PERFORMANCE OF VCSEL AT 10 Gb/s IN G.655 AND G.652 SSMF IN THE 1310 nm AND 1550 nm TRANSMISSION WINDOWS

BY

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DECLARATION

Declaration by the candidate

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DEDICATION

I dedicate this work to Cherutoi’s family and Kapchepkoiwo clan at large for their support and inspiration.

ABSTRACT

Vertical cavity surface emitting lasers (VCSELs) are now major optical sources in optical communication and technology. The VCSEL-based transmission systems satisfy the next generation optical fibre access networks requirements such as low output power, no optical amplification and use of single fibre for signal transmission. High speed and long wavelength, 1310 nm and 1550 nm VCSELs, are attractive candidates for use in short distance transmission system due to its cost effectiveness and low current requirements. Direct modulation of VCSEL with separate optical and current apertures enables high modulation bandwidth operating at single mode at low current density. However, dispersion and attenuation is a major hurdle to VCSELs transmission at bit rate of 10 Gb/s and above. This therefore motivates the need to investigate and characterize VCSELs and determine their performance in different fibres at different transmission windows. In this study, a 1310 and 1550 nm VCSEL was directly modulated with 10 Gb/s NRZ PRBS 2^7-1 and transmitted over 25 km ITU.T G.652 and ITU.T G.655 fibres and optimized for metro-access distances. The VCSELs systems were simulated and verified experimentally using the bit error rate (BER), Q factor and optical signal to noise ratio (OSNR) performance indicators. The power penalty suffered by the system was evaluated at BER=10^{-9} communication threshold. Power penalty of 1.5 dB was attained experimentally for 1310 nm VCSEL on 25 km G.652 fibre. When a 1550 nm VCSEL was used on G.652 fibre, the system operated on an error floor region without crossing the communication threshold region of BER=10^{-9}. The high dispersion in 1550 nm VCSEL on G.652 fibre gave rise to high power penalties hence bit errors. However, when a 1550 nm VCSEL was used in G.655 fibre transmission, the error-free receiver sensitivity was measured to be -19.3 dBm for back to back (B2B) and -17.6 dBm after 25 km. The transmission penalty suffered by the system was 1.7 dB. The error floor region occured when a G.652 fibre was used in 1550 nm transmission window. OSNR was observed to vary inversely with fibre length. Small values of OSNR of less than 6 dB were achieved experimentally. OSNR was also observed to reduce with the increase in the received power. The Q factor was used theoretically to quantify the performance of the VCSELs. The Q factor increased with the increase in the output power at the receiver. High Q factor values of 6 and above were achieved when 1310 nm and 1550 nm VCSELs were transmitted over G.652 and G.655 fibres respectively. The results clearly indicates that 1550 nm transmission over G.655 fibre would highly be recommended while 1310 nm is suitable for transmission over G.652 fibre. The findings of this study is significant for high bit rate data transmission for passive optical networks (PON) application. These results show the feasibility of long-wavelength VCSELs in the deployment of enhanced optical access networks.

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LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

ASE- Amplified Spontaneous Emission

BER- Bit Error Rate

CD- Chromatic Dispersion

CW- Continuous Wave

DBR- Distributed Bragg Reflector

DCF's- Dispersion Compensation Fibres

DGD- Differential Group Delay

DM- Direct Modulation

DQPSK- Differential Quadrature Phase Shift Keying

DWDM- Dense Wavelength Division Multiplexing

DSP- Digital Signal Processing

DSF- Dispersion Shifted Fibre

EAM- Electro Absorption Modulator

EEL- Edge Emitting Laser

EDFA-Erbium-Doped Fibre Amplifier

FWM- Four-Wave Mixing

FPM- Four Photon Mixing

ITU- International Telecommunication Union

IV- Current-Voltage

ISI- Intersymbol Interference

LO- Local Oscillator

MZM- Mach-Zehnder Modulator

MMF- Multimode Fibre

NRZ- Non Return to Zero

OOK- On-Off Keying

OSNR- Optical Signal to Noise Ratio

PON- Passive Opical Network

PMD- Polarization Mode Dispersion

PSP- Principle State of Polarization

QPSK- Quadrature Phase Shift Keying

RZ- Return-to-Zero

RF- Radio Frequency

SNR- Signal to Noise Ratio

SEL- Surface Emitting Laser

SHB- Spacial Hole-Burning

SPM-Self- Phase Modulation

SOP- State of Polarization

SMF- Single Mode Fibre

SBS- Stimulated Brillion Scattering

VCSEL- Vertical Cavity Surface Emitting Laser

WDM - Wavelength Division Multiplexing

XPM- Cross-Phase Modulation

L_B- Beat Length

B_m - Modal Birefringence

B- Propagation Constant

D- Chromatic Dispersion Parameter

S- Fibre Dispersion Slope Coefficient

B- Channel Bandwidth

P_p- Peak Power

Ω- Angular frequency of light

C- Speed of light in a vacuum

H- Refractive index of light

λ - Wavelength of Light

τ - Differential Group Delay

R.m.s- Root Mean Square

V_g - Group Velocity

$\delta\lambda$ - Spectral Width

Γ- Nonlinear coefficient

Φ_{NL}- Nonlinear phase shift

A_{eff} - Effective fibre area

Δf - Channel Spacing

I_o - Nonlinear Intensity Scale factor

σ - Fibre Attenuation Coefficient

k_o - Wave number

ρ - Duty cycle

$\Delta\nu$ - Frequency Chirp

α' - Linewidth enhancement factor

p_{in} - Input optical power

p_{out} - Output optical power

η_i - Injection frequency

η_o - Optical frequency

ν - Frequency

h - Planck’s constant

e - Elementary charge

I - Injected current

I_{th} - Current threshold

β_2- Group velocity dispersion parameter

T_o - Ambient temperature

R_{th} - Thermal impedance

τ_{th} - Thermal time constant

s - Area

ξ - Thermal conductivity

R_s - Series resistance

V_T - Thermal voltage

I_s - Saturation currents

$P(t)$ - Instantaneous optical power

k - Structure dependent constant

R - Bit rate

T- Bit period

P_p- Peak power

μ_1 - Value of the binary 1

μ_0 - Value of the binary 0

σ_1 - Standard deviation of the binary 1

σ_0 - Standard deviation of the binary 0

η_x - Modal refractive index in the x-axes

η_y - Modal refractive index in the y-axes

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Glory be to God, it has taken His mighty hand to take me this far

CHAPTER ONE

INTRODUCTION

1.1 Background

The advances in information and communication technology (ICT) have enabled tremendous increase in the amount of data transfer through the networks. This has been supported by high bandwidth optical fibre and also the emergence of fast computer processors, whose speed has been increasing every now and then. Wavelength division multiplexing (WDM) technology has recently shown its potential to support high data bandwidth transfer. It allows multiple wavelengths to be simultaneously transmitted in a single fibre, hence increasing fibre capacity.

WDM based technology in passive optical network (PON) has emerged as the most promising next generation access solution that can provide an evolutionary upgrade to the current time division multiplexing technique (Sasanthi *et. al.*, 2012). PON is a form of fibre optic access network that uses point to multipoint fibre to the premises in which unpowered optical splitters are used to enable a single optical fibre to serve multiple premises. The advantages associated with PON include;

1. Low cost connectivity for a large number of users with high security into relatively low management needs.
2. High speed and robust performance.

3. None requirement of repeaters, switches, cooling and other gears that are expensive to purchase, install and operate.
4. They are environmentally friendly.

The advent of WDM technique started a revolution and increased the capacity of a light wave system enormously. However, there are factors which limit simultaneous transmission of multiple signals in a fibre. These factors are both linear and non linear. Linear effects include attenuation, polarization mode dispersion (PMD), chromatic dispersion (CD) and optical signal to noise ratio (OSNR). The non-linear degrading effects include self-phase modulation (SPM), cross phase modulation (XPM) and four wave mixing (FWM) (Hayee and Willner, 1999).

In an effort to overcome some of the transmission challenges many modulation formats have been proposed. Among them is the non return to zero (NRZ) (Wang *et. al.*,2009). This is because of its compact spectrum suitable for dense wavelength division multiplexing (DWDM), high receiver sensitivity and fair tolerance against non-linear effects (Zhang *et. al.*, 2010). In the recent years, research has shown constant progress and growth on the long wavelength data transmission using vertical surface emitting lasers (VCSELs) as light sources. VCSEL is a special laser diode that promises to revolutionize fibre optic communications by improving efficiency and increasing data speed.

VCSELs are being developed as light sources for optical interconnections. A number of breakthroughs within the area of VCSELs have resulted in the emergence of 1310 nm and

1550 nm VCSELs. Due to cost-effectiveness and low drive voltage, the system has become the most attractive candidate for future PONs (Kapon and Sirbu, 2009). VCSEL is a preferred light source for high-speed data generation in short distance optical communication links (Iga, 2000). It is attractive for a number of advantages which include; cost-effective fabrication and testing, high fibre coupling efficiency, low power consumption and excellent high-speed modulation characteristics at low current and power (Soderberg *et. al*., 2007). However, VCSELs have a number of drawbacks based on large frequency chirp and polarization insensibility which limit their performance in optical fibre systems as well as causing transmission impairments in high bit rates (Chrostowski, 2004). These limitations points out the need to characterize and optimize these optical effects on different fibres over long distance transmission. In modern optical fibre systems, wavelength division multiplexing (WDM) has enabled a dramatic increase in the fibre capacity. However, assembling and packaging discrete lasers with different wavelengths is expensive and time consuming (Qader *et. al*., 2011). Multiple-wavelength arrays of VCSELs are desirable sources for WDM systems due to reduced production costs (Karim *et. al*., 2001). However, the most important effect is exhibited in the devices Light-Current (L-I) curve (Karim *et. al*., 2000). VCSELs exhibit temperature-dependent threshold current. Therefore, as the device temperature increases with injection current, the output power rolls over and begins to decrease thereby limiting the device maximum power output.

When an optical signal is transmitted through a fibre, modal and chromatic dispersion (CD) become limiting factors due to differential delay and frequency components and as a result introduces error-bits. Single mode lasers not only allow one lasing mode but also have narrower spectral width compared to multimode lasers. This therefore ensures high emission powers and error-free transmission for longer distances (Ly *et. al*., 2008). Rapid progress in VCSEL development over the last decade has allowed 850 nm and 980 nm transmissions windows to be deployed in optical networks (Bjorlin *et. al*., 2001). In short-haul applications such as fibre channel and Gigabit Ethernet, the efficiency and high speed at low power of VCSELs have made them the light source of choice. However, for longer reach applications, long wavelengths 1300 nm and 1600 nm laser diodes are required in order to operate fast with low loss and dispersion. Single-mode VCSELs at 1310 nm and 1550 nm are widely anticipated as low-cost light sources in telecommunication networks. 10 Gb/s Ethernet standards are expected to focus on low-cost high performance laser diodes such as long-wavelength VCSELs. Therefore, lower voltage operation should also be possible due to the narrower band gap of long-wavelength materials

1.2 Statement of the problem

The interaction between channels in DWDM systems limits the transmission capacity of the fibre. Hence, more losses are experienced as a result of interaction between these channels. In high bit rate and long distance fibre optical systems operating at 10 Gb/s and above, linear factors can become troublesome. The optical modulation format is the main issue which has much influence on the transmission quality, distance and spectral efficiency. As a result of this, there is need to investigate and characterize VCSELs and determine their performance in different fibres at different transmission windows. There has been increasing interest in VCSELs due to its unique advantages such as small size, single longitudinal mode, short cavity length, low power consumption and small light beam divergence. It is therefore significant to investigate and fully understand optical signal transmission using SMF for high bit rate in low loss transmission windows.

1.3 Objectives

1.3.1 General objective

To study the performance of VCSEL at 10 Gb/s in G.655 and G.652 SSMF in the 1310 nm and 1550 nm transmission windows

1.3.2 Specific objectives

1. To characterize the performance of 1310 nm and 1550 nm VCSELs using NRZ modulation format at a bit rate of 10 Gb/s.
2. To analyze the performance of G.655 and G.652 fibres using VCSEL at 1310 nm and 1550 nm transmission windows.
3. To analyze the OSNR in G.652 fibre for a VCSEL signal at 1310 nm.

1.4 Justification

DWDM based on PON are the most promising next generation access solution that can meet the growing demand of both existing and forth coming multimedia services. This can be attained by minimizing linear impairments over the transmission fibre and by using the optimal modulation format. VCSELs have emerged as the light source of choice for modern high speed, short wavelength communication system. The single transverse mode operation of the device increases the efficiency of coupling light into the fibre optic cable hence significantly reduces the CD dispersion in the fibre. This study is of great significance in improving the transmission capacity of long-haul system and transmission of data with higher bit rates per second. This is a great contribution to information and communication technology (ICT) sector and contributes to the achievements of vision 2030 of Kenya.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Vertical cavity surface-emitting lasers (VCSELs) is a type of semiconductor laser with light beam emission perpendicular from the top surface contrary to edge-emitting semiconductor lasers which emit from the surface formed by cleaving the individual chip out of a wafer (Wiki and Kunz, 2000). In recent years, research has shown rapid progress and growth on the long wavelength and high speed data transmission using VCSELs light sources. VCSELs have been studied extensively for use in fibre-optic networks and as optical interconnects due to potential advantages when compared to the traditional in-plane laser (Karim *et. al.,* 2000). High-volume, low-cost manufacturing is of vital importance for the next generation of active optical devices. This chapter provides an introduction to VCSELs describing their structure and operational characteristics. Some relevant transmission impairments that influence system performances have also been discussed.

2.2 Theory of Optical Fibre Transmission

Fibre optics is a medium for carrying information from one point to another in the form of light, unlike the copper form of transmission which is electrical in nature. A basic fibre optic system consists of a device that converts an electrical signal into light signal, an optical fibre cable that carries the light and a receiver that accepts the light signal and converts it back into an electrical signal (Sahnow *et. al.*, 2000).

Fibre optics transmission is a major building block in the telecommunication infrastructure due to its high bandwidth capabilities and low attenuation characteristics make it ideal for Gigabit transmission and beyond. The demand for optical fibre has grown tremendously. With the explosion of information traffic due to internet, electronic commerce, computer networks, multimedia, voice, data and video the need for a transmission medium with the bandwidth capabilities for handling such vast amounts of information is paramount.

Optical fibres used in optical transmission can be categorized into two types, namely; single mode fibre (SMF) and multimode fibre (MMF). SMF allows only one mode of light to travel within a fibre. In a MMF fibre, several modes of light can be propagated through one optical fibre. The first generation of light wave systems operated at 800 nm and used GaAs semiconductors lasers. After several field trials during the late 1970's, these systems became commercially available in the 1980's. They operated at a bit rate of 45 Mb/s and allowed repeater spacing of up to 10 km. The repeater spacing could be increased considerably by operating the light wave system in the wavelength region near 1300 nm where fibre loss is below 1 dB/km. Furthermore, optical fibres exhibit minimum dispersion in this wavelength region. This realization led to the development of InGaAsP semiconductor lasers and detectors operating near 1300 nm. The second generation of fibre-optic communication systems became available in the early 1980s, but the bit rate of the systems was limited to below 100 Mb/s because of dispersion in MMF. This limitation was overcome by the use of SMF. A laboratory experiment in early 1990s demonstrated a transmission at 10 Gb/s over 40 km using SMF. The repeater spacing of the second generation on lightwave systems was limited by the fibre loss at the operating of 1300 nm (typically 0.5 dB/km). In early 1980s, a 0.2 dB/km loss was realized near a 1550 nm wavelength. However, the introduction of third-generation lightwave system operating at this wavelength was delayed by large fibre dispersion near this spectral region. The dispersion problem was overcome either by using dispersion-shifted fibre (DSF) designed to have minimum dispersion near 1550 nm or by limiting the laser spectrum to a single longitudinal mode. A drawback of the third generation systems is that the signal is regenerated periodically by using electronic repeaters spaced apart typically by 60-70 km.

The fourth generation of lightwave systems made use of optical amplification for increasing the repeater spacing and of wavelength division multiplexing (WDM) for increasing the bit rate. WDM technique started a revolution that resulted in doubling of the system capacity and led to lightwave systems operating at high bit rates. In most WDM systems, fibre losses are compensated periodically using erbium-doped fibre amplifier (EDFA). This performance indicated that an amplifier-based, all-optical transmission system was feasible for long haul optical transmission (Agrawal, 2002).

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of ICT's. The ITU standardization sector is a permanent organ responsible for studying technical, operating and tariff issues and making recommendations on them with a view to standardizing telecommunications on a worldwide basis.

A variety of single mode (SM) optical fibres with carefully optimized characteristics are available commercially, which include; ITU-T G.652, 653, 654, 655, 656 or 657. The design of SM fibre has evolved over the decades and present-day options would deploy G.652, G.655 or G.656 compliant fibres.

Table 2.1: (Allen *et. al.*, 2004) Properties of G.652 and G.655 fibres used in VCSEL optical signal transmission.

Fibre Parameter	VCSEL Fibre Types and Wavelength (nm)			
	G.652 (1310)	G.655 (1310)	G.652 (1550)	G.655 (1550)
Attenuation	0.2	0.3	0.3	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

SMFs are suitable for long haul data transmission when used in 1310 nm and 1550 nm transmission windows (Kapon and Sirbu, 2009). I-TUT G.652 is the conventional SMF that has been in used in most telecommunication networks. It operates on the second window of optical communication. It is optimized for use in the 1310 nm wavelength region (zero dispersion wavelengths, ZDW) but can be used at 1550 nm too. ITU-T G.655 fibre on the other hand offers low attenuation and dispersion when used in 1550 nm transmission window.

2.3 Linear Effects in Optical Fibres

When information carrying light pulses propagates through an optical fibre, they suffer from attenuation and dispersion in the fibre. Attenuation refers to the reduction in the pulse energy due to various mechanisms such as scattering and absorptions. Dispersion is caused by the fact that a light pulse consists of various frequency components and each frequency components travels at a different group velocity (V_g). Dispersion causes the temporal width of the pulse to increase and also reduce in some cases. Attenuation and dispersion causes a change in the temporal variation of the optical power as it propagates through the medium. These effects tend to distort the signals resulting in loss of information or in cross talk among different channels. High bit rates and increased number of channels leads to linear optical effects, this linear effects include chromatic dispersion (CD), polarization mode dispersion (PMD) and optical signal to noise ratio (OSNR).

2.3.1 Chromatic Dispersion (CD)

Chromatic Dispersion (CD) is a pulse broadening phenomenon which is caused by the interaction between the light pulse and the material used to manufacture the optical fibre. For every kilometer of fibre, the travelling pulses are affected by a specified amount of CD resulting in broadening. After some distance, the pulses become broad and overlap with adjacent pulses which increase the zero level in the transmitted beat stream. Dependence of fibre birefringence on wavelength is due to CD. In this case the speed of propagation will vary with wavelength (Emami and Jafari, 2008). The two effects contributing to CD in a fibre are material dispersion and waveguide dispersion.

Material dispersion is caused by variations of refractive index of the fibre with respect to wavelength. Since the group velocity is a function of the refractive index, the spectral components of any given signal will travel at different speeds causing deformation of the pulse.

Waveguide dispersion on the other hand occurs because different spectral components of a pulse travel with different velocities by the fundamental mode of the fibre. It is as a result of wavelength due to existence of one or more boundaries in the structure of the fibre (Barake, 1997).

The CD is the result of wavelength dependence of the group velocity, v_g (Del Rio Campos and Horche, 2012).

The Chromatic dispersion parameter D is given by;

$$D = \frac{d}{d\lambda}\left(\frac{1}{v_g}\right) = -\frac{2\pi c}{\lambda^2}\beta_2 \tag{2.1}$$

The unit of dispersion D is ps/nm.km. The dispersion parameter, D is used to indicate the amount of dispersion in fibre specifications. If D is the less than zero, the medium is said to have positive dispersion and if D is greater than zero, the medium has negative dispersion as illustrated in Figure 2.1 (Haris, 2008).

The CD remains constant over the bandwidth of a transmission channel for long distance of fibre with dispersion mechanisms. In traditional optical fibre communication systems, the CD is usually compensated by the dispersion compensation fibres (DCF's) (Xu, 2012).

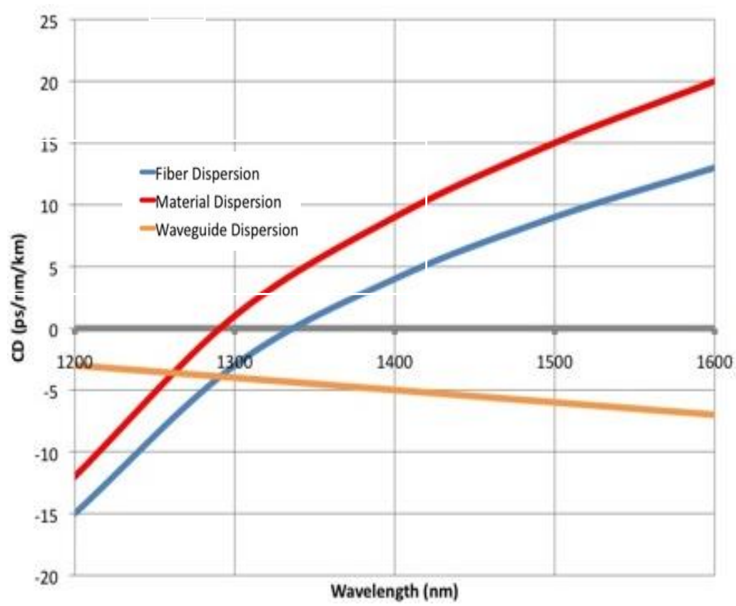


Figure 2.1 Measure of the variation of dispersion parameter D with wavelength for a single-mode fibre.

If we consider a signal propagating along a transmission distance L with propagation constant β, the Taylor expansion of propagation constants β about center frequency we can be written as;

$$\beta(\omega) = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega - \omega_0)^2 + ... \quad (2.2)$$

Where β_1 is the inverse of group velocity, v_g hence is written as;

$$\beta_1 = \frac{1}{v_g} \quad (2.3)$$

The signal group delay τ , can be calculated by multiplying (2.3) by L as follows

$$\tau = \beta_1 . L = \frac{L}{v_g} \quad (2.4)$$

In WDM system, every optical carrier travels at different speed. This is due to the wavelength dependence of the fibre refractive index. This phenomenon is represented by fibre dispersion slope coefficient, S i.e.

$$S = \frac{D}{\Delta\lambda} \quad (2.5)$$

where $\Delta\lambda$ is the WDM wavelength range. The unit of S is $ps/nm^2.km$.

2.3.2 Polarization Mode Dispersion (PMD)

Polarization mode dispersion (PMD) is the broadening of the input pulse due to a phase delay between input polarization states. It is a limiting factor to data carrying capacity of a telecommunication network (Gordon and Kogelik, 2000). PMD leads not only to random changes of the polarization state of light but also to pulse broadening (Karlsson, 1998). The broadening (splitting) occurs because the group delay of some fibre span depends on the input polarization. The difference of group delay between the two principal states of polarization (PSP) is called differential group delay (DGD).

Asymmetries and stress distribution in the fibre core leads to birefringence i.e. a polarization dependent refractive index (Sunnerud, 2001).

The difference in optical fibres can be expressed as a difference in the refractive index and hence propagation constant β, for the orthogonal polarization mode;

$$\Delta\beta = \beta_s - \beta_f = \frac{\omega\eta_s}{c} - \frac{\omega\eta_f}{c} = \frac{\omega\Delta\eta}{c} = \frac{2\pi}{\lambda}\Delta\eta \qquad (2.6)$$

Where $\Delta\eta = \Delta\eta_s - \Delta\eta_f$ >0 is the refractive index difference between the slow and the fast axis. The birefringence can also change the state of polarization (SOP) of light as it travels along the fibre (Agrawal, 2007) as shown in Figure 2.2.

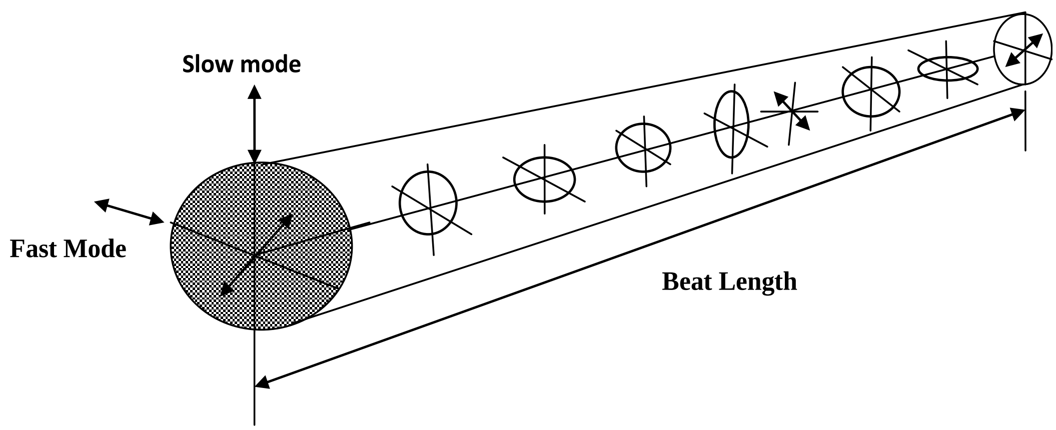


Figure 2.2: Polarization state of light along the fibre

One of the intrinsic causes of PMD is due to the asymmetry of the fibre core. The other causes are derived from deformation of the fibre including stress applied on the fibre, the aging of the fibre, the variation of temperature over time or effects from a vibration source (Le, 2008).

The delay between these two PSP is normally small in 10 Gb/s optical transmission system. However, at higher transmission bit rate for long haul systems, the PMD effect becomes much more severe and degrades the system performance. Ideally, the core of an optical fibre is perfectly circular and therefore has the same index of polarization for both polarization states. However, mechanical and thermal stresses introduced during manufacturing result in asymmetries in the fibre core geometry.

Under ideal conditions (perfect cylindrical symmetry and stress free fibre), a mode excited with its polarization in the x-direction would not couple to the mode with the orthogonal y-polarization state (Govind, 2001).

The modal birefringence is defined as:

$$B_m = \frac{|\beta_x - \beta_y|}{k_o} = |\eta_x - \eta_y| \tag{2.7}$$

Where $k_o = \frac{2\pi}{\lambda}$.

For a given value of B_m the two modes exchange their powers in a periodic fashion as they propagate inside the fibre with period.

The beat length is given by:

$$L_B = \frac{2\pi}{|\beta_X - \beta_y|} = \frac{\lambda}{B_m} \tag{2.8}$$

The axis along which the mode index is smaller is called the fast axis because the group velocity is larger for light propagation in the direction. The axis with the larger mode axis is called the slow axis.

Currently, PMD is the major factor affecting the pulse broadening and power degradation in optical fibre communication system operating over transmission rates of 5 Gbps. Therefore, it must be reduced to achieve reliable high bit rate communication. PMD is a statistical effect depending on two orthogonal modes transmitted instead of a single mode in circular symmetric SMF (Barlow, 1981).

PMD changes the propagation constant β resulting in a DGD. The presence of DGD causes the rotation of SOP's of the birefringence signal limiting the signal pump interaction leading to different arrival times of the signal at the output as illustrated in Figure 2.3 (Sait and Gunes, 2007).

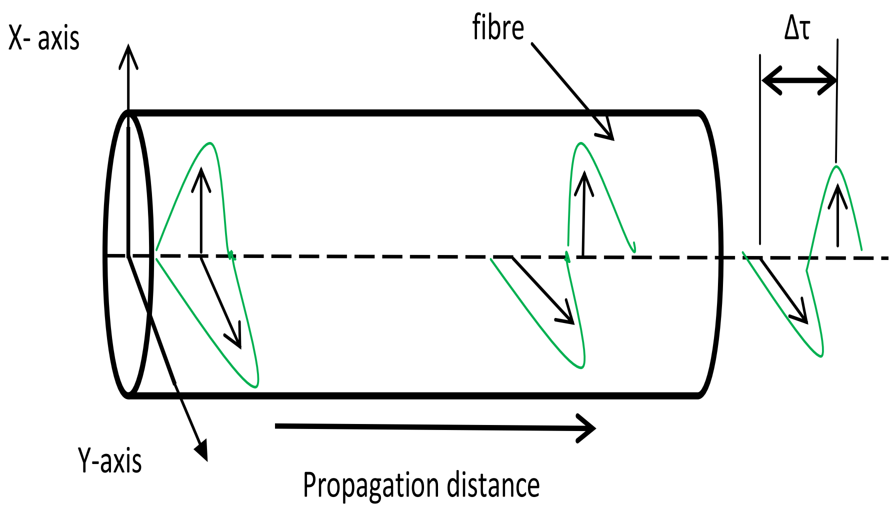


Figure 2.3: Diagram illustrating the effect of PMD in an optical fibre

For short fibre mean DGD is proportional to the length L,

$$< \tau > \alpha \, L \tag{2.9}$$

For long fibres, mean DGD is proportional to the square root fibre length,

$$< \tau > \alpha \, \sqrt{} \, L \tag{2.10}$$

This is because of the random mode coupling and the rotation of the birefringence axes along the fibre. Pulse broadening induced by PMD is generally calculated by the following formula

$$\Delta \tau_{PMD} = D_{PMD} \sqrt{L} \tag{2.11}$$

Where D_{PMD} is the PMD coefficient, unit is ps√km and L is the fibre length (Wang and Bi, 2012).

2.3.3 Optical Signal to Noise Ratio (OSNR)

The optical signal-to-noise ratio (OSNR) specifies the ratio of the net signal power to the net noise power and thus identifies the quality of the signal. OSNR is measured in decibels. The OSNR is the key performance parameter in optical networks that predicts the bit error rate (BER) of the system. OSNR is conventionally obtained by measuring the total signal power in the channel passband and the amplified spontaneous emission (ASE) noise levels in the gaps between the optical channels (Moench *et. al.,* 2008). Over time and distance, the receivers cannot distinguish the signal from the noise, and the signal is completely lost. Regeneration helps mitigate these undesirable effects before they can render the system unusable and ensures that the signal can be detected at the receiver. Optical amplifiers add a certain amount of noise to the channel. Active devices, such as lasers, add noise. Passive devices, such as fibre, can also add noise components. The higher the ASE, the lower the OSNR (Ajibodu *et. al.,* 2016). In the calculation of system design, however, optical amplifier noise is considered the predominant source for OSNR penalty and degradation. During the fibre transmission, the ASE noise generated by optical amplifier degrades the OSNR, which has direct relationship with bit error rate of the system (Chen *et. al.*, 2012).

OSNR is a key parameter to estimate the performance of optical networks (Durand *et. al.*, 2016). By defining SNR and relating it to BER helps in evaluating the quality of the transmission system. In optical transmission system, there are three major noise sources, which are noise from the transmitter, that added in the transmission channel, and that generated at the receiver. The noise generated by the transmitter can either be from inherent source or induced by optical reflections (Wiedenmann *et. al.*, 1999). The noise generated in the transmission channel is determined by the transmitter but mainly depends on the properties of the optical fibre. WDM systems allow multiple channels at different wavelengths to share the same optical fibre increasing the effective transmission rate of that fibre. The key parameters providing direct information on system performance (such as BER and BER estimation techniques like Q-factor or eye analysis) cannot be measured directly on a multichannel system. These parameters require spectral demultiplexing prior to making an individual evaluation of the BER on each demultiplexed channel. Alternatively, OSNR can be derived for each individual channel from an optical spectrum measurements to obtain indirect information about the performance of this channel and hence of the system. One of the key parameters to be monitored is the OSNR, especially in WDM reconfigurable networks, where each channel may be routed through different paths and accumulate a different amount of noise (Annoni and Morichetti, 2013).

OSNR can be directly correlated to BER using the following equation which justifies the fitting function used when performing BER verses received power.

$$BER(SNR) = \frac{1}{\sqrt{2\pi}} \int_{SNR}^{\infty} \exp\left(\frac{-t^2}{2}\right) dt \qquad (2.12)$$

A poor OSNR leads to a degraded BER. OSNR is an average-power low-speed measurement. It does not allow for the detection of rare bit errors. However, its correlation to the BER makes OSNR a key parameter to extract from the spectrum in order to provide preliminary performance diagnosis of multichannel system. In digital system, an SNR of 10 dB is usually enough to yield a 10^{-9} bit error rate. Analogue multiplexed system requires an SNR that is typically larger than 50 dB (Chrostowski, 2004).

The BER is an optical amplifier transmission system that is set by electrical SNR of the data signal at the decision circuit. Therefore, SNR is a natural figure of merit for transmission performance and system health. The received SNR is set by optical noise and waveform degradation accumulating over entire length of the system. At the physical transmission level, channel performance is directly determined by the BER which in turn depends on OSNR, dispersion and nonlinear effects (Pan *et. al.,* 2010). OSNR is considered as the dominant performance parameter in link optimization with dispersion and nonlinearity being limited by proper link design. In multichannel optical communication systems, a signal over the same optical link can be regarded as an interfering noise for others which lead to the OSNR degradation. Transmission impairments are quantified by calculating the required OSNR needed to obtain a target BER with optimal decision threshold and sampling instant (Wickham *et. al.,* 2004). The Q-value model, the ASE and the PMD can be both considered and transformed into bit error rate to judge the usability of lightpath (Bai *et. al.,* 2015).

In a fibre optic link, the laser source used at the transmitter has noise relative intensity noise (RIN). Additionally, amplifies in the link will contribute to the total noise. The noise will degrade the signal to noise ratio. It is thus important to design a link with a low noise at the transmission frequency band. For semiconductor laser, the distortion physically originates from the nonlinear characteristics of the laser including nonlinearity of the light-current (L-I) curve, the carrier photon interaction or from spatial hole-burning (SHB) (Ahmed *et. al.*, 2014). Transmission distortion is most important for multi-channel systems where some of the power from interacting carriers can be transferred into other channels. This leads to a reduction in the dynamic range of the system.

Semiconductor lasers modulated at low frequency exhibit signal distortions due to the non-linearity of light output-current curve. For lasers with very linear L-I curves, very low distortions have been observed at low frequency (Kuchta *et. al.*, 1993). However, for high frequency modulation (GHz), distortions increases significantly and originate from nonlinear rate equations. The frequency dependence of the intensity noise can be analytically identified by investigating how the spontaneous emission affects the characteristics of the laser (Hashemi, 2012). In analogue application, SNR is used to quantify the quality of the signal with respect to the noise. Thus excess noise can make it hard for the system to reach a certain required SNR. For digital applications, without taking the noise into consideration, a decision level at the midpoint defines whether a ‘0’ or ‘1’ is detected. However, noise in digital signals can cause errors at the decision level. A certain amount of noise from the laser can thus be acceptable in order to satisfy the BER criteria which typically less than one in 10^{-9} dB (Chrostowski, 2004).

2.3.4 Fibre Attenuation

Attenuation is the most fundamental impairment that affects signal propagation and limit transmission distance in fibre. It is the property of the fibre and it is as a result of the different materials used, structural and modular impairments in the fibre. When optical signal is transmitted over a fibre, its power is lost and its amplitude is reduced. This amplitude reduction or attenuation coefficient α is expressed in dB/km. Power attenuation inside an optical fibre is governed by Beer's Law: i.e

$$\frac{dP}{dz} = -\sigma p \tag{2.13}$$

Integrating equation (2.13) gives the output power, P_{out} as:

$$P_{out} = P_{in} \exp(-\sigma L) \tag{2.14}$$

The attenuation constant σ can be written in common units of dB/km and is referred as the fibre loss. The decibel (dB) is defined in terms of logarithm of a power or intensity ratio by using the following relation.

$$\sigma(dB/km) = -\frac{10}{L}\log_{10}\frac{P_{out}}{P_{in}} \tag{2.15}$$

Fibre dispersion limits the performance of optical communication systems by broadening optical pulses as they propagate inside the fibre. Fibre losses represent another limiting factor because they reduce the signal power reaching the receiver. As optical receivers need a certain amount of power for recovering the signal accurately, the transmission distance is inherently limited by fibre losses.

The fibre exhibited a loss of about 0.2 dB/km in the wavelength region near 1550 nm, the lowest value first realized in 1979 (Agrawal, 2002). This value is close to the fundamental limit of about 0.16 dB/km for silica fibres. Minimum loss is also found near 1310 nm window where the fibre loss is below 0.5 dB/km. The Figure 2.4 shows the loss spectrum $\sigma(\lambda)$ of a single-mode fibre made in 1979 with $9.4\mu m$ core diameter and $1.1\mu m$ cut off wavelength (Ablowitz and Clarkson, 1991). Fibre losses depend on the wavelength of transmitted light (Liu *et. al.*, 2007).

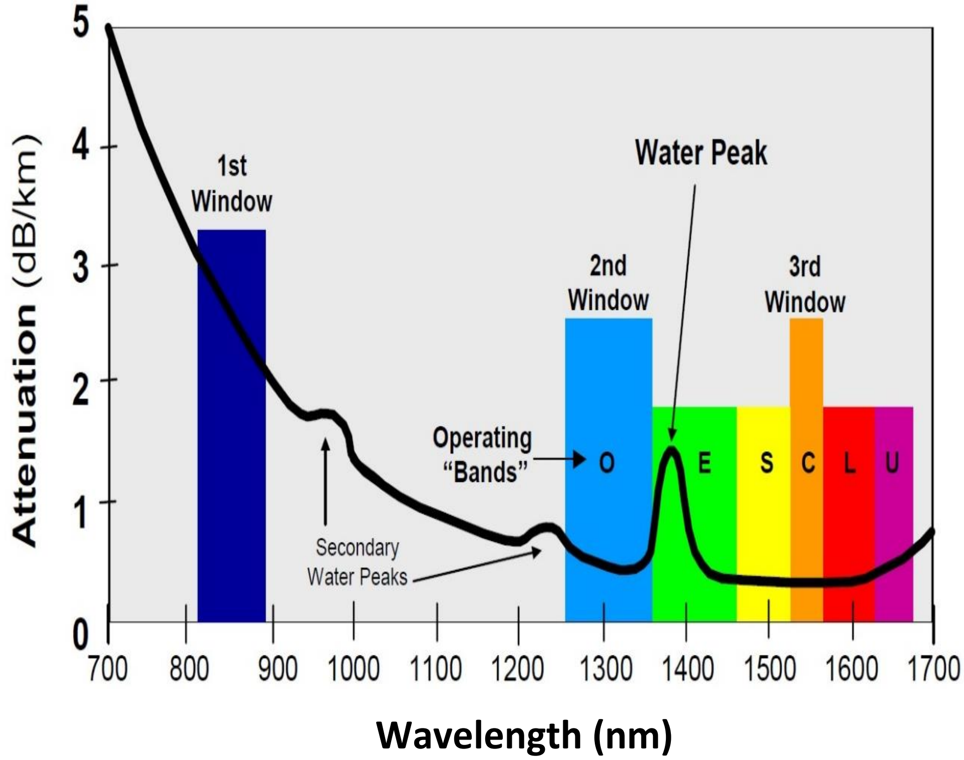


Figure 2.4: Attenuation at different transmission windows

Since fibre dispersion is minimum near 1300 nm, this low-loss window was used for second generation light wave systems. Fibre losses are considerably higher for shorter wavelengths and exceed 5 dB/km in the visible region hence making it unsuitable for long-haul transmission. Optical signal suffers more than only attenuation (Kilper *et. al.*, 2004). In amplitude, spectrally, temporary signal interaction with light-matter, light-light, light-matter-light, lead to other signal disturbances such as; power reduction, dispersion, polarization and unbalanced amplification. Thus leading to random noise which causes misalignments, jitter and other disturbances. This results in erroneous bits, or bit error rate (BER). Attenuation can be compensated for by amplifying the optical signal. However, optical amplifiers amplify the signal as well as the noise.

2.4 Vertical Cavity Service Emitting Laser (VCSEL)

Vertical cavity surface-emitting lasers (VCSELs) are semiconductor sources that emit a light beam that is perpendicular to the planes of an active region or perpendicular from the top surface of the cavity. VCSEL have become important light sources for optical access applications, such as central-office interconnects, parallel-optical data links or metro-feeders where they could allow for the low-cost deployment for short links (Fidler *et. al.*, 2006). VCSELs offer high bandwidth, single mode operation within C-L bands, wavelength tunabilities, the convenience of direct modulation and energy efficiency at low drive currents (Bjorlin *et. al.*, 2001). Figure 2.5 illustrates the typical layout of a VCSEL **(**Michalzik**,** 2012).

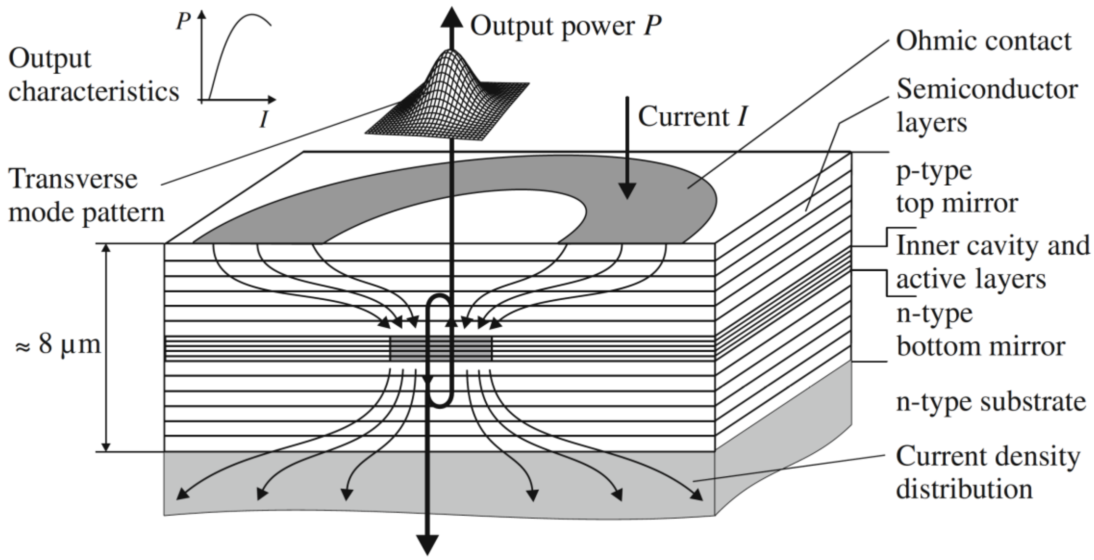


Figure 2.5: schematic layer structure and operating principle of a VCSEL

The inner cavity contains the amplifying layers surrounded by electrically conductive layers stacks to form the laser mirrors which provide optical feedback. VCSELs designed for emission wavelength in the 850-980 nm spectral range require about $8\mu m$ of epitaxial grown material, whereas the active region is composed of just a few quantum well (QWs) with some ten nm thickness. In most simple device layouts, electric current is injected from ohmic contacts on the top epitaxial side and the backside of the substrate. Several methods have been successfully employed to achieve current confinement to predefined active area (Geels *et. al*., 1990). Among these is simple etching of the top mirror, ion implantation to create highly resistive semiconductor regions or selective lateral oxidation of some ten nm thick semiconductor layer. This selective oxidation introduces less optical losses in the cavity and has produced devices of unrivalled performance. The active diameter of VCSEL can be reduced to a few micrometers in order to obtain lowest threshold currents in the sub-100 mA. The light-current curve of a VCSEL has a constant slope above the threshold as common for laser diodes but shows a characteristic roll-over for higher currents due to internal heating. Unlike for edge emitting lasers (EELs), it is uncritical to operate VCSELs up to their maximum output powers since power densities remain in the lower kW/cm^2 range and cannot induce optical damage to the semiconductor material or laser facet. Depending on the wavelength and material composition, VCSELs can be designed for top emission through a ring contact or bottom emission through a transparent substrate (Higuchi *et. al*., 2012). VCSELs are one of the most important laser sources in optical communication systems (Rodes *et. al.*, 2011). The main difference of VCSELs light sources in respect to conventional edge emitting lasers (EEL) is the emission being normal to the surface of the device. This unique characteristic makes VCSEL convenient for 2-D array integration on wafer testing with potential low-cost manufacture and circular emission with high fibre-coupling efficiency. Besides, the small cavity volume enables for low thresholds and high-speed modulation at low currents. This combination of features has led to a high interest and rapid development of VCSELs for short reach high-capacity optical interconnects. VCSELs are promising candidates for light sources at customer premises because of their cost-effective production and capability for chirp integration (Jensen *et. al.*, 2011). However, small optical power coupled into the optical fibre in VCSEL restricts the coverage range for application in PON links with a large splitting ratio and long distance.

The advantages of VCSEL to other laser diodes are (Gibbon *et. al.*, 2010):

1. They have low drive currents.

2. Relatively lower cost manufacturing.
3. Energy efficiency.
4. High modulation bandwidths.
5. Wavelength tuneability.
6. Single mode operation.
7. Low power consumptions.
8. Potential for producing integrated modules and arrays on wafer.

The main application of the VCSEL today is in optical interconnects such as channel Gigabit Ethernet and parallel transceiver modules based on multimode fibre ribbons (Michalzik and Ebeling, 2003). Figure 2.6 illustrates the structure of the VCSEL (Charlier and Krüger, 2012).

The power dissipated in the laser cavity induces to VCSEL self-heating. The internal temperature rise as the result of self-heating has an impact on VCSEL modulation performance. Increase in threshold current increases the temperature hence contributing to a reduction in gain. These effects cause the output power and the resonance frequency to saturate at a certain current level called the thermal rollover current. Due to important losses in harsh environment conditions, there is also need to maximize the extinction ratio (ER) (Tan, 2013). Also bit error rates (BER) performances are influenced by turn-on delays and jitter. Turn-on event is accompanied by a further delay when currents lower than the threshold biasing is applied.

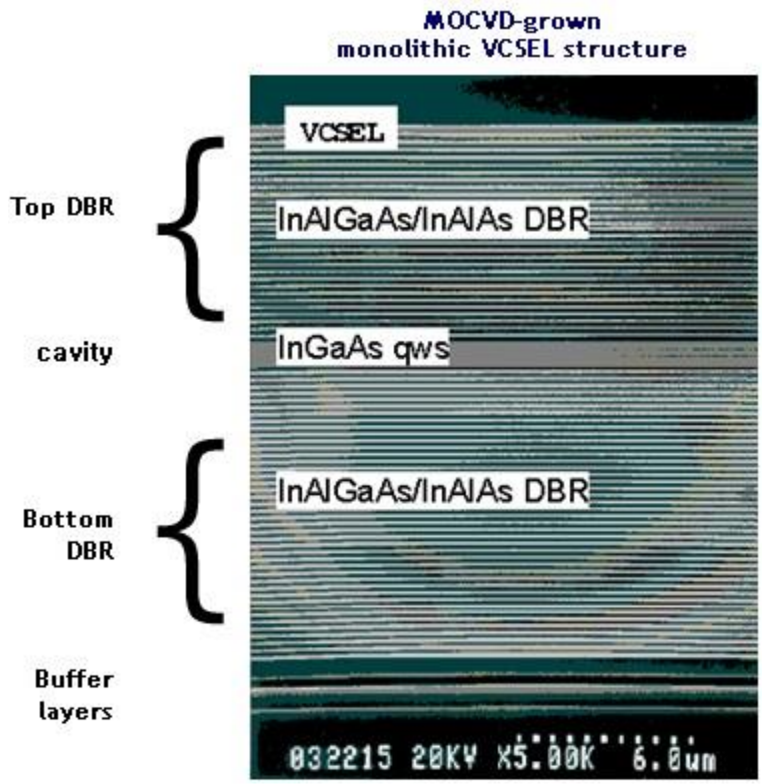


Figure 2.6: Raycan VCSEL structure

Due to their poor heat dissipation, typical VCSELs undergo relatively severe heating and consequently can exhibit strong thermally dependent behavior (Mena *et. al.*, 1999).

The optical power of a VCSEL can be calculated as; [Lopez, 2013]

$$P_{out} = \eta_i \eta_0 \frac{hv}{e}\left(I - I_{th}\right) \tag{2.16}$$

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

$$p_d = p_{in} - p_{out} \tag{2.17}$$

The use of short pulses allows measurements at high currents without heating up the VCSEL device.

The power dissipated in the laser induces self heating to VCSEL. The internal temperature within the VCSEL can be described as;

$$T = T_o + P_d . R_{th} - \tau_{th} . \frac{dT}{dt} \tag{2.18}$$

The device thermal impedance for small–diameter VCSEL mounted on top of a relatively thick substrate can be approximated as:

$$R_{th} = \frac{1}{2\xi s} \tag{2.19}$$

Thermal impedance is obtained by assuming a heat source with circular area. The internal temperature rise caused by current self-heating has an impact on VCSEL modulation performance. Increasing temperature contributes to a reduction of differential gain and internal quantum efficiency leading to an increase of the threshold current. These effects eventually cause the photon density and therefore the output power and the resonance frequency to saturate at a certain current level. This is called the thermal roll over current.

The current-voltage (IV) relationship can be modeled in great detail based on the diode-like character of the VCSEL (Mena *et. al.,* 1999). The voltage across the device is an arbitrary empirical function of current and temperature using;

$$V = f(I, T) \tag{2.20}$$

The relationship which accounts for a resistance in series with a diode is given by;

$$V = IR_s + V_T L_n \left[1 + \frac{I}{I_s} \right] \tag{2.21}$$

Generally V_T is a function of temperature. However, when IV data is only available at one temperature, a constant value can be used.

In short-haul applications such as fibre channel and Gigabit Ethernet, the efficiency and high speed at low power of 850-980 nm VCSELs have made them the light source of choice. However, for longer reach applications, long wavelength (1.3-1.6 μm) laser diodes are required in order to operate with low loss and dispersion. Single-mode VCSELs at 1300 and 1500 nm are widely anticipated as low-cost light sources in telecommunication networks (Karim *et. al*., 2000). Ten gigabits Ethernet standards are expected to focus on low-cost high performance laser diodes such as long-wavelengths VCSELs. Low voltage operation should also be possible due to narrower band cap of long wavelength materials. The principal obstacle in long-wavelength VCSEL development has been lack of high quality distributed bragg reflector (DBR) that can be integrated with InP-based active regions. The performance demands for long-wavelength VCSELs are particularly stringent. High reflectivity, high thermal conductivity and possibly high electrical conductivity must be included in the mirror design. The considerations must be balanced in order to optimize VCSEL performance. Due to short gain length of the cavity, VCSEL mirrors must have high reflectivity.

The peak reflectivity of a DBR is given by;

$$R = \frac{(1-qap^{m-1})^2}{(1+qap^{m-1})^2}\left(1-\frac{q\alpha\lambda}{n_H(1-p^2}\right) \qquad (2.22)$$

Where a, q and p are refractive index ratios that characterize the incident mirror and exit media and have value less than 1. Factor q is the ratio of incident medium and first DBR section refractive indexes. Factor a is the ratio of exit medium and final DBR section refractive indexes. Factor p is the ratio of low and high index mirror period refractive indexes. The number of mirror layers is given by m. The refractive index of the high-index DBR material is given by n_H. The absorption may be due to scattering in amorphous layers or absorption in semiconductor material. The maximum reflectivity of a DBR is limited by index contrast and absorption loss in the mirror.

VCSEL light sources have a relatively high series resistance compared to edge emitting laser (EEL). The DBR mirrors in the VCSEL structure are composed of multiple layers with small potential barrier. The addition of all DBR layers produces a significant voltage drop represented as a resistance in series with diode. The electrical power into the laser is represented as;

$$P_{in} = I^2R_s + IV_d + IV_s \qquad (2.23)$$

Due the apparent requirement of a stable phase and frequency relation between signal and local oscillator (LO), coherent detection has belonged to the realm of externally modulated low line width lasers far from the domain of the frequency chirped signals from Directly Modulated (DM) VCSELs. But it is exactly this chirp which enables us to employ the envelope detection based coherent detection of DM-VCSELs. The frequency chirp $\Delta\upsilon$ associated with direct modulation of a VCSEL can be described as (Jensen *et. al.*, 2014);

$$\Delta\upsilon(t) = -\frac{\alpha'}{4\pi}\left(\frac{d}{dt}\ln P(t) + kP(t)\right) \tag{2.24}$$

The differential term $\frac{d}{dt}\ln P(t)$ in equation (2.24) describes the transient chirp relating to the time derivative of the changing instantaneous optical power with rising and falling pulse edges. The term $kP(t)$ describes the adiabatic chirp related to the instantaneous optical power itself. The transient chirp only affects the leading and trailing edges of the pulse, the optical wavelength of the high power '1' state is lower than the optical wavelength of the '0' state.

The initial motivation of surface emitting laser (SEL) invention was a fully monolithic fabrication of laser cavity. Based on this concept, the current issues include high sped modulation capability at very low-power consumption level, reproductive array production and in expensive modeling. The VCSEL structure may provide a number of advantages as described by (Iga, 2000);

1. Ultra low threshold operation is expected for its small cavity volume reaching microampere levels.

2. $(I - I_{th})I_{th} > 100$ is possible, where $I =$ driving current and $I_{th} =$ threshold current.

3. Wavelength and thresholds currents are relatively insensitive against temperature variation.
4. Dynamic single-mode operation is possible.
5. Large relaxation frequency provides high-speed modulation capability.
6. High power conversion efficiency i.e. 50%.
7. Long device lifetime is due to completely embedded active region and passivity surfaces.
8. Vertical emission from substrate.
9. Easy coupling to optical fibres due to good mode matching from single mode through thick multimode fibres.

The Raycan VCSEL was mounted on a Finisar evaluation board shown on Figure 2.7. The VCSEL with the flexible printed circuit board (FPCB) was attached to its position on the Finisar board using a holder. VCSELs used in this study are of class IIIb from Raycan, South Korea.

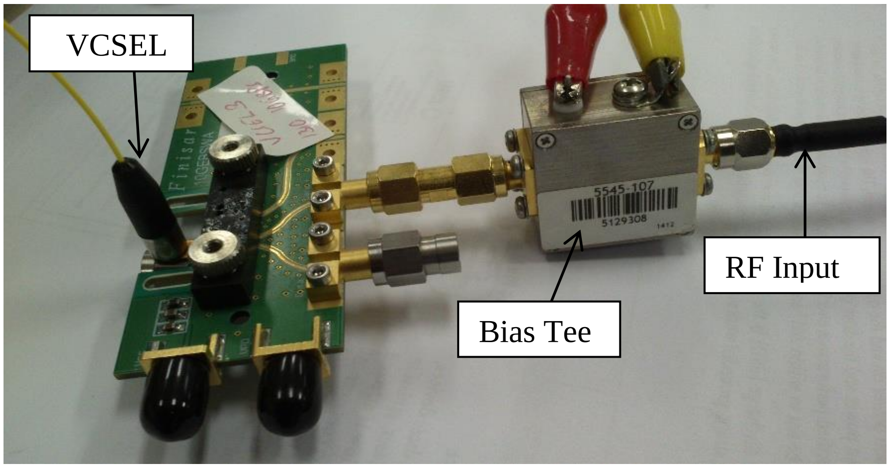


Figure 2.7: Photo of raycan VCSEL used in this study (Source: Author, 2016)

The bias tee has two electrical inputs and one output, the two inputs are basically a direct current (DC) which powers the device while the other input is the alternating current (AC) couple which feeds the data / pattern into it. Laser diode controller supplies DC to the VCSEL

2.5 Modulation Format Analysis

Modulation is the process of varying one or more properties of a periodic waveform called the carrier signal with a modulating signal that typically contains information to be transmitted (Arya, 2015). The modulation operation consists of transferring the data to be transmitted from the electrical to optical domain. Normally a high-frequency sinusoidal waveform is used as carrier signal. If the variation in the parameter of the carrier is continuous in accordance to the input analog signal, the modulation technique is termed as analogue modulation and if the variation is discrete then it is termed as digital modulation. Basically, there are two forms of modulation; direct and external modulation.

In direct modulation, the light is emitted from a semiconductor laser when a ‘mark’ is transmitted. In this modulation format, Radio Frequency (RF) signal is directly applied to the laser. The output power of the device depends directly on the input current. VCSELs are utilized in direct modulation (Khwandah *et. al.,* 2015). This technique can be operated with a low power requirement at safe levels without the need for cooling making the device ideal for use in DWDM system architecture. A critical consideration with directly modulated laser devices is that of matching the drive impedance of the VCSEL to that of the RF device supplying the signal. Direct modulation was facilitated by the use of a bias tee inserted between the RF signal sources and the anode of the VCSEL. This optical modulation is simple, cheaper and no complex circuitry is involved during modulation process. However, directly modulated lasers suffer poor yield due to the high degree of linearity needed. Direct modulation also produces frequency chirp which causes nonlinear distortion when combined with fibre CD, wavelength-dependent variations in optical amplifier gain or multipoint reflections (Gnauck *et. al.,* 1992). Direct modulation is possible at high data rates > 10 Gb/s.

In external modulation, an external device is incorporated to modulate the intensity/phase of the light source. Here the light source is kept ON and external modulator is used which functions as switch/shutter. This switch is controlled by information to be transmitted. In this modulation format, a modulator is put between the optical carrier (a laser source) and the communication channel (a fibre optic cable). The most well-known external modulators operating at the low attenuation 1550 nm window include the electro-absorption modulator (EAM) and the Mach-Zehnder modulator (MZM). The use MZM’s that have bias variable phase characteristics and lasers, require cooling for stability leading to system complication and consequently also have cost implications (Quinlan *et. al.*, 2011). The advantages of this modulation format includes; it is faster in processing, it can be used with high power laser devices, it can be employed in high speed applications e.g long haul telecom or cable head ends. However, this modulation format requires high frequency RF modulation circuit for operation making it more expensive.

To increase the capacity of light wave systems, or bit rate-distance product, high speed data rate per channel and tighter channel spacing in DWDM are the possible solutions. In high speed DWDM systems at 10 Gb/s and 40 Gb/s, linear and non linear impairments become severe. Therefore, an optimal modulation format is desired to combat both the linear and the non linear impairments over the transmission fibre. A modulation format with narrow optical spectrum can enable closer channel spacing and tolerate more dispersion distortion (Mehra and Joshi, 2004). A modulation format with constant optical power can be less susceptible to non linear factors. A modulation format with multiple signal levels will be more efficient than binary signals and its longer symbol duration will reduce the distortion induced by CD and PMD.

The simplest optical modulation format is on-off keying (OOK) intensity modulation which can take either of two forms: Non Return to Zero (NRZ) and Return to Zero (RZ). The optical modulation is the main issue which has much influence on the transmission quality and spectral efficiency. Earlier, RZ and NRZ was the main modulation format in optical systems. The demand for high transmission capacity leads to the creation of new modulation formats. In order to mitigate nonlinear transmission impairments because of the increasing distances, channel bit rates and also decreasing channel spacing, more advanced modulation formats have been proposed and one of this is NRZ. This modulation format is widely considered one of the effective methods of dealing with the influence of dispersion and nonlinearity in 40 Gb/s and 100 Gb/s optical fibre communication system (Yao *et. al.,* 2014).

2.5.1 NRZ Modulation Format

In NRZ format, the pulse remains on throughout the bit slot and its amplitude does not drop to zero between two or more successive bits. As a result, the pulse width varies depending on the bit pattern (Chen *et. al.*, 2009). In commercial system, NRZ are used in fibre optical communication because of the following reasons:

1. It is not sensitive to laser phase noise

2. It requires a relatively low electrical bandwidth for transmitters and receivers

3. It has the simplest configuration of transmitter and receiver

NRZ modulation format has been extensively used in many data communication mainly because of its signal bandwidth which is about 50% smaller than the RZ and less costly. NRZ line code is binary code where a ‘1’ is represented as a positive voltage. The longer the pulse width, the greater the amount of data. However, NRZ modulation is found to be more susceptible to intersymbol-interference (ISI) than RZ (Bobrovs *et. al.*, 2015).

Figure 2.8 shows NRZ modulation format used in communication system (Muthana *et. al.*, 2011).

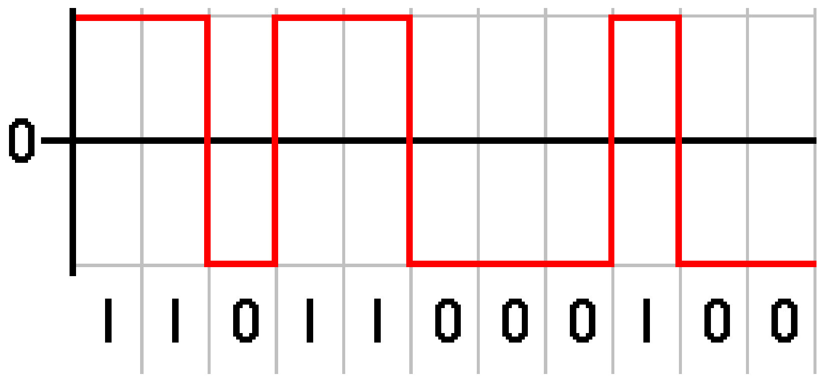


Figure 2.8: NRZ data signal format

Increasing the capacity of optical systems may require either an increase in the bit rate, usage of WDM or ultimately both. At high bit rates, the modulation format, type of compensation scheme and channel power become important issues for optimum system design. In particular, it has been demonstrated numerically and experimentally that the conventional NRZ modulation format is superior compared to the RZ modulation when dealing with large WDM systems as RZ modulation causes significant eye closure penalty near end channels (Hayee and Willner, 1999). In 10-40 Gb/s dispersion managed systems, NRZ is more adversely affected by dispersion. In particular, RZ pulses have a better performance in situations where nonlinear effects of the fibre severely impact the quality of transmission. Moreover, since RZ pulses have shorter duty cycle, temporal spread of the transmitted symbols causes less performance degradation due to ISI compared with NRZ pulses. The longer pulse time and longer interaction time between wavelengths make the NRZ to suffer more nonlinearities. For a long time, NRZ has been the dominant modulation format in intensity modulated/ direct detections (IM/DD) fibre optical communication systems. The major reasons for using NRZ in the early days of fibre optical communication are probably because it requires a relatively low electrical bandwidth for the transmitter and receiver compared to RZ and is not sensitive to laser phase noise.

In NRZ, a constant power is transmitted during the entire bit period T. Each channel in optical wavelength division multiplexed communication system is intensity modulated with bit rate;

$$R = \frac{1}{T} \tag{2.25}$$

The 'one' symbols are transmitted using rectangular pulses with duration ρT (Forghieri *et. al*., 1997).

The duty cycle takes the values $0 < \rho \leq 1$. The peak power of each pulse is given by;

$$P_P = \frac{P}{\rho} \tag{2.26}$$

For NRZ;

$$P_P \approx \rho \tag{2.27}$$

The effect of CD is to introduce a delay among the spectral components of the signal. Since the lower the duty cycle, the larger the bandwidth, it is expected that the effect of dispersion is larger for smaller ρ .

The dispersion length L_D (the length at which the eye opening has a relevant penalty) can be obtained assuming that the pulse is compared of two overlapping pulse separated by R. Therefore,

$$L_D = \frac{c}{\lambda^2} \frac{\rho}{R^2 D} \tag{2.28}$$

XPM is a dominant nonlinearity in the optical design on a given channel by edges on interfering pulses in other channels. The spectral broadening induces a temporal broadening due to dispersion which should be kept below the bit time T.

2.6 System Performance

The overall system performance of a communication link is quantified by analyzing three important parameters namely bit error rate (BER), quality factor (Q-factor) and eye diagram at the receiver sensitivity. The receiver sensitivity relates the amount of optical power needed to obtain the minimum BER. Q-factor and BER is one of the most important parameters that determine the transmission distance in optical communication system. In order to transmit signals over long distances, it is necessary to have a low BER and high Q-factor within the fibre (Hossain *et. al.*, 2015).

2.6.1 Bit Error Rate (BER)

BER is the ratio of the number of bit errors detected in the receiver to the number of bits transmitted. It is the number of received binary bits that have been altered due to noise and interference divided by the total number of transferred bits during a studied time interval (Abdullah and Talib, 2012). For example, a transmission having a BER of 10^{-6} means that out of 1,000,000 bits transmitted, one bit is an error. An error happens as a result of incorrect decision being made in the receiver due the presence of noise on a digital system. The decision to sample and whether the sampled value represents a binary 1 or 0 is affected by noise and signal distortion in the real system and there is nonzero probability of an erroneous decision. Therefore, the received signal quality is directly related to the BER, which is a major indicator of the quality of the overall system.

BER is affected by attenuation, noise, dispersion, crosstalk between adjacent channels or jitter. Its performance may be improved by launching a strong signal into a transmission system.

$$BER = \frac{1}{2} erf\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{\exp\left(\frac{-Q^2}{2}\right)}{Q\sqrt{2\pi}} \tag{2.29}$$

Generally, the BER decreases as the Q-factor increases. For a Q-factor ranging from 6 to 7, the BER is obtained as of 10^{-9} up to10^{-12}. BER can be increased by either increasing the difference between the high and low levels in the numerator of the Q-factor or by decreasing the noise terms in the denominator of the Q- factor.

Factors that cause BER are:

1. Signal bandwidth; where BER is inversely proportional to bandwidth

2. Energy per bit; it can be increased by using high power transmission but this will increase the non linear effects in the fibre

3. Bit rate; a lower bit rate increases the energy per bit, but will decrease the transmission capacity of the system hence lowering the BER

2.6.2 Q-Factor

Q-factor is a measurement of the signal quality and it is proportional to the system signal to noise ratio (Kanwar and Bhaskar, 2013).

The Q-factor is a parameter that directly shows the quality of the optical communication system. It specifies the minimum required OSNR used to obtain a certain value of BER. It includes all physical impairments of the signal which includes noise, non-linear effects and dispersion (chromatic and polarization). These impairments degrade the signal and cause bit errors. The Q-factor, a function of the OSNR, provides a qualitative description of the receiver performance. A higher value of the Q-factor means a better SNR and therefore a lower BER (Payne and Stern, 1986). The higher the value of Q, the better the quality of the system. Q-factor is expressed in following equation (Hossain *et. al.,* 2015).

$$Q[-] = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0} \tag{2.30}$$

Where μ_1 is the value of the binary 1, μ_0 is the value of the binary 0, σ_1 is the standard deviation of the binary 1 and σ_0 is the standard deviation of the binary 0.

2.6.3 Eye Diagram

The eye diagram is a conventional and visual tool used to monitor the complete waveform of the modulated laser signal and is illustrated in Figure 2.9 (Moustafa *et. al*, 2015). The eye diagram represents a superposition of all bits in the signal on top of each other. There are basically two types of adverse effects visible in the eye diagram as in Figure. 2.9; first, the effect of ISI and second the effect of jitter (Freude *at. al*., 2012). ISI is caused by overlap of individual modulation pulses and it leads to the amplitude errors at the sampling instances. Jitter is defined as short-time deviations of a digital signal from its ideal position in time. Eye diagram gives the BER and Q-factor (Hill and Meltz, 1997). Larger eye opening signifies less noise or distortions and therefore a higher signal quality (Vladimir *et. al.*, 2010).

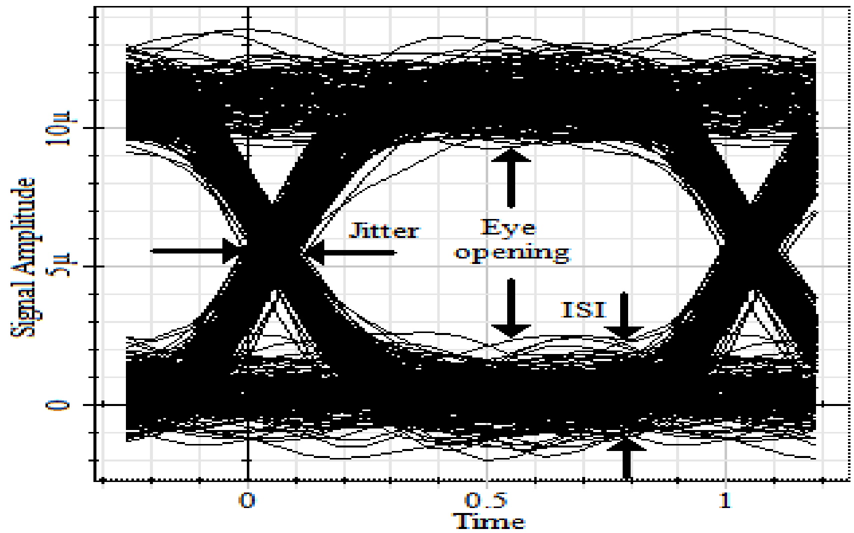


Figure 2.9: An example of an eye diagram with main properties marked

The thick horizontal borders of both the ‘1’ and ‘0’ levels of the eye diagrams are manifestation of laser and receiver noises. The budge on top of eye diagram are due to the bit-pattern effect raised because the bit slot T_b is shorter than the setting time of the relaxation oscillations. This bit-pattern effect is also the origin of the random rising and falling paths between the ‘0’ and ‘1’ levels and the associated turn on and turn off jitters.

2.7 Overview of VCSEL Signal Transmission

In recent years, there has been a great interest in digital optical modulation formats for ultra-long distance optical transmission. The impact of optical modulation formats on transmission fibre types and data-rates in WDM systems is critically important for sprint to make strategic decisions on the fibre plant investments and fibre-optic equipment purchasing (Hiu *et. al.,* 2004). Because of the rapid growth of capacity requirement on long distance transmission, fibre-optic telecommunications is advancing into high data rate and dense wavelength division multiplexing (DWDM). In order to maximize the system capacity and minimize the performance degradation caused by transmission impairments, system engineering and optimization are important. Similar to other telecommunication systems, signal modulation format is a key issue, which determines transmission quality and spectral efficiency. The first single-mode fibre was specified in recommendation ITU-T G.652 (Montmorillon *et. al.,* 2009). This fibre formed a key foundation to the modern VCSEL optical networks that form the basis of all the modern telecommunication. VCSELs have become an ideal source of communication for relatively short distance; high speed optical communication networks (Gibbon *et. al.*, 2011). Recently, VCSELs have attracted considerable interest due to their single longitudinal mode operation, high bandwidth, wavelength tunabilities and energy efficiency at low drive currents. However, data transmission using VCSEL is limited by wavelength chirp and CD. This therefore, motivates the need to investigate and characterize high speed VCSEL signal transmission over SMFs using optimal modulation format.

A lot of research on modulation formats has been carried out on recent advancement in access networks like Ethernet Passive Optical Networks (EPON) and Gigabit Passive Optical Networks (GPON). These techniques are now used as optical access network solutions to distribute reasonably high bandwidth to the costumers through an optical fibre network infrastructure (Singh and Kaler, 2014). These components are used to achieve high data rate transmission. Recent research is focused on the next-generation PON. However, this system needs complex scheduling algorithms and framing technology to support different applications. Several modulation schemes have been proposed which include DQPSK and OOK (Zhang *et. al*., 2008).

To maximize optical network capacity, system design and optimization have to take into account all the contributing facts, such as channel data rate, transmission distance, signal optical power, amplifier, channel wavelength spacing, fibre dispersion and nonlinear parameter. One of the most important facts in the system, which affects the choices of all other system parameters, is the signal optical modulation format. Non-return-to-zero (NRZ), on-off key (OOK) had been the dominant optical modulation format in intensity-modulation, direct-detection (IM/DD) fibre-optic systems (Sen, 2004). Transmission of binary modulated signals over SMF has attracted significant attention due to a multitude of factors including high tolerance to CD, ease of implementation and improved spectral efficiency (Haris, 2008). These are key performances indices of an optimal modulation technique that enables the realization of next generation high data rate DWDM transmission networks. As a result several modern fibres have been developed that are of low PMD and low dispersion. Most single mode fibres (SMFs) operate at 1310 nm and

1550 nm windows where attenuation is minimum and hence their suitability in long distance transmission. Multimode fibres are designed for short transmission and operate mainly at 850 nm and some at 1310 nm. In this research, two modern fibres of different optical characteristics have been used, namely; G.655 and G.652 fibres. Their performance was studied in terms of BER and Q factor.

CHAPTER THREE

METHODOLOGY

3.1 Research Design

The approach to this study involved both simulations and experimental analysis. An optical communication system was developed using OptiSytem software platform (OptiSystem, 2008). It is an innovative optical communication system package which was developed by Optiwave Company in order to meet the technical requirements of the system designers, optical communication engineers and researchers. This software is an optical communication system simulation package for designing, testing and optimizing of virtually any type of optical link in the physical layer of a broad spectrum of optical networks. The advantages of this optisystem software include; in build of most components in the library, easy to integrate with other software platforms and parameter modification is easier compared to real optical communication system.

Optical communication is a novel technology that offers special features and merits over conventional electrical communication. It provides high speed data rate and enormous capacity. The approach to this study involved simulations as well as experimental analysis on the 1310 nm and 1550 nm VCSEL. Data was modulated directly into the VCSEL. This system provided high bit rate data transmission over long distance with appropriate optical modulation format.

3.2 Experimental Set-up

The setup shown in Figure 3.1 was used in the experimental work done at Nelson Mandela Metropolitan University-Port Elizabeth, South Africa, during a research visit. The experimental results and the simulation work were compared for different fibres and transmission wavelengths.

The 1310 nm and 1550 nm VCSELs were modulated at 10 Gb/s. The G.655 and G.652 single mode fibres were used to investigate the transmission capabilities of the VCSELs.

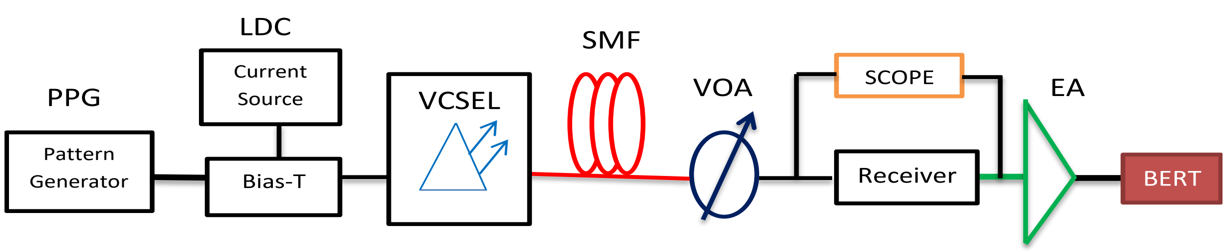


Figure 3.1: Experimental set up of the directly-modulated VCSEL

3.2.1 VCSEL Characterization

A programmable pattern generator (PPG) directly modulated a VCSEL by a 10 Gb/s with non-return-to-zero (NRZ) pseudo-random binary sequence (PRBS) of length 2^7-1 via a bias-T. The bias –T combined the laser diode controller (LDC) bias current with pattern generator output to directly modulate the VCSEL. The bias current of the VCSEL was restricted to 10 mA so as to avoid damaging the VCSEL device. Both 1310 nm and 1550 nm VCSELs were considered in this study. The output power of the VCSEL was measured as the bias current was increased from 0 mA to 10 mA. Biasing was done above the threshold current preferably the mid region in P-I curve so as to enable optimum performance. Wavelength tuneabilities were investigated by increasing the bias currents. The VCSELs was being tuned to different channels using 3 mA, 5 mA, 7 mA and 9 mA bias currents. The wavelength stability and tuneability allows for wavelength multiplexing which is used to increase the data rate over a single fibre in the array.

3.2.2 VCSELs Transmission Performance

The 10 Gb/s signal was propagated over standard ITU-T G.652 and G.655 fibres. The length of the fibre was varied from 11 km, 17 km and 25 km as the BER and OSNR were measured. The bias current and voltage were adjusted to achieve a better VCSEL modulation index. The overshoot was as a result of over modulation. In order to measure and monitor the optical power going into the receiver, a variable optical attenuator (VOA) and optical power meter were placed after the transmission fibre. An electrical amplifier (EA) was used to amplify the electrical signal to meet the operational requirements of the bit error rate tester (BERT). The BERT determined the number of errors received and compares the errors to the total number of transmitted bits. The quality of the optical signal was then characterized by observing the optical spectrum, electrical data patterns, eye diagrams, BER measurements and transmission penalties in the system.

3.3 Simulation Set-up

Optical communication system performance was obtained by analyzing the received signal. In this research, an optical communication system was designed using OptiSystem software (7.0) platform. NRZ modulation format was used in the simulation as shown in Figure 3.2.

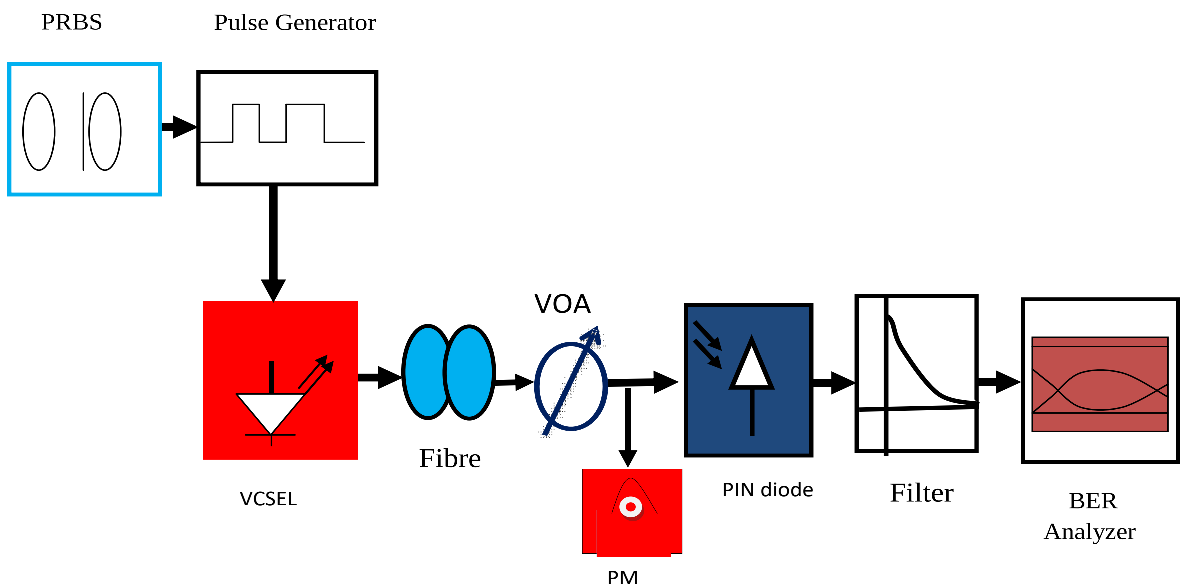


Figure 3.2: Simulation Setup of VCSEL

The simulation of the optical transmission system in optical fibre has been discussed by analyzing the NRZ modulation format using G.655 and G.652 fibres. This system consists of a transmitter, optical fibre and a receiver. The transmitter consists of VCSEL, PRBS and pulse generator. VCSEL biasing was performed by varying the current using the laser diode controller (LDC) and directly modulating the VCSEL with a 10 Gb/s non-return-zero (NRZ) pseudo-random binary sequence (PRBS 2^7-1) from a programmable pattern generator (PPG) via a bias-tee (BT). The signal was then transmitted using 1310 nm and 1550 nm VCSEL with the bias current kept at 6 mA. The fibre length was varied between 11 km and 25 km. The signal was then transmitted using G.655 fibre with dispersion of 2.6 ps/(nm.km) in the 1550 nm transmission window and G.652 fibre with dispersion of 0 ps/(nm.km) in the 1310 nm transmission window. The receiver used consisted of positive-intrinsic-negative (PIN) photo diode, low pass optical filter and bit error rate (BER) analyzer. A variable optical attenuator (VOA) was used to vary the optical signal power into the photodiode (PD) to emulate the typical losses in a fibre-link. The output signal was displayed by the optical spectrum analyzer (OSA). The value of different parameters has been investigated in terms of BER, Q factor and Eye diagram. The power meter (PM) was used to measure received power at the output. The optical signal was then converted electrical signal via PIN photo diode. The low pass filter was then employed to reduce noise. The filtered signal was analyzed for the Q-factor and BER.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, experimental and simulation results are presented to study the optimum performance of the device. The characterization of the VCSEL source is first reported since it is essential for the study of quantum performance of the device. The direct modulation of a 1310 nm and 1550 nm VCSELs with 10 Gb/s PRBS pattern is presented. The signal is then transmitted over different lengths at G.655 and G.652 SSMF. The signal transmission performance for these fibres is finally reported using eye-diagrams, bit error-rate (BER) and Q factor.

4.2 VCSELs Characterization

The biasing and ability to tune the emission wavelength of 10 Gb/s VCSELs technologies for high speed signal transmission are presented in this section. The charactarization of the VCSELs dynamic behaviour is necessary in determining the bias current for optimum performance for direct modulated DWDM systems. The wavelength stability and tuneability allows for wavelength multiplexing which is used to increase the data rate over a single fibre in the array.

4.2.1 VCSELs Biasing

Figure 4.1 shows the P-I characteristics of 10 Gb/s VCSEL transmitting at 1310 nm and 1550 nm respectively. The output power of the VCSEL was measured as the bias current was increased. The experimental and simulated VCSEL behaviors at constant temperature agree as depicted in Figures 4.1. At a bit rate of 10 Gb/s, the 1310 nm and 1550 nm VCSELs showed similar characteristics in terms of power output. Both 1310 nm and 1550 nm VCSELs operate in the mA range showing the energy efficiency of the device.

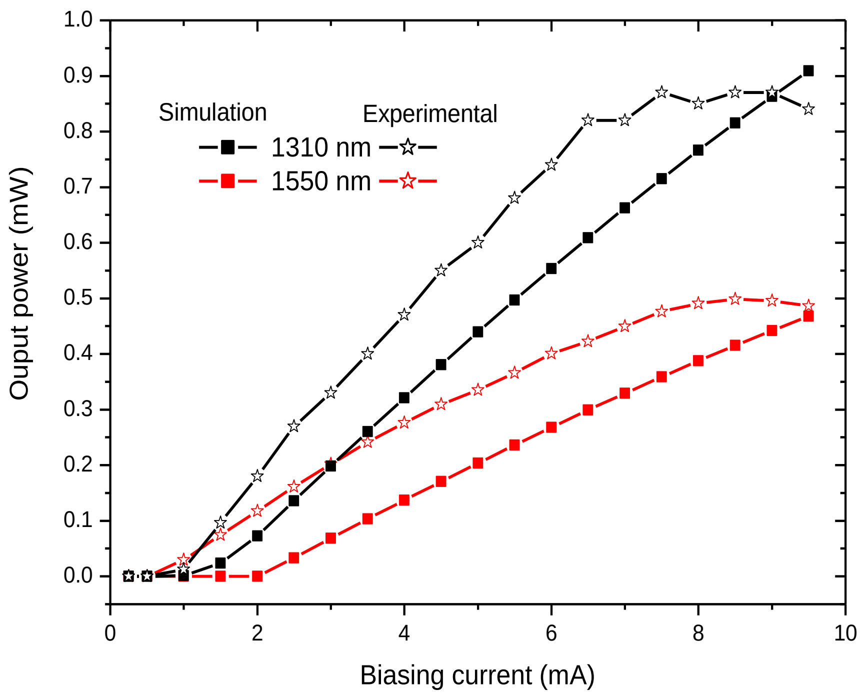


Figure 4.1: Biasing of VCSEL at 1310 nm and 1550 nm

From the experimental results, the threshold currents of the device range between 0 and 1 mA. However, from the simulation results, the VCSELs threshold currents were found to be 1 mA and 2 mA for 1310 nm and 1550 nm VCSELs respectively. Above the threshold, the output power from a VCSEL varied linearly with current and we can determine slope (mW/mA) over some operating region. Experimentally, the saturation current of the device were found to be 6 mA and 8 mA for 1310 nm and 1550 nm VCSEL respectively. Above the saturation level, the output power of the VCSEL reduced as the current was further increased. As a result, the best operational bias points for the VCSEL are between the threshold and the saturation current point's i.e the linear region. Under theoretical simulation, it was assumed that constant temperature was maintained hence the VCSELs devices didn't heat up hence there was no saturation.

4.2.2 Wavelength Tuneability

The optical spectrum of the 1310 nm and 1550 nm VCSEL at different biasing currents is plotted in Figure 4.2.

From Figure 4.2, a wavelength tuneability of 6 nm and 5 nm for 1310 nm and 1550 nm VCSEL respectively was obtained. The shifting of the emission spectra with increasing bias current indicates internal heating of the VCSEL. This implies that VCSEL can be tuned to different wavelengths using the different bias currents.

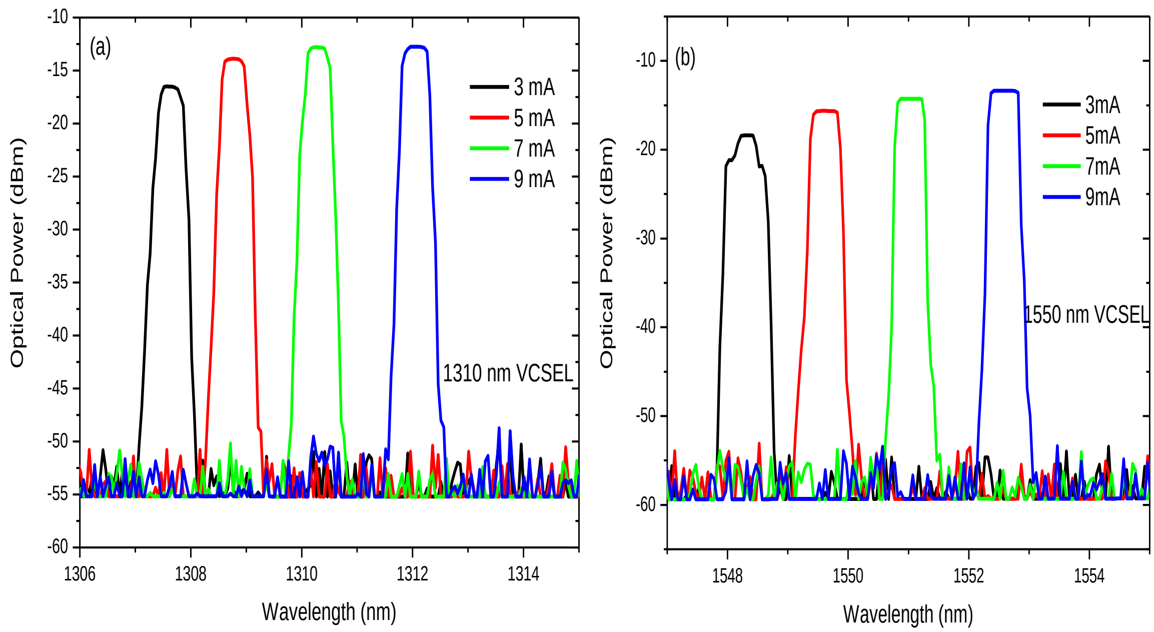


Figure 4.2: Experimental characterization of the VCSEL wavelength tuneabililty for (a) 1310 nm (b) 1550 nm

The wavelength stability and tuneability allows for wavelength multiplexing which is used to increase the data rate over a single fibre. By operating the VCSEL up to the 9 mA saturation current point, the maximum optical output power recorded was below -10 dBm. This show the energy effeciency of the device.

4.3 Performance of 1310 nm VCSEL using G.652 Fibre

To optimise the peformance of the device, a bias current, I_b of 6 mA was set above the threshold current, I_{th} giving a wavelength tuneability of 6 nm (1307 to 1313 nm). Modulation voltage/depth of the set up was set at 2 V. Figure 4.3 shows a plot of -Log (BER) curves for 1310 nm VCSEL modulated at 10 Gb/s.

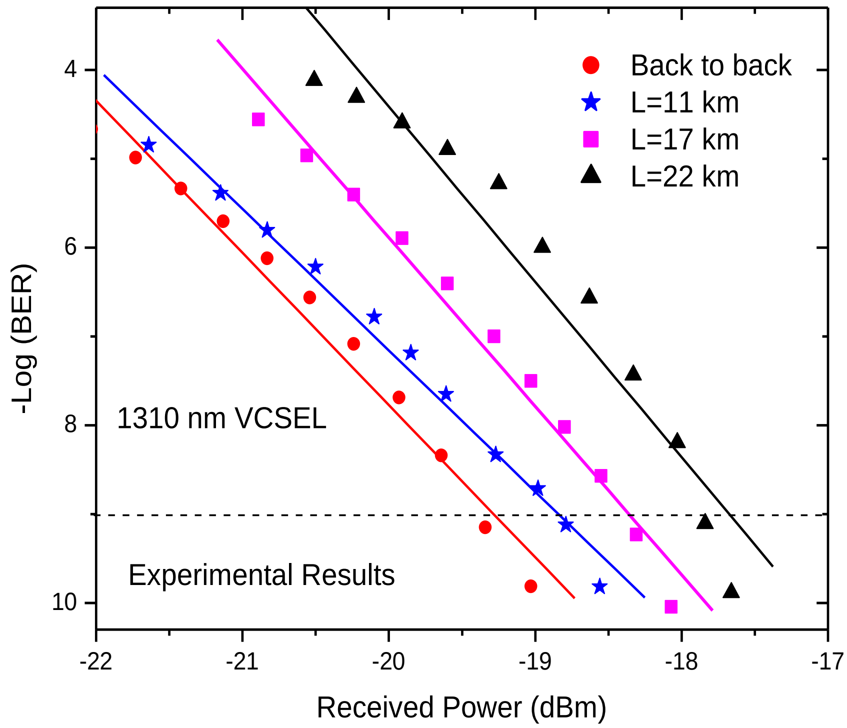


Figure 4.3: Plot of -Log (BER) verses output power at different fibre length.

It can be seen from Figure 4.3 that BER reduces with increase in the received power. Receiver sensitivities (received optical power at a BER of 10^{-9}) of -19.3 dBm, -18.8 dBm, -18.3 dBm and -17.8 dBm were obtained for back to back, 11 km, 17 km and 22 km respectively. Therefore, less power was required at the receiver for smaller lengths in order to achieve the acceptable BER value of 10^{-9}. The increase in receiver sensitivity with length was as a result of the accumulation of dispersion in the fibre hence causing more bit errors. A small dispersion penalty of about 1.5 dB was obtained for up to 22 km G.652 fibre. The presence of chirpings and chromatic dispersions (CD) which increases linearly with length of the fibre introduces bit errors and hence power penalties during transmission.

4.4 Transmission penalties and the corresponding receiver sensitivity verses fibre length

Figure 4.4 shows transmission penalties and receiver sensitivities for different fibre lengths under theoretical and experimental measurements.

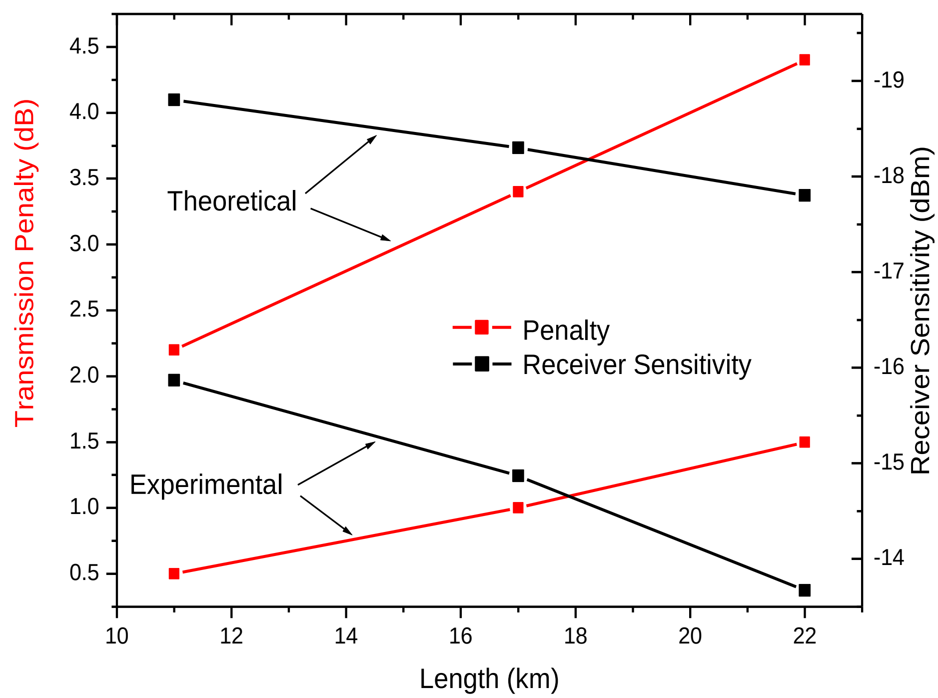


Figure 4.4: Transmission Penalties and the corresponding receiver sensitivity verses fibre length for a 1310 nm VCSEL on G.652 Fibre.

The figure shows that the receiver sensitivity increases with fibre length. When the experimental measurements were done, the receiver sensitivities of -18.8 dBm, -18.3 dBm and -17.8 dBm were obtained for 11 km, 17 km and 22 km respectively. Compared to -19.3 dBm (back to back case), then a small power penalty was achieved for smaller lengths. The simulation results gave a higher receiver sensitivities compared to the experimental results. For 11 km, 17 km and 22 km case, the receiver sensitivity was -15.6 dBm, -14.8 dBm and -13.8 dBm respectively. This is because as the length of the fibre increases, the linear degrading factors accumulate over the fibre length hence affecting the receiver sensitivity. A Dispersion cause broadening of the signal as it is transmitted down the fibre and therefore large fibre length leads to more losses. For shorter lengths, there are minimum losses in the fibre hence low receiver sensitivity.

For laser transmitters, transmission penalty is useful to determine the maximum fibre length that a signal can propagate for a given fibre. It can be seen that the transmission penalty increases with increase in length. As the length of the fibre increases, the dispersion effect becomes stronger leading to increased optical power penalty. In a transmission system, the maximum acceptable penalties range between 3-5 dB though it's possible for a system to tolerate a large dispersion penalty if the optical attenuation is low. In the experimental measurements, at transmission lengths of 11 km, 17 km and 22 km the power penalties suffered by the system were 0.5 dB, 1 dB and 1.5 dB respectively. The limitation of the transmission length stems mainly from accumulated dispersion in the fibre which increases linearly with the length. The simulation results in Figure 4.4 were obtained with fibre of same lengths and characteristics. These results show a similar trend to the experimental results. The power penalties of 2.2 dB, 3.4 dB and 4.4 dB were recorded for 11 km, 17 km and 22 km fibre lengths respectively. The simulation results gave a higher penalties compared to that attained in the experimental measurements.

This penalty is far offset by the cost saving of using VCSEL with no dispersion compensation or optical amplification in a transmission system. Consequently, when the receiver sensitivity is high, the penalty is reduced as the transmission length is increased. The apparent change in the receiver sensitivity is due to the distortions of the signal waveform during its transmission over a specified path. These findings agree with acceptable penalty budget of 3-5 dB for typical network designers.

4.5 Experimental OSNR analysis in G.652 SMF

The transmission OSNR data are the values that were measured for each distance at the receiver while the back to back OSNR data was produced by the noise loading the signal at the receiver. The experimental results from Figure 4.5 show the OSNR variation with length and power.

From Figure 4.5(a), an OSNR of 6.8 dB, 5.6 dB, 4.5 dB and 3.2 dB were obtained for back to back, 11 km, 17 km and 22 km respectively. In digital communication system, an OSNR of 10 dB is usually enough to yield a 10^{-9} bit error rate. The OSNR degradation with increase in fibre length is attributed to noise accumulation within the transmission fibre and also from the laser source. Optical noise effects in optical fibre are very significant in regard to the operation and stability of modern optical communication systems as well as optical devices. Therefore it is important to design a link with a low noise at the transmission frequency band.

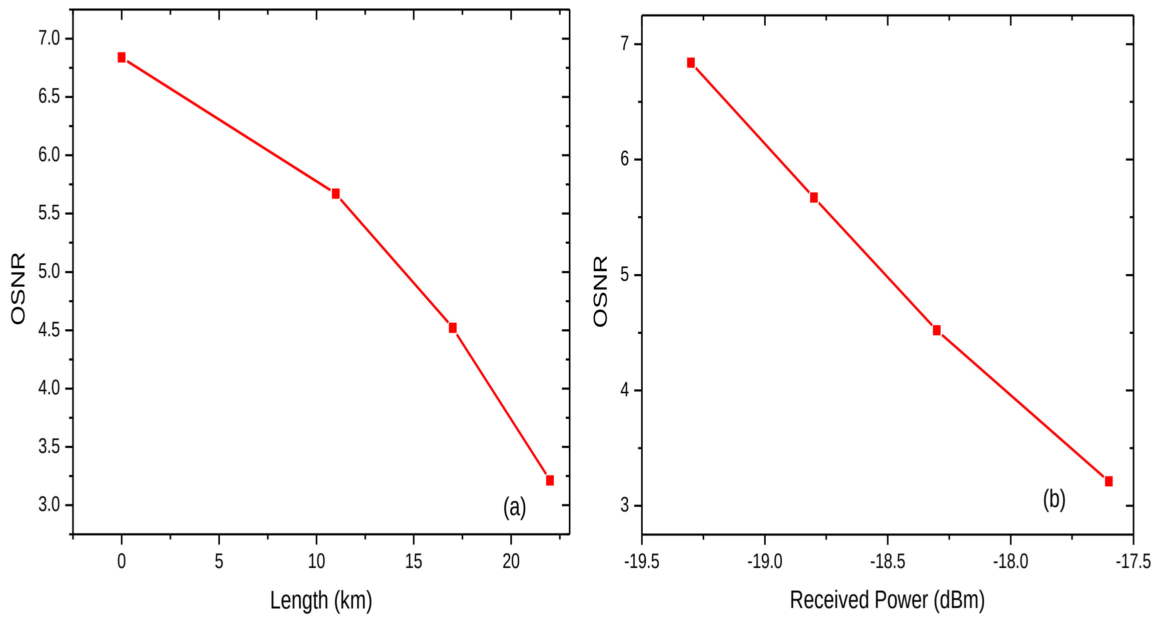


Figure 4.5: Experimental results on variation of OSNR with (a) Length (b) Power for G.652 SMF at different fibre lengths

Figure 4.5(b) shows the relationship between OSNR and received power. As the received power increases, the OSNR reduce. The OSNR was 6.84 dB, 5.67 dB, 4.52 dB and 3.21 dB when the power at the receiver was -19.3 dBm, -18.8 dBm, -18.3 dBm and -17.8 dBm respectively. Channel performance in a communication system depends on OSNR, dispersion and nonlinear effects. In multichannel optical communication system, a signal over the same optical link can be regarded as an interfering noise for others which lead to OSNR degradation. Hence the need to optimize OSNR level in optical networks (maintaining the desired OSNR for each channel) while minimizing the input power which may result to nonlinearity hence reducing the power at the receiver.

4.6 1310 nm and 1550 nm VCSEL Signal Transmission on G.652 and G.655 Fibres

The 1310 nm and 1550 nm transmission windows used in high-speed optical fibre communication systems were investigated to determine the optimized transmission distance on G.652 and G.655 fibre. The VCSELs transmission is presented in Figure 4.6.

4.6.1 BER comparison between G.652 and G.655 fibre

Figure 4.6 shows experimental and theoretical plot of -Log (BER) measurements of G.652 and G.655 fibres of lengths 25 km with the 1310 nm and 1550 nm VCSELs transmitting at 10 Gb/s.

The experimental results from Figure 4.6 (a) shows a receiver sensitivities of -15.8 dBm and -15.9 dBm when G.652 fibre was transmitted on 1310 nm and G.655 fibre on 1550 nm VCSEL respectively. From simulation results in Figure 4.6 (b), the sensitivity for G.652 and G.655 fibres were found to be -15.9 dB and -16.1 dB when transmitted on 1310 nm and 1550 nm window, respectively. It is therefore evident that 1310 nm signal transmission are best suited for long distance G.652 fibre while 1550 nm signal transmission are best suited for long distance G.655 fibre. The dispersion effects are lower for G.652 fibre on 1310 nm and G.655 on 1550 nm window.

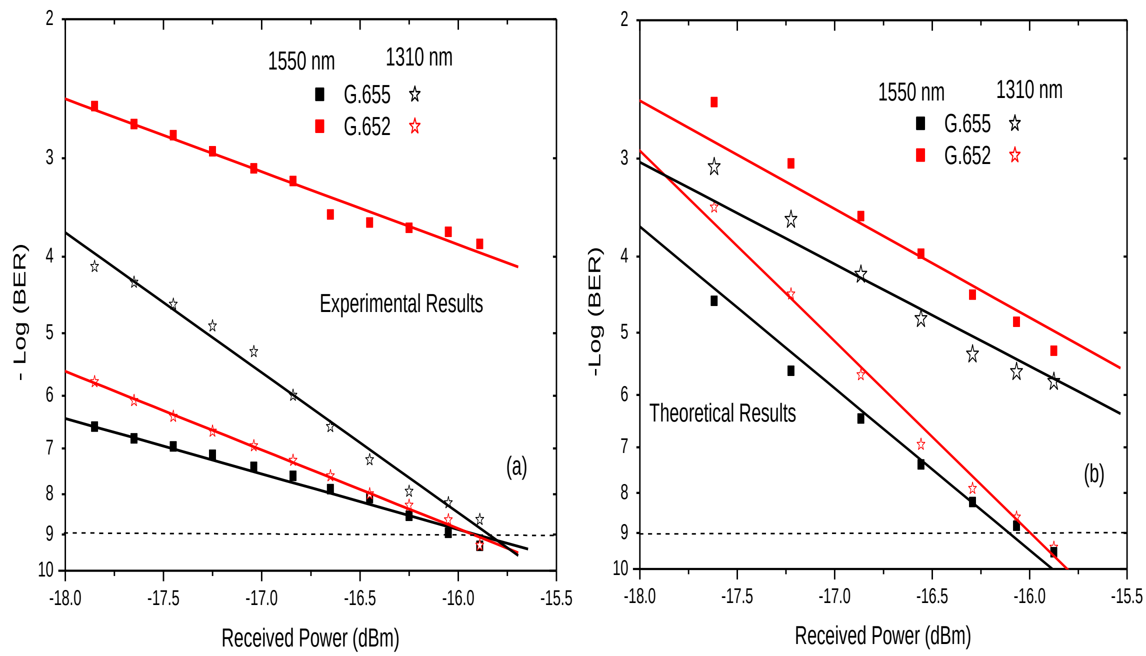


Figure 4.6: VCSELs transmission using G.655 and G.652 fibres (a) Experimentaly (b) Simulation

Experimental and theoretical results in Figure. 4.6, shows that G.655 and G.652 fibres operated at the error floor region in 1310 nm and 1550 nm respectively. Error floor refers to a point at which the BER flattens without crossing the telecommunication threshold ($BER=10^{-9}$). The error floor was due to the high dispersion that affected the signal resulting in the increased number of errors hence limiting the transmission distance. Therefore, fibre choise is vital in matching the transmission wavelength. In high speed signal transmission using VCSEL, fibre transmission should be optimized to achieve both long distance and error free transmission within 1310 nm and 1550 nm transmission windows.

The performances of 1310 nm and 1550 nm VCSEL was compared using G.652 and G.655 fibres and plotted in Figure. 4.7.

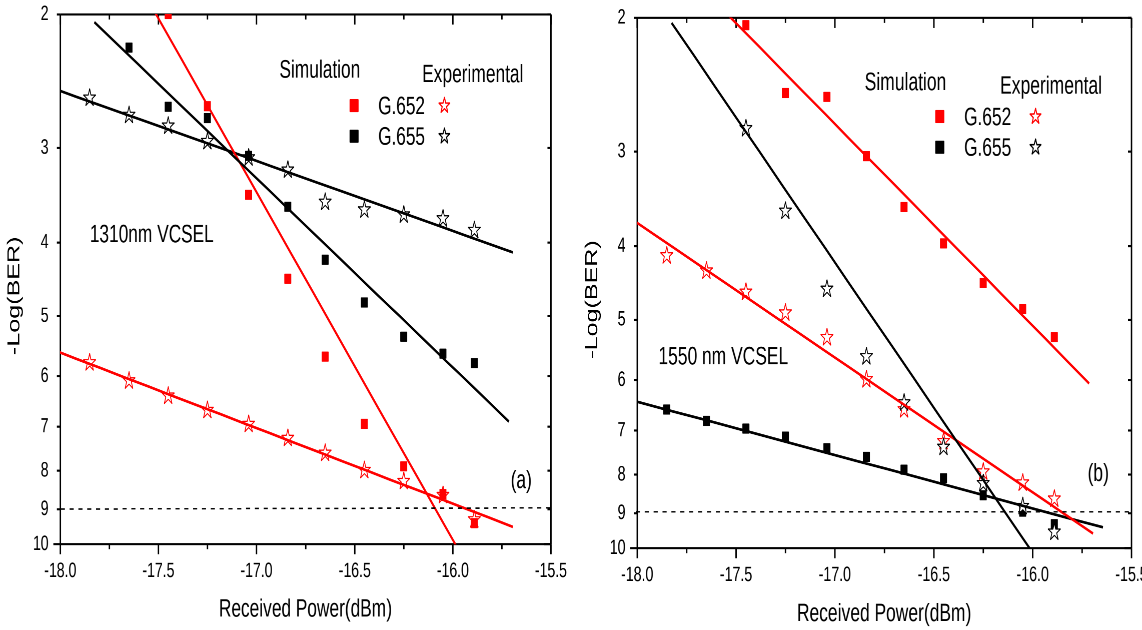


Figure 4.7: BER measurements of G.652 and G.655 fibres on (a) 1310 nm (b) 1550 nm VCSEL

A 1550 nm transmission experinces a 17 ps/(nm.km) dispersion in a G.652 fibre. The low dispersion penalties of G.655 fibre on this transmission window extended the VCSEL reach. The 1310 nm VCSEL has high dispersion of about 17 ps/(nm.km) on a G.655 fibre, thus resulting to transmission errors. Therefore, 1310 nm transmission window is best suited for long distance G.652 fibre since dispersion and attenuation are lower at the 1310 nm transmission window. In optical fibre communication system, the low dispersion and attenuation values of G.655 fibre on 1550 nm transmission window supports long-haul transmission. In the other hand, G.652 fibre is optimized to support long-haul systems using a 1310 nm window.

4.6.2 Q-Factor Analysis in G.655 and G.652 Fibre

The Q-factor is used to specify the receiver performance since it is proportional to SNR required to achieve a specific BER. From Figure 4.8, it can be seen that the log of BER is inversely proportional to the Q-factor. If the system error decreases, the BER will thus decrease.

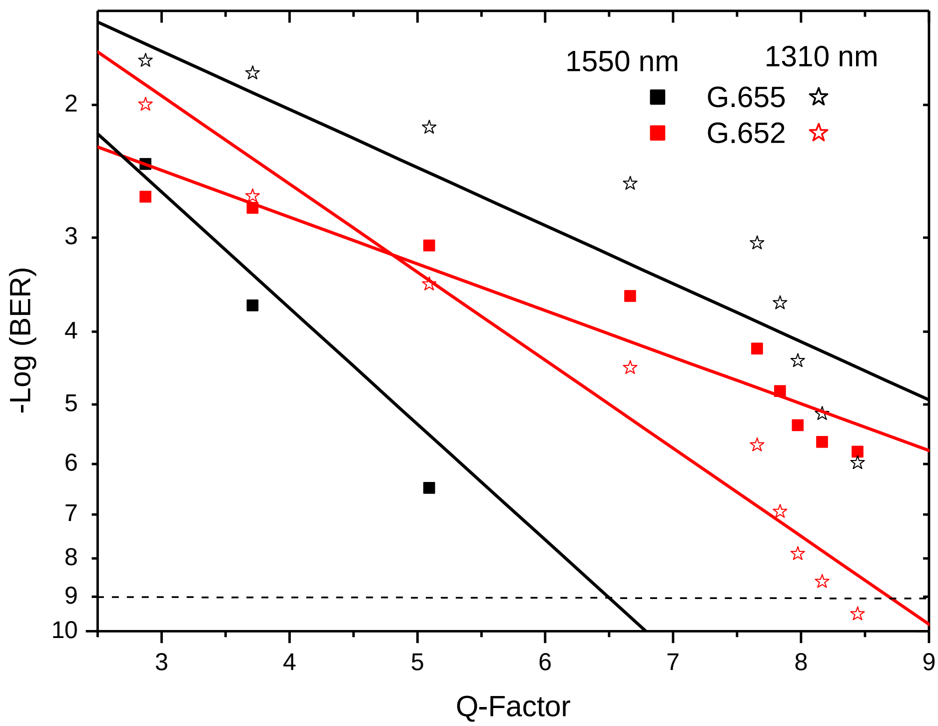


Figure 4.8: Plot of -Log (BER) as a function of Q-factor

The signal was transmitted at bit rate of 10 Gb/s using 1310 nm and 1550 nm VCSEL over 25 km G.652 and G.655 Fibres. The higher the value of Q-factor means the better the OSNR and therefore a lower BER values. The system performance is quantified through the Q-factor and it is related directly to the BER.

The simulation results shows that G.655 fibre recorded Q factor value of 6.0 on 1550 nm VCSEL when the BER measurements were performed at 10^{-9} threshold level. When G.652 fibre was transmitted over 1310 nm VCSEL, high Q-factor value of 8.4 was attained. The minimum value of Q-Factor that will enable a system to operate in region below BER of 10^{-9} is 6 and this is the most used value in telecommunication systems. However, the G.652 and G.655 fibres exhibited the worst performance with high BER values when transmitted over 1550 nm and 1310 nm windows respectively. Therefore, to reduce the BER we must increase the Q-factor. Higher values of Q-factor mean better performance.

The Q-factor increases with the increase in the output power of the receiver as illustrated in Figure 4.9.

Low Q value corresponded to lower output power and this is because at lower power, the system error increases due to attenuation in the fibre which decreases the Q-factor of the system. At a bit rate of 10 Gb/s, the 1550 nm VCSEL transmission over G.655 fibre and 1310 nm VCSEL on G.652 fibre recorded high quality (Q) factor values above the threshold value of 6. A minimum power of -17.4 dBm and -16 dBm were required at the output for 1550 nm VCSEL on G.655 and 1310 nm VCSEL on G.652 fibres respectively to achieve the Q-factor of 6. However, when 1310 nm and 1550 nm wavelengths were transmitted over G.655 and G.652 fibres respectively, Q-factor below 6 was recorded. This is because dispersion introduces uncertainty at the receiver due to accumulated chromatic dispersion over distance of transmission hence the reduction in the Q-factor.

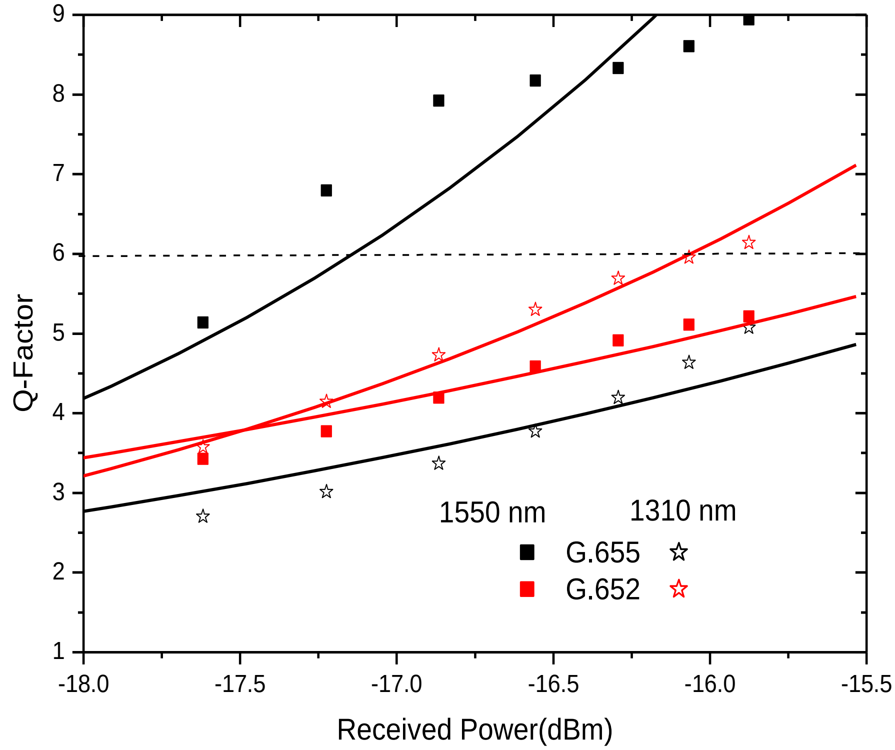


Figure 4.9: Variation of Q-Factor with received power at 1310 nm and 1550 nm VCSELs.

Therefore, 1310 nm VCSEL is best suited for long distance G.652 fibre since dispersion effects are lower at 1310 nm transmission window. Similarly, G.655 fibre experiences minimal dispersion when transmitted over 1550 nm VCSEL hence its suitability on this window.

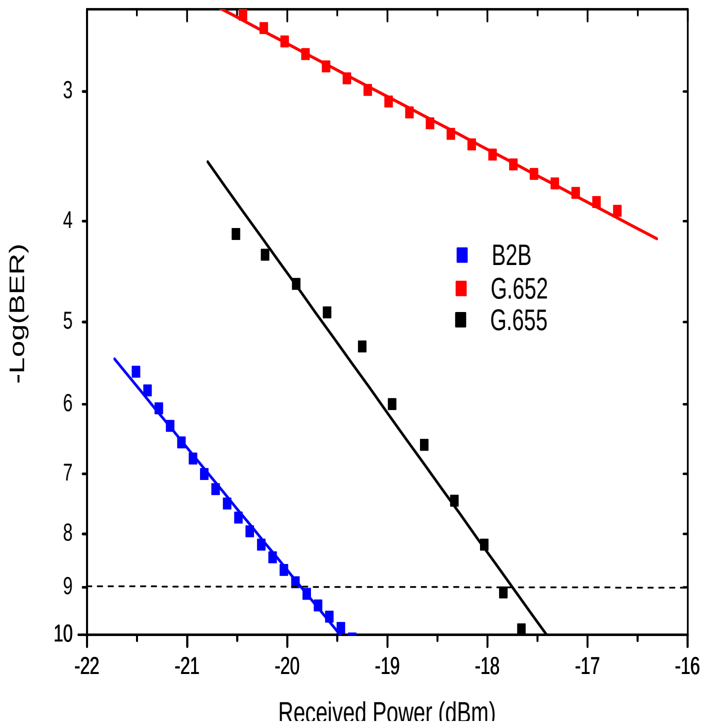
4.7 Experimental Comparison of G.655 and G.652 Fibre on 1310 nm and 1550 nm VCSEL

In this section, we demonstrate the experimental results of how flexible spectrum signals can be transmitted in optimized optical fibre networks. The 1310 nm and 1550 nm transmission windows have been optimized for up to 10 Gb/s speeds to a maximum of 25 km distances using back to back, G.652 and G.655 fibres.

4.7.1 Performance Comparison of G.655 and G.652 Fibres on 1310 nm VCSEL

The peformance of the system was evaluated for back-to-back (B2B) and after 25 km using the 1310 nm VCSEL as shown in Figure 4.10. The error-free receiver sensitivity for B2B at the 10^{-9} BER threshold level was measured to be -19.9 dBm. From the figure, for 1310 nm transmission over G.652 fibres, we were able to determine the BER measurements at 10^{-9} threshold. The receiver sensitivity of G.652 fibre was found to be -17.7 dBm corresponding to a 1.2 dB penalty compared to back to back case. The low dispersion resulted in less error-bits being received and therefore longer distance transmission over the G.652 fibre. However, when a G.655 fibre was used to transmit a 10 Gb/s signal over 1310 nm VCSEL, the system fails to cross the telecommunication 10^{-9} BER threshold. The flooring is as a result of poor extiction ratio caused by attenuation and dispersion in the fibre thus requiring high fibre launch powers, dispersion compensation mechanisms, use of shorter fibres hence limiting its usefulness for practical systems.

Using the eye diagram, one is able to make qualitative analysis of the output signal at the receiver. The larger the size of the eye opening the lower the error rates hence the better signal transmission.



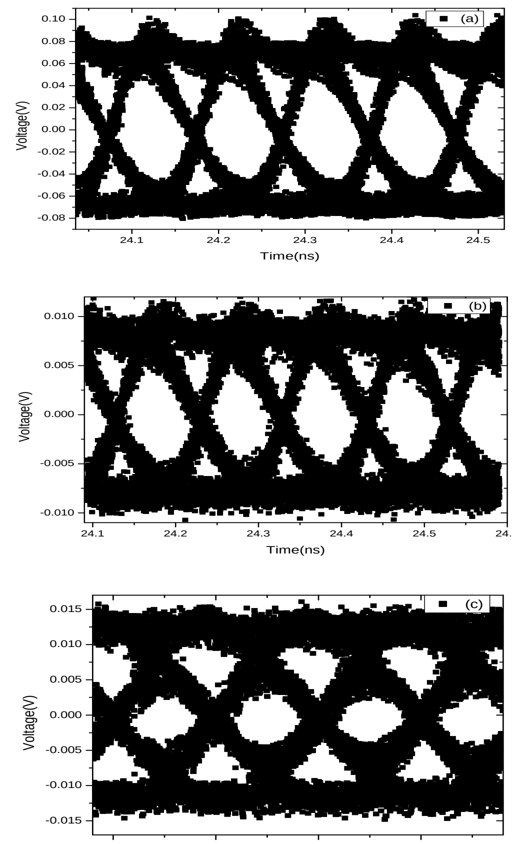
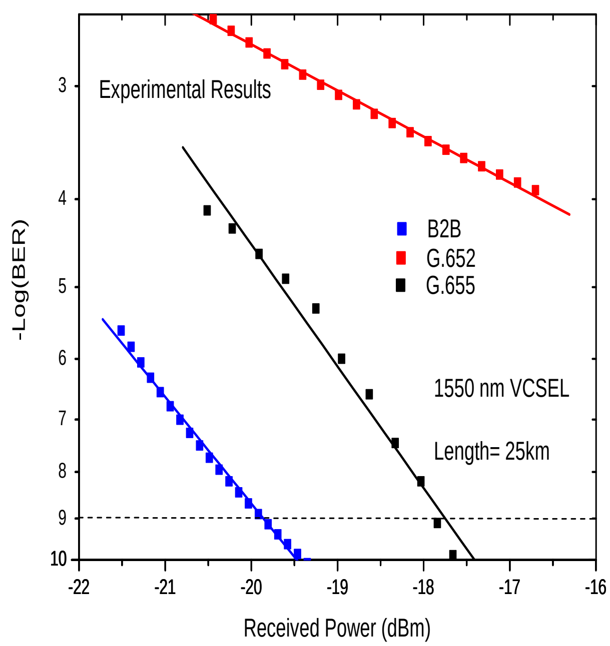


Figure 4.10 -Log(BER) measurements of back to back, G.652 and G.655 fibres. The figures on the right are corresponding eye diagrams for (a) B2B (b) G.652 (c) G.655 fibres using 1310 nm

The most important information is the size of the eye opening since it is limited by the bandwidth and the additive noise. Hence, for reliable transmission it is essential that the eye is kept open. When the eye was open, the receiver was able to distinguish between the ‘1’ and ‘0’ and therefore few errors were detected. However, the over-shoots in the “1” level of the eye-diagram was as a result of VCSEL chirping hence closure in the eye opening as seen in the G.655 fibre. The reduction in the eye opening was as a result of reduced OSNR as the signal power was attenuated. The wide and open eye in G.652 fibre signifies better performance hence suitable for long reach in telescope networks and long access network when used in 1310 nm transmission window.

4.7.2 Experimental Results of G.655 and G.652 Fibres on 1550 nm VCSEL

Figure 4.11 shows -Log (BER) curves for signal transmission over G.652 and G.655 fibre using a 1550 nm VCSEL.



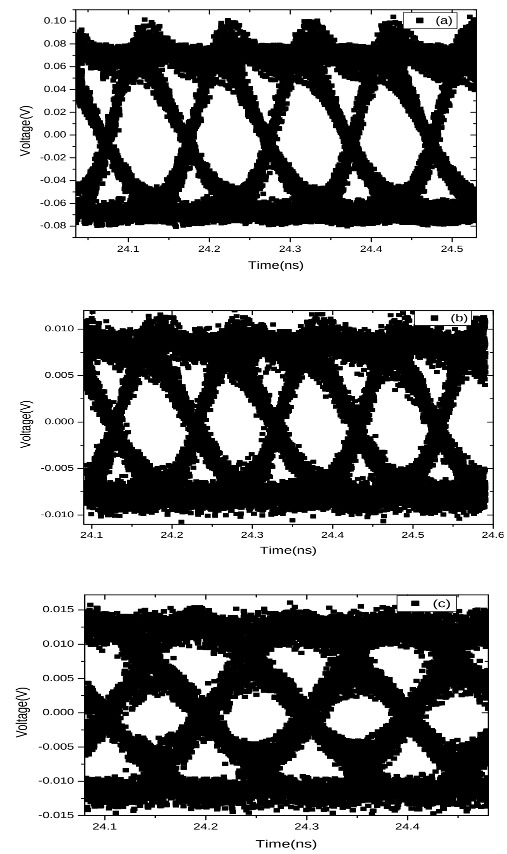


Figure 4.11 BER measurements of back to back, G.652 and G.655 fibres and their eye diagrams for (a) B2B (b) G.655 (c) G.652 fibres at 1550 nm VCSEL

It can be seen from Figure 4.11 that, for a G.655 fibre transmission over 1550 nm VCSEL, the sensitivity was -17.8 dBm. Compared to back to back case, a transmission penalty suffered by the system was 1.1 dB. This was attributed to dispersion in the fibre and chirp experinced by the high speed signals resulting in the data overlap. It can also be seen from the figure that the system operates in the error floor region when a G.652 fibre was used in a 1550 nm VCSEL. The error-floor was due to the high dispersion 17 ps/(nm.km) effects that affected the signal resulting in the increased number of error-bits received.

A wide and open eye represented an error-free transmission. After 25 km, the fibre attenuation reduced the OSNR and the fibre dispersion has distorted the data pulses resulting in the reduction of eye opening in amplitude as well as in time domain. The small eye size for 25 km G.652 fibre implies received many bit errors and therefore poor signal transmission in the fibre.

Therefore, the best performance is seen when a 1550 nm VCSEL was used on a G.655 fibre. G.655 fibre is optimised to support long-haul transmision sytem at 1550 nm transmission window. Since 1550 nm experiences low dispersion over G.655 fibres, a 1550 nm VCSEL is therefore siutable for G.655 fibres.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Optical dispersion and attenuation in optical fibres and communication systems has been a subject of great interest and concern in the implementation of optical fibre technology. In this thesis, the effects of fibre dispersion in modern optical fibres were investigated. Characterization of 1310 nm and 1550 nm VCSEL were studied. The sources were optimized to provide wavelength tuneability of 10 Gb/s bit rate used for signal transmission over G.652 and G.655 SMF. The 1310 nm and 1550 nm VCSELs have low threshold currents between 1- 2 mA. Both VCSELs operate in the mA range. Experimentally, the output power of the VCSEL reduced as the current was further increased at the saturation level. It was shown that VCSEL is a low power device with wavelength tuneability. Wavelength tuneabilities of about 6 nm and 5 nm for 1310 nm and 1550 nm respectively were experimentally obtained.

The performance of VCSEL in G.652 and G.655 fibres on 1310 nm and 1550 nm transmission windows were investigated. It was found that BER reduces with increase in the received power. When a 1310 nm VCSEL was used, the signal was transmitted over error free region with 25 km G.652 fibre with a receiver sensitivity of -17.8 dBm. Compared to back to back (B2B) case a 1.5 dB penalty was achieved. However, when 1550 nm VCSEL was used in this fibre, the system operated at error floor region. The best performance was seen when a 1310 nm VCSEL was used on a G.652 fibre. G.652 fibre is optimized for use in 1310 nm wavelength region but can also be used in 1550 nm region with dispersion management systems. Theoretical results have also achieved low power penalties of less than 5 dB for 10 Gb/s 1310 nm VCSEL when used in G.652 fibre. When a 1550 nm VCSEL was used in transmission, the error-free receiver sensitivity was measured to be -19.3 dBm for B2B and -17.6 dBm after 25 km in G.655 fibre. The transmission penalty suffered by the system was 1.7 dB. Therefore, minimum dispersion penalty was realized when a 1550 nm VCSEL is used on a G.655 fibre and when a 1310 nm source was transmitted over a G.652 fibre.

The experimental and simulation results on the OSNR and BER of an optical network using a directly modulated 10 Gb/s 1310 nm VCSEL on a G.652 SMF were also presented. OSNR was observed to vary inversely with fibre length. Small values of OSNR of less than 6 dB were also achieved. OSNR was also observed to reduce with the increase in the received power. The Q factor was used theoretically to quantify the performance of the VCSEL. It was noted that Q factor increases with the increase in the output power at the receiver. Simulation results showed high quality values when a 1550 nm and 1310 nm VCSELs were transmitted over G.655 and G.652 fibres respectively. However, when a 1550 nm and 1310 nm VCSELs was transmitted over G.652 and G.655 fibres respectively, Q factor below 6 was recorded. It has also been shown that BER was inversely proportional to Q-factor so it can be concluded that the signals with smaller bit rate travel more than the one with higher bit rate. BER was also observed to vary linearly with length; hence as the fibre length increased the received power was also reduced.

The system is of great advantage for PONs with no need for optical dispersion compensation or optical amplification. The potential cost reduction and good performance of our proposed system make directly modulated VCSEL a strong candidate in future PONs. The long wavelength VCSEL offer the capabilities of high bandwidth together with very low power consumption and therefore suitable candidate for 10-Gigabit Ethernet applications and high bit-rate datacom networks

With the demand of high transmission capacity with increasing distance, then these results are vital in realizing that data transfer using optical fibres is enhanced in long haul transmission. The results will also improve the integrity of DWDM system and its spectral efficiency.

5.2 Recommendations

In this research work, we highly recommend the use 1310 nm VCSEL on G.652 fibre and 1550 nm window on G.655 fibre in high bit rate and long haul optical transmission systems. This is due to their low attenuation and low dispersion values that enables high performance. To support a high-capacity dense wavelength division multiplexing (DWDM) transmission, then standard single-mode fibre (SMF) should be upgraded to overcome the dispersion limit. Future work should be done in VCSEL signal transmission at high bit rate of > 10 Gb/s over long distance.

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APPENDICES

Appendix I

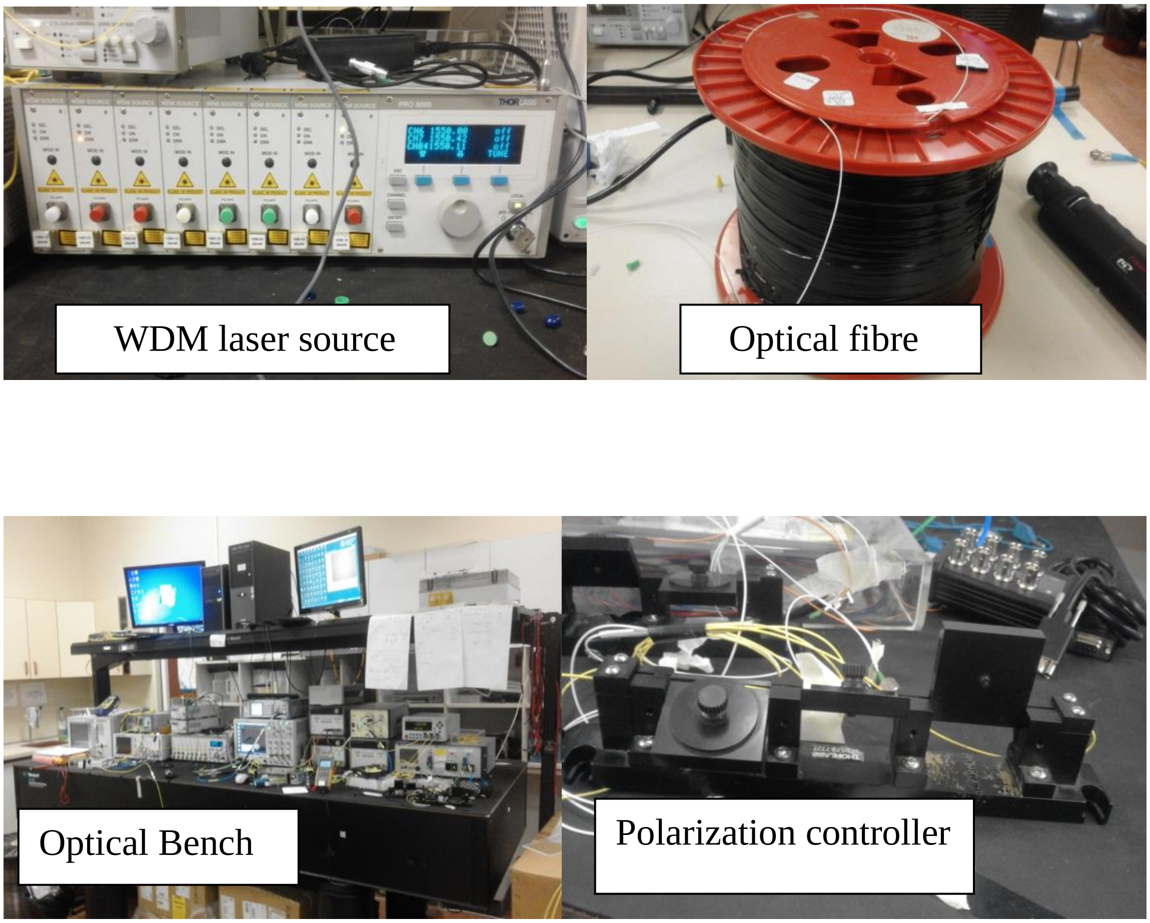
Journal and conference publications

1. **H. C. Cherutoi**, K. Muguro, D. W. Waswa, and G. M. Isoe Performance of DQPSK, NRZ and RZ modulation formats in different optical fibres. Proceedings of the 2016 Annual Conference on Sustainable Research and Innovation, held at Jomo Kenyatta University of Agriculture and Technology (JKUAT) from 4th - 6th May 2016, pg 186-189.

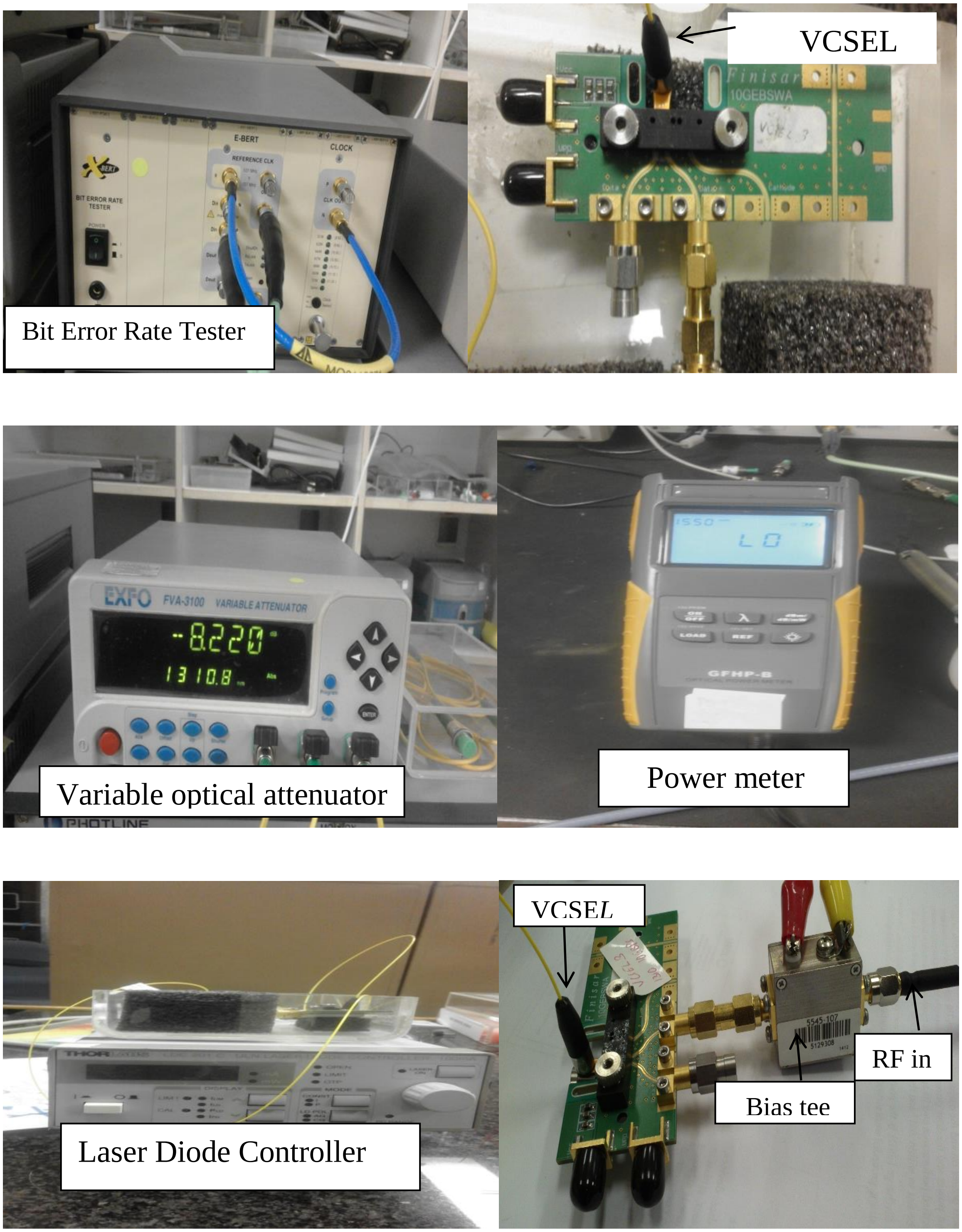
2. **H. C. Cherutoi**, D. W. Waswa, K. M. Muguro, G. M. Isoe, D. Kiboi Boiyo, A. W. R. Leitch and T. B. Gibbon, "10 Gb/s 1310 nm VCSEL Transmissions over Standard G.652 fibre for WDM PON". Submitted to journal of Optics and Photonics.

Appendix II

Components used in experimental work



(Source: Author, 2017)



(Source: Author, 2017)

Appendix III

Polarization state of a fibre

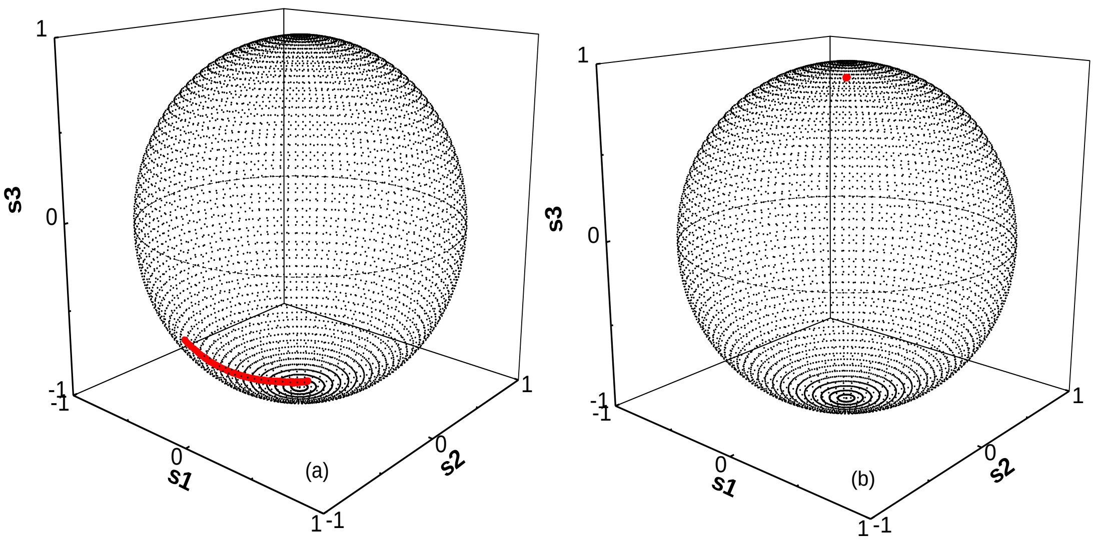


Figure 1. Polarization states of an undisturbed fibre (a) PMF (b) SMF monitored over 10 minutes.

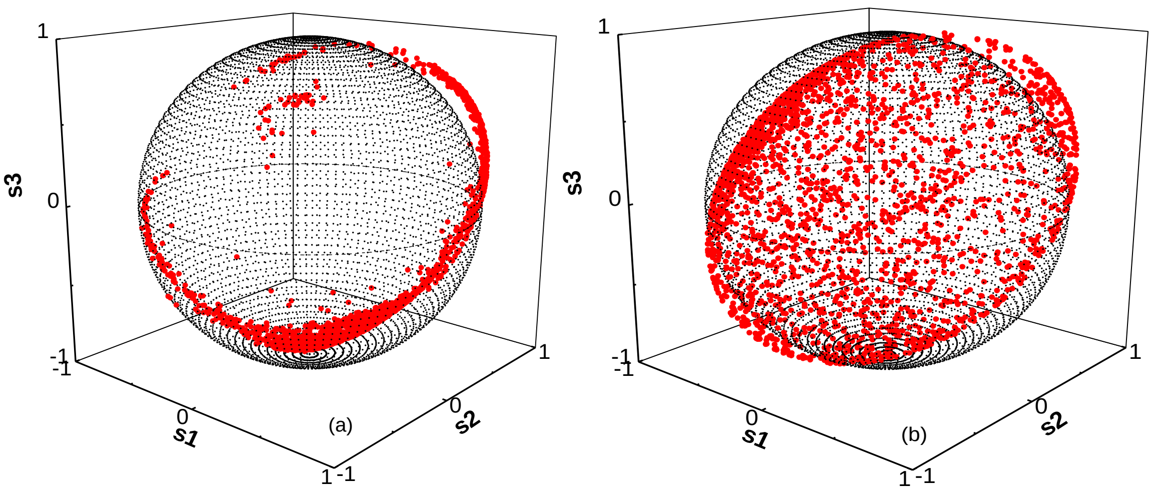


Figure 2. SOP representation of a disturbed fibre (a) PMF (b) SMF monitored over 10 minutes.

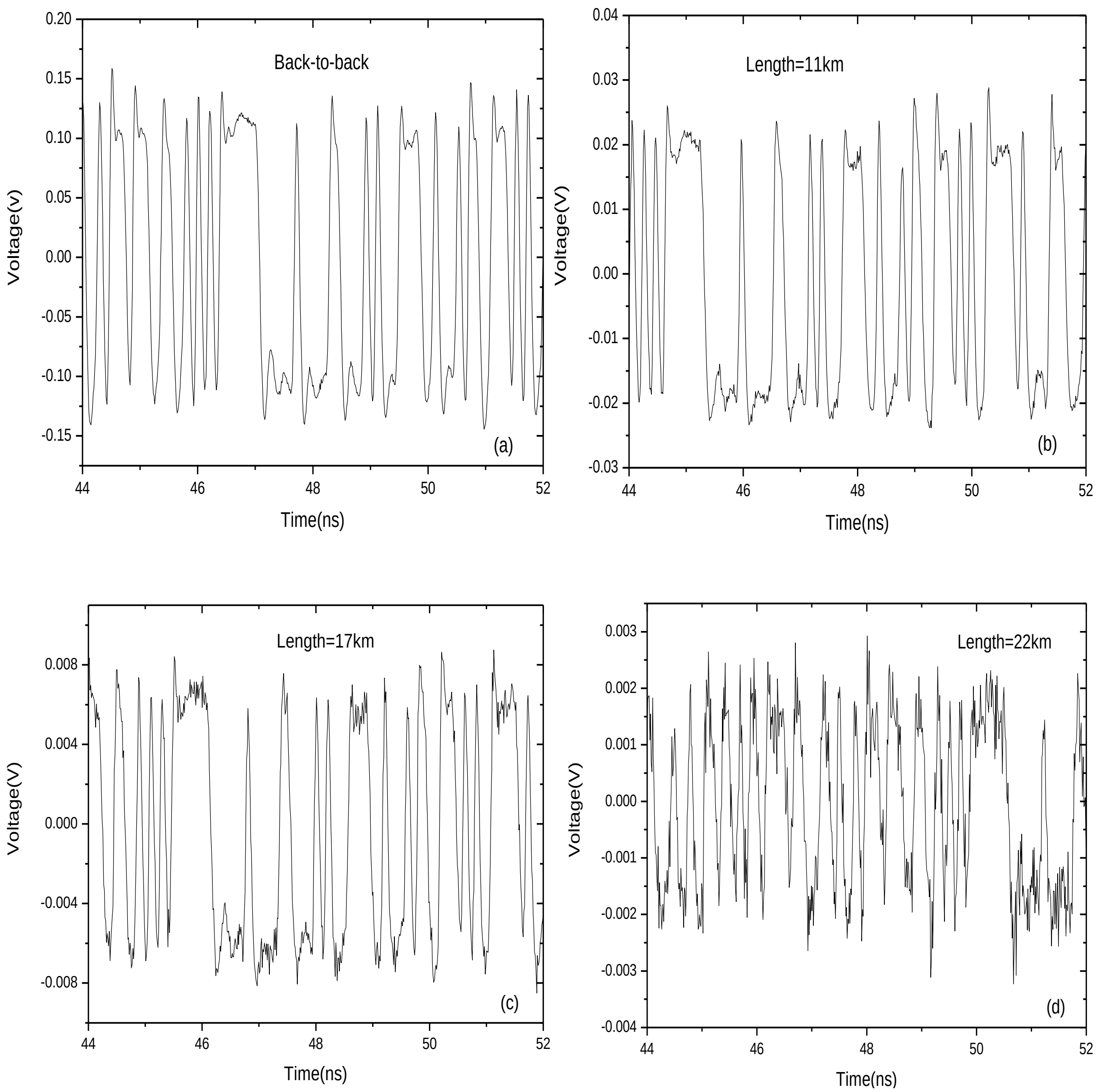


Figure 3. Experimental graphs showing individual bits as detected by the receivers at different transmission lengths.

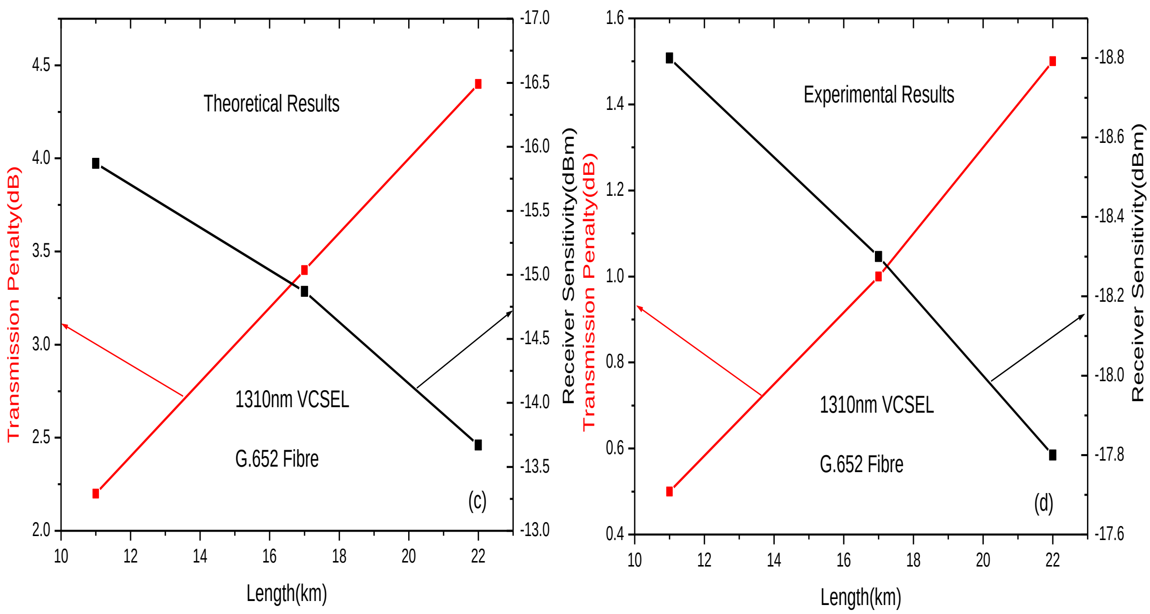


Figure 4. Transmission penalties and the corresponding receiver sensitivity verses fibre length