce off the walls of the optical fiber, thereby transmitting end to end data.

The power of the signal transmitted along the optical fiber is given by;

$$P_T = P_o e^{(-\alpha L)} \quad (2.1)$$

where P_T and P_O represent the transmitted power and initial or launched power respectively, α is the attenuation coefficient and L is the fiber length in km. Traditionally, the attenuation coefficient is given by Equation 2.2

$$\alpha\left(\frac{dB}{km}\right) = -\,{}^{10}/_{L}\, Log_{10}\,(P_I/P_0) \quad (2.2)$$

and is expressed in units of dB/km (Agrawal, 2012). Optical attenuation is a result of both intrinsic and extrinsic effects related to the fiber. Intrinsic losses include Rayleigh scattering and material absorption within the fiber core area. Extrinsic loss mechanisms include bending-losses, core/cladding losses, connector losses and splicing losses. In the last 30 years, optical fiber sensing has quickly advanced. It has been commonly used for structural health monitoring, geology, industrial infrastructure, aircraft and the environmental sensing wang (Measures & Abrate, 2002). Thanks to its benefits, including immunity to electromagnetic interference, multiplexing, and distribution of sensing resources, fiber-optic sensing technology is an acceptable choice for power grid applications.

2.6.2 Optical Monitoring of Power Grid

The optical fiber composite overhead ground wire (OPGW) and optical phase conductor (OPPCs) on the other hand, are commonly applied as transmission lines that show the value of the fiber-optical sensing technology principle. With the distribution and competitiveness of the grid and power industries, investment in optical fiber networks is increasing. The design of optical fiber cables that have the ability to detect temperature within the transformers and power lines is efficient in improving power reliability and delivery (Measures & Abrate, 2002). The optical fiber cables can optimize the grid in several ways (Liu, 2018). In most instances, these cables have a silica glass lining and are not affected by electromagnetic interference (EMI) generated by large transformers even when the cable is wrapped around a power transformer's metal. It is possible to get thousands of temperature readings and distribution in a very short time (Janacek et al., 2014). With the use of optical fiber, information can get to the utility at any point along the cable. This form of technology can enhance the components monitoring of a substation as well as other infrastructure that are high power and offer immediate information concerning the smart grid's health.

A typical power grid is usually made up of three key components namely the transformers, overhead transmission lines and power tower as illustrated in Figure 2.3.

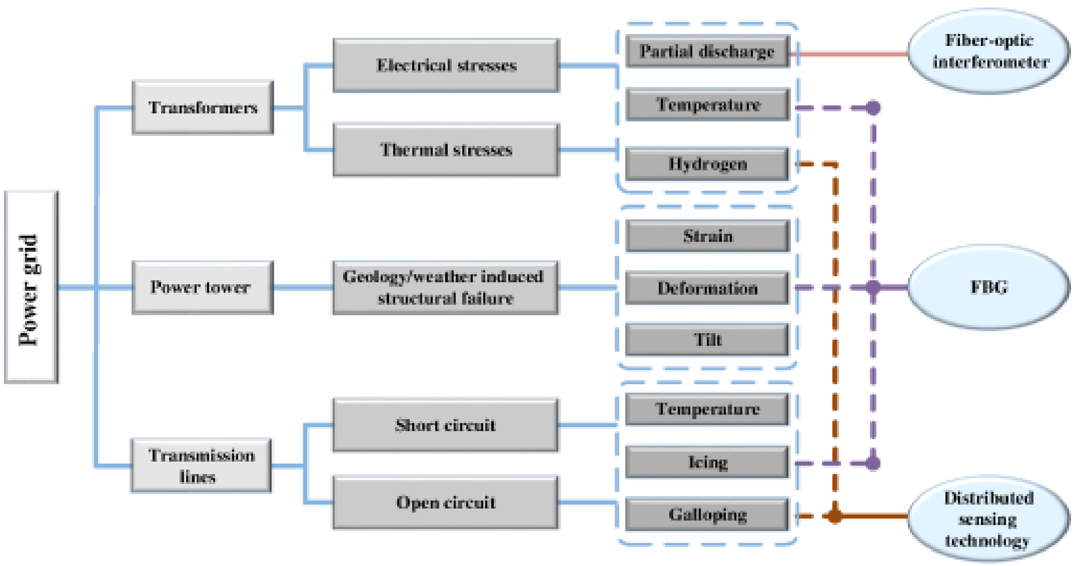

Figure 2.3: The smart grid structure and fiber optic sensing technology (Chai et al., 2019)

Thermal stresses and electrical failures are the two primary causes of transformer failures. The measurements of weather induced strain, deformation and tilt of power tower can be conducted using fiber optic sensors (Chai et al., 2019). The evaluation of transmission lines open circuit or short circuit can be done by temperature measurements, galloping and even icing the designing of sensors that are fiber-optic interferometeased can be done with super high sensitivity but they are used in the detection of partial discharge. There has been the utilization of Fiber Bragg Gratings (FBGs) in all types of applications. This is because they possess an ultrasound multiplexing capability and also appeared as one of the best optical fiber devices in commercialization (Chai et al., 2019). Distributed fiber-optic sensors have been utilized in many applications and have also proved to be among the most promising schemes of sensing due to OPPC/OPGW extensively used in power grids.

2.6.3 Analogy of the Smart Grid and Smart Meter Applications to FTTx Technology

In order to ensure uninterrupted and seamless flow of data in an ever-growing digital era, smart meters require the support of better communication channels (Solipurum, 2016). Integrating the fiber to the x (FTTX) architecture into the power grid can assist the key players in the electricity distribution industry to easily meet the growing demand of high band width. It can also assist them to better arm themselves and be ready to deliver up to date and next generation services (Solipurum, 2016). The communications service providers (CSPs) consider FTTx as the most effective means of delivering telecommunication services to their subscribers. Currently CSPs are deploying fiber across the network. FTTx networks have multiple variations depending on the point of termination (Solipurum, 2016). These can be premises (FTTp), curb/cabinet (FTTc), home (FTTh), utility (FTTu) and node (FTTn).

Fiber to the home (FTTH) is a communication signal from operator to home, or company, over optical fiber, replacing out-dated copper networks such as telephone cables and coaxial cables (Muthana et al., 2011). The FTTH technology in developed countries, it is widely developed more so in American, Asian, and European continents. This network connects multiple central end users to a common point of focus (Kipnoo et al., 2017). FTTH is a modern and rapidly growing way to give customers and companies substantially higher bandwidth and thus make video, internet and voice services more robust. Connecting households with fiber-optical cables provides customers with tremendous bandwidth benefits. Optical fiber technology currently available can deliver two-way transmission speeds of up to 100 Gbps (Muthana et al., 2011). Furthermore, while cable modems face challenges in increasing their bandwidth, optical fiber infrastructure upgraded offer a solution by expanding available bandwidth without requiring changes in the network.

Data can be transported in many ways across smart grid components. In many cases, various structures have been used simultaneously Power Line Communication (PLC), general packet radio services (GPRS) and fiber networks (Kipnoo et al., 2017). Users are traditionally using the optical fiber cables to link their transformer station. PLC or GPRS are used between the transformer plant and the houses. In certain cases, the lack of a fiber-optic network between transformers and customers limits the capability of the grid. In this situation utilities can only conduct remote meter reading (Muthana et al., 2011). For this type of application, PLC or GPRS are the suitable options. Increased fiber network is the only physical solution that can provide security, reliability and speed on demand once the need for bi-directional control and intervention frequency (Janacek et al., 2014). When the FTTH network has already been developed, using SG fiber can be helpful in reducing transmission costs for GPRS providers.

2.7 The Vertical Cavity Surface Emitting Laser (VCSEL)

A VCSEL is a laser diode that is semi-conductive in nature with a monolithic laser resonator where the beam laser emission leaves the system in the direction perpendicular to the chip's surface (Karim et al.,2000). Commercially interconnected data-center networks primarily include low-cost VCSEL, Multimode Fiber (MMF), and directly visible photodiodes (PDs) systems. In addition, VCSEL/multimode fiber-based technologies optimized to operate in the 850 nm transmission window are a feasible solution to sustainable shorter-speed interconnections in the planned fuels (Isoe et al., 2019). VCSEL promises to make a transformation in the fiber optic communication through enhancing efficiency and increasing the speed of data (Kapon & Sirbu, 2009). The development of 1310 nm and 1550 nm VCSELs from the earlier 850 nm has been made possible by a number of advances in the field.

When it comes to long haul transmission, single mode fibers are suitable when utilized in both the 1310 and 1550 nm transmission windows. Because of low drive voltage and cost effectiveness, the VCSEL-based system has emerged as the most promising option for next passive optical networks (PONs) (Kapon & Sirbu, 2009). VCSEL is the preferred source for short distance transmission in an optical link (Iga, 2000). There are a number of its features that make it an attractive candidate. These include cost effective testing and fabrication, low power consumption, high fiber coupling efficiency, tunability with respect to bias current, low power and current, low cost in the sense that its buying price is cheaper than that of a DFB and excellent high- speed modulation characteristics (Soderberg et al., 2007).

VCSELs typically experience significant heating due to their poor heat dissipation as well as high frequency chirps (Lopez, 2013). As a result, they may exhibit strong thermally dependent behaviour. The calculation of a VCSEL's optical power is a crucial parameter in optical communication network (Lopez, 2013). This can be achieved by the following equation;

$$P_{out} = n_i n_0 \frac{hv}{e}(I - I_{th}) \tag{2.3}$$

where P_{out} is the output power, n_i is the injection frequency,

n_0 the optical frequency, I is the injected current and I_{th} is the threshold current.

The power dissipated in the VCSEL is the difference between the electrical power going into the laser and the optical power coming out of the laser.

$$P_d = P_{in} - P_{out} \tag{2.4}$$

Where P_d represents the dissipated power,

P_{in} is the input optical power and P_{out} $r$epresenting the output optical power. Utilizin g short pulses allows measurements to be performed at relatively high currents without heating the VCSEL. The VCSEL self–heats as a result of the laser's power loss. The built–in temperature of the VCSEL is as follows;

$$T = T_O + P_d . R_{th} - \tau_{th} . \frac{dT}{dt} \tag{2.5}$$

Where T is the bit period, T_O is the ambient temperature,

P_d represents the dissipated power,

τ_{th} is the thermal time constant, R_{th} is the thermal impedance.

The small-diameter device's thermal impedance VCSEL set on top of a relatively thick substrate can be approximated as:

$$R_{th} = \frac{1}{2\varphi s} \tag{2.6}$$

Where R_{th} is the thermal impedance, φ thermal conductivity and s is the area.

By assuming a source of heat with a circular surface area, thermal impedance is achieved. The overall VCSEL modulation performance is impacted by the intrinsic temperature increase brought on by current self-heating. The above theory assisted in achieving the objective of data transmission using a VCSEL since the output optical power of the VCSEL is one of the most crucial parameters in its characterization.

The performance of VCSELs in optical fiber networks is constrained by their polarization insensibility and significant frequency chirp, which are caused by over-modulation and impede transmission at high bit rates (Chrostowski, 2004). Additionally, they can only transmit over small distances. These flaws highlight the requirement to characterize and enhance these optical effects on various fibers during long-distance transmissions (Chepkoiwo, 2017). Wavelength division multiplexing has made it possible to expand the fiber's capacity in modern optical fiber systems. However, it takes a lot of time and money to package and assemble individual lasers with different wavelengths (Qader et al., 2011). Due to their lower production costs, multiple-wavelength VCSEL arrays are suitable WDM systems sources. The Light-current (L-I) curve is where the effect is most clearly visible (Karim et al., 2000). Temperature-dependent threshold current is seen in VCSELs. This implies that as the device's temperature rises in response to injection current, the output power rolls over and begins to fall, effectively restricting the device's maximum power output (Gibbon et al., 2010). According to Pozo and Beletkaia (2019), VCSELs combine high power density with clear IRED packaging, spectral width, and laser speed. In the gain range of the active zone, VCSELs have the ability to modify the reflector layer thickness. Table 2.2 gives the properties of the G.652 and G.655 VCSEL fibers used in signal transmission. This was a crucial area in the simulation part of the study as it assisted with setting up the right parameters for the G 655 fiber transmitting at the 1550 nm window used in the study.

Table 2.2

Properties of G.652 and G.655 VCSEL Fiber Used in Signal Transmission

Fiber Parameter	VCSEL fiber types and wavelengths (nm)			
	G 652(1310)	G 655 (1310)	G652 (1550)	G655 (1550)
Attenuation	0.2	0.2	0.2	0.2
Dispersion Coefficient [ps/(nm.km)]	0	17	17	2.6
Dispersion Slope [ps/nm^2.km]	≤ 0.045	≤ 0.05	≤ 0.05	≤ 0.045
PMD Coefficient [ps/√km]	0.2	0.5	0.5	≤0.04

Source: Allen et. al. (2004)

The fiber parameters are used in communication technologies of a long-wave nature, such as in metro systems, transmission networks and fiber to home (FTTH) communications, more generally in all communications technologies. FTTH networks are based on passive optical Network (PON) (Kipnoo et al., 2017).

VCSELs are also useful in passive optical network systems (PON). A PON system is shown in Figure 2.4. It consists of numerous optical network units (ONUs) located close to end users and an optical line terminal (OLT) at the headquarters of the communications corporation (Kipnoo et al., 2017). The majority of splitters typically support ONUs. The PON technology's rapid evolution has recently been accelerated by the necessity to accommodate modern requirements of such a system. The PON transmitter is designed to connect different consumers to a single mode optical fiber. In this case, a VCSEL is useful in the optical modulation of an RF signal. The VCSEL supplies the modulator with an optical carrier necessary for performing signal modulation. In addition, the input bias current of the VCSEL is also useful in the design of a PON system. The VCSEL's ability to vary its central wavelength of emission with a variation of the bias current offers a great potential for its utilization in PON systems where there is the requirement of wavelength tuning for the achievement of signal transmissions like in the case of electrical meter reading systems (Gibbon et al., 2010). This also presents the VCSEL as an attractive and promising technology for the aggregation of data within smart grid optical fiber networks. This VCSEL tunability enables various users to be assigned specific wavelengths in the optical network.

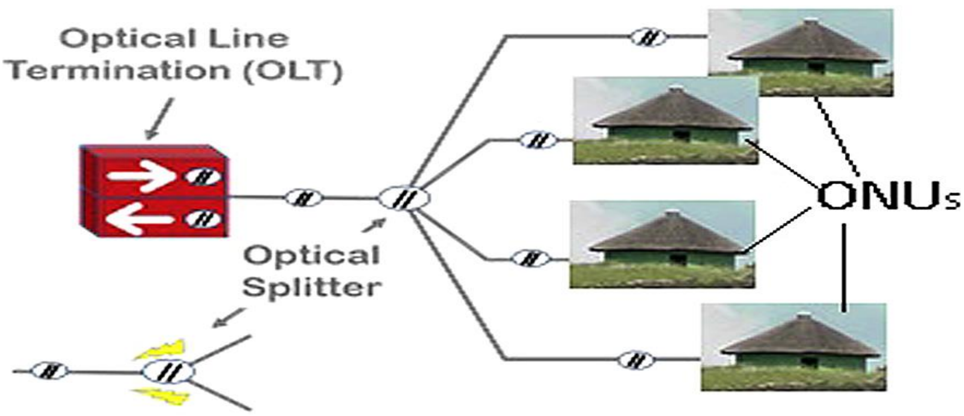

Figure 2.4: A schematic diagram of a typical PON representation (Kipnoo et al., 2017)

2.8 The Distributed Feedback Laser (DFB)

With an edge emitter and an active pump, a DFB laser can be defined as one in which the optical gain is evenly distributed between the two output facets of the grating. It is possible that the grating is passive (refractive index gratings) or active (gain or loss gratings). One or even more phase-shift regions may also be included. As the DFB grating functions as an out-coupler with low reflection, this is the most common configuration for higher power applications because it eliminates phase shifts and has a high reflectivity dielectric coating (> 90%) (Zervas et al., 2013). Due to its narrow spectral width and wavelength stability, the distributed feedback laser (DFB) is broadly used as a source of light for metro, undersea and long-haul applications (Zervas et al., 2013).

2.9 Modulation Techniques

Modulation refers to the process of sending signal to the end receiver via communication channel by means of varying its properties with the carrier signal like frequency, amplitude and phase (Hui et al., 2004). In other words, it refers to the variation process of one or more periodic wave form properties known as the carrier signal, which carries a signal of modulation containing the information that is meant to be delivered.

There are basically two modulation forms namely the external modulation and the direct modulation (Hui et al., 2004). In direct modulation, there is the emission of light from the semiconductor laser when there is the transmission of a mark. In this format of modulation, there is the direct application of the radio frequency to the laser. The device's output power directly depends on the input current. VCSELs and other DFBs utilize the direct modulation (Khwandah et al., 2015). In addition, this modulation format has the advantage of low cost. However, it has a disadvantage of being unable to provide a high gain due to laser limitations (Hui et al., 2004). External modulation has the ability to provide a high gain but it is expensive and complex. There are several modulation formats that have been utilized in the transmission of data or signal. On-off keying (OOK) intensity modulation is the simplest optical modulation format based on the binary logic '1' or '0' (direct modulation). It can be implemented in two ways: Non-Return to Zero (NRZ) or Return to Zero (RZ).

When compared to other methods of modulation, OOK is much simpler and less expensive. However, the transmission distance is limited by the modulation bandwidth and the induced frequency chirp (i.e., the difference in optical frequency just at turn ON state just before the turn OFF state of laser) that limit its application. An external modulator can be used to transmit data in a digital optical format. A semiconductor's optical absorption edge's wavelength is observed to be lengthened by an electric field when using an electro absorption modulator (EAM) (Zervas et al., 2013)**.** When an electric field is applied, the Pokels effect, a linear electro-optic effect, causes a change in the refractive index of a material, and thus changes the phase of the optical signal. Mach–Zehnder (MZ) interferometers use a phase change to modulate the intensity of a light wave. Transmission quality and spectrum efficiency are greatly affected by the optical modulation. Until recently, optical systems used RZ and NRZ as their primary modulation formats (Ghayal & Jeyachitra, 2020).

New modulation formats are being developed in response to the growing need for increased transmission capacity. In order to combat nonlinear transmission losses brought on by growing distances, channel bit rates, and contracting channel spacing, NRZ modulation has been recommended. Figure 2.5 represents the data signal format for NRZ modulation where the binary high (1) and low (0) states are transmitted by constant and specific direct current (DC) voltages.

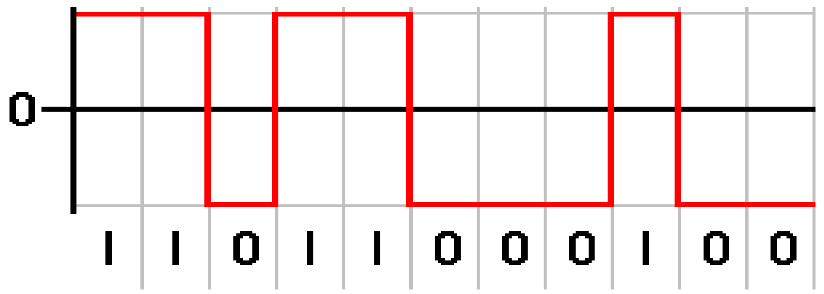

Figure 2.5: Data signal format for NRZ modulation (Muthana et al., 2011)

This modulation technique is frequently regarded as one of the best ways to deal with the impacts of dispersion and nonlinearity for 40 Gbps and 100 Gbps optical fiber communication systems (Yao et al., 2014). Data transmission from the electrical domain to the optical domain makes up mode of operation of the modulation process. A high frequency carrier is typically used. The modulation method is known as analogue modulation if the carrier parameter modification is at all continuous with respect to the input analogue signal. Similarly, if the change is discrete, it is referred to as a digital modulation.

Digital modulation is preferred than analogue because of security, error correcting, noise detection and bandwidth reasons (Lohani, 2012). Different digital modulation techniques have been developed so far, and the use of specific technique is related to characteristics of the channel or message signal or even the performance of the overall communication system (Rajanna et al., 2016). General packet radio services (GPRS) and power line communication (PLC) are utilized for Automatic Meter Reading (AMR) applications. Using Binary phase Shift Keying (BPSK) modulation with PLC communication shows that it is possible to even do smart metering in smart micro grids in rural areas.

2.10 Multiplexing Techniques

Multiplexing refers to the simultaneous transmission of multiple analogue or digital signals into a single signal over a shared medium. The primary aim of using this method of multiplexing is to ensure that there is the sharing of a resource that is scarce. Orthogonal frequency division multiplexing (OFDM) is effective in overcoming the channel conditions in low frequency power lines (Rehmani et al., 2019). Advanced modulation and channel coding techniques are used for the effective utilization of limited bandwidth. The OFDM architecture ensures the facilitation of robust communication over the channel of power lines (Sanz, 2011). The multiplexing technique is able to rectify the problem of signal attenuation and multipath propagation.

The SG requires efficient communication between the generator and the consumers. To avoid the cost of establishing a network of communication parallel to the distribution grid, there is the need to have a power line communications technology (PLC) (Sanz, 2011). OFDM offers the ideal and appropriate carrier technology even though the considerations required for its efficient implementation in smart grid are beyond the choice of the carrier.

2.11 Data Erasing Technique

Data erasing refers to the procedure of removing or eliminating the transmitted bits from an optically modulated carrier signal. While doing this, the same wavelength could be immediately reused after the data erasure process. There has been a long-standing recommendation of the utilization for semiconductor optical amplifiers (SOA) for data erasing, data routing and data receiving in wavelength division multiplexing (WDM) optical networks (Conforti et al., 2002). During data erasure, the spectral efficiency of the network is likely to be enhanced which can thereby improve the overall efficiency of the network. Consider the wavelength reuse for an optically modulated pseudo random bit sequence (PRBS) signal case getting to the forwarding node. Prior to the signal being sent into the linear amplifier, the signal with a reasonably low extinction ratio (ER) is first amplified. The two power logical levels of an intensity modulated optical carrier only become visible once the signal has been given a pattern. These are the low level, represented by "0," and the high level, represented by "1."

WDM technology has been widely employed in metro/access networks and passive optical networks (PONs). This is due to the fact that using this WDM technology provides individual users with a wide bandwidth and wavelength flexibility (Takesue & Sugie, 2003). For these kinds of systems, the erbium doped fiber amplifier (EDFA) has been proposed as a way to increase the network's coverage area. There has been the proposal of these PON-WDM networks together with light sources for the fiber-to-the home (FTTH) applications (Park et al., 2004). The two-wave channel arrangement used by the majority of PON-WDM networks assigns one carrier for upstream transmission and another for downstream transmission. Even though this is feasible, the network’s capacity might be a limited by the finite bandwidth which will call for wavelength reuse and reservation for the bandwidth flexibility (Ribeiro et al., 2011). Wavelength reuse and reservation procedures that are opto-electronic based such as the use of SOA are attractive candidates for WDM applications. Despite this, they are still faced with some limitations (Cao et al., 2014). For instance, due to constrained bandwidths, circuits capable of down-converting the standard wireless signal (SWS) for a radio frequency (RF) carrier to an intermediate frequency before upstream transmission may be required for applications such as wireless transmissions (Cao et al., 2014). The suppression of an optical bit pattern utilizing the erbium doped fiber amplifier (EDFA) gain saturation and a holding beam is a viable technique that provides a simple erasing method of a downstream bit pattern which makes the reuse the wavelength in the power grid network for meter reading possible (Wassin et al., 2019). For flexible optical access network applications operating at 10 Gbps data rates, the all-optical wavelength re-use technique is suitable and efficient. The low and high-power levels, represented by the symbols P_o and P_1, comprise the optical carrier. As shown in Figure 2.6, the EDFA's input-output transfer curve was used in the erasure of the incoming signal's data (Šprem, & Babić, 2019).

From Figure 2.6, it is evident that the EDFA 's output power saturation is achieved with an increase in the optical signal power above the linear region. However, data suppression or extinction takes place only when the EDFA is operated in the saturation region or somewhere near the saturation region (Charbonneau & Vokkarane, 2011).

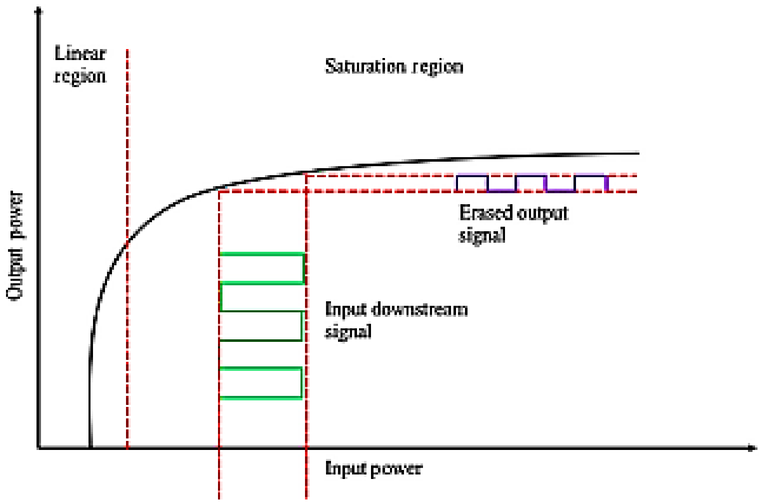

Figure 2.6: EDFA characterization used to achieve saturation for data erasing showing the output power as a function of input optical power (Takesue & Sugie, 2003)

In the sense that the input power to the second stage EDFA falls inside the zone of saturation, the first stage optical amplifier amplifies the incoming carrier signal. As a result, the data from the optically modulated input signal is muted and then deleted.

According to Ribeiro et al. (2013), the extinction ratio (ER) decreases when an intensity modulated signal is amplified within the amplifier's saturation area. The wavelength of the erased output can then be utilized and re-modulated right away.

2.12 The LoRa Technology

LoRa (long range radio) is a wireless modulation technique offering low power, long range and secure transmission of data for IoT applications (Döníz, & Lajos, 2022). It is a wireless communication technology that can be applied in smart metering. Even though smart metering possesses many advantages, it is also faced with some challenges including the introduction of risks from cyber-attacks to the metering system (Döníz, & Lajos, 2022). This is a challenge that may as a result bring about the leakage of the user's privacy or even a risk of the smart metering system.

Even though many of the meters are situated within a regional area of power supply, some nodes that are hard to reach are located far from the clustered area. This accounts for a huge portion of the whole operation cost of smart metering (Raychowdhury & Pramanik, 2020). The above challenges can be overcome by developing a safe and secure metering infrastructure that is smart in nature based on the integration of the LoRa and optical fiber technology. The LoRa facilitates the long-range wireless communication and the optical fiber on the other hand also facilitates long range wired communication (Döníz, & Lajos, 2022). A combination of LoRa devices with optical fiber is able to extend the range of communication between endpoints of the utility and end users (Raychowdhury & Pramanik, 2020). The connection can be done by connecting each LoRa gateway to the optical fiber network by the use of appropriate media converters or fiber optic transceiver (optical fiber and VCSEL technology) to allow the collected data by the gateway to be reliably and quickly transmitted over the network of fiber.

2.13 Software Defined Networks (SDN)

The current power grid is no longer a solution which is feasible because of the ever-rising demand for electricity, reliability issues and even old infrastructure. This is why there is the need to have a better grid. Despite having these advantages, the SG communication system has certain specific issues. For example, there is a complexity in the management of network of the current SG system, it is manually done and due to that it is also time consuming. Furthermore, the SG communication system is established on various vendor specific protocols and equipment (Rehmani et al., 2019). The current SG systems are therefore, not protocol independent thereby leading to issues in interoperability. The Software Defined Network (SDN) can be integrated into the SG communication infrastructure to manage and monitor the global communication networks.

With the aid of Intelligent end devices (IEDs) and Remote Telemetry Units (RTUs), such advanced computing and networking devices can expose a larger attack surface to attackers, who can penetrate the control network via various means (Zhang J, et al., 2013). SDN can help network operators to effectively and flexibly manage the network by separating the control plane from the data plane (Rehmani et al., 2019). With its protocol independence, granularity features and programmability, SDN can be able to help the SG in integrating different protocols and standards. This will assist in coping with the diverse systems of communication and also to help the SG perform traffic flow orchestration to meet specific requirements of quality of service. The current grid has traditional mechanisms such as firewalls which are not very efficient. This is why there is the need to ensure improvements in the grid system (Zhang J, et al., 2013). Unprecedented capabilities for stopping such attacks will be made possible by SDN approaches.

2.14 Research Gap

The study aimed to bridge the primary gap of unreliability in the communication between the end users and utility for meter reading and billing. Metering communication is an essential component of developing a smart grid (Fan et al., 2012). This is a two-way communicating device that is able to measure energy consumption of the utilized electrical home appliances. The home area network (HAN) that is an information and communication network formed by devices and electrical appliances within the home support various distributed applications including the management of energy at the end user's home (Fan et al., 2012). Therefore, there has to be an efficient communication system in between the HAN and the utility to timely report issues such as inefficient billing and untimely reporting of blackouts whenever they occur.

The optical fiber technology is widely considered for this operation because of its ability to support the transfer of high-speed data. The system is also considering the aspect of cost and it therefore aims at proposing a cost-effective method of signal transmission. In this case, the all-optical wavelength data erasing approach would be a cheaper method of reusing the same wavelength for communication without having to introduce more optical sources.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter describes the design and methodology that was used in the research. The grid communication system consisted of both transmitter and receiver channels. The methodology consisted of both experimental and simulation work. The simulation approach using optisystem 7 software was elaborated together with the requisite experimental tools to elicit data for analysis. The analysis of the data was results based and no statistical analysis was conducted.

3.2 Research Location

The study was conducted at the Nelson Mandela University Center for Broadband Communication Lab in South Africa courtesy of a research visit. All the apparatus and the test bed were in the lab and the experiments were conducted in the lab.

3.3 Research Design

3.3.1 Experimental Work

The experiment used the setups illustrated in Figure 3.1 (a) (b), 3.2, 3.3 and 3.4 respectively. Parameter modifications such as attenuation, bias current power among others were done to configure the system to the required standards. The experimental work was entirely conducted at the Center for Broadband Communication Lab where all the equipment were located.

3.3.2 Simulation Work

The simulation reported in this work used an optisystem software. This software is among the ones used in modelling telecommunication networks. Optiwave Software has since its inception in 1994 been licensed to more than 1000 leading companies and universities worldwide in over 70 countries (Optiwave, 2021). OptiSystem has several advantages that include easier integration capabilities with other software platforms, most of the library components are in-built, and finally, compared to the optical communication system used in the actual world, parameter changes can be made more easily. (Optical communication system, 2008).

3.4 Research Materials

3.4.1 Signal Generator

A Rohde & Schwarz SMB100A RF and Microwave signal generator was used in the study. This electronic device generated both electronic signals and waveforms with variable output by setting the amplitude and the frequency. Its basis is on the sine wave oscillator with distinction in design of RF and audio frequency signal. The signal generator covers an array of frequencies that need to be generated for various applications. In this work, the signal generator was operated at 10 GHz RF clock tone.

3.4.2 Laser Diode Controller

The Thorlabs LDC 201C laser diode controller was used with a current range from 0.5 to 9.5mA. The current limit can be adjusted and cannot be exceeded. A 5-digit LED displays the laser current, photodiode monitor, or current limit. Laser diode is driven with respect to the ground, an operation that provides current transient suppression and stability and also low noise. In this study, it was used to tune the bias current of both the DFB laser and VCSEL.

3.4.3 Vertical Cavity Surface Emitting Laser (VCSEL)

The study utilized a RayCan 1550 nm vertical cavity surface emitting laser (VCSEL). This light source is a semiconductor laser diode which emits highly efficient optical beam in the vertical cavity. The emission of the light is perpendicular to the laser's surface layer. The optimization of the laser was done to operate at current ranging from 0.5 mA (the threshold current) to 9.5 mA, with wavelength adjustable between 1548 nm to 1556 nm, and 0.5 mW typical optical power output. The relatively low power is favorable for short distance transmission and use in applications such as access network.

3.4.4 Distributed Feedback (DFB) Laser

The distributed feedback laser is made up of a diffractive grating in its active region. This diffractive grating is a periodic structure made with phase shift in its middle. It operates as a Bragg reflector to offer the optical feedback. It reflects a narrow band of wavelengths to produce a single lasing mode and optical guiding improving efficiency. The divide electrode structure on one of the surfaces of the DFB laser permits injected current distribution to be modified so as to enable control of the laser output power and wavelength. In this work the DFB laser with use of a laser diode controller at bias current 94.4 mA achieved an optical power output of 7.98 dBm at 1552.5nm wavelength for all optical wavelength reuse. This Laser compared to the VCSEL provides more power and is suitable for long-haul transmission.

3.4.5 Positive Intrinsic Negative (PIN) Photodiode

The invention of the PIN photodiode was in 1950’s. It has a wide undoped intrinsic semiconductor region between the p and n-type heavily doped semiconductor regions used for ohmic contact. The Intrinsic region’s width is larger than the space carrier width of normal p-n junction. The photodiode plays a pivotal role in the conversion of the optical signal to electrical. It functions with an applied reverse bias voltage, with space charge region entirely covered by intrinsic region.

3.4.6 Optical Fiber Spools

The study made use of the optical fiber as a transmission medium for upstream and downs stream communication. The optical fiber transmission was 25 km using a VCSEL and 25/50 km using a DFB. The optical fiber as a transmission medium was preferred for the study due to the vast advantages that come with the use of this medium. High data rates, insusceptibility to electromagnetic interference and high speed characterize it as a medium of choice for the study.

3.4.7 Long Range Radio (LoRa) Device

The study used the LoRa Technology for wireless communication. Using the LoRa technology, it was possible to maintain a long-term security of the proposed smart metering system through the designing of a key management protocol necessary for the periodic update of the keys. The LoRa devices were able to further push the signal in free space and coupled to a fiber to extend the reach of the communication signal for meter reading.

3.5 Experimental Procedures

3.5.1 VCSEL and DFB Characterization and Signal Transmission

The unmodulated Raycan Company VCSEL was characterized to determine the output power vs bias current behaviour as shown in Figure 3.1 (a). This was done experimentally and by simulation. The DFB laser was experimentally characterized and the output power vs temperature relationship as well as the output power vs bias current curves were shown. The VCSEL and DFB characterization was done for the establishment of optimum performance points for the devices and for power budgeting in the network. Wavelength tunability was also investigated for the VCSEL by increasing the bias current. Bias currents of 2 mA to 9 mA were used to adjust the VCSEL's channel tuning. Using a 10 Gbps non-return to zero (NRZ) pseudo-random binary sequence (PRBS- (2^7-1)), a Raycan Company VCSEL lasing at 1550 nm with a - 0.9 dBm operational output power was modulated with a programmable pattern generator (PPG) through a bias tee with the modulation depth maintained at 0.3 mV. NRZ PRBS modulation was chosen because it is a simple line coding technique than the return to zero (RZ) technique since the pulse does not return to zero in the process of data mapping.

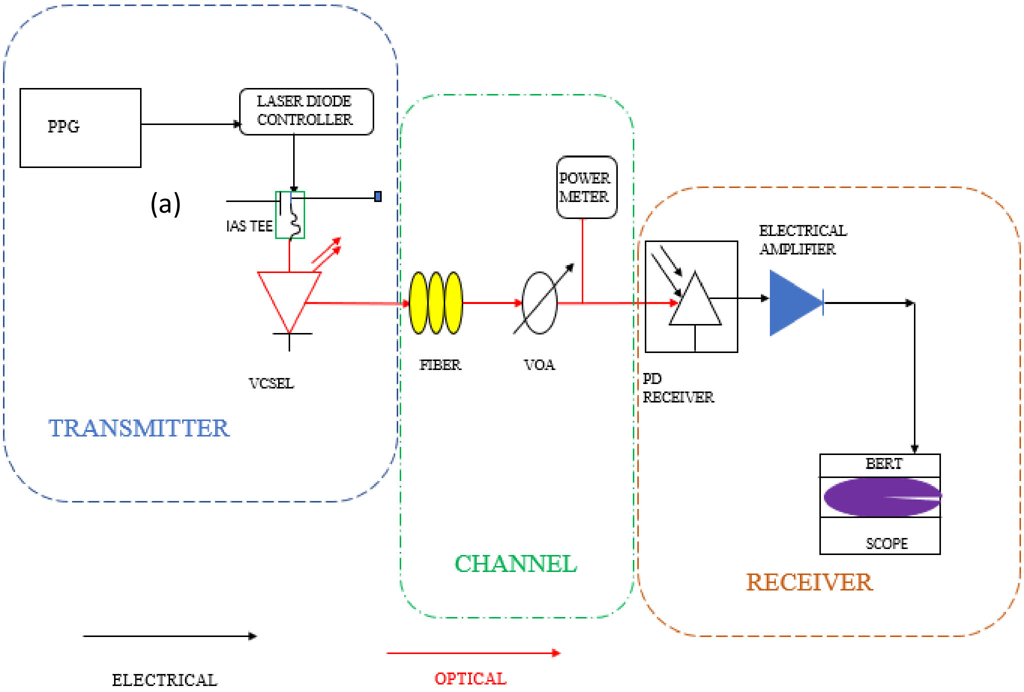

Figure 3.1 (a): The experimental characterization set up of a 10 Gbps directly modulated VCSEL

The VCSEL was driven by a laser diode controller (LDC) with operational drive currents between 0.5 and 9.5 mA which was controlled by a bias tee to set the DC bias points. This was repeated for the DFB while operating it using a thermoelectric cooler (TEC)as shown in Figure 3.1 (b). The TEC was not used to drive the VCSEL since it is a low powered laser.

The transmission channel was then monitored and transmission performance for the VCSEL using a fiber under test (FUT) was conducted.

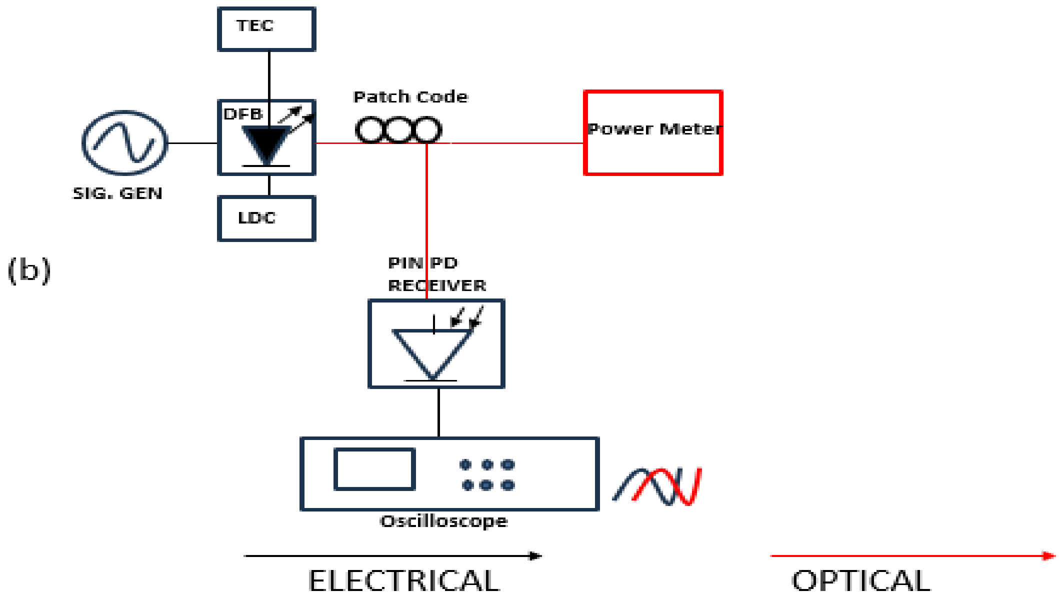

Figure 3.1 (b): The experimental characterization of unmodulated DFB laser

The bit error rate (BER) was then measured for B2B and 25 km at the receive channel. VCSEL transmission was limited to 25 km due to the low powered nature of the laser. The transmission performance was repeated using a WDM DFB laser source at B2B, 25 km and 50 km. For the VCSEL, the transmission distance was limited to 25 km since the VCSEL compared to the DFB is a low powered laser and therefore a single VCSEL is not suitable for long haul transmission. Measurements of BER and associated eye diagrams were taken at the critical telecommunication threshold (10^{-9}). The BER was measured by adjusting the power incident on the photo diode detector, which was achieved with the help of a variable optical attenuator (VOA). The electrical amplifier (EA) was used to increase the voltage of the received signal to the level necessary for BER measurement. The eye diagrams, resultant electrical waveforms and Q-factors were recorded for the various transmissions.

On the data transmission, on-off keying (OOK) amplitude modulation was utilized to add 10 Gbps of data to the optical carrier signal. Amplitude-modulated 0.4 GHz clock signal was used to transmit the data over 25 km of single-mode fiber of G.655 standard. To demonstrate simultaneous data and clock signal transmission, a clock signal was coupled into a 10 Gbps data and transmitted. This was done by setting the frequencies on the signal generator at 0.4 GHz and 2.5 GHz, and the input power maintained at -14 dBm. The two frequencies were selected to see the effect of a higher and lower frequency on data and clock transmission. In addition, the devices operate on a bandwidth and it is therefore necessary to select an optimum channel.

VCSEL modulation voltage was tuned, and bias current ranged from 5.88 to 6.88 mA. A 1550 nm VCSEL was modulated using a 10 Gbps data. Amplitude-modulated 0.4 GHz clock signal was used to transmit the data over 25 km of single-mode fiber of G.655 standard. In this case, the clock signal was used to regulate the data transmission to ensure the transmission of each signal in its designated time slot. The clock signal determined how each time slot started and ended. It also ensured the transmission of each signal at the correct time. The clock's input power was maintained at -31.94 dBm. The electrical signal generator's depth of modulation was set at 0.2 mV for its RF level to generate the clock signal at 0.4 MHz Data and Clock transmission was done using a VCSEL alone. The DFB comparison in the study was only in characterization and single data signal transmission using a transmission medium.

3.5.2 Data Erasing

The data erasing process of in principle is composed of two stages, a linear optical amplifier that is then followed by an EDFA. In the experiment, EDFA was used to attain saturation. EDFA was preferably used over the semiconductor optical amplifier (SOA) because it was available in the lab and was able to achieve the intended purpose of data erasure.

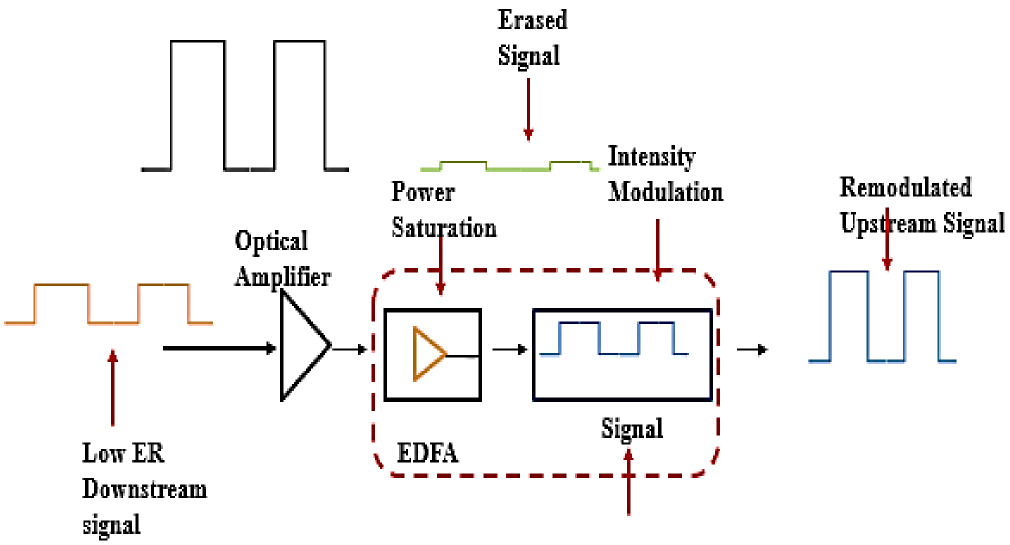

Figure 3.2: Wavelength channel data erasure principle

In the case of an optically modulated PRBS signal, there was the amplification of a signal having a relatively low ER by an optical amplifier prior to its injection into the EDFA as illustrated in Figure 3.2. The low extinction ratio attributes to a signal whose intensity have not been boosted by optical amplification. In the Figure, it is demonstrated that the EDFA performs both amplification and erasure of the remodulated signal. The all-optical wavelength reuse experimental technique was demonstrated using the set up in Figure 3.3. The experiment involved the recovery of the optical carrier utilized in the downstream signal transmission and re-using the same recovered wavelength for upstream communication.

The DFB was utilized in place of a VCSEL to demonstrate data erasure because the VCSEL in the laboratory malfunctioned and could therefore not accurately demonstrate the data erasing process.

It is however, possible to use a VCSEL for the same procedure. It has an advantage of low power operation, high temperature operation, low cost and direct data modulation. It can therefore provide an alternative low power and cheaper all optical wavelength reuse. A temperature stabilizer thermoelectric cooler (TEC) was used to operate the DFB laser bias current, which was set at 94.4 mA. By adjusting the TEC to 9.954 kΩ, the DFB's peak sender wavelength was maintained at 1552.3 nm. In order to demonstrate the flexibility of the signal carrier and alter the emission wavelength of the DFB laser source, the thermistor resistance of the DFB was varied. The sender peak wavelength was changed to 1551.2 nm to ensure wavelength utilization. The optical spectrum was utilized effectively to ensure the utilization of the available10 Gbps bandwidth. The G.655 nonzero dispersion fiber (NZDF) was used to transmit the intensity modulated PRBS optical signal into a reduced slope.

The holding beam was a -3.9 dBm continuous wave (CW) produced by the EXFO M2100 broadband laser light source running at 138.9 mA current. Owing to the long transmission distance the required transfer curve was to have a low saturation which is a condition necessary for achieving a full optical data erase. The EDFA was also supposed to operate close to saturation point. High saturation point operation would not have been able to realize full erasure. The function of the holding beam was to optimize the EDFA data erasure by means of adding more photons through amplified stimulated emission to ensure the sharing of resources thereby shaping the transfer curve. The continuous wave (CW) holding beam from the EXFO M2100 broadband laser light source and the modulated signal from the DFB were combined into the EDFA using a 3 dB optical coupler. There was the optical attenuation of the two signals before coupling them into the EDFA so that they could be able to meet the EDFA’s optimal saturation input power. At 1050 mA and 750 mA, respectively, EDFA was operated at the saturation region biased to execute data erasure from the input signal. A comparison of the output power levels' variations with the input power was demonstrated by biasing the EDFA at the two currents.

The holding beam was filtered out, and the noise from the broadband source was suppressed, using an adjustable band pass filter centered at 1550.1 nm. A positive intrinsic negative (PIN) photodiode receiver and a variable optical attenuator (VOA) comprised the receiver unit. An Agilent Infiniium wide bandwidth digital sampling oscilloscope was used to analyze the eye diagram and the corresponding ERs on the resultant electrical signal output.

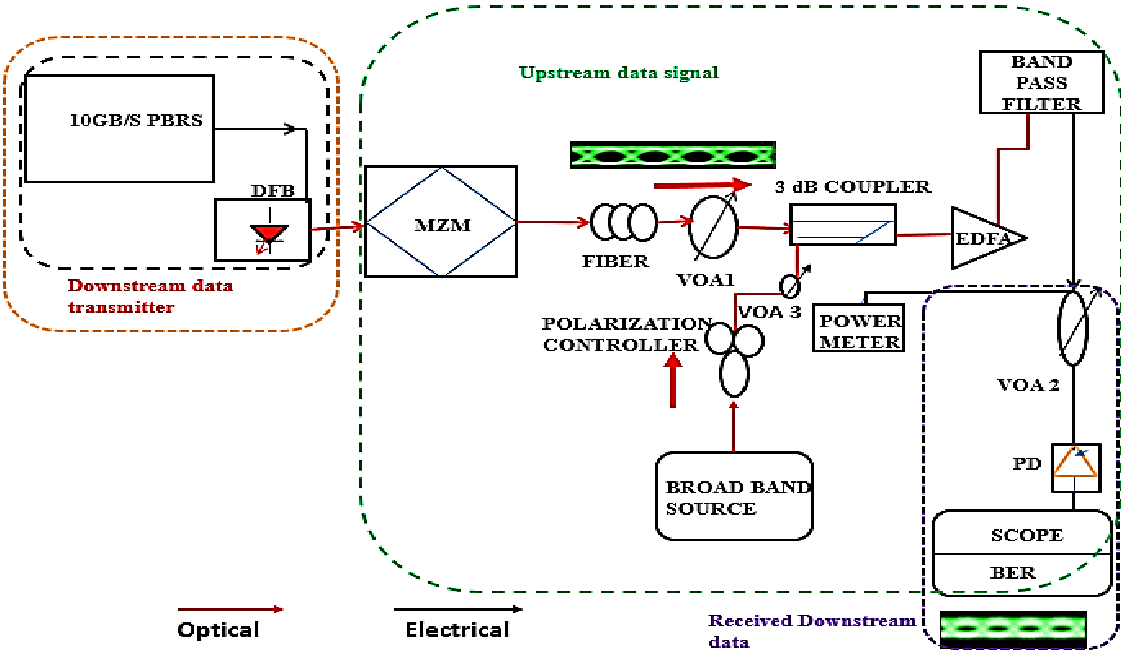

Figure 3.3: Experimental schematic illustration of all optical wavelength reuse

After successful data erasure, upstream data transmission was perfomed with the reused wavelength over 50 km fiber length. Bit error rate curves were measured for the confirmation of the quality of re used wavelength's signal. Results for back-to-back downstream, 50 km downstream transmissions, back-to-back upstream after the data erasure and 50 km wavelength reuse and the upstream transmission of fiber were obtained.

3.5.3 LoRa Characterization

The set-up used to characterize the TTGO LoRa ESP 32 Dev module board is shown in Figure 3.4. The LoRa module has both a transmitter and a receiver component. The LoRa input power was maintained at -8.13 dBm and the frequency was set at a range of 600 MHz to 800 MHz using a signal generator and a signal and spectrum analyzer from Rohde and Schwarz. This was done to give a broadband frequency spectrum to choose the frequency that would give the highest maximum output power necessary to push the strongest signal required for signal transmission.

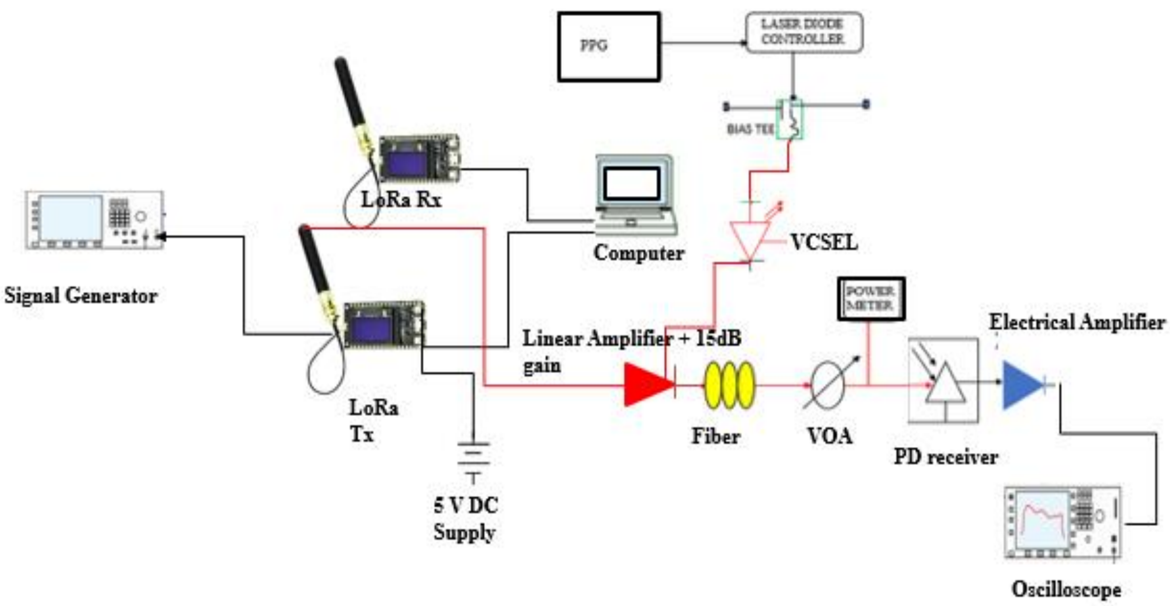

Figure 3.4: LoRa module connected for signal analysis on the scope

The two LoRa devices (Transmitter and Receiver) were first programmed as a transmitter and receiver respectively using the Arduino IDE program (refer to Appendix III). The program was run on the computer for programming the LoRa device. This was done by starting the program by adding the required libraries, initializing the pins and using the sender and receiver codes. After establishing the transmitter and receiver, a signal was generated from the signal generator into the LoRa transmitter and the output signal observed on an Agilent oscilloscope.

The LoRa transmitter was powered using a DC power supply that was able to generate 5 V necessary to operate the signal to the TTGO ESP 32 board. A linear amplifier with a +15 dB gain was used to boost the signal during propagation. After characterizing the LoRa devices, signal analysis method was conducted. The frequency on the pattern generator clock signal was set at 730 MHz giving the highest output power of -35 dBm required to carry the signal. The signal input to the LoRa transmitter was thereafter observed on the Agilent oscilloscope after monitoring the signal on the optical channel. The oscilloscope had both the optical and electrical channels and since the signal input to the LoRa is an optical signal it was observed on the optical channel. The VCSEL was coupled to the LoRa module and the signal monitored before the introduction of an optical fiber.

The output signal of the LoRa was coupled to an externally modulated VCSEL and the resultant signal giving an output power of -4 dBm. The signal was then observed on the oscilloscope. The signal from the LoRa and the VCSEL were obtained after amplification using a linear amplifier with a +15 dB gain. The amplified signal was then coupled into an optical fiber. The fiber was used as the transmission medium and the signal was transmitted 25 km. Coupling the LoRa device to the fiber was meant to create a scalable communication infrastructure for the utilities which could enable the collection, analysis and management of meter data. The VOA was used to step down the power going into the photo diode receiver to prevent it from saturating due to excess power. At this point the signal power was monitored using a power meter and the converted electrical signal from the LoRa/VCSEL pair was amplified using an electrical amplifier before the signal could be observed on the scope.

3.6 Validity and Reliability of Research Tools

The research tools used in the lab were found to be valid, necessary and useful in the study. Validity was characterized by the accuracy that the data was transmitted with to ensure the conveying of the signals without a lot of imperfections. The VCSEL was able to emit coherent light as well as maintaining the integrity of the signal over the 25 km transmission distance. The optical fiber on the other hand was able to enhance the validity of the results by minimizing the losses. However, there were various challenges experienced while using the apparatus such as fiber imperfections, VCSEL faultiness, malfunctions of some devices such as the signal generator and oscilloscope which slowed down the experimental procedure.

3.7 Chapter Summary

In this chapter the experimental and simulation procedures that were used for obtaining the results have been presented. VCSEL and DFB optical sources were characterized for the establishment of optimum performance points for the devices as well for power budgeting. Optisystem software 7.0 was used in performing simulation work. Experimental procedures for all optical data erasing, transmissions and LoRa characterization and signal analysis have also been discussed in this section. Some of the vital experimental apparatus used in the study are explained in the chapter. The tools were found to be valid and useful for the study. The study was done at the Nelson Mandela Center for Broad Band Communication Lab in South Africa, funded by the National Research Fund, South Africa.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

The chapter certain the results and the respective discussions of the findings. These are VCSEL and DFB characterization, transmission performance, Q-factor analysis, clock and data signals transmissions, data erasing and LoRa characterization in sections 4.1,4.2, 4.3, 4.4, 4.5 and 4.6 respectively.

4.2 Results on VCSEL and DFB Characterization

Figure 4.1 (a) shows the VCSEL's ability to tune the lasing wavelength and the output power. In the Figure, a tunability range of 1548-1556 nm was obtained when the bias current was varied from 2-9 mA. This illustrates that the current variation from 2 -9 mA shifted the whole spectrum towards a region of higher wavelength. Furthermore, an 8.0 nm wavelength tunability was achieved indicating that the used VCSEL when used as an actuator can be able to apply a phase correction across a wavelength band width of 8.0 nm.

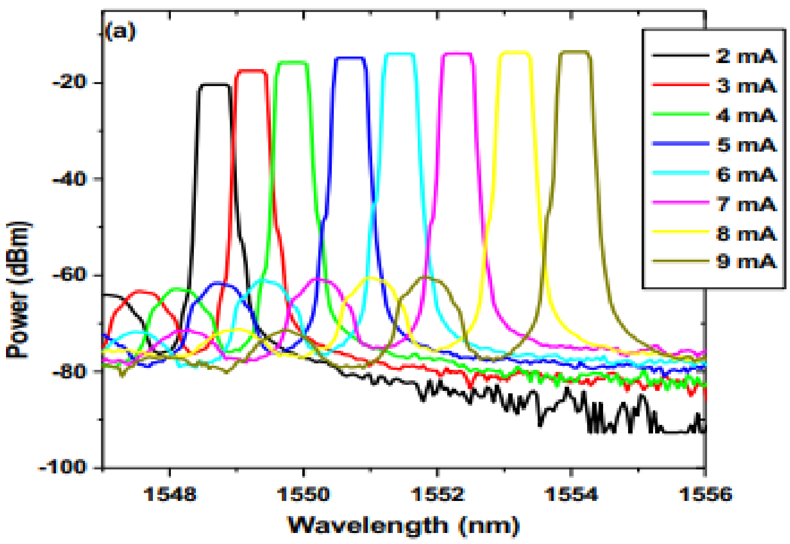

Figure 4.1 (a): Wavelength tunability of VCSEL with bias current

Figure 4.1 (b) shows the output power vs bias current correlation for the source. From Figure 4.1 (b) the lasing threshold was experimentally determined to be 1 mA. In simulation on the other hand, the lasing threshold was obtained at 2 mA. The variation in the lasing threshold was due to real world complexities including environmental factors that cannot be captured in simulation. The low bias currents obtained from the results indicate that the VCSEL operates at a very low power. From the experimental and simulation results in Figure 4.1 (b), it was observed that above the threshold currents of 1 mA and 2 mA respectively, the VCSEL's output power varied linearly with current. VCSEL's saturation current was measured at 8.5 mA.

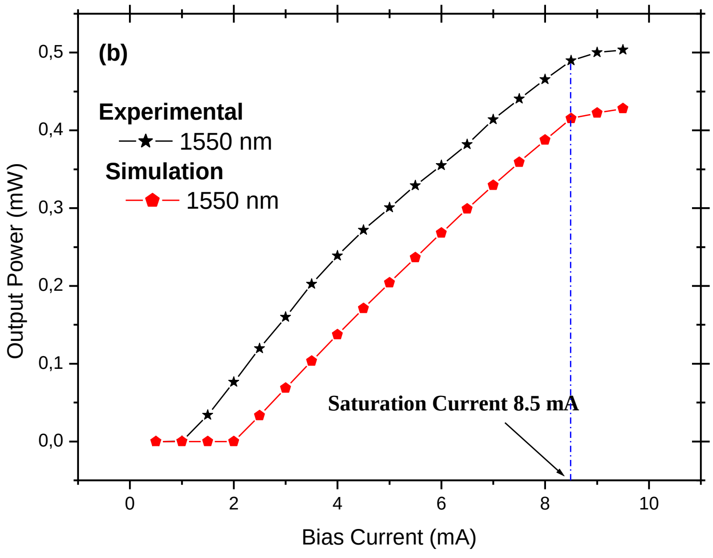

Figure 4.1 (b): Measured input current-output optical power characteristics of VCSEL at 1550 nm based on simulation and experiment

As current increased above saturation, VCSEL's output power presented signs of saturation. The VCSEL operates best in the linear region between the saturation current levels and threshold at around 5 mA.

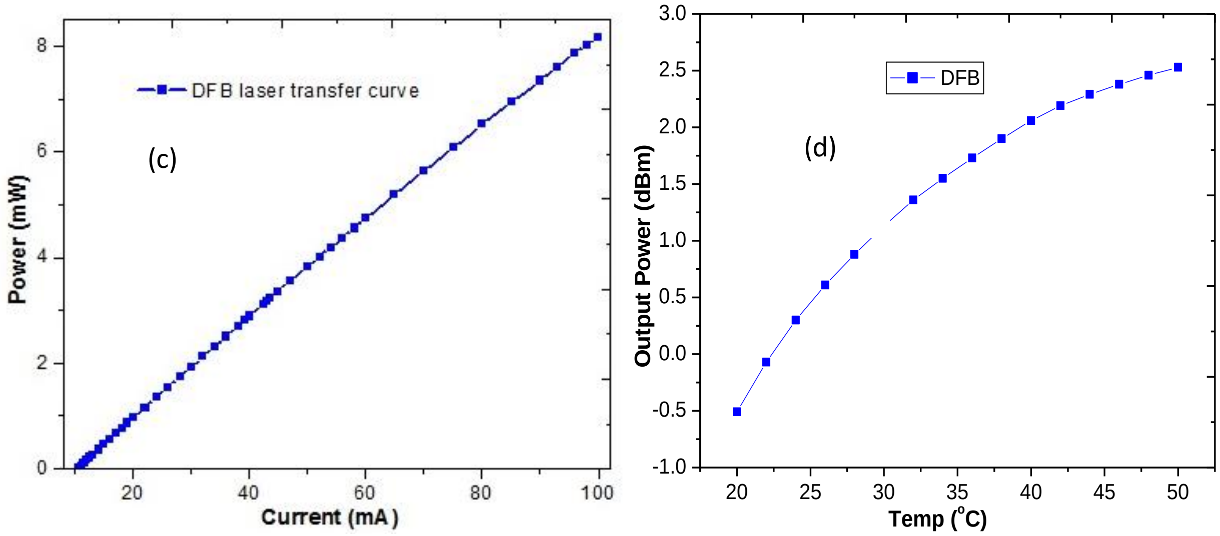

Figure 4.1 (c): Input current-output optical power characteristics of DFB measured experimentally at 1550 nm (d) Temperature-power characteristics of DFB at various temperatures.

The operational behaviour of a high speed unmodulated 1550 nm DFB laser source is demonstrated experimentally in Figure 4.1 (c). The Figure displays the unmodulated static characteristic of the DFB laser with varying bias current. It is evident that the bias current has a linear relationship with the DFB's output power. According to the figure, the DFB is a high-powered laser because the lasing threshold was measured at 10 mA and the saturation current was 94 mA, which is higher than the VCSEL's 8.5 mA saturation current. A DFB bias current of 50 mA was maintained with an optical output power of 3.95 dBm. Furthermore, the DFB laser was operated within the linear region of the transfer curve at this bias current setting to allow for a complete swing between the on-off states of the laser. In Figure 4.1 (d), It was discovered that a DFB laser's output power increases as the temperature rises, suggesting that the DFB generates greater power at higher temperatures.

4.3 Results on Transmission Performance

4.3.1 The Vertical Cavity Surface Emitting Laser (VCSEL)

Figure 4.2 (a) depicts the system's performance for back-to-back B2B and after 25 km Using the 1550 nm VCSEL. From the Figure, a 10 Gb/s signal's error free receiver sensitivity was determined experimentally using a VCSEL to be -17.15 dBm in B2B. After 25 km transmission there was the measurement of the incident power at -14.48 dBm indicating a 2.67 dB power penalty that was introduced by the transmission length of the fiber.

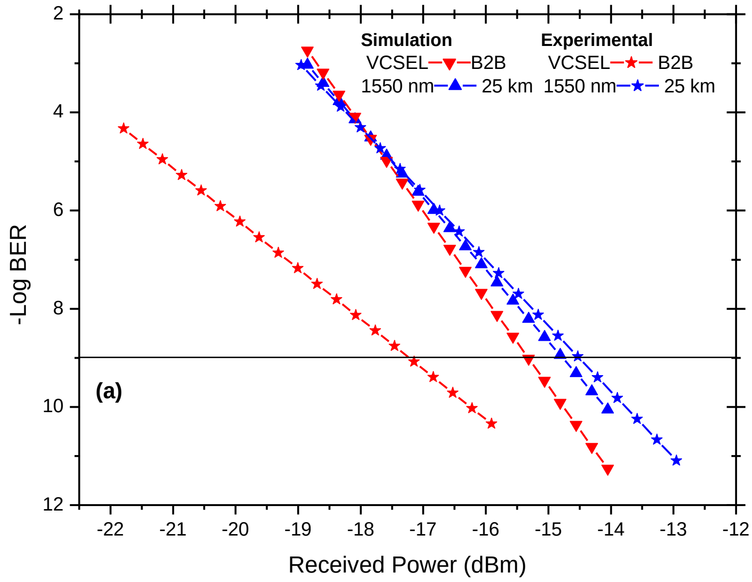

Figure 4.2 (a): Simulation and experimental plots of –Log BER curves for B2B and 25 km transmission using 10 Gbps 1550 nm VCSEL

The source of the power penalty was as a result of fiber dispersion which affected the optical receiver's sensitivity. In addition, since the VCSEL being a directly modulated laser is susceptible to frequency chirpings, together with fiber dispersion, this degraded the sensitivity of the receiver thereby introducing a larger power penalty than in the case of the externally modulated DFB laser in Figure 3 (b). In simulation however, the B2B receiver sensitivity was -15.33 dBm and after 25 km the incident power was measured at -14.67 dBm indicating a 0.66 dB transmission penalty introduced by the fiber transmission length.

In simulation however, the incident receiver powers were -14.69 dBm and -15.40 dBm for B2B and 25 km respectively resulting to a 0.71 dB transmission penalty introduced by the fiber during the signal transmission. The B2B curves for simulation and experimental work varied due to parameter modifications and setting of the photodiode receiver. In simulation, there was a direct control over the parameters and could be adjusted to come up with different scenarios. In experimental work, some parameters were affected by external factors which made the precise parameter manipulation challenging.

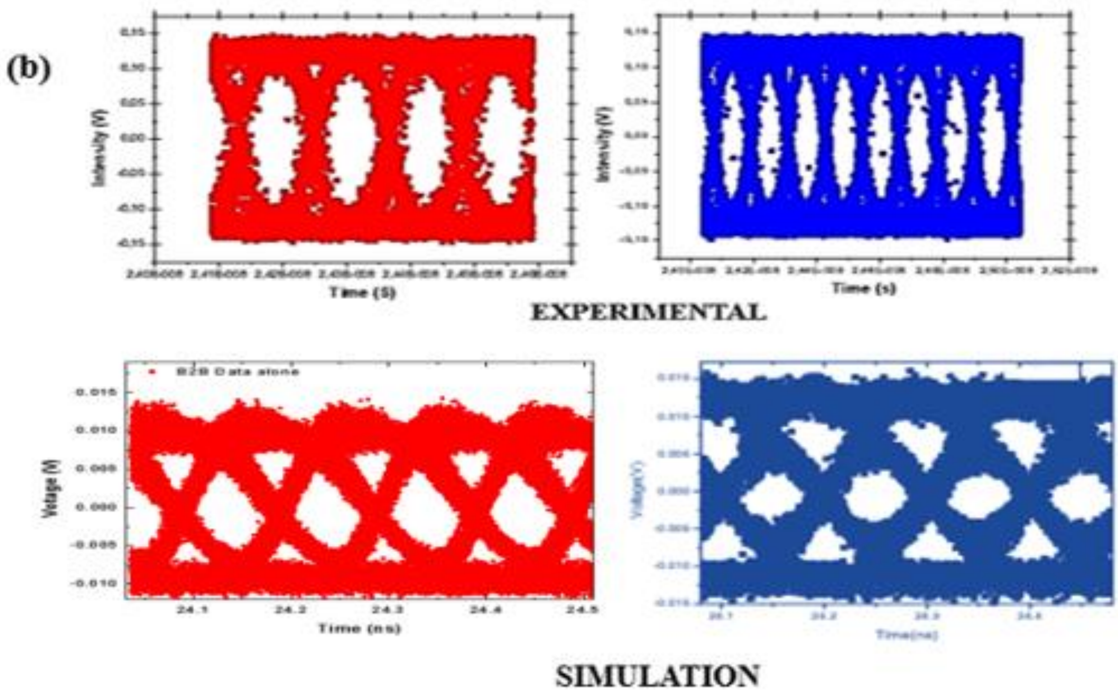

Figure 4.2 (b): Experimental and simulated eye diagrams for B2B (Red) and 25 km (blue) transmission using a VCSEL

Figure 4.2 (b) represents the collected eye diagrams for B2B and 25 km transmission using a VCSEL. The eye intensity reduced with increase in fiber length (25 km) over time. This is in agreement with equation 2.1 in chapter 2. There was also a notable splitting of the eyes due to modulation depth that cannot be accurately computed. The eye opening and the overall extinction ratio reduced with fiber length. An error free and successful transmission is characterized by a clear, wide and open eye. The implication of the eye opening is that the receiver was able to distinguish the transmitted bits ('1' and '0') correctly. These simulation results were able to verify the experimental analysis that the extinction ratio and the intensity of the eye-opening decrease with an increase in the transmission distance by comparing the eye intensity in both scenarios i.e. for B2B and 25 km.

4.3.2 The Distributed Feedback Laser (DFB)

Figure 4.3 (a) shows the experimental results for the performance of the DFB laser. The receiver input power of error free transmission was -21.58, -20.46 and -20.72 dBm for B2B, 25 km and 50 km transmission respectively.

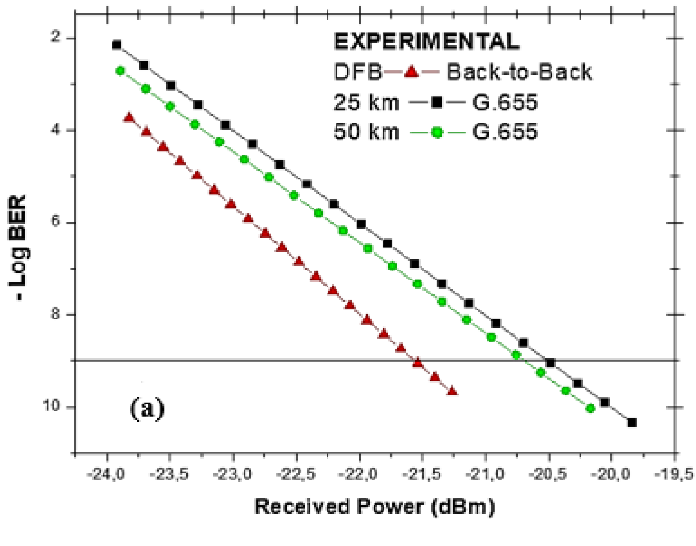

Figure 4.3 (a): Experimental –Log BER curves for 25 km and 50 km WDM DFB transmission on a G.655 fiber

The transmission penalties for 25 km and 50 km of fiber were 1.02 dB and 0.86 dB respectively. The illustration in Figure 4.3 (b) shows the eye diagrams and the resultant waveforms on a 25 and 50 km fiber using a DFB. From the Figure, it was observed that there was a reduction in the extinction ratio of the eye diagram at 50 km fiber transmission compared to 25 km transmission. This shows that the longer length introduced more optical effects in the system that affected the signal quality hence lowering the extinction ratio. The further splitting of the eye resulted from a combination of optical effects as well as the applied modulation depth. There was signal deterioration at 50 km compared to 25 km as illustrated by the presented waveforms. These waveforms are in correspondence with the eye diagrams. Error free transmission at 50 km fiber length was realized for incident input powers greater than -20.50 dBm. On the 25 km fiber length, receiver powers greater than -20.40 dBm were realized.

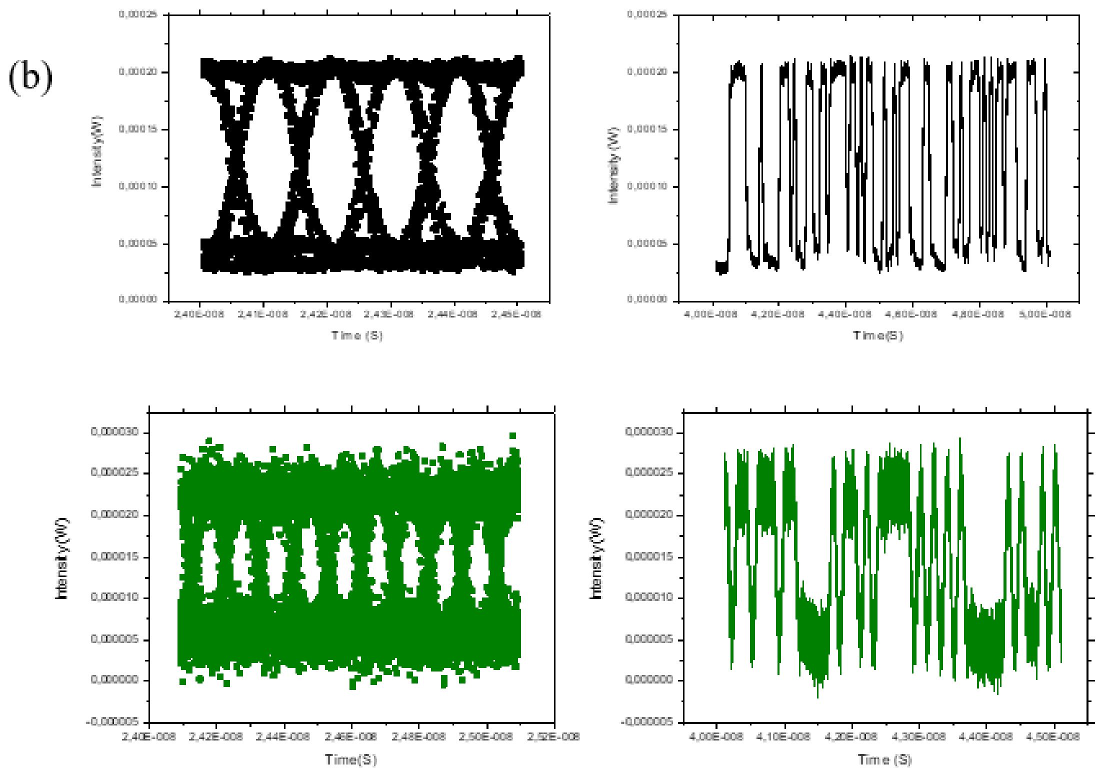

Figure 4.3 (b): Eye diagrams and resultant waveforms for 25 km (black) and 50 km (green) transmission using a DFB

The VCSEL was able to transmit up to 25 km while DFB extended the reach to 50 km. Therefore, the VCSEL is appropriate for distances less than 25 km while the DFB suits longer transmission distances of up to 50 km. Thus, in optical networks extending up to 25 km, VCSEL would be the most suitable candidate.

4.4 Quality Factor (Q-factor) Analysis

The Q-factor is another signal metric employed in performance analysis. Due to its relationship to the signal-to-noise ratio (SNR) required to achieve a certain BER, it was the metric utilized to perform receiver performance specification. From the results in Figure 4.4 (a), it was observed that there is a direct relationship between the Q-factor and BER in the communication systems. A higher Q-factor value gives a better BER. The minimum Q-factor of 6 corresponds to a BER of 10^{-9} as a marker of a good signal reception as shown below.

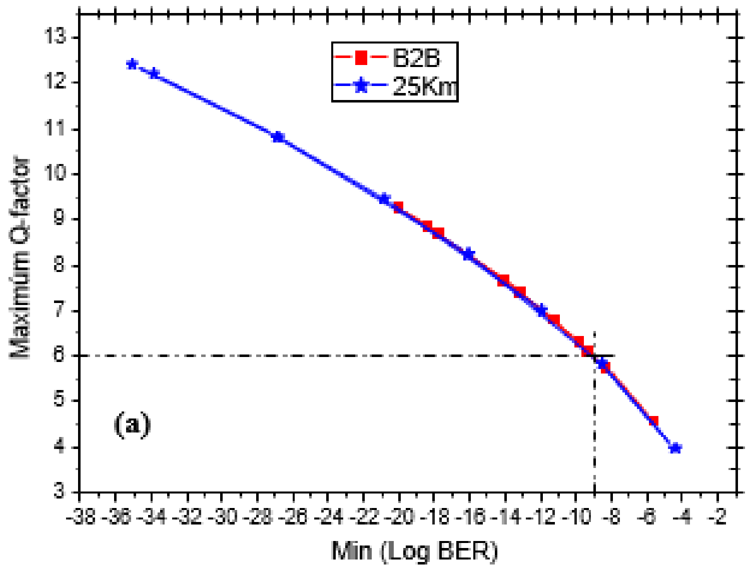

Figure 4.4 (a): Plot of Q-factor against min log BER B2B and 25 km G.655

The simulation results show that for both B2B and 25 km transmission, a Q-factor value of 6.0 was crossed. The results also show that the B2B and 25 km results were in the same transmission line implying that there was no penalty at 25 km length for the used bit rate. The receiver power was -24.45 dBm and attenuated at steps of 1 dB. The minimum Q-factor of 6 corresponds to the telecommunication threshold. Therefore, any Q- factor greater than 6 is error free.

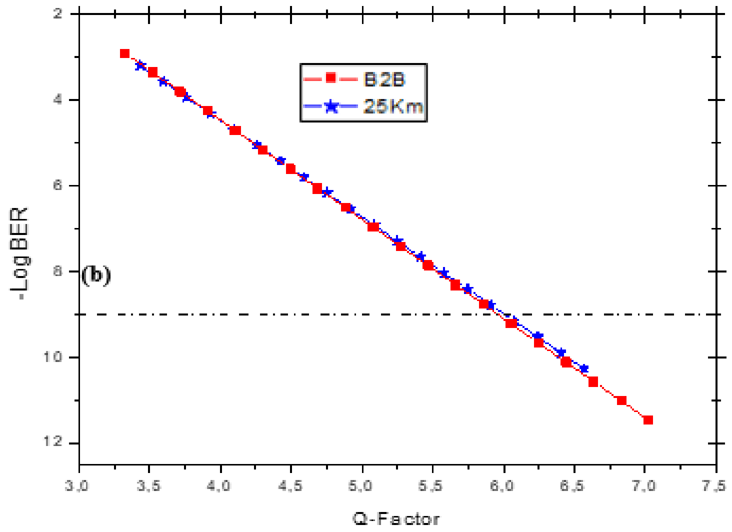

Figure 4.4 (b): Plot of -Log (BER) as a function of Q-factor

The -log of BER is inversely related to the Q-factor, as seen in Figure 4.4 (b). From the results, the study found that the optical signal to noise ratio (OSNR) was better with a high Q-factor, which generally translates to error-free transmission. This means that in the case of a lower Q-factor, the resultant OSNR will be low. When the OSNR is low, the signal is degraded, which raises the bit errors.

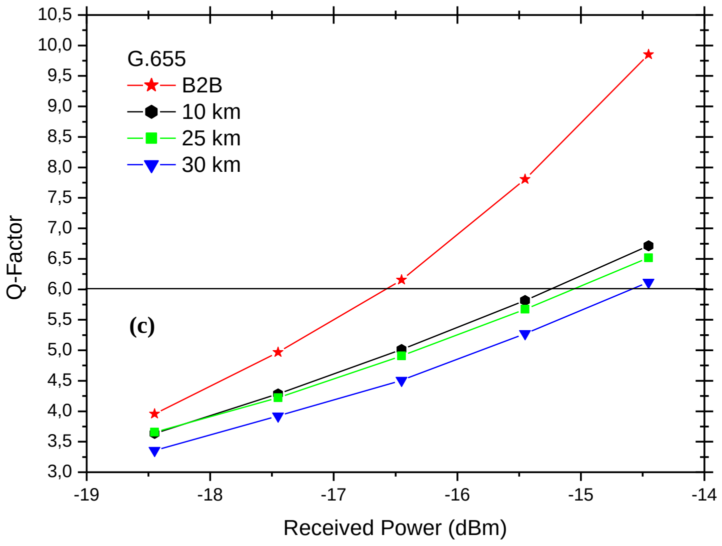

Figure 4.4 (c): Simulation variation of Q-factor with received power B2B, 10 km , 25 km and 30 km G.655 1550 nm VCSEL

As illustrated in the Figure 4.4 (c), the simulated relationship between the received power and the Q-factor was done for B2B, 10 km, 25 km and 30 km transmissions. It was observed that the Q-factor increases with increase in the receiver's input power. In addition, the Q-factor was found to be better in the 10 km transmission distance than in 25 km and 30 km respectively with B2B acting as the reference point giving the best variation.There was a correspondance of low Q-factor value to lower input power because of the receiver's inability to clearly distinguish the two levels. As expected the transmitted power reduced with increase in fiber length due to attenuation and other intrinsic optical fiber losses such as absorption, dispersion and scattering. From the graph, 30 km is the threshold length yielding error free transmission as per the curve

4.5 Results on Clock and Data Signals Transmission

Figure 4.5 illustrates the experimentally measured spectrum of the electrical clock signal at 0.4 GHz. With a power 0f -36.01 dBm, the clock signal was seen to operat above the noise region at the selected 0.4 GHz operational frequency on the signal generator. The 0.4 GHz gave the maximum power necessary for the clock signal. In the 0.4 GHz operational frequency, the stability and performance of the clock was achieved. The 0.4 GHz operational frequency offers a balance between efficiency and transmission power. It can be used to send the request on time while reducing the power consumption during signal request transmission.

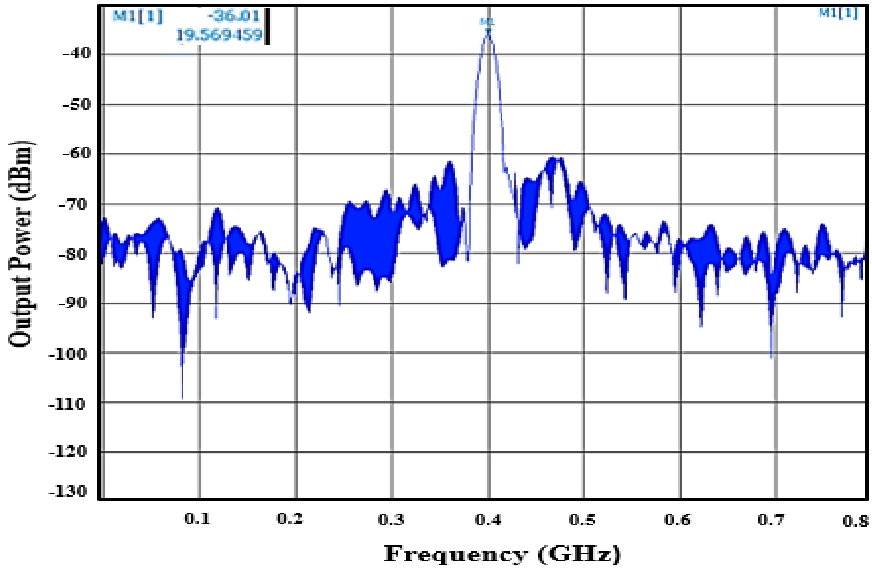

Figure 4.5: Experimentally measured electrical clock signal spectrum at 0.4 GHz

In Figure 4.6 (a), it was observed that setting the clock signal at a lower frequency of 0.4 GHz produced a smooth waveform pattern. The superposed transmitted bits were able to form a repetitive pattern suggesting the transmitted signal's quality. On the other hand, increasing the clock frequency to 2.5 GHz (Figure 4.6 (b)) produced closely packed bits and the intensity reduced indicating an attenuated and less clear clock signal.

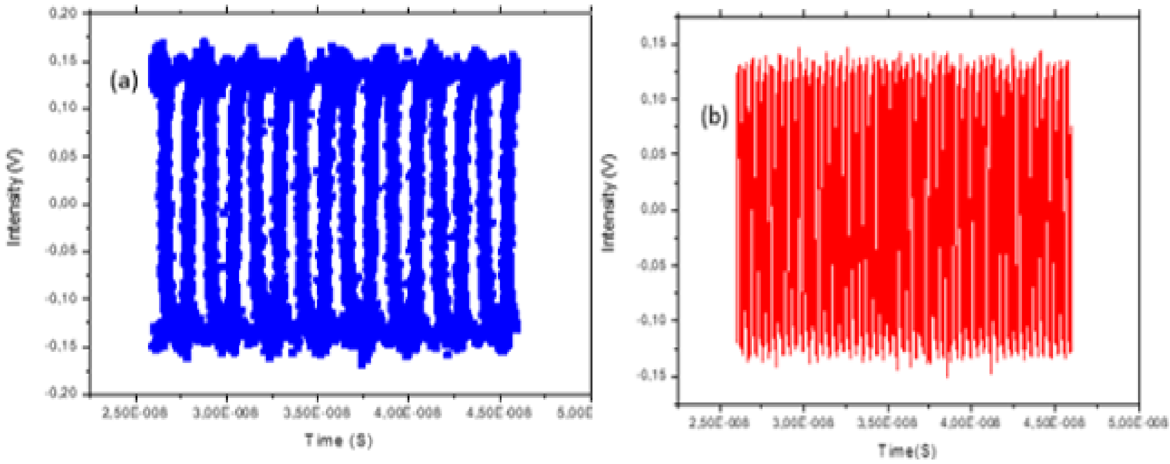

Figure 4.6: Electrical clock signal at a frequency of (a) 0.4 GHz (b) 2.5 GHz frequency

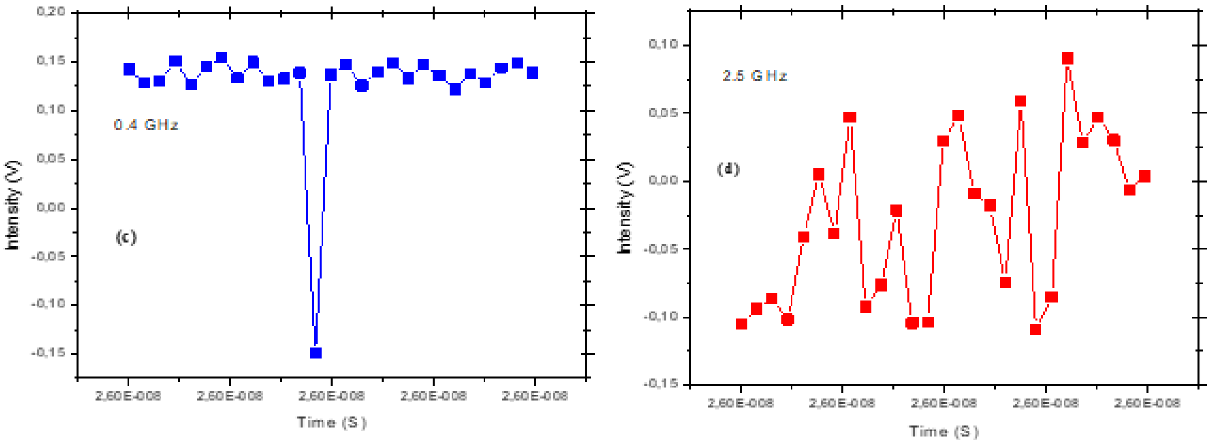

Figure 4.6: Sampled 27 transmitted bits in (c) 0.4 GHz and (d) 2.5 GHz

By sampling the smallest time span and equal number of transmitted bit (27 bits) in Figure 4.6 (c) and (d) it was observed that the signal intensity still varied with the same time span of propagation on the two frequencies. However, there was a reduction in amplitude between the two frequencies with 0.4 GHz giving a maximum of 0.17 V while 2.5 GHz yielding a maximum of 0.10 V. Note that the time of propagation on the two frequencies remained constant on the x-axis after sampling the bits. This is because the time of the repetitive signal propagation increased by a very small range since only a small sample was taken at a small span of time.

Figures 4.7 (a) and (b) compare the addition of a clock to a data signal on a 25 km transmission.

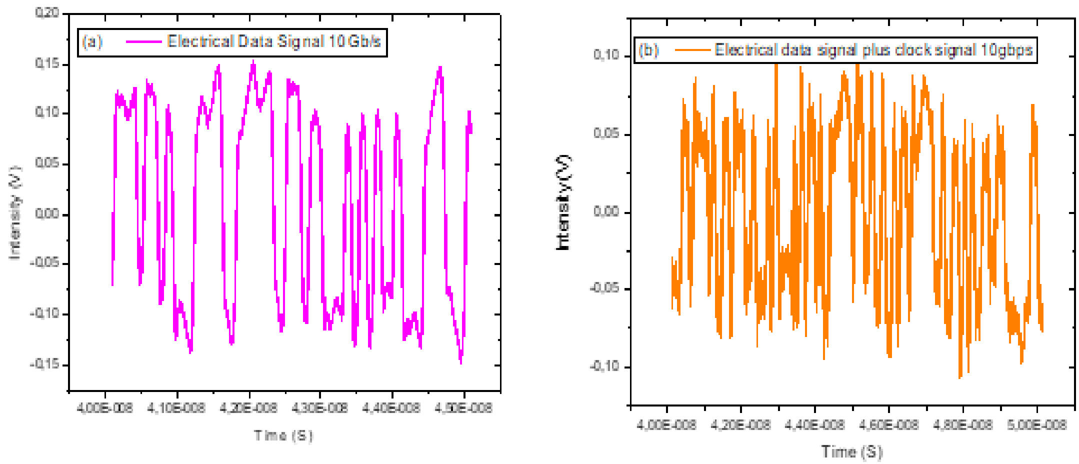

Figure 4.7: (a) A graph of 10 Gbps data signal sent over 25 km fiber using a VCSEL (b) A graph of 10 Gbps data signal plus clock signal sent over 25 km using a VCSEL

Figure 4.7 (b) refers to the data plus clock while (a) corresponds to data only. These are the waveforms as observed on the digital scope. Note that on the 2-signal transmission (clock and data transmission), signal clarity and intensity decreased compared to data transmission in (a). This was due to the interaction of the two signals that created cross talk/ interference hence affecting the signal clarity. When the data-carrying optical carrier was modulated with data and transmitted with the clock-carrier, there was insignificant interference implying both can be achieved simultaneously.

4.6 Results on Data Erasing

Demonstration of wavelength re-use technique was done using a DFB. The DFB released a 7.98 dBm output power after setting its bias current at 94.4 mA and was driven with a temperature stabilizer thermoelectric cooler (TEC) as explained in chapter 3 section 3.4 of the thesis. The high output power is a saturation condition for EDFA. When the bias current was reduced to 23.97 mA the output power of - 0.83 dBm was realized. This indicates that the output power of the DFB varies linearly with the bias current. Bias current was able to control the population inversion that is necessary for DFB lasing. The decrease in bias current cased less electrons to be injected in the laser's active region thereby leading to a lower population inversion and a lower output power.

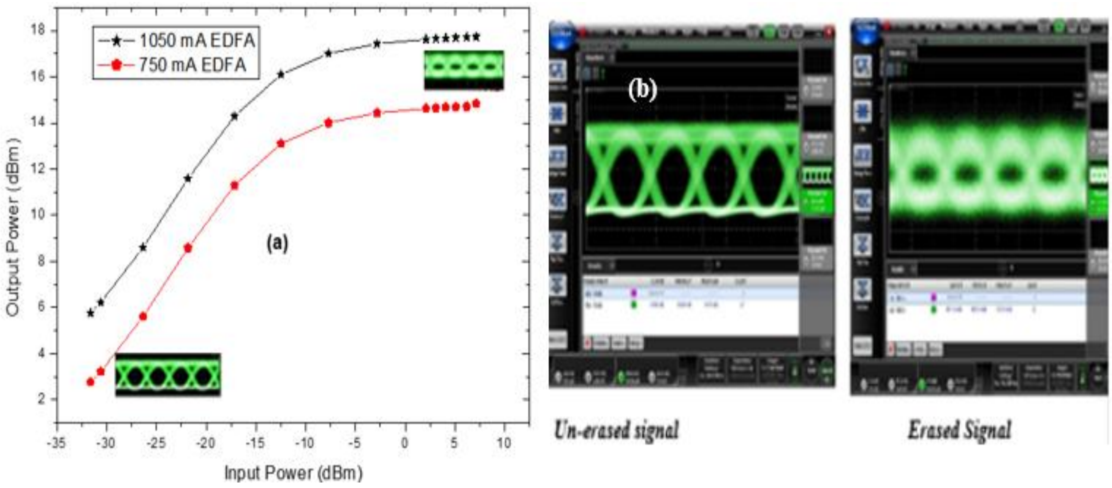

Figure 4.8: (a) EDFA characterization at 1050-mA and 750-mA currents (b) analysis of eye diagrams for unerased signal at ER of 9.678 dB and the erased signal with an ER 0.701 dB

Figure 4.8 (a) represents the measured output power of the EDFA at 1552.5 nm as a function of input optical power at bias currents 1050 and 750 mA respectively. The output power continued in the linear region for input powers lower than - 22.5 dBm using both the 1050 mA and 750 mA EDFA current. Figure 4.8 (a) shows there was a notable saturation at the input powers from -10 dBm to 7.1 dBm. An exploitation on the gain saturation of the EDFA showed that the difference between the '1' level and the '0' level remained low due to the gain saturation from EDFA thereby erasing the data. From the above results the trend for the different EDFA currents is similar, with an increased output power when bias current is increased. The un-erased signal with a clear ER of 9.678 dB had an initial output power of -14.26 dBm as shown in Figure 4.8 (b). After fiber the output power was reduced to -23.8 dBm with an ER of 5.391 dB just before data erasing using a DFB laser source at 1552.3 nm wavelength. After the erase, the signal had an ER of 0.701 dB with a -10.45 dBm output power at the saturation point as shown in Figure 4.8 (b). This demonstrates that the EDFA was able to ensure the attainment of a 13 dB amplification on the signal while at the same time erasing the data with the aid of the holding beam.

It is evident from the observation in Figure 4.8 (b) (un-erased signal) that the eye appears more open with a high ER, which indicates that the signal data is still there. Similarly, it was noted that the output characteristics of the EDFA at relatively low optical input power exhibited a linear behaviour in the transfer curves shown in Figure 4.8 (a). It was observed that the behaviour was non-linear at high optical input power. There was a noticeable drop in gain as the input optical power increased, which ultimately led to saturation at higher powers. The eye level drops and the ER drops to 0.701 dB, indicating the successful erasure of the data, as shown in Figure 4.8 (b) (erased signal). As can be observed in Figure 4.8 (b) the results agree with EDFA's input-output characteristic of the depicted in Figure 4.8 (a) and confirmed that the data of the intensity modulated signal were completely erased when the EDFA was operating in the highly saturated region.

4.6.1 Analysis of Transmission Performance

The upstream and downstream transmission the analysis of performance was investigated upon data erasing. The erased data can allow the remodulation of the same channel which can be used in meter reading. After the achievement of a successful data erasure, upstream data was transmitted with the re-used wavelength over a fiber length of 50 km.Due to its high power output, the DFB laser allowed for transmissions of upto 50 km.As the length of the fiber transmission increased, the ER decreased. BER measurement was performed so as to ascertain the reused wavelength. Figure 4.9 is a representation of the experimentaly measured results for B2B and 50 km downlink and uplink transmissions. Uplink transmission in this case is the re-used wavelength obtained after erasing. A 2 dB power penalty was observed between B2B downlink and uplink as well as in 50 km downlink and uplink. This high penalty was as a result of cumulative noise transferred during data erasure which affected the signal thus leading to penalty. The corresponding incident power at communication threshold for B2B and after 50 km downstream transmission link were -20.10 and -19.40 dBm giving a power penalty of 0.7 dB.

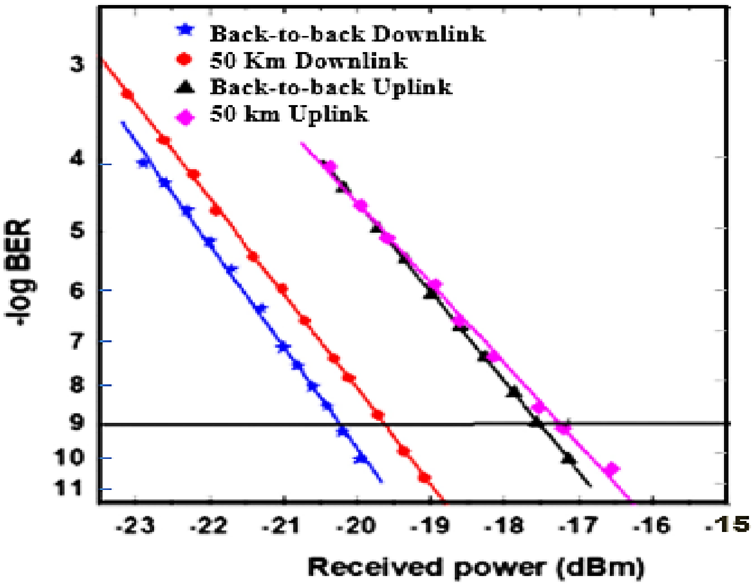

Figure 4.9: Experimentally obtained BER curves with EDFA gain saturation for B2B, 50 km downlink transmission and B2B, 50 km uplink (after data erasure) transmission

In uplink transmission, the incident power for B2B and 50 km transmission measurements at 10^{-9} threshold were recorded as -17.48 dBm and -17.02 dBm respectively giving a 0.46 dB power penalty. Transmission penalty increased due to remodulation.

4.6.2 Eye Diagram Analysis

Figure 4.10 displays the eye diagrams that depict the attained ERs. For B2B downstream and at 50 km downstream, respectively, an ER of 7.016 dB and 5.391 dB were attained.

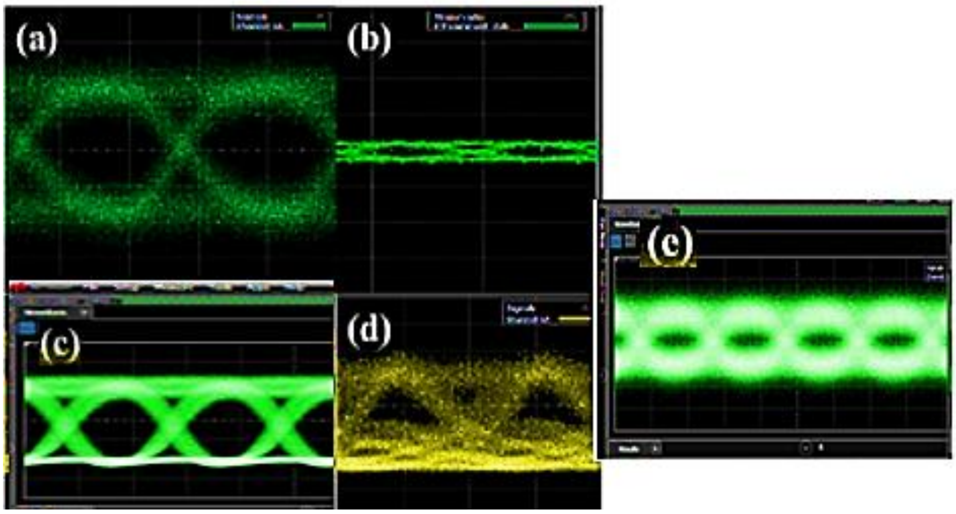

Figure 4.10: Eye diagrams measured at (a) B2B ER 7.016 dB, (b) 50 km downstream link transmission ER 5.391 dB, (c) B2B (upstream) link ER 9.678 dB, (d) 50 km (upstream) ER 6.756 and (e) erased channel ER 0.701 dB

Furthermore, the 50 km upstream wavelength re-use transmission achieved an ER of 6.756 dB, while the investigation of the B2B upstream link transmission following data erasure was able to achieve an ER of 9.678 dB. The ER of the successfully eliminated signal was 0.701 dB. This implies that the extinction ratio of the erased signal was reduced. Also, the extinction ratio reduced with an increase in transmission distance. Lower data rates are expected to extend the reach. In such a case, there can be the trading off of the splitting ratio, aggregated capacity and extended reach against each other to maximize the overal performance potential of the system.

4.7 LoRa Characterization

The characterization of the LoRa transmitter in the experiment was done to assess the reliability of the transmitter under the environmental conditions in the Lab. In addition, it was able to enable interoperability and compatibility testing between the communication network and the LoRa device. Understanding the characteristics of the transmitter allows for seamless communication between the LoRa devices. Finally, the characterization was done to offer insights into the performance metrics of the transmitter including error rates and sensitivity.

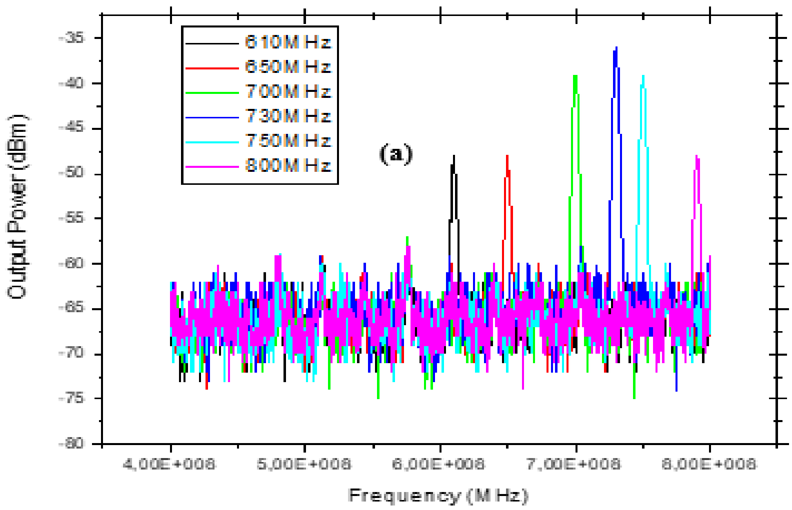

Figure 4.11 (a): Experimental frequency characterization of the LoRa TTGO ESP 32 Dev Module

The 730 MHz frequency from the experiment was able to give out the maximum output power of -35 dBm for signal transmission. Figure 4.11 (b) is the graphical representation of the frequency characterization in Figure 4.11 (a). From the results in

Figure 4.11 (a) and (b), it was observed that the range between 670 MHz and 800 MHz was able to give a broadband of frequencies to choose the best frequency to work with.

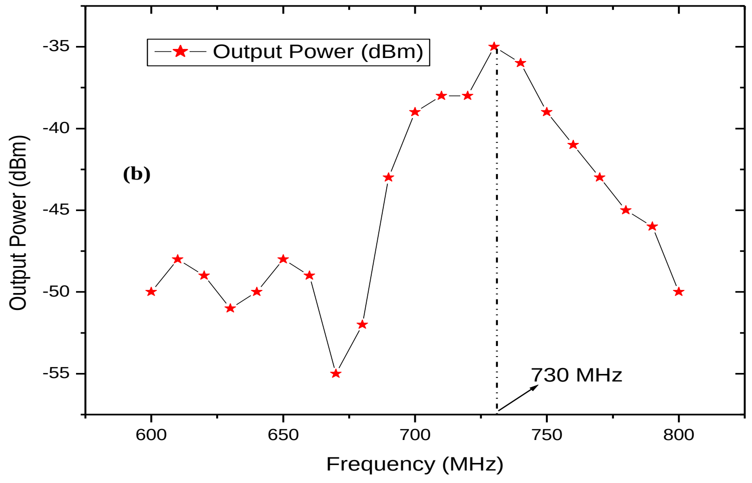

Figure 4.11 (b): A graph of output power Vs frequency for the LoRa TTGO ESP 32 Dev module

From the broadband of frequencies, the 730 MHz was the frequency that was able to give out the maximum output power necessary to push the strongest signal for transmission and the actuation of gates necessary for the collection of the meter reading results.

4.7.1 Signal Analysis

The coupling of the LoRa Module and VCSEL through an optical fiber was done and the resultant electrical signal as observed in the scope is shown in Figure 4.12.

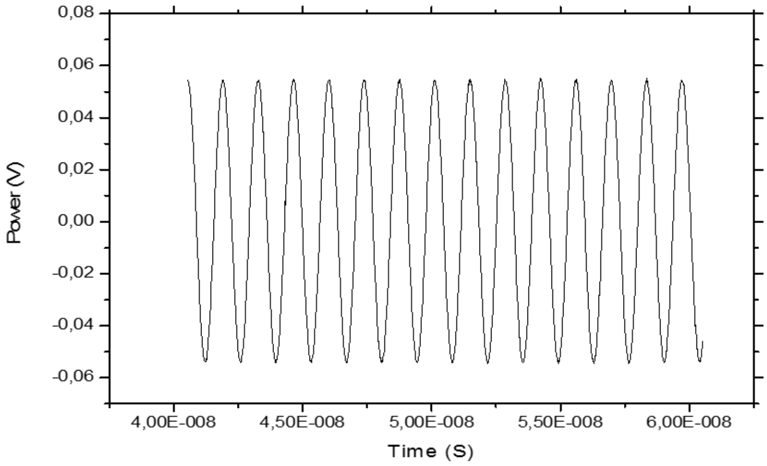

Figure 4.12: Optical input signal to LoRa at 730 MHz (signal generator)

From Figure 4.12, it can be observed that the signal input to the LoRa sender was about 0.05 V amplitude. This serves as a signal to be detected by the LoRa receiver requesting the necessary meter readings. The LoRa module is a free space device. The sent signal is detected by the LoRa receiver. At the 730 MHz frequency generated from the signal generator, the LoRa signal was able to give out the maximum power necessary to drive the strongest signal that could be monitored on the scope.

The resultant electrical waveform in Figure 4.13 is clear, less dispersed and with low noise level which implies that it is actually possible to monitor the waveform of a LoRa signal as it propagates over time on the scope.

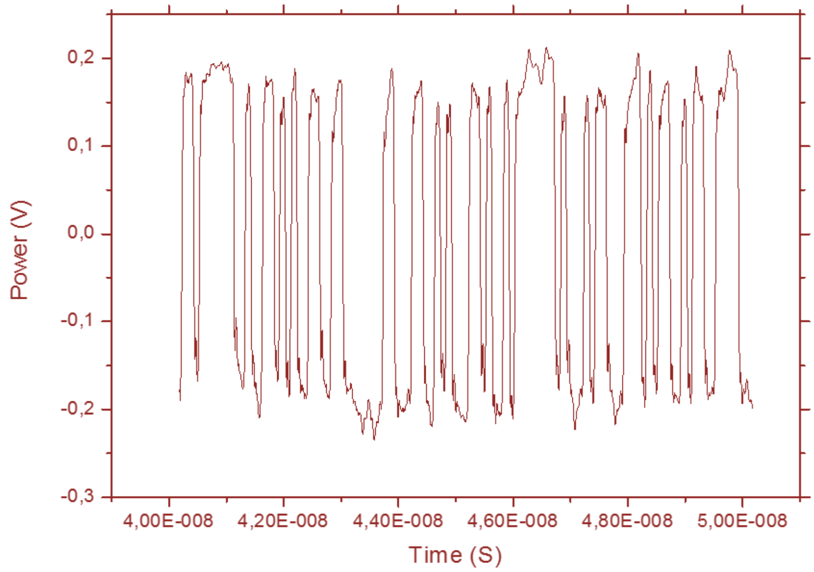

Figure 4.13: Electrical data input to the LoRa module

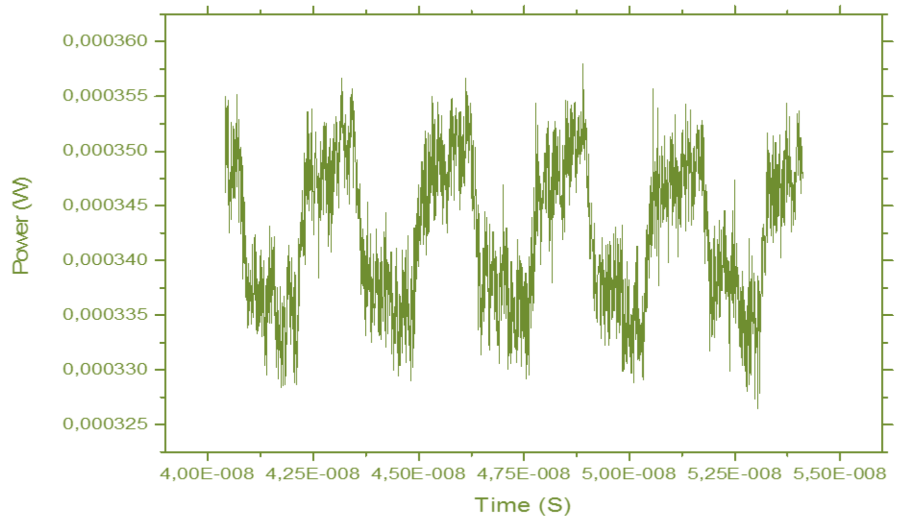

Figure 4.14: LoRa-VCSEL B2B output signal before electrical amplification

The signal exhibited in Figure 4.14 makes it abundantly evident that the signal transmission displayed dispersion with periodic chirping when the VCSEL was connected to the LoRa system. This dispersion was caused by the VCSEL's inherent characteristics as a directly modulated laser. Even with a maximum output power of

0.0003577W, the VCSEL's susceptibility to chirps caused by high modulation depth worsened the signal quality.

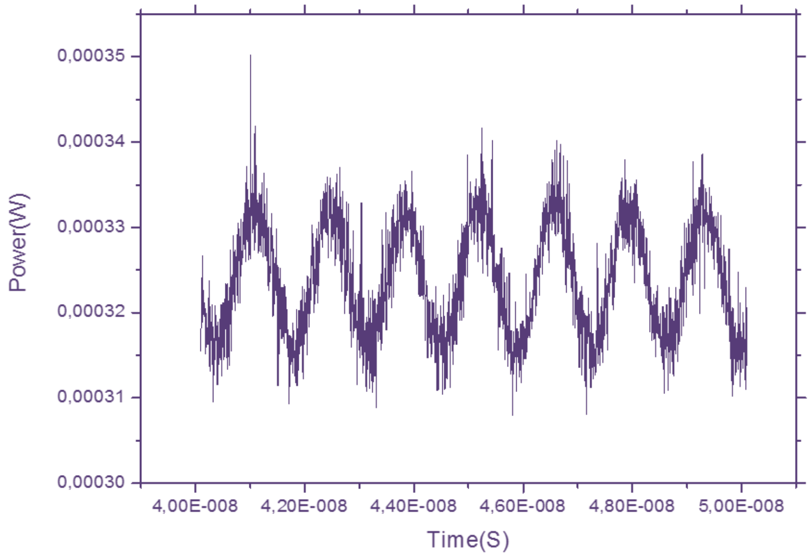

Figure 4.15: LoRa, VCSEL and optical fiber output signal after electrical amplification

Upon coupling the LoRa and VCSEL into a fiber and monitoring the combined signal the resultant signal is illustrated in Figure 4.15. It was observed that the output signal presented some chirps. This was attributed to the electrical amplification that introduced some noise into the signal. The signal was then passed through a filter to reduce the noise and give a smoother signal. It was seen that on amplification, the signal's output power after the fiber had significantly increased from -14 dBm to -4 dBm indicating a 10 dB gain. Optical attenuators were then used to step down the power. This wireless communication is tailored for the end user meter reading. The wirelessly received signal is then coupled into a fiber via a VCSEL or DFB to the control room. This scheme of cabled and wireless network serves to sufficiently address the SG communication in the designed network.

4.8 Chapter Summary

Based on the obtained results, the study was able to characterize the light source of choice (VCSEL) and transmit the obtained signal over 25 km fiber. The DFB laser compared to the VCSEL is suitable for long haul transmission which could also be an alternative for meter reading application. However, VCSEL was preferably used in this study for this signal transmission owing to the fact that it is cheaper than DFB and because the designed communication system ought to be cost effective. The results show that increasing the bias current shifted the spectrum toward higher wavelengths. The source of the transmission power penalty was due to the cumulative dispersion effects over the fiber length. The extinction ratio as a maker of signal quality in telecommunication is dependent on the transmission distance i.e., the longer the transmission distance/ fiber length, the lower the extinction ratio. Power penalty of the signal can be reduced when the extinction ratio is also reduced.

This work demonstrated the viability of all-optical wavelength reuse in addition to the effective erasing function performance of the Erbium-Doped Fiber Amplifier (EDFA), which represents a major breakthrough in optical communication technology. This discovery makes it possible to use resources more effectively and efficiently in optical networks. The work demonstrated the possibility of reusing the same optical wavelength for many uses, including meter reading, by successfully erasing optical wavelengths. This represents a noteworthy accomplishment in terms of optimizing the use of optical spectrum resources, which may lead to cost savings and improved network performance. Additionally, the research carried out thorough assessments of the resulting eye diagrams for transmission over long distances 50 km as well as for Back-to-Back (B2B) scenarios. The fact that both upstream and downstream applications were evaluated shows how adaptable and useful the shown technology is for a range of network setups and needs.

Ultimately, the research resulted in a thorough characterization and transmission analysis of LoRa modules that use a novel combination of VCSEL and optical fiber technology. The goal of this ground-breaking experiment was to demonstrate that wireless and wired networks can coexist together, especially when it comes to the crucial meter reading application. Through the utilization of optical fibers and VCSELs, the study demonstrated the possibility of surpassing conventional communication limitations. This discovery not only emphasizes how flexible contemporary communication networks are, but also how they have the potential to fully revolutionize utility management and other vital industries that depend on precise and effective data transfer.

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter offers a brief summary, conclusions and recommendations of the study, covering the most important findings from studies on data erasure, signal transmission, and LoRa technology. The given results provide useful insights into the efficiency and effectiveness of these processes, demonstrating their contribution to the broader understanding and utilization of communication technology across diverse settings.

5.2 Summary of Findings

A summary of the findings is provided in this chapter including the results obtained from signal transmission, data erasing and LoRa. It also provides suggestions for future studies regarding the study. The study was able to demonstrate the performance of optical fiber and LoRa communication system for smart power grid applications. The optical fiber communication was demonstrated as an attractive technology because of high speeds, capacity and immune to electromagnetic interference. Optical effects have an effect on the propagation of optical signals. The study also characterized the VCSEL and compared the transmission performance to that of the DFB laser technology. The study found that an integrated technology of VCSEL and fiber (transceiver pair) can be essential for SG meter reading. In addition, a successful data erase would enable the re use of the same wavelength for upstream and downstream communication between the utility and the users at the receiving end. The LoRa transmitter signal was analysed using a VCSEL and optical fiber.

5.3 Conclusions

VCSEL and DFB characterization was successfully achieved. An experimental test bed was successfully designed so as to investigate the network performance. The research characterized the 1550 nm wavelength VCSEL and DFB before investigating their performance in bidirectional communication in the grid. The characterized VCSEL and DFB were then modulated with 10 Gbps signal and transmitted over fiber. The threshold current of the used 1550 nm VCSELs was 1 mA and 2 mA for simulation and experimental results while experimentally for the DFB it was 10 mA. Both the VCSEL and DFB can handle currents in the milliampere range but a VCSEL is a low powered laser compared to the DFB laser. The lasing threshold of the VCSEL both in simulation and experimentally qualifies it as a low powered device while that of a DFB characterizes it as a high-powered laser. In the VCSEL experiment, increasing the bias current increased the output power up to -0.9 dBm. However, the output saturated at a bias current of about 8.5 mA. It was demonstrated that VCSEL is wavelength tuneable. A bandwidth of 2.9 nm (1549- 1551.9 nm) was obtained. Successful transmission of 10 Gbps data over 25 and 50 km of optical fiber was achieved for VCSEL and DFB respectively.

Using a 10 Gbps VCSEL transmission, a 2.67 dB penalty was achieved at 25 km, and an experimental DFB laser yielded a -1.12 dB transmission penalty. Frequency chirps and fiber dispersion combined to reduce the receiver sensitivity, which resulted in a greater penalty when utilizing a VCSEL. The investigation showed that signal transmissions up to 25 km are the ideal range for VCSELs. For the DFB laser, error-free signal transmission across 50 km at 10 Gbps was accomplished. In theory, the performance of the VCSEL was quantified using the Q-factor. Theoretical and experimental results were in agreement. The utilization of the 1550 nm VCSEL on the G.655 fiber in long-haul optical transmissions is efficient because of its low dispersion as well as attenuation that facilitates the overall performance. The long wavelength VCSEL provides the capabilities of high bandwidth together with very low power consumption and therefore suitable candidate for 10 Gb applications and high bit-rate datacom networks.

Performance evaluation of VCSEL and DFB sources in transmitting data at 10 Gbps over 25 km and 50 km optical fiber was successfully achieved for B2B, 25 km and 50 km. The various eye diagrams were analysed. In the simultaneous data and clock transmission, a clock signal at 0.4 GHz over a 25 km fiber transmission was achieved. The study demonstrated that a frequency of 0.4 GHz was necessary to drive the clock signal as a reference signal in making request for meter reading. It can be concluded that for an accurate clock signal transmission, the requirement is a low drive frequency. The collected data was then transmitted through an optical fiber cable and the resultant signal observed on the scope

It was successfully demonstrated that a completely saturated EDFA and just optical signals can be used for data erasure and wavelength reuse. According to the study's findings, any optical wavelength can be utilized in an SG communication system, and meter readings can be obtained downstream using the same wavelength without the need for additional optical sources. The study demonstrated that the EDFA's optical input power significantly affected how well the data could be erased from the incoming signal, with the saturation region of the gain curve showing the most effective suppression. The EDFA was shown to be capable of erasing data and reducing the incoming signal's ER from 9.678 dB to 0.701 dB at 10 Gbps.

Following data erasure, a DFB was utilized to send the residual carrier wave 50 km upstream. The holding beam enhanced the performance of the EDFA by raising the optical intensity and the quantity of photons generated inside the active layer.

The LoRa wireless area network is a new technology in the smart metering system. This technology can connect smart meters miles away in rural areas and can enable smart meters tracking without necessarily having a GPS. It can also penetrate areas and perform indoor meter reading. The study concluded that it is possible to characterize the LoRa transmitter and couple the wireless LoRa signals to a fiber and extend the reach of the meter reading signal in SG communication system. The transmitter was characterized and signal analysis performed. It is a promising wireless technology that can be used together with the optical fiber technology to extend the transmission of communication signals between the control station and the users in the grid system. The best operational frequency for the LoRa was measured to be 730 MHz which yielded the maximum output power necessary to transmit the strongest signal that can reach the clock and make the requests for meter reading request. This also means that the requirement for the LoRa operation is low frequency. The LoRa/fiber alliance technology would assist in delivering continuous expansion and support in the SG metering communication technology. This technology can be a protocol of choice even for IoT networks situated locally.

5.4 Recommendations

From the first specific objective, it would be recommended to perform comprehensive characterization studies on VCSEL devices, covering topics such as thermal stability, reliability, wavelength spectrum, optical power output and modulation bandwidth. To fully characterize the VCSEL, it would be necessary to make use of methods including optical power measurements and analysis, frequency response, and thermal imaging.

Based on the second specific objective, the study recommends the conduction of experiments to compare the data transmission speeds of 10 Gbps across 25 km and 50 km optical fiber between VCSEL and Distributed Feedback (DFB) laser sources. It would be necessary to assess each source's compatibility for the designated transmission distances by measuring factors such power budget, and signal quality. During the evaluation, it would be necessary to take into account elements like attenuation, dispersion and nonlinear effects in the optical fiber.

Based on the third specific objective on all optical wavelength reuse, it would be appropriate to create and carry out experimental configurations to show that all-optical wavelength reuse data erasure is feasible for applications involving smart meter reading. To efficiently erase data while preserving signal integrity, the use of modulation techniques, wavelength-selective components and optical switches is highly recommended. It would also be crucial to analyze the system's effectiveness in terms of data integrity, erasure efficiency, and compatibility with the current smart metering infrastructure.

Finally, based on the fourth specific objective, the study recommends a thorough characterization of the power consumption, sensitivity, interference resilience, transmission range, data rate and robustness of the LoRa sender and receiver devices. It would be crucial to conduct field tests in a range of environmental circumstances to evaluate the devices' functionality in practical situations. It would also be essential to examine how the topography, flora, and urban buildings affect the LoRa devices' dependability and communication range.

5.5 Suggestions for Further Studies

The optical fiber technology is a nice upgrade over the current conventional model used where utility providers have to be called by individuals and notified on power outages and thereafter individuals on trucks squint and drive around power lines to see whether they are broken. The proposed transmission techniques from this study are suggested in future to assist in the transition to optical applications that are high speed and of the next generation including cloud computing and big data science. The LoRa wireless and optical fiber technology should be considered in future communication studies for detailed transmission performance. The LoRa technology has the ability to allow power station controllers and sensors to communicate data to a center responsible for monitoring through buildings, walls among other barriers. In addition, this wireless network suits densely populated areas such as storey flats. Studies on environmental effects on the LoRa performance during wireless signal transmission for meter reading should also be done in future studies to see how the factors affect the LoRa device signal transmission.

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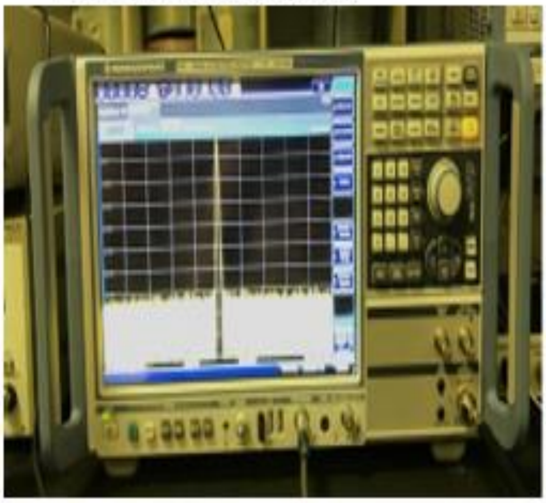
APPENDICES

Appendix I. Experimental Apparatus

Temperature Stabilizer Thermoelectric cooler

Laser Diode Controller (LDC)

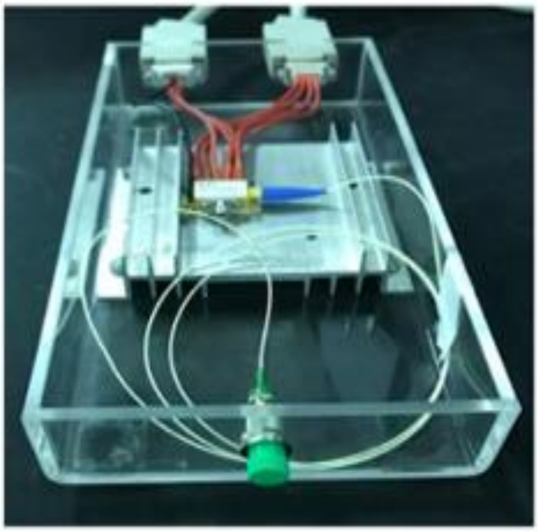



Rhode and Schwartz Signal generator

Rhode and Schwartz

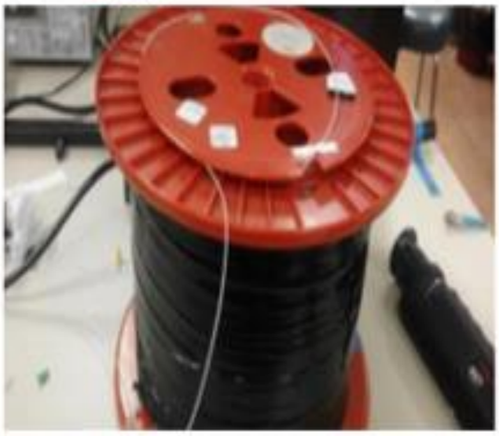
Spectrum

Analyzer



DFB Laser

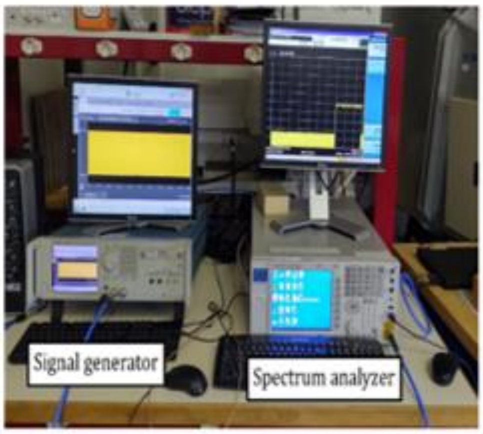
RayCan VCSEL

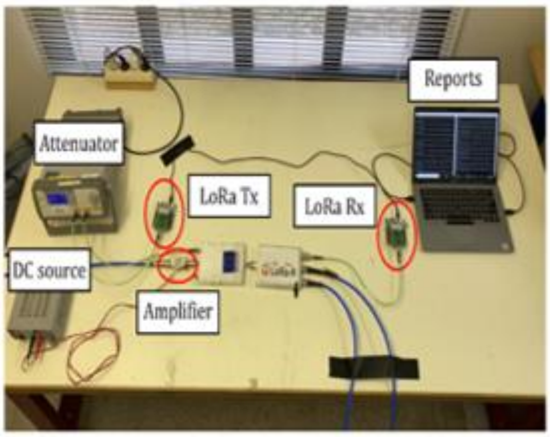


A PRO 8000 WDM laser transmitter source from THORLABS

Optical Fiber Spool

with the different transmitter channels





LoRa module experimental setup for signal analysis

Appendix II. Approval Letter from BGS

UNIVERSITY OF KABIANGA
ISO 9001:2015 CERTIFIED
OFFICE OF THE DIRECTOR, BOARD OF GRADUATE STUDIES

REF: PGC/PHY/002/19

DATE: 25TH MAY, 2022

Hillary Endeche Aradi ,
MAPS,
University of Kabianga,
P.O Box 2030- 20200,
KERICHO.

Dear Mr. Aradi,

RE: CLEARANCE TO COMMENCE FIELD WORK

I am glad to inform you that the Board of Graduate Studies during its meeting on 12th January 2022 approved your research proposal entitled **"Design of a Smart Power Grid Utilizing the Optical Fiber Technology".**

I am also acknowledging receipt of your corrected proposal via email and hard copies. You are now free to commence your field work on condition that you obtain a research permit from NACOSTI.

Please note that, you are expected to publish at least one (1) paper in a peer reviewed journal before final examination (oral defense) of your Masters thesis.

Thank you.

Yours Sincerely,

UNIVERSITY OF KABIANGA
25 MAY 2022
BOARD OF GRADUATE STUDIES

Prof. J. K. Kibett
DIRECTOR, BOARD OF GRADUATE STUDIES.

cc 1. Dean, SST
2. HOD, MAPS
3. Supervisors

Appendix III. NACOSTI Research Permit

REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

Ref No: **248616**

Date of Issue: **30/June/2023**

RESEARCH LICENSE

This is to Certify that Mr.. Hillary Endeche Aradi of University of Kabianga, has been licensed to conduct research as per the provision of the Science, Technology and Innovation Act, 2013 (Rev.2014) in Kericho on the topic: Design of a Smart Power Grid Utilizing the Optical Fiber Technology for the period ending : 30/June/2024.

License No: **NACOSTI/P/23/26992**

248616

Applicant Identification Number

Director General

NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

Verification QR Code

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See overleaf for conditions

Appendix IV. The TTGO Esp32 Lora Dev Module Transceiver Codes using the Arduino IDE 2.0.2

```
//Libraries for LoRa
#include <SPI.h>
#include <LoRa.h>
//Libraries for OLED Display
#include <Wire.h>
#include <Adafruit_GFX.h>
#include <Adafruit_SSD1306.h>
//define the pins used by the LoRa transceiver module
#define SCK 5
#define MISO 19
#define MOSI 27
#define SS 18
#define RST 14
#define DIO0 26
//433E6 for Asia
//866E6 for Europe
//define BAND 915E6 for North America
#define BAND 866E6
//OLED pins
#define OLED_SDA 4
#define OLED_SCL 15
#define OLED_RST 16
#define SCREEN_WIDTH 128 // OLED display width, in pixels
#define SCREEN_HEIGHT 64 // OLED display height, in pixels
Adafruit_SSD1306 display(SCREEN_WIDTH, SCREEN_HEIGHT, &Wire, OLED_RST);
String LoRaData;
```

```
void setup() {
 //initialize Serial Monitor
  Serial.begin(115200);
  //reset OLED display via software
  pinMode(OLED_RST, OUTPUT);
  digitalWrite(OLED_RST, LOW);
  delay(20);
  digitalWrite(OLED_RST, HIGH);
  //initialize OLED
  Wire.begin(OLED_SDA, OLED_SCL);
  if(!display.begin(SSD1306_SWITCHCAPVCC, 0x3c, false, false)) { // Address 0x3C
for 128x32
    Serial.println(F("SSD1306 allocation failed"));
    for(;;); // Don't proceed, loop forever
  }
  display.clearDisplay();
  display.setTextColor(WHITE);
  display.setTextSize(1);
  display.setCursor(0,0);
  display.print("LORA RECEIVER ");
  display.display();
  Serial.println("LoRa Receiver Test");
  //SPI LoRa pins
  SPI.begin(SCK, MISO, MOSI, SS);
  //setup LoRa transceiver module
  LoRa.setPins(SS, RST, DIO0);
  if (!LoRa.begin(BAND)) {
    Serial.println("Starting LoRa failed!");
    while (1);
  }
```

```
  Serial.println("LoRa Initializing OK!");
  display.setCursor(0,10);
  display.println("LoRa Initializing OK!");
  display.display();
}
void loop() {
  //try to parse packet
  int packetSize = LoRa.parsePacket();
  if (packetSize) {
    //received a packet
   Serial.print("Received packet ");
    //read packet
    while (LoRa.available()) {
      LoRaData = LoRa.readString();
      Serial.print(LoRaData);
    }
    //print RSSI of packet
    int rssi = LoRa.packetRssi();
    Serial.print(" with RSSI ");
    Serial.println(rssi);
   // Display information
   display.clearDisplay();
   display.setCursor(0,0);
   display.print("LORA RECEIVER");
   display.setCursor(0,20);
   display.print("Received packet:");
   display.setCursor(0,30);
   display.print(LoRaData);
   display.print("");
```

```
    display.setTextSize(1);
    display.setCursor(0,40);
    display.print("RSSI:");
    display.setCursor(30,40);
    display.print(rssi);
    display.display();
  }
}
```

Appendix V. Plagiarism Report

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ORIGINALITY REPORT

22%	15%	11%	5%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	H. E. Aradi, E.K. Rotich Kipnoo, F. W. Masinde, D.W. Waswa, J. Jena, T. B. Gibbon. "Demonstration of 10 GBPS Over G.655 Non-Zero Dispersion Shifted Fiber for Smart Grid Meter Reading", 2023 IEEE AFRICON, 2023 Publication	3%
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Appendix VI: Conferences and Publications

Publications

Aradi, H. E., Rotich Kipnoo, E. K., Masinde, F. W., Waswa, D. W., Jena, J., & Gibbon, T. B. (2023). Simultaneous 10 Gbps data and clock transmission for smart power grid application utilizing the optical fiber and VCSEL technology. *Journal of Modern Optics*, *70*(19-21), 1023-1030 https://www.tandfonline.com/doi/full/10.1080/09500340.2024.2380732

Aradi, H. E., Kipnoo, E. R., Masinde, F. W., Waswa, D. W., Jena, J., & Gibbon, T. B. (2024). All-optical wavelength reuse for meter reading application using EDFA saturation and DFB laser." *Optik - International Journal for Light and Electron Optics 312 (2024)* 171946. https://doi.org/10.1016/j.ijleo.2024.171946 https://www.sciencedirect.com/science/article/pii/S0030402624003450

Conference Papers

Aradi, H. E., Kipnoo, E. R., Masinde, F. W., Waswa, D. W., Jena, J., & Gibbon, T. B. (2023, September). Demonstration of 10 GBPS Over G. 655 Non-Zero Dispersion Shifted Fiber for Smart Grid Meter Reading. In *2023 IEEE AFRICON* (pp. 1-6). IEEE. https://ieeexplore.ieee.org/document/10293278

Aradi, H. E., Kipnoo, E. R., Masinde, F. W. *Smart Grid Meter Reading Application Utilizing the All-Optical Wavelength Reuse Technique.* 3rd University of Kabianga Annual Conference, *(*29th- 30th September 2023)