DATA TRANSPORT OVER OPTICAL FIBRE FOR SKA USING ADVANCED MODULATION FLEXIBLE SPECTRUM TECHNOLOGY

By

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Dedication

To my late mother, Ngethembi Pretty Dlamini

Declaration

I, *Phumla Patience Dlamini, Student number: s210140313*, hereby declare that the thesis for PhD award is my own work and that it has not previously been submitted for assessment or completion of any postgraduate qualification to another University or for another qualification.

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Abstract

Flexible Spectrum Dense Wavelength Division Multiplexed (DWDM) optical fibre networks are next-generation technology for handling extremely high data rates of the kind produced by MeerKAT and SKA.We optimise the flexible spectrum for real-time dynamic channel wavelength assignment, to ensure optimum network performance. We needed to identify and develop novel hardware and dynamic algorithms for these networks to function optimally to perform critical tasks. Such tasks include wavelength assignment, signal routing, network restoration and network protection [1]. The antennas of the Square Kilometre Array (SKA) network connect to the correlator and data processor in a simple point-to-point fixed configuration. The connection of the astronomer users to the data processor, however, requires a more complex network architecture. This is because the network has users scattered around South Africa, Africa and the whole world [2]. This calls for upgrade of the classical fixed wavelength spectrum grids, to flexible spectrum grid that has improved capacity, reliable, simple and cost-effectiveness through sharing of network infrastructure.

The exponential growth of data traffic in current optical communication networks requires higher capacity for the bandwidth demands at a reduced cost per bit. All-optical signal processing is a promising technique to improve network resource utilisation and resolve wavelength contention associated with the flexible spectrum. Flexible Spectrum Dense Wavelength Division Multiplexed (DWDM) optical fibre networks are next-generation technology for handling extremely high data rates of the kind produced by MeerKAT and SKA [3], [4]. Each DWDM channel is capable of 10 Gbps transmission rate, which is sliceable into finer flexible grid 12.5 GHz granularity to offer the network elastic spectrum and channel spacing capable of signal routing and wavelength switching for the scalability of aggregate bandwidth. The variable-sized portions of the flexible spectrum assignment to end-users at different speeds depend on bandwidth demand, allowing efficient utilisation of the spectrum resources. The entire bandwidth of dynamic optical connections must be contiguously allocated [5], [6]. However, there is an introduction of spectrum fragmentation due to spectrum contiguity related to the optical channels having different width [7],[8]. Thus large traffic demands are likely to experience blocking regardless of available bandwidth [9], [10]. To minimise the congestion and cost-effectively obtain high performance, the optical network must be reconfigurable, achievable by adding wavelength as an extra degree of freedom for effectiveness. This can introduce colourless, directionless and contentionless re-configurability to route individual wavelengths from fibre to fibre across multiple nodes to avoid wavelength blocking/collisions, increasing the flexibility and capacity of a network.

For these networks to function optimally, novel hardware and dynamic algorithms identification and development is a critical task. Such tasks include wavelength assignment, signal routing, network restoration and network protection. In this work, we for the first time to our knowledge proposed a spectrum defragmentation technique through reallocation of the central frequency of the optical transmitter, to increase the probability of finding a sufficient continuous spectrum. This is to improve network resource utilisation, capacity and resolve wavelength contention associated with a flexible spectrum in optical communication networks. The following chapter provides details on a flexible spectrum in optical fibre networks utilising DWDM, optimising transmitter-receivers, advanced modulation formats,

coherent detection, reconfigurable optical add and drop multiplexer (ROADM) technology to implement hardware and middleware platforms which address growing bandwidth demands for scalability, flexibility and cost-efficiency. A major attribute is tunable lasers, an essential component for future flexible spectrum with application to wavelength switching, routing, wavelength conversion and ROADM for the multi-node optical network through spectrum flexibility and cost-effective sharing of fibre links, transmitters and receivers. Spectrum slicing into fine granular sub-carriers and assigning several frequency slots to accommodate diverse traffic demands is a viable approach. This work experimentally presents a spectral efficient technique for bandwidth variability, wavelength allocation, routing, defragmentation and wavelength selective switches in the nodes of a network, capable of removing the fixed grid spacing using low cost, high bandwidth, power-efficient and wavelength-tunable vertical-cavity surface-emitting laser (VCSEL) transmitter directly modulated with 10 Gbps data. This to ensure that majority of the spectrum utilisation at finer channel spacing, wastage of the spectrum resource as caused by the wavelength continuity constraint reduction and it improves bandwidth utilisation. The technique is flexible in terms of modulation formats and accommodates various formats with spectrally continuous channels, fulfilling the future bandwidth demands with transmissions beyond 100 Gbps per channel while maintaining spectral efficiency.

List of acronyms

ASE - Amplified Spontaneous Emission
BPON - Broadband Passive Optical Network
CO - Central Office
DCF - Dispersion Compensation Fibre
DFB - Distributed Feedback laser
DWDM - Dense Wavelength Division Multiplexed
ECL - External Cavity Laser
EPON - Ethernet Passive Optical Network
FFT - Fast Fourier Transform
FP - Fabry-Perot lasers
FP-LD - Fabry-Perot laser diode
FTTH - Fibre to the Home/Building/Premise/Curb/Node/Telescope
GPON - Gigabit-Capable Passive Optical Network
IDF - inverse-dispersion fibre
ISP - Internet Service Provider
ITU-T - International Telecommunication Union
KAPB - Karoo Array Processor Building
LED - light-emitting diode
LED - Light-Emitting Diodes
MMF – Multimode Fibre
NRZ - Non-Return-to-Zero
NZDSF – Non-zero dispersion fibre
OFDM - Orthogonal Frequency Division Multiplexing
OLT - Optical Line Terminal
ONX - Optical Network Units/Terminal
OOK - On-Off Keying
PIN - Positive Intrinsic Negative
PON - Passive Optical Network
PRBS - Pseudo- Random Binary Sequence
ROADM - Reconfigurable Optical Add-Drop Multiplexer
RSOA - Reflective Semiconductor Optical Amplifiers
SDP - Science Data Processor
SKA - Square Kilometre Array
SMSR - Side-mode suppression ratio
SOA - Semiconductor Optical Amplifier
SSMF - Standard Single-Mode Optical Fibre
TDMA - Time Division Multiple Access
TEC - Thermo-Electric Controller
VCSEL - vertical-cavity surface-emitting Laser
WDM - Wavelength Division Multiplexing
WSS – Wavelength Selective Switching

Chapter 1

1.0 Introduction

The exponentially increasing network traffic driven by high bandwidth-demanding applications such as high definition video streaming, radio telescopes, and cloud computing challenges the capacity of existing optical transport networks. This rapid increase in the traffic demands large capacity and cost-effective optical fibre transmission systems. We have considered WDM and OFDM based networks as an ideal solution for elastic optical network architecture, by providing flexibility and scalability in the spectrum allocation and data rate accommodation without dramatically changing the fibre infrastructure. This is due to the capability to transmit high-speed data using multiple spectral non-overlapping lower speed sub-carriers [1]. Wavelength division multiplexing refers the simultaneous transmission of multiple optical fibre wavelengths within a single optical fibre. Optical fibre technology forms the backbone of the MeerKAT and SKA telescopes, for the distribution of both extremely high data rates and very stable clock tones. These telescopes both rely on highly stable clock tones distribution over optical fibre to each antenna for driving the digitisers, time-stamping the data, and for monitor and control functions, thus making timing everything for these radio telescope arrays. The MeerKAT aims at achieving clock accuracy to within five nanoseconds, but timekeeping can never be too accurate. There has been excellent progress within the MeerKAT as it has established an optical fibre link capable of keeping the time errors below 1.6 nanoseconds [2]. This is in line with the operational requirements of high-bandwidth and low jitter networks that are necessary to manage the enormous amounts of scientific data. High jitter may result in a loss of transmitted data between devices making up the network. Jitter is used to measure any deviation in time it takes for data packets to propagate through the network. The dishes of the MeerKAT and SKA will produce ~ 110 times the current global Internet traffic. In fact, scientists predict that the data traffic volume generated by MeerKAT and eventually SKA will be more than the entire internet by 2020[3]-[7].

This calls for a memory system with a processing power capable of matching the memory size and data bandwidth to keep up with the expected data rates from the MeerKAT antennas which are nearly 40Gbps per antenna[11]. Thus, the interconnectivity and optical fibre links must upgrade from 10 Gbps to 40 Gbps and beyond. Chromatic dispersion is one of the primary limits in optical transport networks operation in high bit rates greater than 10 Gb/s. Standard single-mode optical fibres with a dispersion of 17 ps/nm.km at 1550 nm have a limitation to the transmission distance of less than 100 km for a system with 10 Gbps bit rate or higher[12], [13]. To upgrade the systems to a higher bit rate with the installed fibre links comprising standard single-mode fibres, dispersion compensation, advanced modulation coupled with coherent detection were some proposed technologies to meet the suited requirements of the radio telescope array. Advanced modulation coupled with coherent detection techniques allows for transmission at 100Gbps and beyond over distances above 100km, with no optical amplification. Telescopes, particularly SKA Phase 2, will not function correctly without critical research to develop and implement novel coherent communication systems such as the high capacity multi-cast network allowing the sharing scientific data to be simultaneously amongst several science experiments and astronomers around the world[14]. The MeerKAT and SKA will rely on optical fibre communication technology for transporting tremendous amounts of data which needs aggregation from the individual antenna to the correlator. The correlator comprises of square kilometre array reconfigurable application boards and a large commodity of Ethernet switches which aligns all the signals from the antennas in the array. This enables antennas in the array to be used as if they were a single dish.

The Ethernet switches have demonstrated remarkable performances in high internet traffic volume data centres and cloud network applications such as the high-performance computing facility proposed for the MeerKAT and eventually the overall SKA telescope system[8],[9]. There is a need for techniques for the high-end solutions in the 10/40 Gbps switching and optical fibre link pairs (cable dispersion compensation) acquisitions to provide overall lower cost and power consumption and greater resource efficiency of MeerKAT. The discovery of this technology was through the flexible spectrum Dense Wavelength Division Multiplexed (DWDM) optical fibre networks[3], [15], [16]. Flexible Spectrum Dense Wavelength Division Multiplexed (DWDM) optical fibre networks are next-generation technology for handling extremely high data rates of the kind produced by MeerKAT and SKA in a flexible, adaptive and self-optimising manner. Transporting data between individual telescope subsystems makes the data signals freely available to Astronomers and telescope end users. The network should have some sharing models, as this will maximise the scientific exploration in the telescopic times [10]-[13]. This model will describe how the sharing of the same data collected amongst different scientific experiments and different instruments running concurrently can occur. The optical network should provide an economic solution that efficiently utilises resources to enable large-scale deployment in the field and simplify network management, protection and security to the level of a traditional point-to-point network. Since different services have different requirements for throughput, delay, delay variation and bit error rate, the guarantying quality of service will be a critical issue. The network must be versatile enough to provide value-added services, with smart bandwidth allocation implemented in the network layer. To optimise the operation of such networks, novel hardware, middleware platforms and dynamic algorithms need identifying ,developing and implementation to perform critical tasks. Such tasks include wavelength assignment, signal routing, network restoration and network protection. The technology implemented for MeerKAT and SKA should be suitable for the requirements of the radio telescope arrays at an overall reduced cost, lower power consumption and greater resource utilisation efficiency.

The flexible spectrum optical networks are to meet these requirements demand to rely on complex architectural networks with thousands of individual network components. These components include (transceivers, routers, wavelength selected reconfigurable add-drop multiplexers, optical amplifiers, etc.) Distributed within optical networks spanning thousands of kilometres. The underpinning technologies and control algorithms for real-time dynamic operation of these networks in terms of operations such as wavelength assignment, wavelength routing, network restoration and protection have not yet reached full development and implementation. In this work, we will study the Configuration of a network that can flexibly optimise the spectral efficiency and reach characteristics of each wavelength, improving network capacity and efficiency. We can achieve through the use of high-end Cisco ASR 9000 Series Routers one of the industry's highest-capacity edge platforms, optimised for aggregation of dense 10 Gigabit Ethernet and 100 Gigabit Ethernet connections. For a multi-node network, we optimise the bandwidth by spectrum allocation and wavelength switching of IPoDWDM optical circuit for communication between the origin and destination [14][17]. Literature review on flexible bandwidth optical network describing the spectral resource by dividing the DWDM rigid frequency grid into several narrow frequency segments (frequency slots) was done. In order to match this performance, we designed and developed a lower cost and ready-to-use power consumption transponders using commercial available VCSELs for transceivers and understanding of Fibre Bragg Gratings. These transponders can route incoming optical signals with different bandwidth to any output fibre. Build an O-OFDM/WDM based experiment suited for wavelength conversion, wavelength switching, routing and spectrum allocation, and wavelength assignment that will aim to improve the quality of service and lower blocking probability enabling efficient utilisation of resources. Address the constraints associated with flexible spectrum networks such as spectrum continuity, spectral contiguity, and spectral conflict. We will do this using a VCSEL-by-VCSEL optical power injection scheme varying the driving current with an understanding of the laser source as a transceiver for known physical layer network (optical fibre) element impairments.

1.1 Thesis outline

The structure of this thesis is as follows; Chapter 1 provides an introduction to the exponentially increasing network traffic driven by high bandwidth-demanding applications such as MeerKAT and square kilometre array (SKA) radio telescopes and the challenges imposed on the capacity of existing optical transport networks. The Nelson Mandela University (NMU) Centre for Broadband Communication (CBC) research group presents Wavelength division multiplexing (WDM) and optical frequency domain multiplexing (OFDM) based passive optical network technologies as ideal solutions for elastic next-generation. This technology is capable of handling extremely high data rates of the kind produced by MeerKAT and SKA in a flexible, adaptive and self-optimising manner. Moreover, these network technologies are capable of tasks such as wavelength assignment, signal routing, network restoration and network protection. The technology implementation to MeerKAT and SKA is suitable for the requirements of these radio telescope arrays at an overall reduced cost, power consumption and great resource utilisation efficiency. Chapter 2 describes an overview of the optical transport network for MeerKAT and SKA radio telescope array with the clock stability requirement. This chapter also presents the state-of-the art optical transport network's configurations and the standards of implemented passive optical networks based on reach, bit rates and multiplexing technology.

Chapter 3 illustrates the various key component enablers at the physical layer of a flexible spectrum network. These include flexible transceivers, flexible optical switches, ROADM and the flexible frequency grid for effective and flexible utilisation of network resources. There is a discussion of the characteristics and combination of components to determine the performance of the optical transport networks set up for future dynamic network systems. NMU CBC introduces state-of-the-art components properties and features such as VCSELs speeds, wavelength switching configurations, Bragg grating application, flexible spectrum and cross gain modulation for wavelength conversion.

Chapter 4 to 9 presents experimental research findings of this work as performed in a laboratory testbed. Chapter 4 begins by demonstrating the performance of vertical-cavity surface-emitting laser (VCSEL) use at the 1550 nm transmission windows as an ideal optical transmitter and the PIN photodiode as a receiver optimised components easily integrable to the next-generation high-speed optical transport systems such as the flexible spectrum technology. These components are cost-effective, reliable, reconfigurable and efficient for high-capacity spectrum utilisation. this chapter presents the Direct modulation technique for VCSEL-based optical fibre transmission optimisation as a function of laser bias current and modulation depth (drive current) . Chapter 4 contains a detailed report on: wavelength tunability, spectrum allocation, low power consumption and NRZ direct modulation up to 10 Gb/s per channel/wavelength signal transmission over a single optical fibre implemented to existing 50 GHz fixed grid spectrum wavelength division multiplexed systems for increased bandwidth. Optimising the PIN photodiode for optical transmission paths to assure the quality of service by overcoming blockage for differentiated bandwidth demands during network congestion incidences. We for the first time to our knowledge presented, an all-optical VCSEL-to-VCSEL injection to attain cross gain modulation as one technique for channel switching, wavelength reassignment, and routing at the transmitter of a flexible spectrum network.

Chapter 5 describes a novel VCSEL-to-VCSEL based technique for achieving purely all-optical power injection using a pair of directly modulated VCSELs operating at the low 1550 nm transmission window for wavelength conversion and routing which are some features of the flexible spectrum which are of crucial in reconfigurable multi-node all-optical networks. Considering the cross-gain modulation technique for all-optical conversion as it is a simple to configure and cost-effective, to transfer data from one wavelength to another without optical-electrical-optical (OEO) conversion. Through this technology we could obtain wavelength reassignment and channel, switching from using semiconductor optical amplifiers for re-modulation via the EDFA saturation gain. The key elements of a flexible spectrum are the dynamic assignable transmission wavelengths for efficient utilisation of the spectrum and source to destination connection implemented to existing WDM-PON infrastructures for next-generation high data rate network. The chapter illustrates bit error rate (BER) curve and eye diagram evaluation, for a Flexible spectrum with optimised transmission distance in optical transport networks (OTNs) with adapting lightpath rerouting and wavelength reassignment capabilities at a reduced number of the transceivers, thus achieving efficient utilisation of resources.

Chapter 6 focuses on designing, producing, and characterising Fibre Bragg Gratings. A broadband source, circulator and optical spectrum analyser configuration were used to measure the Bragg wavelength of the 10 nm FBG designed for sensing in applications such as structural health monitoring. We analysed the strain response of the FBG using a micro screw gauge to stretch the longitudinal length of the grating, and we compared the wavelength shift response to the typical strain sensitivity of this optical component. We observed other inherent features of the FBG such as the narrow-band filtering capability which could benefit WDM-PON as signal restoration.

Chapter 7 experimentally demonstrates a cost-effective uniform Fibre Bragg Grating (FBG) based Add and Drop Multiplexer (OADM) with optical circulators configuration. We implemented this on a 20 Gbps high data speed signal to study the effect of inter-channel crosstalk on flexible spectrum networks. The WDM-PON comprised two multiplexed 1550 nm VCSELs were directly intensity-modulated using a 10 Gb/s NRZ PRBS (27-1) as optical transmitters with one of the emission wavelength that matches the Bragg condition. This was to illustrate the functionality of OADM by adding/dropping different wavelengths to enable greater connectivity and flexibility of the network, for channel reservation, channel switching, wavelength reassignment and lightpath rerouting as a mechanism to reduce optical crosstalk. The OADM configuration was implemented into the optical nodes to perform the task of receiving and inserting a new data signal into the channel. This, therefore, enhances wavelength reassignment, channel conversion and switching, and lightpath rerouting for efficient spectral resource utilisation.

Chapter 8 reports an experimental design and implementation of ROADM as an all-optical subsystem that enables remote configuration of wavelengths at any node of given degree (switching direction) associated with a transmission fibre pair. The cost of each node increases linearly as the direction switched increases, due to each degree requiring an additional wavelength switching element. In this work, we propose and experimentally demonstrate the novel uniform FBG based reconfigurable optical add/drop multiplexer (ROADM) through optically tuning the periodic modulation of the refraction index. Index modulation variation plays an important role as it decides the centre wavelength of the Bragg grating so that a network operator can choose whether add, drop, or pass a wavelength through the node. The all-optical FBG based ROADM is a cost-effective and efficient resource utilisation technique for increasing spectrum capacity through wavelength add/drop for channel reservation. It is this channel management and efficient spectral resource utilisation provided by the ROADM in network nodes that introduces remote wavelength switching and spectral assignment. This makes the ROADM are ideal candidate for adoption in next-generation high-speed telescope array networks that are capable of wavelength assignment and optimised bit-rate transmission verified at different channel spacing and direction of propagation for maximising carrier spectral efficiency.

Chapter 9 comprises the concluding remarks, recommendations and future work. This chapter also presents all research outputs and Novel achievements based on the planned objectives of the Doctoral Thesis.

Chapter 2

2.0 Introduction to MeerKAT and SKA Radio Telescope Optical Transport Network

The square kilometre array (SKA) is a global scientific project in the radio astronomy field aimed at exploring and providing in-depth answers about our universe. The SKA is currently under construction to create a very powerful and most sensitive radio telescope for astronomy. Upon completion, the telescope array will contribute to 110 times the current global internet requiring signal and data processing by a super-computer that is more sensitive than one hundred million computers[18]–[20]. They estimate this to be 50 times more sensitive and tens of thousands more surveying speed than the best current available telescopes[21]. They will build the SKA telescope in two phases and split across two continents which are Africa and Australia. SKA Phase 1 comprises three elements operating individually: SKA1 MID, SKA1 LOW, and SKA1 survey. The SKA1 MID will comprises ~200 dishes (including the 64 MeerKAT dishes) spread around the Karoo region of Western Cape (South Africa) operating in the frequency range of 350 MHz to 14 GHz, covering a total area of ~33 km2 with 150km total distance between dishes, capable of producing 2 terabytes total raw data output per second[22]. SKA1 LOW comprises ~130k dishes spread between 500 stations operating in the frequency range of 50 to 350 MHz, covering a total area of ~0.4 km2 with 65km total distance between stations, capable of producing 157 terabytes total raw data output per second[23], [24]. SKA1 survey comprises ~100 dishes including 36 Australia Square Kilometre Array Pathfinder (ASKAP) dishes operating in the frequency range of 650 to 1670 MHz. The SKA1 LOW and survey elements will be in Western Australia. SKA phase 2 will be achieved by adding long haul spiral arms, integrated to the mid-frequency components of SKA phase 1[15], [25]. South Africa has already demonstrated its excellent science and engineering skills by designing and building the MeerKAT telescope as a precursor to the SKA, with each dish linked to the central point with up to 12 km maximum distance of optical fibre to the Karoo Array Processor Building (KAPB)[2], [25]. This is where the central computing engine is located for beamforming and correlation of the combined scientific data. Transmitting the collected data in the Karoo to the science data processor (SDP) in the South African regional office and to astronomers all around the world[23]. This optical transport network topology corresponds to the typical carrier network configuration. A detailed comparison will be made between a conventional telecommunication network and MeerKAT and SKA telescope array network thorough discussion in the following section.

2.1 Typical Carrier Network Configuration implementation to the Optical Transport Network for MeerKAT and SKA

The MeerKAT and SKA telescopes both rely on the optical fibre to transmit the tremendous amounts of scientific data from the individual dish elements to the correlator in the Karoo Array Processor Building (KAPB). The optical fibre network forms the backbone of the telescope array as a key element of the signal and data transport network required to aggregate the astronomical data from individual dishes to central computing engines. Optical fibres also distribute highly stable clock tones over optical fibre to each individual antenna from the Karoo Array Processor Building (KAPB). These clock signals are crucial for driving the digitisers, data time-stamping, and for monitor and control functions. This optical signal and data transport network resembles a passive optical network (PON) of conventional telecommunication technology architecture based on optical fibre implemented in fibre to the home (FTTH) for delivering broadband network access to end-users. The network comprises of an optical line terminal (OLT) at the internet service provider's (ISP) central office (CO) and multiple optical network units/terminals (ONU/ONTs) near the end-users[2], [3]. This point-to-multi-point architecture uses a single optical fibre to serve multiple endpoints by using optical fibre splitters to divide the fibre bandwidth between multiple access points. This architecture reduces the amount of optical fibre and central office equipment required compared with point-to-point architectures.

These are some differences between passive optical network differ and telescope array networks, where the high volume of scientific data traffic converges to a central computing engine resulting in the huge upstream transmission. For a passive optical network, the downstream bit rate exceeds the end-users' upstream bit rate traffic transmission. The central office of these networks houses the costly sensitive equipment. Further equipping the optical network units/terminals with cheap ready-to-use transceivers that do not require any manual installations and configuration. The tremendous data rates of telescope array networks such as MeerKAT and SKA demand that each antenna contains high-end transceivers, digitisers and other essential electronics. It subjects these transceivers to harsher conditions than those in a temperature-regulated central office transceiver installation can be in the focus or within the pedestal of the antenna. To avoid reducing the detection sensitivity of the scientific data collected by the radio telescope array networks, the transceivers should produce low levels of radio frequency interference. In MeerKAT, the scientific data is digital with each antenna linked to the Karoo Array Processor Building (KAPB) by buried optical fibre spanning a baseline of up to 12 km. The scientific data may also be radio-over-fibre as proposed for the SKA Low-Frequency Aperture Array. While optical fibres are incredibly stable and suited to transport the astronomy data, mechanical stresses and thermal changes affect the optical fibre, degrading the signal stability over long-distance transmission. However, there are properties of the optical fibre that limits this inter-continental connection at high transmission rates. Eventually thousands of antennas will be spread over continental scales i.e. SKA Phase 2, antennas addition beyond 1000 km in long haul type spiral arms and therefore thousands of kilometres of fibre. One of the most complex technical challenges for the SKA to function properly is to make sure it aligns the signals from the antennas with extreme precision for successful combination by the SKA's supercomputers.

Passive optical networks can simultaneously transmit signals over a bidirectional optical fibre in both the upstream and downstream directions to and from the end-user. PONs utilize the optical splitters to divide the downstream signal from a single OLT into multiple downstream paths to the end-users. The same splitters combine the multiple upstream paths from the end-users back to the OLT [26], [27]. There are several ways of dividing/splitting the downstream OLT signal before reaching the end-user to provide service to 128 users (splitting ratio 1:128) with an ONU/ONTs converting the signals and providing users with internet access[28]. Another way to achieve simultaneous transmission is to integrate wavelength division multiplexing to PON, using one wavelength for upstream data and a different wavelength for downstream data. These dedicated wavelengths vary depending on the PON standard in use and can be present simultaneously on the same optical fibre. To prevent multiple ONU/ONT transmitting data upstream which results in wavelength collision optical splitters/OLT, OLT can allocate the upstream bandwidth to each end-user for a specific time period based on time division multiple access (TDMA) technology [29], [30].
A typical PON, as shown in Figure 2.1, uses a single wavelength for downstream transmissions (from OLT to ONUs), and another wavelength for upstream transmissions (from ONUs to OLT), multiplexed on a single optical fibre. These networks have a typical reach that may span up to 20 km with a splitting ratio of 1:128 and beyond. It uses the large splitter sizes in PON architectures in order to maximise the number of shared components amongst all end-users. It assigns the wavelength based on the desired bandwidth, data speed rate for both upstream and downstream data, splitting ratio and the maximum reach. This passive optical network is like the MeerKAT where the central office replaces the Karoo Array Processor Building and 64 antennas instead of multiple optical network units/terminals. For a more cost efficient solution to strengthen the optical technology, proposing a long-reach PON architecture has with the ability to displace electronics and combine tiers to simplify the network. These networks have a typical reach that may span up to 100 km with a splitting ratio of about 1:1024 for 10 Gb/s optical network solution[2], [31]. SKA Phase 1 MID comprises ~200 dishes spread around the Karoo region with 150km total distance between dishes shares similarities with the long reach PON. Adding long haul spiral arms will help achieve SKA phase 2, integrated to the mid-frequency components of SKA Phase 1 and added beyond 1000 km. The MeerKAT and SKA data rates are more similar to that of the long haul than PON when coupled with digital signal

processing platform capable of very specialised high performance parallel computing[32]. These promise reduced operational cost, lowered power consumption and simplified network maintenance with a memory system that will match the processing power to the memory size. The main benefit of the PON is data bandwidth upgrading the interconnectivity from 10 to 40 Gb/s data rate as expected from the MeerKAT antennas.

It divides passive optical networks into three main types depending on the data multiplexing system. Time Division Multiplexing (TDM) PON is the earlier deployed technology uses a single wavelength where traffic from and to multiple ONU/ONTs are TDM multiplexed onto the upstream and downstream wavelength. The system requires some type of synchronisation to avoid collision between the traffic coming from different ONU/ONTs with up to 32 utilising the same wavelength and sharing a common optical fibre transmission lightpath[26], [33]. The simplest method for an OLT to control end-user traffic and to assign bandwidth dynamically is to use Time-Division Multiple Access (TDMA) protocol, wherein each end-user transmits information within a specifically assigned time slot at a prearranged data rate[34].Multiplexing and broadcasting the downstream signals to all the ONU/ONTs, where depending on the packet header address of each ONU/ONT discards or accepts the incoming information. Sending signals in the upstream direction is more complicated as all the end-users have the same wavelength to timeshare[29], [35], [36]. Where the end terminals are at different distances from the central office, a range of techniques are used to measure this reach between the end-users and the OLT, to enable each ONT proper adjustment of its transmission timing. It categories TMD PON into three major systems which are Broadband PON (BPON), Ethernet-PON (EPON) and Gigabit-Capable PON (GPON). Therefore, TDM PON can provide more channels but moderate bandwidth[36][37].

Long term PON solutions have been discussed by Full Service Access Network (FSAN) and International Telecommunication Union (ITU) as 10 GxPON standards have matured and are fast becoming a mainstream technology for FTTx networks. This long term PON solution should be able to provide higher bandwidth, higher split ratio, longer transmission distance, and greater access capacity while full using existing optical distribution network. The next-generation PON development and implementation to existing technology options such as high-speed TDMA-PON, WDM-PON and OFDM PON are achievable. The other two types making up the passive optical network systems are Orthogonal Frequency Division Multiplexing (OFDM) and Wavelength Division Multiplexing (WDM) PON that support the scientific community for large-scale data transport and processing. Both these technologies have a potential of enabling PONs to provide data rates higher than 40 Gbps[34]. The WDM-PON uses multiple wavelengths in a single fibre to multiply the capacity without increasing the data rate to provision bandwidth to ONU/ONTs and increase the number of end-users served in the network. Orthogonal frequency division multiple access PON (OFDMA PON) employs many orthogonal sub-carriers (narrow-band channels) to transmit traffic from and to ONU/ONTs as the data modulation scheme to increase the provisioning data rate. The OFDM PON system divides the upstream/downstream bandwidth baseband into multiple sub-carriers with orthogonal frequencies[38]. The sub-carriers dynamic allocation to different ONU/ONTs are based on the real-time incoming traffic information. This allows the OFDM PON to have colourless ONU/ONTs. This is one advantage it has compared to WDM-PON. Other advantages include high-speed transmission, fine granularity of bandwidth allocation, being robust against channel dispersion and simple phase and channel estimation in an environment varying with time. Traditionally the modulation and demodulation is done utilising fast Fourier Transform (FFT) for OFDM, which is analytically expressed by using overlapped yet orthogonal signal sets between any two sub-carriers[16], [36]. Where the spectrum has frequency side lobes of each OFDM sub-carrier prominent, the system becomes highly sensitive to frequency offset and phase noise, this is a major drawback of the OFDM technology. Other drawbacks include high peak-to-average power ratio especially in systems that employ many sub-carriers as this results in inter-sub-carrier intermixing distortion.

WDM-PON uses multiple wavelengths in single fibre infrastructure, connecting the optical line terminal (OLT) at the internet service provider’s (ISP) central office (CO) to multiple optical network units/terminals (ONU/ONTs) are placed near the end-users and contain passive splitters or/and multiplexers and demultiplexer. This reduces the number of active components in making WDM-PON scalable, which provides cost advantage since power and maintenance are being intrinsically clear to channel bit-rate and have no power-splitting losses. WDM-PON utilises a distinct wavelength channel from the OLT to each ONU/ONT, for it employs spectral slicing in both downstream and upstream directions cheap light sources in the OLT. Therefore, easily transmitting the upstream data which results to colourless ONU/ONTs. As a result, WDM still represents a valid solution for next-generation optical networking, providing several advantages, including higher aggregate bandwidth per fibre, high bandwidth with good data service, great splitting ratio, developed transmission access, and collected backhaul for traffic. This solution offers a simple structure, new flexibility for automated network management and control, transparency to different data formats, low bit error rates and better network configurability, all leading to more cost-effective networks. Despite the advantages of WDM-PON mentioned above, a major drawback of this technology is the need for an optical transmitter in the customer ONU to produce an optical data signal which is accurately in alignment with an especially distributed WDM fixed grid[39]. This makes the network not to be economically viable, as lasers for ONT transceiver configuration that are able to tune to the correct wavelengths in upstream and downstream during end-user provisioning are expensive. Using optical transmitters composed of Fabry-Perot (FP) lasers or even light-emitting diodes (LEDs) as data carriers may overcome this limitation and challenge is to identify the degree of capacity and flexibility that can deliver the target benefits at the lowest possible cost[38].

However, the most conventional way to create a WDM-PON is by utilising a distinct wavelength channel from the OLT to each ONU, for both downstream and upstream directions, as shown in figure 2.1. In this configuration, an adjustable laser at the OLT can access each ONU/ONT by changing the wavelength of the optical carrier. In this way, the downstream bandwidth spends only half of the data rate while the upstream spends the remaining half using an external modulator. Consequently, this configuration may lead to a round-trip signal loss of the shared laser source and change of the external modulator output from the input signal polarization, a consideration of direction of the electric field that normally changes in a standard single-mode optical fibre (SSMF) for power margin and polarization is essential. This is due to the fact that slight deviation of one channel from the specified wavelength will lead to the distortion of both the channel and its neighbour ones, results in inter-sub-carrier intermixing distortion. Since each ONU/ONT is critical and expensive, we should note it that a problem for the practical use of a modulator at each ONU is its cost. Another alternative is to use all optical sources, obtainable from the OLT to modulate the ONU/ONT optical signal transmitters. Modulation of this signal at high-speed could make it suitable for upstream transmission. The ONU splits the downstream signal and a part of that with the aid of a semiconductor optical amplifier (SOA) saturation gain is used to configure to an external modulator device. Modulation of just a sectional temporary region for downstream (dominant mode) and using the remaining to modulate regions of upstream (side-mode), leads to a solution in which it can exploit one wavelength channel in both directions.

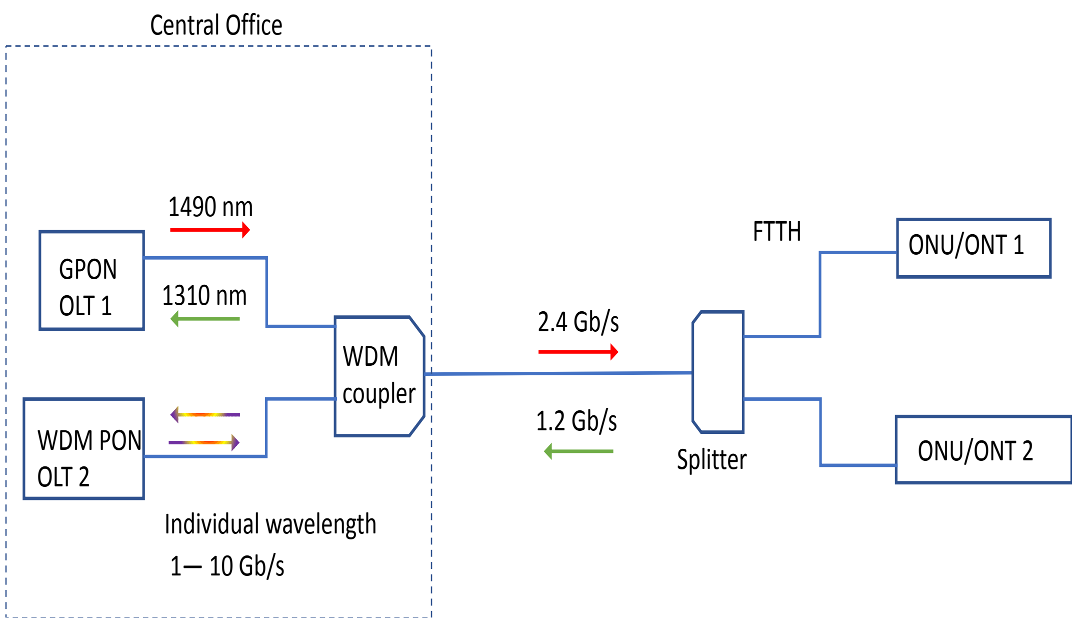


Figure 2.1: Typical Passive optical networks (PON) Architecture

PON network is a cost-efficient network using optical fibre and only passive components such as couplers and splitters without any active (power consuming) components such as repeaters and optical amplifiers. The main drawback of PON is its limitation in the reach (typical distance of ~20 km), the shorter reach is to ensure that the intensity of the input power remains within the receiver sensitivity to reduce signal distortion[3]. Thus, there is a trade-off between the reach and bit rate since at low power consumption, the reach-capacity obeys the inverse square law. Even with the use of WDM-PON capable of increasing the bit rate >10 Gb/s through the use of low-cost transceivers; non-return-to-zero (NRZ) modulated such as 1550 nm VCSEL directly detected with PIN photodiode, the reach remains a challenge due to high chromatic dispersion of standard single-mode optical fibre. This is based on the relationship between the reach and bit rate of this technique, where the transmission distance of a link decreases as the value bit rate square: approximated at 80 km at 10 Gb/s, 20 km at 20 Gb/s, and only 5 km at 40 Gb/s[29], [40]. Based on the cost associated with each ONU/ONT and the stringent requirements to keep channel deviations from the specified wavelength extremely low to avoid signal distortion and channel cross talk, research suggest the removal of optical transmitters from the ONU/ONT. As a way to solve this problem a lot of research demonstrations have presented experiments were unmodulated optical transmitters are obtained from the OLT to be modulated by the ONU/ONT. In this technique one wavelength channel is capable of being exploited in both directions by modulating just a sectional temporary region for downstream and using the remaining unmodulated region for upstream through the employment of an external modulator and Semiconductor Optical Amplifier (SOA). The downstream signal is split at the ONU/ONT and a part is sent to the external modulator, for upstream transmission upon having this signal being high-speed modulated. Practically having an external modulator at each ONU/UNT and using SOA suggested to be applied as a shared source has benefits to network such as efficient resource utilisation and round-trip signal loss compensation. However, the total cost of the PON system is still a problem which needs to be addressed before being considered as a potential commercial product.

A summary of different PON technologies with corresponding standards and recommendations for various optical transmission system scenarios is shown in table 2.1. In optical transport systems, the amount of data transmitted has experienced an exponential growth, and the increase rate will also be continue going forward; therefore, particular attention should be paid to these networks to sustain and keep up with future internet traffic volumes. The Passive Optical Networks (PON) are considered as one of the most successful transmission systems architecture in the development of the Fibre to the Home (FTTH) networks that can provide high capacity and long reach[3]. This technology has the potential to improve the quality of the received signal, whilst the distance covered by the transmitted signal is increased and the number of errors in the received signal is reduced when compared to conventional transport systems. In these networks, both the ONU/ONTs and the OLT are equipped with optical transceivers providing for generation, modulation, detection and demodulation of optical signals. The use of laser diodes as optical sources is common in PON, these allow high power emission (typically ~ 100 mW) and high frequencies (typically ~ 25 GHz) to be directly modulated[41], [42]. The great gain bandwidth as a result of inherent multimodality is unsuitable for a high-speed modulation WDM-PON application, in which narrow bandwidth (less than a few megahertz) are preferred.

Table 2.1: PON technologies standards and recommendations

	BPON	EPON (GEPON)	GPON	10G EPON	WDM-PON	XG-PON (NGPON1)	NG-PON2
Standard(s)	ITU-T G.983.1[26], [43]	IEEE802ah [43]–[45]	ITU-T G.984 [46], [47]	IEEE P802.3av [43]–[45]	ITU-T G.983 [46], [47]	ITU-T G.987 [29], [37], [48]	ITU-T G.989.1[29], [37], [48]
Downstream Bit Rate	622 Mbps	1.244 Gbps	2.488 Gbps	Broadcast;5 Gbps On-demand; 2.5 Gbps	1-10 Gbps per channel	9.953 Gbps	≥4 * 9.953 Gbps
Downstream wavelength	1490 and 1550 nm	1550 nm	1490 and 1550 nm	1550 nm	Individual wavelength/channel	1575 to 1580 nm	1575 to 1580 nm
Upstream Bit Rate	622 Mbps	1.244 Gbps	1.244 Gbps	2.488 Gbps	1-10 Gbps per channel	2.488 Gbps	≥4 * 9.953 Gbps
Upstream wavelength	1310 nm	1310 nm	1310 nm	1310 nm	Individual wavelength/channel	1260 to 1280 nm	1260 to 1280 nm
Splitting ratio	1:32	1:32	1:64	1:128	1: (16/100s)	1:4	1:4
Reach (km)	20	20	60	10	20	40	40

Distributed Feedback (DFB) lasers are an example of optical sources where network operators can use temperature as the primary parameter of control technique to switch the wavelength in the upstream direction from the ONU/ONT to the OLT. These thermo-electric controlled lasers are available today and can be used in the ONT, but they are still relatively expensive and should require a thermo-electric controller (TEC) module necessary to compensate the wavelength shift of about 0.1 nm/°C[49], [50]. This makes vertical-cavity surface-emitting lasers (VCSELs) potentially more suitable for low-cost mass production. These kind of sources emitting at 1550 nm are commercially available because their optical and thermal properties at this wavelength are improved enough making them a transparent, energy and cost effective solution for the next-generation PON. The tremendous traffic volume increase in end-user bandwidth demand strains the current optical transmission systems capacity, future networks need to be improved to support over Gigabit data rates in both upstream and downstream full bidirectional connectivity. The available semiconductor lasers could be modulated up to 40 Gbps. External modulator such as Mach-Zehnder interferometers and electro-absorption for systems operating at 10 Gb/s or higher bitrates are used in order to increase both bandwidth and extinction ratio and reduce the insertion losses[36], [51]. Without using the chromatic dispersion compensation the signals transmitted are distorted and lose form, the maximum achieved transmission distance (typically 20 km) and speed (2.5 Gbps) are significantly limited. In order to achieve a data transmission speed in NGPON systems of 2.5 and 10 Gbps for each end-user, accumulated chromatic dispersion compensation is a very significant aspect is the.

However, the chirp effect in such systems is severe and causes spectral broadening, this combined with the optical fibre group delay velocity dispersion results in the limit on available reach. In next-generation PON deployments, bidirectional transmission of symmetrical upstream and downstream data capacities will be a viable option to address the continued growth in demand for intrinsically bidirectional signalling rates in optical fibre-based transmission systems. In ideal bidirectional systems the network designers consider wavelength division multiplexing (WDM) PON as a promising solution. Wavelength reuse can be adopted to achieve colourless duplex operation at different network ONU/ONTs therefore reducing the overall network installation/maintenance cost. As a result, WDM passive optical networks such as 10 Gbps -based PON have already been made available for practical large scale market commercialization as defined by Ethernet standards (IEEE 802.3). All these standards propose the use of VCSELs. VCSELs offer attractive features to PON types of links as demonstrated by a number of reported in table 2.2. They have ability for direct modulation at very high data rates exploiting on-off keying (OOK) equalization for optical fibre-based transport networks such as fibre-to-the-X (FTTX).

Table 2.2: Summary of WDM passive optical networks experiments with VCSELs in the 1550 nm transmission window.

data capacity per ONU/ONT in terms of Bit rate	Modulation format /Detection method	Multiplexing technique	Maximum reach	Amplification	Dispersion compensation
4 X (1, 2.5 and 4 Gbps) 4 x (10 and 40 Gbps) [36]	NRZ-OOK/DD	OTDM	125, 80 and 34.45 km 5.7 km and 730 m	erbium doped fibre amplifier (EDFA) 20 dB gain	N/A
4 x (10 and 40 Gbps) [36]	NRZ-OOK/DD	OTDM	202.32 and 182.367km	erbium doped fibre amplifier (EDFA) gain : 20 dB	dispersion compensation fibre (DCF)
622Mb/s [52]	NRZ-OOK	Hybrid WDM/SCM	10 km SMF	RSOA gain : 24 dB	
10.7 Gbps [42]	NRZ-OOK/DD 1550 nm VCSEL directly modulated	Proposed for WDM-PON upstream transmissions	35 and 40 km	erbium-doped fibre amplifier (EDFA) with 35 dB gain	N/A
10.7 Gbps [42]	NRZ-OOK/DD 1550 nm VCSEL directly modulated	Proposed for WDM-PON upstream transmissions	50 and 99.7 km	erbium-doped fibre amplifier (EDFA) with 35 dB gain	Inverse-dispersion fibre was utilised to realize a dispersion-matched
28 Gbps [53]	NRZ-OOK/DD Direct modulation on VCSEL	Proposed for low-cost WDM 100 Gb/s (i.e., $4\lambda\times28$ Gb/s)	10 km	N/A	N/A
2 X 20 Gbps [54]	NRZ-OOK/DD Direct modulation on tunable laser sources	WDM-PON based on flexible spectrum for SDN application	12 km	N/A	N/A
10.9 Gbps [55]	NRZ-OOK/DD 1550nm VCSEL directly modulated		5 km	N/A	N/A

8.5 Gbps [56]	NRZ-OOK/DD 1550 nm VCSEL directly modulated	Proposed for applications such as access networks and WDM-PON where wavelength switching is required.	24.7 km	N/A	N/A
8.5 Gbps [57]	NRZ-OOK/DD 1550 nm VCSEL directly modulated	key concept for adoption in high capacity wavelength flexible extended reach optical interconnects	50.7 km	Raman Amplification with 6.1 dB gain	N/A
1.25 and 2.5 Gb/s [58]	NRZ-OOK/DD external cavity laser (ECL)	Demonstrated the feasibility of an optical source for upstream WDM-PON based on RSOA and Fibre Bragg Grating.	20 km and 40 km of	RSOA gain : 30 dB	RSOA and FBG
10 Gbps [6] This work chapter 4 and 5	NRZ-OOK/DD 1550 nm VCSEL directly modulated	development of a novel defragmentation approach for flexible spectrum networks wavelength switching in WDM-PON to satisfy the spectrum contiguity constraint associated with flexible spectrum networks	25 km	EDFA	N/A
2 X 10 Gbps This work chapter 7 and 8	NRZ-OOK/DD 1550 nm VCSEL directly modulated	Evaluated increasing the data transmission speed from 10 to 20 Gbps in two-channel spectrum sliced WDM-PON systems, to investigate the effect of crosstalk and intersymbol interference as a function of channel spacing.	25 km		

Amongst the various multiplexing technologies in the literature there are several dispersion compensation technologies that appear to hold immediate management which have been classified broadly promising solutions being dispersion compensating fibre (DCF) including inverse dispersion fibre (IDF) and dispersion matching, chirped Fibre Bragg Gratings (FBG), and reflective semiconductor optical amplifiers (RSOA). The reconfigurable semiconductor optical amplifiers are used to maintain the signal power at a level where the signal to noise ratio is corrected and sufficient for acceptable bit-error rate for efficient quality of service of the optical transport network. Dispersion compensation through the inverse dispersion and matched fibres can manage and maintain the through self-reinforcing shape of the signal by balancing the average group velocity while it propagates the whole system such that it is zero, this is referred to as dispersion management transmission techniques[36] [52]. Wavelength division multiplexed-passive optical network (WDM-PON) is a promising solution for the future high- speed optical networks such as FTTX by reasons of large capacity, transparency, simplicity and upgradability. The WDM-PON technology can be relatively expensive especially when high cost optical sources are used in each optical network units/terminals (ONU/ONT), with optical sources individually modulated by an electric data signal as per number of the splitting lightpaths NRZ data format channels form the data downstream of the network. To design an efficient network in terms of cost and resource utilisation, the downstream data signals are re-modulated and reassigned for the upstream links. This can be achieved through the saturated semiconductor optical amplifier modulator approach that is used to re-modulate the high-speed modulated downstream signal[42] [57].

Another approach uses spectrum slicing method to control the wavelength assigning optical source from the central office (CO) rather than controlling it from the ONU/ONTs. This technique requires additional coherent or non-coherent optical sources in CO for upstream wavelength source to the downstream wavelength source, this spectrum-sliced source can be a light-emitting diode (LED), amplified spontaneous emission (ASE) of erbium-doped fibre amplifier (EDFA), or an ASE injection-locked Fabry-Pérot laser diode. This is paired with wavelength-seeded reflective semiconductor optical amplifiers (RSOA) thus eliminating any wavelength-registered source at the ONU/ONT[38], [52], [59]. The use of RSOA has been demonstrated in [52], [59] where it was reported that the downstream wavelength carrying high-speed downstream data was direct intensity modulated using distributed feedback laser diode (DFB-LD) and an amplified-spontaneous-emission (ASE) injected Fabry-Perot laser diode (FP-LD) [38]. Further the upstream signal was re-modulated using a RSOA in WDM-PON technique. For the injection locking operation , the locking threshold which is related to the wavelength difference between the master laser injection beam and the selected mode in the slave laser, should be lower than the power of the injected beam[38], [60]. Once slave side-mode injecting locked with input power exceeds the threshold, the state is maintained even if the input power is lowered than the initial threshold [27]. The injection-locked FP-LD will emit the same wavelength as the downstream signal with the original data content largely suppressed. Thus potentially configures a low-cost upstream data transmitter/transceiver with improved signal quality can be realised. This technique greatly improves the side-mode suppression ratio (SMSR), increases the tolerance to fibre chromatic dispersion and thus enhancing the network transmission reach.

In this work, VCSEL-to-VCSEL optical power injection through saturation gain of erbium-doped fibre amplifier (EDFA) was proposed as a novel demonstration of ‘colourless’ spectrally-sliced low-cost transceiver with the effective transmission rate of 10 Gbps in each subcarrier of the optical signal via OOK-NRZ modulation to obtain high spectral efficiency. In this WDM-PON configuration the EDFA serves both re-modulation and amplification functions, operating in the gain saturation region to reduce the optical signal intensity noise thus increasing the quality of service of the network at the maximum data rate per channel and transmission distance. The proposed configuration utilizes the same wavelength for the downstream transmission signal that is a directly modulated master VCSEL by a PPG from the CO to the ONU/ONTs. At the receiver end of the network wavelength reassignment and channel conversion is established through the optical power injection to the side-mode of the slave VCSEL then the upstream transmission is achieved with subcarrier optical signal from the dominant mode of the downstream transmission signal spectrum at each ONU/ONT. The EDFA satisfies system margin and injection power level due to large slicing loss and low output power of the VCSELs. The simple concept of this bidirectional WDM-PON and the ability to share the same wavelength for both up and down stream transmission promote efficient resource utilisation of low-cost optical components and low power consuming active components will result to in overall energy and cost efficient network. In the next section this low-cost WDM-PON proposed is further developed as a potential technology for implementation is considered in optical interconnected data centres and > 100 Gbps next-generation access, metro and long haul networks to handle the tremendous data rates of telescope array networks such as MeerKAT and SKA.

2.2 Implementation of WDM-PON Technology to MeerKAT and SKA Radio Telescope

The PON basically referred to as the “last mile” between the service provider and user, or the Fibre to the X (FTTX). In the notation FTTX, the “X” signifies the home (FTTH), building (FTTB), premises (FTTP) , curb (FTTC), node (FTTN) or other location, depending on where the optical fibre is terminated[28], [61]. The concept can be extended to form Fibre-to-the telescope (FTTt). In this case, 64 MeerKAT dishes will represent the ONU/ONTs and the Karoo Array Processor Building (KAPB) consists of optical line terminal (OLT) as it is the central office (CO) as shown in figure 2.2. The clock signal transmitted from the KAPB is the downstream data to the dishes within a 12 km reach, whereas the upstream data is transmitted from the individual dish elements to KAPB for processing and storage. The collected science data will be transmitted from KAPB to the science data processor (SDP) in the regional office, Cape Town, South Africa for > 1000 km and to be freely available to Astronomers and telescope end users outside South Africa. Advanced modulation coupled with coherent detection techniques allow for transmission at 100Gbps and beyond over distances in excess of 100km, without the need for optical amplification. The transmitted data amount experiencing a rapid increase so will the need for higher data transmission speeds increases will also be needed. Therefore, particular attention should be paid specifically to these networks evaluates the development of fibre optical transmission systems. it will be necessary to update the existing network infrastructure and to introduce a high-speed WDM-PON technology, which can provide higher data transmissions speeds (2.5 and 10 Gbps per channel) at a bigger distance (over 20 km) than the existing form of Fibre-to-the telescope (FTTt) technology Karoo Array Processor Building (KAPB) consists of an optical line terminal (OLT) with the incoming data flow being divided to all dishes which will represent the ONU/ONTs as seen on the figure below.

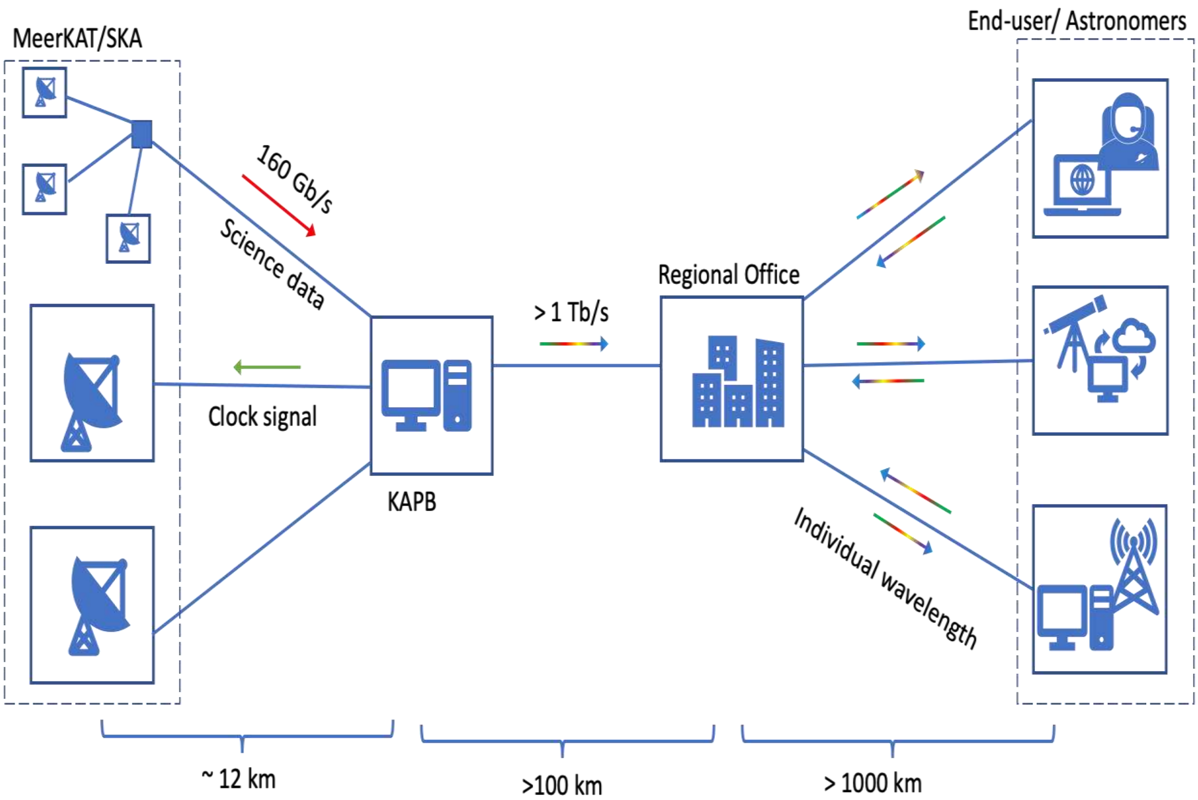


Figure 2.2: MeerKAT and SKA radio telescope array network architecture

As the number of end-users for a communication network increases, the service providers must ensure that the infrastructure designs can implement the development of hardware and middleware platforms. These will address the growing bandwidth demands for scalability, flexibility and cost-efficiency. Demand relies on the complex technologies and networks, which contain thousands of individual network components such as transceivers, routers, wavelength selective switching reconfigurable optical add-drop multiplexers (WSS-ROADMs) and optical amplifiers. These are all suitable for core and metro optical networking applications ranging from simple point-to-point to complex mesh configurations distributed within optical networks spanning thousands of kilometres[24], [40]. Moreover, real-time, control and monitoring, and timing signals will require extensive and reliable fibre connectivity and development of algorithms and software to remotely track each antenna [23][62]. This next-generation PON system can be implemented to the existing form of Fibre-to-the telescope (FTTt), where the 64 MeerKAT dishes will represent the ONU/ONTs and the Karoo Array Processor Building (KAPB) consists of optical line terminal (OLT). This is the central office (CO) infrastructure where the optical power splitter is replaced with an optical signal splitter according to specified channel wavelengths. Application of wavelength division multiplexing in FTTt networks enables the option for each end-user/astronomer to be assigned a separate optical wavelength to access the scientific data and have experiments run simultaneously without any disturbances. Upon considering the available bandwidth on the optical fibre transmission system, spectrum slicing can be introduced to the WDM-PON technology, thereby developing a fully suitable for a higher speed NGPON2 technological solution. The underpinning technologies and control algorithms for real-time dynamic operation of these networks in terms of operations such as wavelength assignment, wavelength routing, network restoration and protection will be developed using flexible spectrum technology, as will be discussed thoroughly in the following section.

2.3 Flexible Spectrum Technology for MeerKAT and SKA Radio Telescope

Flexible Spectrum Dense Wavelength Division Multiplexed (DWDM) optical fibre networks are next-generation technology. This technology is capable of handling extremely high data rates distributed over optical networks spanning thousands of kilometres of the kind produced by MeerKAT and SKA radio telescopes. Flexible spectrum refers to non-statically fixed channel/wavelength assignment, dynamically optimized in real-time to ensure the best network performance [48], [63]. For these networks to function optimally, novel hardware and dynamic algorithms must be identified and developed to perform critical tasks[64]. In a typical flexible spectrum network, through algorithms, the network itself chooses arbitrary data channels and assigns sections of the spectrum and the suitable paths/routes to take. Moreover, the selected channels have mixed modulation formats, bit rates and bandwidth optimized for specific channels as per the end-user requirements [63], [65]. Such tasks include wavelength assignment, signal routing, network restoration and network protection, to support dynamically varying traffic volume, managing the spectral resources efficiently.

There are two main requirements that affect the tasks of the network i.e. ensuring high-frequency throughput band and data transmission speed, and ensuring sufficiently low network delay or latency. All this must be achieved while maintaining network architecture as simple as possible. Electrical and optical-electrical components of the high-speed NGPON located in the transmitter and receiver block (transceiver) are the driving force of the network's efficiency. They feature a limited frequency throughput band and transmission speed. Therefore, it is necessary to seek for an all-optical solution to increase this frequency throughput band, typically from 2.5 to 10 GHz of optical access networks. This technique will be implemented on existing transceiver as will be the focus of this study, through flexible spectrum dense WDM PON development.

This section focuses on developing, implementing and testing modulation formats, hardware technologies and algorithms for optimization and operation of such flexible networks. Flexible spectrum networks have attractive features such as reconfigurable nodes, bandwidth variable transmitters, adjustable wavelength and spectrum allocation and the centralized network management[66][66], [67]. This is achieved by having centralized network management in unified software-defined networking (SDN) controller platforms responsible for channelization, bandwidth allocation, signal routing and wavelength assignment. This will be from the telescopes' collecting data to the end-user/astronomers connectivity and service restoration in case of fibre faults in any link, as seen in figure 2.3. The cloud-based network consists of a transmitter/source (Regional office) connected to the receiver/destination (OLT of end-user/astronomers) via interconnected DWDM fibre links that propagate channels through colourless, directionless and contentionless reconfigurability to route individual wavelengths from fibre to fibre across multiple nodes[68]. With the ability to route each wavelength through different lightpaths, network delay or latency parameter of the optical transmission system becomes ever more important. By increasing the data transmission speed and distance, depending on the contents of the transmitted information, latency increases as the optical signal propagates through fibre or other elements, affecting the overall data transmission speed.

Through dynamic optimization control algorithms in conjunction with a dense wavelength division multiplex (DMDM) flexible spectrum network architecture as a solution, the latency parameter can be addressed. Such algorithms and control plane offer the power and flexibility for real-time implementation. Algorithms under consideration include genetic algorithms, evolutionary algorithms, particle swarm optimization, ant colony optimization etc. For a network with multi-nodes, the ant colony optimization is used to allocate route and spectrum for an incoming transmission request, at the desired rate and modulation format. This takes into consideration the shortest path for efficient utilization of the resources. This approach saves network components including shelves, processors, and interfaces cards and hence it permits one to reduce the power consumption, operational expenditure (OPEX) and capital expenditure (CAPEX). This approach brings also a simplification of the network.

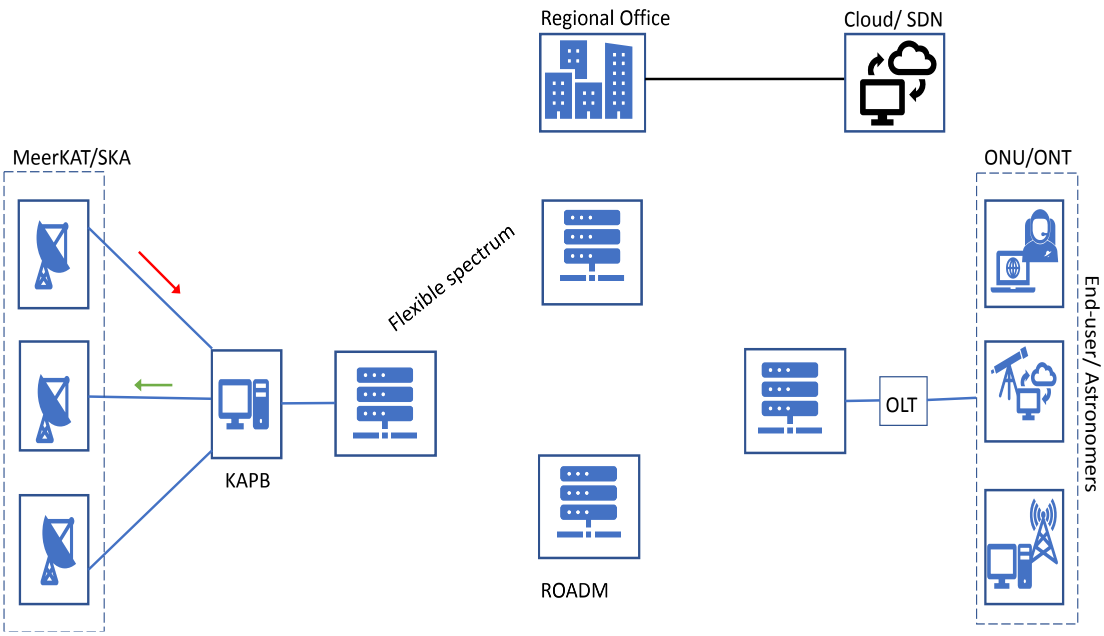


Figure 2.3: Software defined network for telescope array and end-user connectivity using flexible spectrum technology

The network consists of a transmitter/source (Regional office) connected to the receiver/destination (OLT of end-user/astronomers). It includes interconnected DWDM fibre links that propagate channels through colourless, directionless and contentionless reconfigurability to route each wavelength from fibre to fibre across multiple nodes. Colourless refers to the functionality that enables any wavelength to be added/dropped on any port of a node remotely. Reconfiguration without site visits refers to simply tuning the transceiver to the desired wavelength. Directionless is the ability to remotely route wavelengths across any viable lightpath in the network without requiring physical rewiring of the transceiver connection to change the direction of a specific wavelength at any node. This restoration enables a highly-resilient, programmable network foundation that can support changing service requirements from end-users. Contentionless is used to eliminate wavelength blocking so that the service provider can add or drop the same wavelength at the same node. This capability together with Colourless and Directionless are what provide ultimate flexibility at the optical layer of a network. These nodes have wavelength selective switch capability and ROADM. This is used to convert optical signals from one wavelength to another for spectral efficiency and routing the user demands through spatial efficient lightpaths [18]. Based on the transmission system network topology, the optimization of frequency throughput bandwidth is achieved and used efficiently with regards to the number of elements in use. These elements include lightpath length and data flow parameters such as transmission speed, data packet length. This means that the multiple channels are transmitted using variable bandwidth transceivers, through reach and capacity-optimized links for each of the many arbitrary channels generated using one of the many possible modulation formats. Thus, the spectral and spatial flexibility in optical transport networks is optimized in the network management system (SDN), controlling the modulation level of a channel according to maximize spectral efficiency while maintaining the required quality of service[69].

Optical signals with high spectral efficiency are highly sensitive to physical layer impairments, which are seen as bit error rate rise or degradation of the signal to noise ratio of the affected optical link. This is useful in understanding the quality of service achievable by different modulation conditions of transmitters and the corresponding sensitivity expected at the receiver. These are further analysed considering the impact of the fibre characteristics through all-optical conversion through cross gain modulation power injection[48], [70]. This analysis is done to properly size the spectrum for each demand based on its bit rate and the transmission distance for a bandwidth variable transmitter. It can be adjusted to a modulation format occupying less optical spectrum and can still perform error-free due to the reduced impairments. This is to maximize the reach (fibre length), effectively use the network resources and broaden the spectral width (routing, wavelength assignment, spectral efficient technique for defragmentation and channel switching). With the demand for bandwidth of internet-based emerging applications, high-speed networks have consequently received extensive research interest.

2.4 Summary

Passive optical networks can simultaneously transmit signals over a bidirectional optical fibre in both the upstream and downstream directions, to and from the end-user. The concept of PON can be extended to form Fibre-to-the-telescope (FTTt), such as the MeerKAT and SKA telescope array. The clock signal transmitted from the KAPB is the downstream data to the dishes, whereas the upstream data is transmitted from the dishes. The PON network is a cost-efficient network using optical fibre and only passive components such as couplers and splitters without any active components such as repeaters and optical amplifiers. The main drawback of the PON is a limitation in the reach (a typical distance of ~20 km). Even with the use of WDM PON capable of increasing the bit rate >10 Gb/s with the use of low-cost transceivers reach, there will still be a challenge due to high chromatic dispersion of the standard single-mode optical fibre. This will be more difficult once the SKA telescope is completed as the collected science data will be transmitted from KAPB to the science data processor (SDP) in the regional office, Cape Town, South Africa for > 1000 km. The scientific data collected should be freely available to Astronomers and telescope end-users outside South Africa. The underpinning technologies and control algorithms for real-time dynamic operation of these networks in terms of operations such as wavelength assignment, wavelength routing, network restoration and protection will be developed using flexible spectrum technology. The several advantages of flexible spectrum in optical fibre networks include reconfigurable nodes, bandwidth variable transmitters, adjustable wavelength and spectrum allocation and the centralized network management.

Chapter 3: Flexible Spectrum Technology

Flexible spectrum for optical transport network based on dense wavelength division multiplexing (DWDM) technology was proposed as a viable option to accommodate the exponential growth in data traffic volumes to over 100 Gb/s. This is due to their dynamic routing and spectrum allocation capability. In flexible spectrum optical networks, the spectrum is sliced into finer granularity forming an arbitrary number of sub-carriers. These subcarriers can then be combined to form super-channels, thus enabling a more elastic spectrum allocation to match the end-user's bandwidth demands. With ever changing traffic volume requirements, efficient super-channels need to have tightly packed subcarriers offering elastic bit rate allocation ranging from a few tens of Gb/s to Tb/s, hence spectrum efficient super-channels. By efficiently utilizing spectral resources available in conventional ITU-T fixed grid DWDM networks, a whole spectral efficient, flexible wavelength channel can be realized to accommodate the ever-changing traffic demands. For experimental optimization of spectrum resource allocation process, network components and infrastructures such as available bandwidth and variable transceivers, reconfigurable optical add-drop multiplexer (ROADM) optimization in the context of flexible spectrum optical network need to be addressed. In this chapter, the proposed network also has drawbacks such as fragmentation due to the limit of spectrum continuity constraints and other concepts; these will be addressed in this chapter.

3.0 Introduction to Flexible Spectrum Networks

The concept of flexible spectrum network has received great interest in recent years due to its ability to dynamically assign resources. These resources include features such as optical bandwidth and flexible modulation format dictated by network traffic and end-user bandwidth demand requirements. The rigid connections to each transceiver limit this flexibility in conventional WDM-based networks that can be assigned to different wavelengths with fixed channel spacing of 50 GHz at a fixed bit rate (i.e. 10 ,40 and 100 Gb/s). The channels are modulated with a fixed modulation format and the reconfigurations allowed by the network node routing optical switch [71]. Commonly used modulation formats are on–off keying (OOK), differential phase-shift keying (DPSK), or quadrature phase-shift keying (QPSK) and multi-level Quadrature amplitude modulation (QAM)[71], [72]. The multiplexing technique proposed has achieved greatly increased and improved spectrum efficiency when coupled with different advanced modulation formats such as QPSK, DPSK and QAM. These formats have an increased number of bits per symbol for transmitted signals. However, high-capacity per channel of these narrow bandwidths results in low bit receiver sensitivity due to poor signal to noise performance which is a major drawback. The need for higher capacity transport system at a low-cost per drive at high spectral efficiency has motivated this study to be conducted utilising non-return-to-zero (NRZ) on-off keying (OOK) modulation technique and direct detection due to their cost and simplicity. Additionally, there is a growing awareness that the utilized bandwidth of deployed optical fibres is approaching its maximum limit. Therefore, the advancement of conventional fixed optical networks is necessary to accommodate bandwidth-consuming and highly dynamic traffic demands. Efficient utilization of spectral resources has become an intensely researched parameter in attempts to improve optical transport systems to meet the exponentially increasing dynamic demand for bandwidth in backbone networks that support different modulation formats. This is particularly relevant for the emerging cloud-based interconnected networks that such as the MeerKAT and SKA radio telescope array data and clock signal optical transport networks telescope/dish-to-end-user/astronomer service. These services include real-time multimedia, 5G and cloud computing operating in bit rates > 100 Gb/s realizing higher spectral efficiency while maintaining terminal distance (reach)[72].

The introduction of sub-carrier signals makes it possible to efficiently utilize spectral resources These sub-carrier signals are aggregated to form super-channels and routed through the network along the single lightpath. Super-channels consist of tightly packed subcarriers offering elastic bit rate allocation ranging from a few tens of Gb/s to Tb/s, hence there is spectrum efficient channels[73], [74]. The drawback of the approach is that super-channels with a capacity above 100 Gb/s will not fit within conventional ITU-T 50 GHz fixed grid DWDM channel spectrum while still maintaining equivalent terminal distance (reach). Hence the dynamic DWDM grid/ flexible spectrum approach is considered, where the spectrum is considered as a flexible, continuous resource rather than the rigid ITU-standard grid allocated as a fixed chunk of spectrum, wavelength selective switching. We consider the finer granularity spectrum of 12.5 GHz in which integer multiples can be combined to flexibly allocate channel spectrum based on the channel and guard band requirements[75], as shown in figure 3.1. This allows a flexible selection of channel bandwidth from 50 to 200 GHz in granular increments of 12.5 GHz.

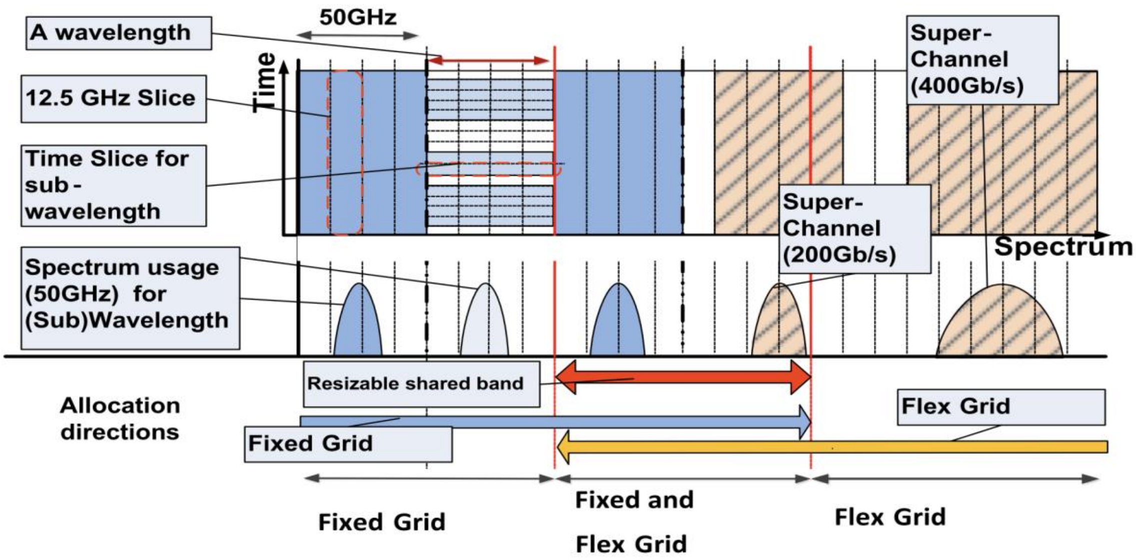


Figure 3.1: finer granularity spectrum of 12.5 GHz for formation of Super-channels consist of tightly packed sub-carriers[75]

In a flexible grid the allocation of channels on the spectrum is based on their capacity and reach requirements. To make the flexible spectrum a reality, new technologies must be utilized. These technologies may include flexible spectrum ROADMs, bandwidth variable transceivers (that can tune to center frequencies in 12.5 GHz increments) and programmable channel bandwidth filters [76]. As opposed to implementing the conventional ROADMs and conventional ITU-grid tunable transponders of 100 Gbps wavelength capacity to existing WDM systems, these systems are conventionally designed to add/drop or lock on to channels anchored to centre frequencies of the ITU grid. Since the development of a flexible spectrum is based on the flexible grid systems incorporation to traditional fixed grids, the challenges of wavelength assignment need to be taken into consideration. This is to solve the issues associated with routing and spectrum assignment by integrating distance-adaptive and capacity constraints[76][77]. The physical layer technological aspect of the flexible spectrum network is discussed in the following section.

3.1 Physical Layer of Flexible Spectrum for Optical Transport Networks

In this section, we focus on the physical layer technological aspects of flexible optical networks. Figure 3.2 presents the key component enablers at the physical layer: flexible transceivers, flexible optical switches, ROADM and the flexible frequency grid for effective and flexible utilization of network resources. The characteristics and combination of these components determine the performance of the optical transport network's set up as well as the cost and power consumption in the physical layer of the flexible spectrum. These optical transport networks are essential for handling large internet traffic volume such as those contributed by cloud-based applications of future dynamic network systems.

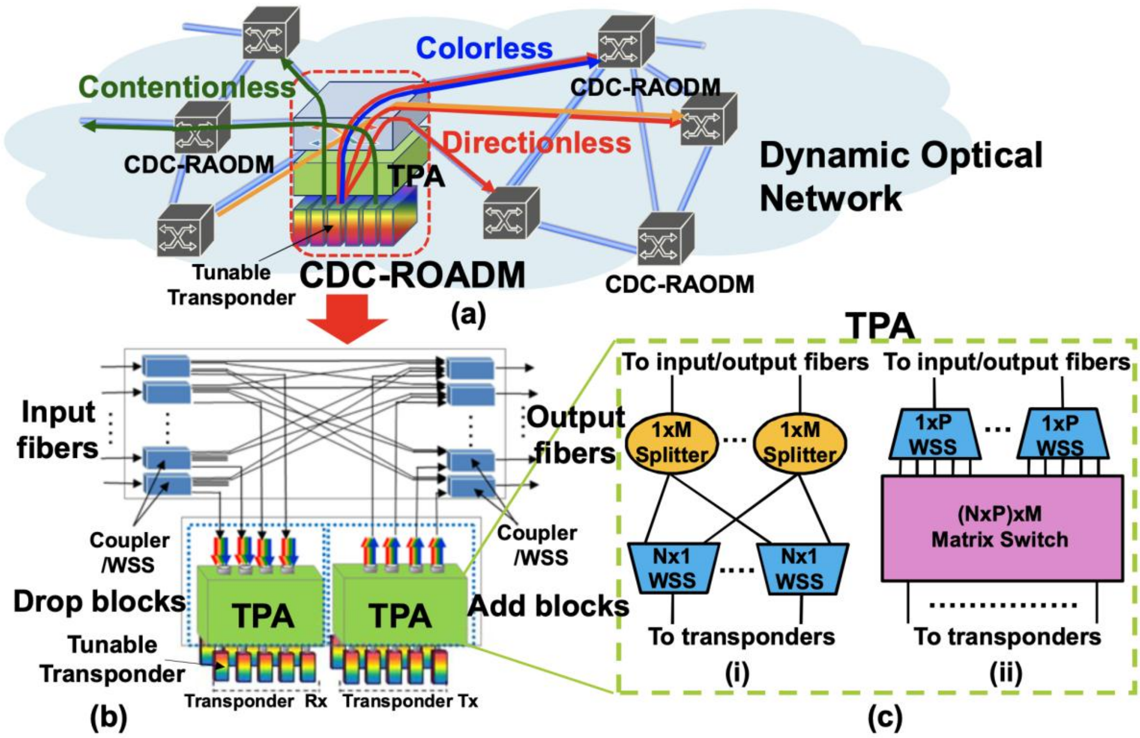


Figure 3.2:configuration of dynamic network systems (flexible spectrum) for optical transport networks[78]

transport network without regenerator. These are commonly costly components (transparent reach), a bit rate transported without overheads such as forward error correction (effective capacity), a ratio of the effective capacity over the amount of required spectrum allocated a bandwidth demand (spectral efficiency), and the ability to dynamically adapt the network characteristics to meet requirements of the end-user requests (tunability)[79], [80]. The objective is to accommodate the end user connection to the service provider requests through adequate spectrum allocation such that there is no overlapping allowed and a minimum spectrum is utilized (spectrum continuity constraint). Through the distribution of signals over several lower data rate subcarriers (thereby providing finer granularity capacity to connections by the elastic allocation of subcarriers according to the connection demands), spectrum continuity constraints can be reduced[71], [74], [76]. The signal is transmitted over the optical path utilizing the available spectrum efficiently, it is then routed through bandwidth variable flexible optical (wavelength selective) switches towards the flexible transceivers that configure their switching window in a contiguous manner. This is what is considered as the routing and spectrum allocation (RSA) in the flexible optical transport network, where the traffic matrix with the requested transmission rates of all connections is given. The use of bandwidth variable and highly spectrum-efficient modulation format can provide scalable and flexible sub- and super-wavelength granularity, which translates to non-overlapping spectrum allocation to all connections for their requested rates. Another way of achieving efficient spectrum resources utilization is provisioning bandwidth. The fine granularity of low-rate subcarrier level achieves a possible reduction in power consumption by partially deactivating the flexible transceiver, adjusting it to the specific rate at a given time[81]. This bandwidth provision is performed through adding/ dropping data signal through assigning several contiguous subcarrier slots to be transmitted/reflected from one node to another using a ROADM. There have been several ROADM configurations with different capabilities in terms of offered connection-level metrics that incur different degrees of development and manufacturing complexity, reflected in the required costs for the network equipment.

3.2 Technologies Enabling Flexible Spectrum

Key component enablers at the physical layer can offer different degrees of flexibility concerning bit rate, modulation format, effective capacity, spectral efficiency and the number and the spacing of the subcarriers making up a super-channel, as well as channel spacing between them. Not all these degrees of flexibility will be simultaneously available as in some optical network architecture, flexibility can be in the number of subcarriers allowed, while others are single carrier transmission with dynamic/elastic data rate. There is improvement in the network tunability with increased available degrees of flexibility at the expense of more complex and potentially cost-intensive flexible spectrum topology design. In this section, the effect of flexibility for different physical layer parameters on the connection performance of each key enabling components is discussed.

3.2.1 Flexible transceiver

Transporting a larger number of bits per symbol in multilevel modulation format, increases the effective capacity and spectral efficiency at reduced all-optical transparent network reach, as they do not use all-electronic switching. This tradeoff is also observed when the symbol rate is increased. Spectral efficiency is improved by keeping the spacing between subcarriers and the super-channel spacing constant [8]. In long-reach passive optical networks, there are a significant number of factors that may degrade the quality of signals, making the data unrecognizable at the receiver end. These factors include polarization mode dispersion, chromatic dispersion, nonlinear effects, optical noise and crosstalk. Thus, within an optical transport network, there is a limit to the maximum transparent reach for signal transmission[82]. Conventional transceivers allocate the full capacity available to only one end user-service provider demand request, hence the traffic demand must fill the capacity of the transceiver. To improve spectral utilization, the concept of flexible transceivers that adapt to the dynamic traffic need has emerged. Flexible transceivers can adapt to dynamic traffic needs required to meet these challenges. The flexible transceivers are software-programmable, allowing various transmission schemes or modulation formats, data rates, forward-error correction (FEC) protocols, and many subcarriers set up to make the best use of the available channel bandwidth [9], [10]. These transceivers can maximize data throughput for each the subcarriers and super-channel, optimize reach, maximize spectral efficiency and/or increase the number of subcarriers and the super-channels on deployed optical fibre links/available optical lightpath. Flexible transceivers also allow for simplified operations to allow remote configuration at minimized costs. Moreover, they support seamless upgrades to new services and optimize spectral resource utilization and defragmentation of optical line/source -destination connection (especially in the presence of 400 Gb/s and 1 Tb/s super-channels).

This calls for an upgrade of the traditional fixed grid, to improve capacity, reliability, cost and simplicity in the network through spectrum flexibility and cost-effective sharing of fibre links, transmitters and receivers. The proposed WDM PON solution was suggested for the development and testing of novel next-generation highspeed VCSEL based flexible transceivers. It will be implemented in future flexible spectrum optical transmission systems, by using the electrical and optical-electrical components existing in the optical transport networks. These networks are capable of wavelength assignment, channel switching and routing capabilities for a restricted frequency throughput bandwidth, to transmit higher-bitrate signals. This is achieved through the wavelength tunability of the VCSEL with a response to the bias current, drive modulation depth effect optimization for efficient resource utilization. The WDM spectrum is sliced into fine granular subcarriers and assigning several frequency slots to accommodate diverse traffic demands is a viable approach. This work contains experimental demonstrations of techniques for bandwidth variability and wavelength selective switches in the nodes of a network, capable of removing the fixed grid spacing. Wavelength switching using the low-cost, high bandwidth and power efficient and wavelength tunability properties of a VCSEL, will be presented and described in detail in the chapters to follow. In the study, the driving current of a 1550 nm VCSEL was varied from (2 mA to 8 mA), therefore attaining different channel spacing 0.8 nm (100 GHz), 0.4 nm (50

GHz), 0.2 (25 GHz), 0.1 nm (12.5 GHz) and 0.05 nm (6.25 GHz) over a constant wavelength range of 5 nm. Majority of the spectrum was utilized at finer channel spacing, wastage of the spectrum resource as caused by the wavelength continuity constraint was reduced and bandwidth utilization was improved. Moreover, the laser was then direct intensity-modulated with 10 Gbps non-return-to-zero (NRZ) electrical signal from a pseudo-random binary sequence (PRBS) of length 27-1 with maximum input VPP of 1.0 V. The electrical voltage swing was varied between 1 and 8 mA drive current and fed to a 10 GHz, 3-dB bandwidth VCSEL. This led to the generation of a range of optical signals with different optical output powers depending on the bias current of the transmitter. The optimized modulation domain of VCSEL as a bandwidth variable transceiver was found by considering both the receiver sensitivity and the extinction ratio as a function of the bias and drive currents.

3.2.2 Wavelength Selective Switch

Desirable characteristics of optical switches include support for switching of fine granularity while maintaining low-level physical layer impairments. This is done while minimizing the cost capital expenditure (CAPEX), operational expenditures (OPEX) and power consumption which depend on the physical size of the equipment and the overall complexity of the network architecture[83], [84]. In conventional optical switches, the wavelength channel switching occurs without requiring optical-electrical-optical (OEO) domain conversion, which is costly. In flexible optical switches, the super-channel switching performed at finer granularity with variable bandwidth characteristics, tunable optical bandwidth and centre flexible frequency grid per channel[85]. This bandwidth variable characteristic of the wavelength selective switches is the key element for flexible optical switches. The wavelength selective switches contain a filter with edges with a finite slope. However, this introduces penalties when the signal transverses multiple flexible optical switches, thus affecting the subcarriers of the edge of the super-channel[80]. These penalties are a function of the filter shape, optical filter bandwidth and the number of WSSs traversed by the data signal.

The super-channels also get affected by crosstalk due to interference with neighbouring channels. These penalties are alleviated by increasing the optical filter bandwidth and introducing higher spectrum guard bands between super-channels, resulting in reduced spectral efficiency[72], [86]. Hence there is a trade-off between the spectral efficiency and the flexible optical switch filtering characteristics and the number of filtering stages accommodated in the entire configuration. The flexible optical switches are improved by implementing wavelength blockers to the building blocks. These provide support for optically grooming signals at a granularity of wavelength by flexibly selecting lightpaths.

Once the optical signals are received at the optical transport units/node, add/drop multiplexer create an internal optical cross-connection lightpath and outputs the signal at the specified port corresponding to a specific transmission path. The transmission path of optical signals are remotely controlled by creating and adjusting cross-connection lightpaths on the network management system, to enable the aggregation and distribution of the traffic directly at the optical layer[21]. This brings about more complexity to the network architecture and has the potential to affect the cost and power consumption of the system[79], [84]. Adaptation of broadcast-and-select structures occur where the overall filtering passband of the wavelength selective device are reconfigured to group adjacent subcarriers, offering enhanced switching flexibility at arbitrary channel spacing. The approach causes degradation to the transmitted signal due to loss and group delays that appear at each slot boundary.

The dishes in the Square Kilometre Array (SKA) network are connected to the correlator and data processor in a simple point-to-point fixed configuration. The connection of the end-user/astronomer to the data processor, however, requires a more complex network architecture. This is because the users are scattered around South Africa, Africa and indeed the whole world. This calls for upgrade of the classical fixed wavelength spectrum grids, to a flexible spectrum grid that has improved capacity, reliable, simple and cost-effectiveness through sharing of network infrastructure. Real-time spectrum slicing into fine granular subcarriers and assigning of several frequency slots to accommodate diverse traffic demands is a viable approach. We present a wavelength allocation technique for creating a flexible spectrum exploiting a low-cost, high bandwidth, power-efficient and wavelength tunable vertical cavity surface-emitting laser (VCSEL) transmitter to develop an all-optical wavelength converter for channel conversion, wavelength switching and reassignment/reuse. A major attribute of all-optical wavelength converters is the ability to tune the wavelength of the laser during the conversion. This makes tunable lasers an essential component for future flexible spectrum with application to wavelength switching, routing, wavelength conversion and reconfigurable optical add and drop multiplexer (ROADM) for multi-node optical networks[14], [19]. VCSELs lasing at 1550 nm with 10 Gbps are commercially available. These offer low manufacturing cost as construction enables the use of traditional semiconductor manufacturing techniques. The manufacturing yield is increased due to the capability for efficient testing at the wafer level [20]. By varying the bias current, VCSELs can easily and inexpensively provide wavelength tuning over a relatively large range. They further emit a highly circular beam that can be coupled into the optical fibre with very high efficiency [1], [14], [19], [20]. They also offer compact size, high speed, low threshold, and low drive current. All these advantages promise a cost-effective all-optical injection for spectral defragmentation and switching. For flexible future networks this makes the VCSEL a key component as a transmitter in reconfigurable optical networks. To reduce the transmitter's power consumption, the VCSELs are directly modulated as opposed to using external modulation [21].

The exponential growth of data traffic in current optical communication networks requires higher capacity for the bandwidth demands at a reduced cost per bit. All-optical signal processing is a promising technique to improve network resource utilization and resolve wavelength contention associated with the flexible spectrum. Network resource utilization is achieved without optical-to-electrical signal conversions. In this doctoral study, we experimentally present a novel, spectral efficient technique for defragmentation and wavelength switching on a cascade of vertical-cavity surface-emitting lasers (VCSELs). This defragmentation and wavelength technique is based on cross gain modulation of the optical transmitter. A 10 Gbps intensity-modulated master VCSEL lasing at 1549 nm was used for optical power injection into the side modes of a slave VCSEL. Exploiting all-optical VCSEL-to-VCSEL injection to attain cross gain modulation, the optical transmitter is optimized for optical transmission paths to assure the quality of service by overcoming blockage for differentiated bandwidth demands during network congestion incidents. The injection results in the energy transfer between the lasing modes, causing data inversion on the transmission wavelength. The master lasing wavelength (with a tuning range from 1546.5 to 1551.7 nm) resulted in a 5.2 nm or 650 GHz spectral width by varying the bias current. A total of 9 continuous 50 GHz spaced WDM channels with non-overlapping nominal frequencies and uniform guard bands were generated. This is used to attain seamless defragmentation and bandwidth optimization for effective spectral resource management. The novel technique is flexible in terms of modulation formats and accommodates various formats with spectrally continuous channels, thereby fulfilling the future bandwidth demands with transmissions beyond 100 Gbps per channel while maintaining spectral efficiency.

The proposed technique achieved a 1.3 dB penalty for transmission over 25 km G.655 non-zero dispersion-shifted single-mode optical fibre, a value within the transmission media and optical systems characteristics of 3 dB as recommended by the International Telecommunication Union-Telecommunication (ITU-T). The Shannon limit was considered for higher transmission rates with the problem decomposed into degraded routing and spectrum assignment and chromatic dispersion in the optical transmission link penalties. The number of transceivers, switches and optical transmission links in the network were reduced, increasing the number of satisfied bandwidth requests, thus optimizing the spectral resource utilization.

3.2.3 Reconfigurable Optical Add-Drop Multiplexer (ROADM)

As the demand for bandwidth rapidly grows, the wavelengths in WDM systems have scaled up to about 48 – 96, with each wavelength having routed to different paths in mesh connectivity between nodes[87]. This comes with challenges for the network operators having to improve the DWDM systems to add new wavelength assignments and being able to reroute the optical paths within the network. The network must be capable of monitoring the allocated connections and assigned wavelengths in non-complex techniques and reduced capital expenditure (CAPEX) and operational expenditures (OPEX)[73], [74]. A reconfigurable optical add-drop multiplexer (ROADM) is an all-optical active network device that can add, block or pass various wavelengths in an optical fibre transport network. The ROADMs are used in systems that employ WDM to enable dynamic software-driven provisioning of wavelengths from a remote management system without major network changes or redesign[88]. In conventional ROADMs, wavelength switching is accomplished without the optical-electrical-optical (OEO) domain conversion. Rather, it operates in three stages: add, drop (block), and cut-through (pass). This means that an incoming wavelength signal is terminated (dropped), outgoing generated (added) and some are cut through (passed) the devices without modification[89].

The ROADM are capable of wavelength switching that enables the end-user to dynamically route any wavelength to and from any node and then seamlessly change connectivity as required. This device monitors and configures the attenuation of the optical power for each wavelength (dynamic balancing of optical power for all channels across the network) [13], [15]. As a result, these functions allow optical signal routing and automatic balancing of the wavelengths' optical power across the network routing of considerable complexity with the reconfiguration at remote stations[77]. This is crucial especially in multiple channel networks containing many optical amplifiers, where penalties and errors are introduced if the power is not balanced. In the following section, we propose a ROADM configuration with low power consumption and low-cost bandwidth variable transceivers for network optimization. This is achieved while maintaining minimization of the network-wide costs, the minimization of network outages, and the maximization of energy efficiency (low power consumption profiles of the respective equipment) at the acceptable quality of service (QoS)[11], [12], [16]. Current optical subsystems employ reconfigurable optical add/drop multiplexer (ROADM) transceivers at remote network nodes to enable wavelength routing with different degrees of freedom. However, pre-existing ROADM technologies are limited to the number of switching directions supported as each degree requires an additional wavelength switching element/algorithm. A seamless, in-complex reconfigurable wavelength routing technique is urgently needed to maximize the robustness of current/future networks under dynamic traffic patterns. In this work, we propose and experimentally demonstrate an all-optical reconfigurable optical add/drop multiplexer employing passive Fibre Bragg Gratings (FBG). Periodic modulation of the refraction index is optically tuned to achieve the dynamic add/drop multiplexer. A ROADM is an all-optical subsystem that enables remote configuration of wavelengths at any node of given degree (switching direction) associated with a transmission fibre-pair. The cost of each node increases linearly as the direction of the switched channels increases, this is due to each degree requiring an additional wavelength switching element.

In this work, we experimentally demonstrate a novel uniform FBG-based reconfigurable optical add/drop multiplexer through optically tuning the periodic modulation of the refraction index. Index modulation variation plays an important role as it decides the centre wavelength of the Bragg grating so that a network operator can choose whether a wavelength is added, dropped, or passed through the node. The all-optical FBG-based ROADM is a cost-effective and efficient resource utilization technique for increasing spectrum capacity through wavelength add/drop for channel reservation. This is due to FBGs being relatively simple to manufacture, small in dimension, low-cost and exhibiting good immunity from the electromagnetic radiations. In this work, we illustrate a ROADM by investigating the FBG's sensitivity and the modulation depth of the input signal. This prototype obtained a tuning range of up to 10 nm based on a directly modulated tunable vertical cavity surface emitting laser achieved by varying the bias current and drive current of the transmitted signal. Preliminary results indicate that this may have great potential for telecommunication applications, as optical tunable FBGs have perfect spectral characteristics for channel reservation in a flexible spectrum network. The bandwidth of the FBG can fit a 6.25 GHz spaced channel within the flexible spectrum grids that can offer up to 3 nm (375 GHz) spectral width accommodating 30 channels to choose from such that the nominal central frequency does not overlap. The Bragg wavelength tuning positions was analyzed in an error-free 10 Gb/s transmission along 25 km G.655 fibre, showing negligible power penalty and bit-error-rate variation.

3.3 State-of-the-art and industry flexible spectrum network with bandwidth variable/spectrum sliced transceivers.

Due to the continued demand for bandwidth in optical transport networks and the need for service providers to dynamically allocate capacity to end-users as per request, major companies such as Cisco and Ciena have designed Compact Broadband Node, routers and packet switches amongst other devices to address the growing internet traffic. These components provide advanced features and benefits to help operators revolutionizing the capital and operational economics of 10 Gigabit Ethernet and 100 Gigabit Ethernet (10GbE and 100GbE) services to reduce costs by simplifying deployments and infrastructure upgrades, which has become the core of network transformation opportunity. The rising recognition of 10GbE and 100GbE ports, connections, and services has created an innovative business requirement to configure a network that is flexibly optimized for 10GbE to 100GbE switching and aggregation that increases the spectral efficiency and reach characteristics of each wavelength (end user-service provider demand request), thereby improving network capacity. This is achieved by utilizing the high-end Cisco ASR 9000 Series Route Switch Processor 440 (RSP 440) and Ciena 8700 Packetwave platform (two of the industry's highest-capacity edge platforms), optimized for aggregation of dense 10 Gigabit Ethernet and 100 Gigabit Ethernet connections. These multi-terabit programmable coherent DWDM packet switch in multi-node networks, the bandwidth is optimized by spectrum allocation and wavelength switching of IPoDWDM optical circuit for communication between the origin and destination. They contain an extensive selection of multiplexing and Ethernet interfaces for flexible deployment in multiservice edge to address the growing need to efficiently aggregate and switch large quantities of packet traffic.

This must be achieved in a manner scalable, low-power consuming, spectrally efficient and that supports next-generation platforms, as well as required by today's service provider networks as these are the main factors that are essential for designing packet networks. These packet networks include different wavelengths, DWDM links, optical fibres, tunable transmitters and receivers, layer switching elements and electro-optic network components, thus it is important to integrate as much bandwidth as possible and use very high-speed links. In the process, power consumption must be reduced by using a minimum number of efficient integrated links for scalability. For example, Ciena's 8700 Packetwave has a maximum of 10 slots, with each capable of providing 1G/10G/40G/100G ports with up to 680 Gb/s, for a total non-blocking capacity of up to 6.8 Tb/s. Therefore, networks should use a highly efficient scalable packet switching fabric to connect those high-speed links. This consists of a four chassis per rack contained in a 483 x 600 x 445 mm^3 dimensions (WXDXH) assembly package weighing 66 kg. The module power consumption is typically 2113 Watts and the DC Input and AC Input are in the range of -40 Vdc to -60 Vdc and 180 Vac to 265 Vac, respectively.

Though the industry-leading high-speed 10GbE and 100GbE ports, connections, and services are a solution, the continued growth in network higher bandwidth demand has driven the need for service providers to dynamically allocate capacity to end-users as per request, in which preexisting networks once optimized for lower, 1GbE rates, are no longer aligned to changing network internet traffic trends. These devices occupy a lot of room as illustrated in the physical characteristics mentioned above, and with space being increasingly limited and expensive this is a challenge for network operators in terms of housing their network equipment or lease space in collocation facilities (which leads to substantial capital expenditures). Thus, addressing bandwidth demand growth by deploying more and larger equipment such Cisco ASR 9000 Series Route Switch Processor 440 and Ciena 8700 Packetwave platform as the solution is simply not an ideal business model. In this work, we propose a solution that utilizes denser passive equipment such as bandwidth variable transceivers based on directly modulated compact Raycon VCSELs to retire active equipment to free space. The VCSEL is mounted on a printable circuit board (PCB) with an input modulation RF to enable injection of drive current via a bias tee's anode and the cathode. This assembly is connected to a 146 x 77 x 320 mm³ dimensions (WXDXH) Laser Diode Controller weighing 3.1 kg, designed for the safe operation of VCSEL.

The aim is to develop and implement these components to innovative networking solutions that consume significantly less energy for powering and operating expenses. These modules provide reliable single-mode 1530- 1570 nm VCSEL solutions with 2.5, 4.25 and 10 Gbps rates at low threshold current, ~ 3 V forward voltage, 0 dBm typical output power and 35 dB side mode suppression ratio (SMSR). This description indicates that the VCSEL is utilized to design a high-speed, high-performance transport network variable bandwidth transceiver, more so the low dependence of electrical and optical characteristics over temperature with applicability to access network for long-distance (>2 km), Metro area network, Gigabit Ethernet, and future next-generation PON. The system will provide greater choice in terms of flexibility, and capacity for high-speed access and massive demand for connectivity fueled by the increasing internet traffic and cloud-based networks that require service aggregation switching scalable to support end-user requests. The proposed transceiver should support seamless routing and spectrum allocation (RSA) of the flexible optical transport network.

3.4 Proposed Low-cost Transceiver and Optical ROADM

The use of vertical-cavity surface-emitting lasers as directly modulated transceivers for optical add/drop multiplexing in the nodes of a flexible spectrum network is promising. Wavelength collision reduces the number of usable wavelengths in the available spectral bandwidth, which negatively affects the quality of service and resource utilization in a flexible spectrum optical network.. This requires that more components such as bandwidth variable transceivers and ROADMs are implemented in each node of the optical transmission network, which increases the overall cost and power consumption of the system. An all-optical ROADM design was proposed and realized through the development and testing of novel control using tunable lasers and direct modulation to design bandwidth variable transceivers for next-generation flexible spectrum optical transport networks, as shown in figure 3.3. The configuration uses the all-optical VCSEL-to-VCSEL power injection technique to achieve wavelength assignment, wavelength allocation and wavelength reuse. This, coupled with the reflective and narrow-band filtering characteristics of the Fibre Bragg Grating gives the system capabilities to add and drop channels to enable dynamic wavelength selective switching and lightpath rerouting. The Fibre Bragg Grating (FBG) based optical add-drop multiplexer (OADM) is thus a key device, as it supports the ability for configuring remote switching traffic for WDM system at the wavelength layer.

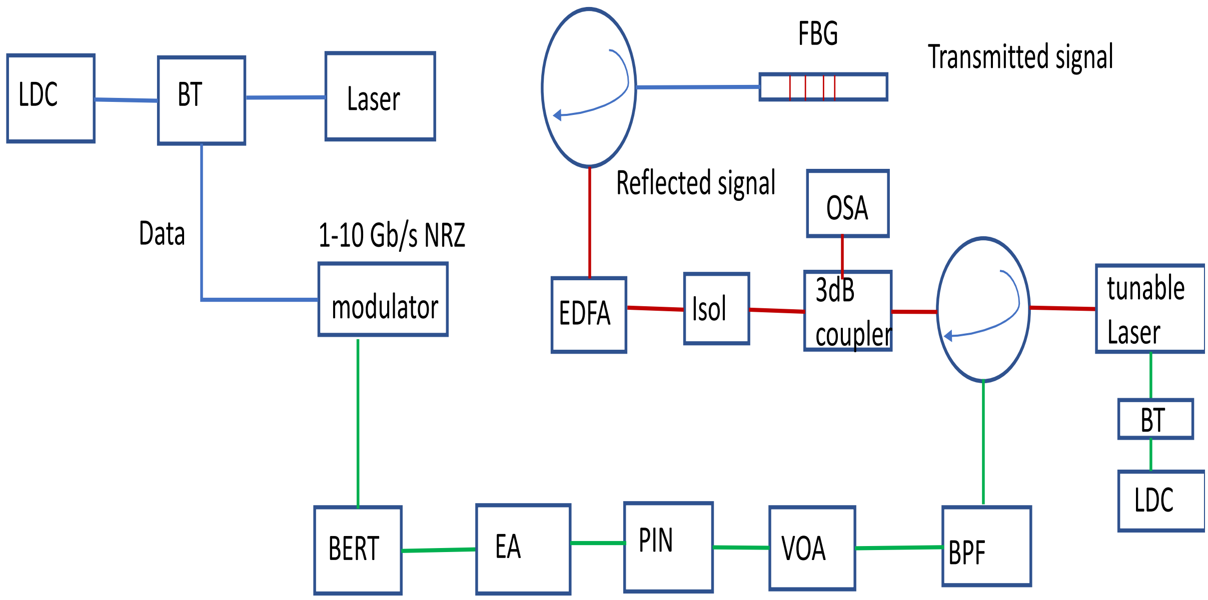


Figure 3.3: Illustration of reconfigurable optical add-drop multiplexer based on FBG and bandwidth variable transceiver from directly modulated tunable lasers

In Flexible Spectrum WDM optical communication networks, this channel reservation technique is used to minimize optical crosstalk, quality of service measured as Bit Error Rate (BER). We propose an effective optical performance monitoring method for routing and wavelength assignment of a flexible bandwidth multimode network that can offer adaptive optimization of the light-paths based on the known impairments. When discussed, the light-paths of a flexible spectrum are assumed to all have an adequate quality of service for a given signal which gets affected by the linear and non-linear impairment due to transmission fibre link. The optical transport system, therefore, must be optimized in terms of receiver sensitivity and extinction ratio as a function of bias current and drive current for a known modulation format, bit rate and laser launch power. This is useful in understanding the quality of service achievable by different modulation conditions of transmitters and the corresponding sensitivity expected at the receiver, and is further analyzed considering the impact of the fibre characteristics through all-optical conversion through cross gain modulation power injection. The first demonstration of the vertical-cavity surface-emitting lasers as directly modulated transceivers with dynamic wavelength allocation and channel reservation is addressed in the next chapter.

3.5 Summary

The third chapter of this Doctoral Thesis suggests a solution for WDM PON that was realized through the development and testing of novel next-generation high-speed VCSEL based flexible transceivers. This will be implemented in future flexible spectrum optical transmission systems, by using the electrical and optical-electrical components existing in the optical transport networks. The network will be capable of wavelength assignment, channel switching and routing capabilities for a restricted frequency throughput bandwidth, to transmit higher-bitrate signals. achieved through the wavelength tunability of the VCSEL with a response to the bias current, drive modulation depth effect optimization for efficient resource utilization.

Optical fibres are the backbone of the optical transport networks whereas the electrical and optoelectronic components are the bottleneck due to the limited frequency bandwidth and the transmission speed. These components are found in the transmitters and receivers and are the building blocks of a transceiver. whose transmission speed and throughput band is restricted by the switching speed of transistors contained in the circuit, as well as the heat originating as a result of the switching process. The solution for the limited throughput bandwidth problem that does not require a complete transceiver replacement, is an electro-optical spectrum sliced bandwidth variable transceiver for high bitrate optical signal transmission and receiving in optical transport networks. In this case, the modulated optical signal containing the transmitted information is sliced into finer sub-carrier signals that can be aggregated to form super-channels and routed through the network along a single lightpath. Super-channels consist of tightly packed subcarriers offering elastic bit rate allocation ranging from a few tens of Gb/s to Tb/s. Hence there are spectrum efficient channels that can resolve the fragmentation effects associated with spectrum continuity constraints. Certain parts of the sliced signal are transmitted through the optical fibre network and the initial signal is used to achieve wavelength reuse and channel switching. This is performed through all-optical injection based on cross gain modulation and signal restoration in the receiver end. Therefore, for the first time to our knowledge, we have experimentally demonstrated a low-cost energy-efficient spectrum sliced variable transceiver developed using the already existing transceivers with a limited frequency throughput bandwidth implementation on the next-generation high-speed flexible spectrum networks.

Chapter 4

4.0 Flexible Spectrum Technology Optimization Based on All-Optical Wavelength Assignment and Routing

This chapter provides an experimental demonstration to characterize vertical-cavity surface-emitting laser (VCSEL) and positive intrinsic negative (PIN) photodiodes, creating an optical transport network where the components are ideal optical transmitters and receivers, respectively. We optimise these components for eased integration into the next-generation high-speed optical transport systems such as the advanced modulation flexible spectrum technology. These components are cost-effective, reliable, reconfigurable and efficient for high-capacity spectrum utilisation offering to 10 Gb/s signal transmission over a single optical fibre. We can implement the components in existing 50 GHz fixed grid spectrum wavelength division multiplexed systems for maximised network bandwidth. In this chapter we present an experimental demonstration of the development of an all-optical spectral efficient VCSEL-based technique for routing and spectrum assignment in optical networks. Take advantage of an all-optical VCSEL-to-VCSEL injection to attain cross gain modulation, to optimise the optical transmitter for optical transmission paths. This is to assure the quality of service by overcoming blockage for differentiated bandwidth demands during network congestion incidences. We then characterize signal transmission performance through bit-error-ratio (BER) measurement and eye diagram representation for the transmitted data signal. This successfully produced a three dimensional (3D) domain surface map for both receiver sensitivity and extinction ratio as a function of laser bias current and modulation depth (drive current) which can be used for optical fibre transmission optimisation.

4.1 Direct Modulation in VCSEL for High-speed Optical Transmission Systems

The industry is moving to flexible spectrum allocation schemes that support arbitrary channel width as opposed to the classical 50 GHz fixed grid. This is due to the advances in tunable technologies such as VCSELs, and dynamic end-user data requirements. This should combine colourless, directionless and contensionless re-configurability to route individual wavelengths across fibres over multiple nodes without optical-electronic-optical conversion, thereby achieving power and cost-efficiency. It therefore requires network designers to implement components that are cost-effective with reduced operational expenses and efficient power consumption while maintaining an end-to-end (transmitter to receiver) communication and quality of service. The major challenge for reconfigurable flexible spectrum networks is the effects of linear and non-linear impairments, especially at higher data rates. VCSELs lasing at 1550 nm with 10 Gbps are commercially available. These offer low manufacturing cost as construction enables the use of traditional semiconductor manufacturing techniques. VCSELs easily and inexpensively provide wavelength tuning over a relatively large range by varying the bias current. These characteristics and advantages of VCSEL technology allow for high-speed signal transmissions such as central nominal wavelength tenability. The ability for direct modulation and detection for optimised flexible spectrum technology was used to experimentally demonstrate spectrum allocation, channel switching and wavelength reassignment.

4.1.1 VCSEL Wavelength Tunability and Spectrum Allocation

One of the main advantages of the VCSEL is that it can be modulated at gigahertz rates while manufactured using very low-cost wafer-scale methods, in which VCSELs complete testing and burned-in occurs while it is still in wafer form, resulting in increased manufacturing yield. Also, the laser has low power consumption due to a small threshold corresponding to the small volume of the VCSEL resonator. It uses optical cavity length of the VCSEL to determine the lasing wavelength controllable by varying the bias current, which results in changes in output power and wavelength. In this work, the output power of two VCSELs was measured as the bias current was increased from 0 mA to 10 mA as shown in figure 4.1 (a). The threshold current of the VCSELs was seen to be at 1 mA with the saturation current seen to be at 7 mA. Above 7 mA, the output power of the VCSEL remains constant (roll-over) as the current was further increased. As a result, for performance at high-speed networks the lasers operate well above the threshold and well undersaturation (linear region of the power versus bias current characterization curve). During modulation, we biased the VCSEL in the linear region to provide a complete ON-OFF modulation swing.

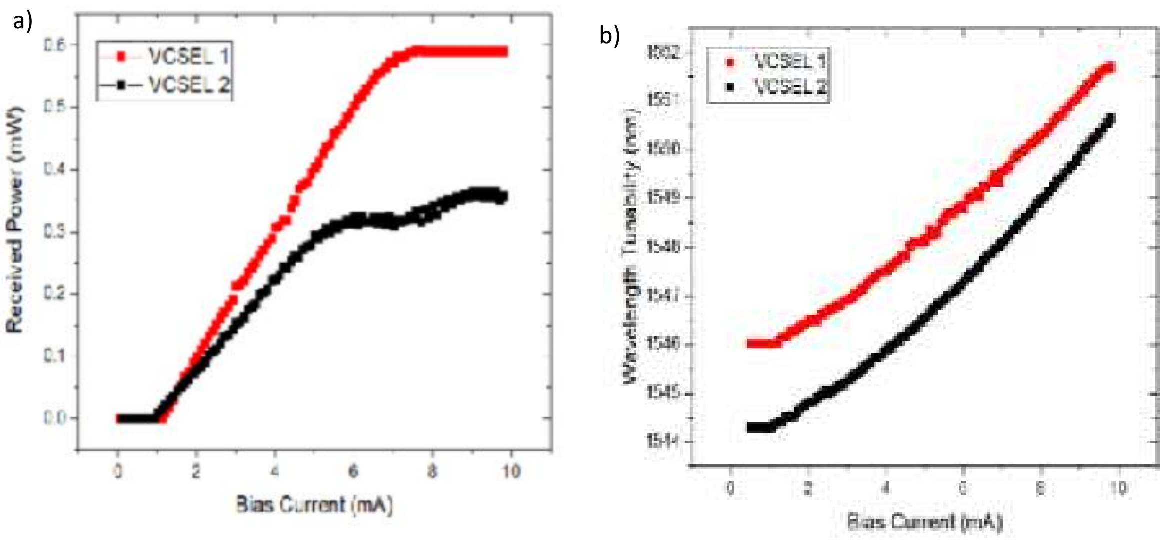


Figure 4.1: Experimental characterization a) Output power and b) wavelength tunability of a VCSEL as a function of bias current.

Also, the laser has low power consumption due to its small threshold current applied. The availability of multiple wavelengths at different bias current points provides a great potential for its adoption into flexible spectrum network applications and in systems that require wavelength tuning to achieve spectrum allocation. The low modulation bandwidth of VCSEL is a significant disadvantage, which we can manipulate through spectral allocation for spectral efficiency using wavelength tunability of the laser. To determine the lasing wavelength of a VCSEL, we simply control the optical cavity length by varying the bias current, which results in changes in output power and wavelength as shown in figure 4.1 b). One can tune the central nominal wavelength for VCSEL 1 and VCSEL 2 by increasing the bias current from 1 mA to 7 mA, tuning the wavelength from 1546.03 to 1549.56 nm and

1544.31 to 1548.12 nm, respectively. The wide bandwidth of 3.53 nm (441.25 GHz) for VCSEL 1 and 3.81 nm (476.25 GHz) for VCSEL 2 was achieved. Therefore we can create 10 Gb/s tunable channels using 1550 nm VCSELs which can allow for 9 WDM channels each at a 50 GHz spacing. In this space the spectrum utilises 4 slices each with 12.5GHz slice size under the flexible spectrum requirements. Therefore, it is possible to tune the wavelength at fixed channel spacing with each VCSEL covering a finite band. In the section below, we discuss the configuration of the system such that the two band formed overlap and the wavelength coverage is continuous to achieve spectrum allocation, channel switching and wavelength reassignment.

4.1.2 Modulation depth effect on the directly modulated VCSEL optimization optical transmitter for flexible spectrum network

For optimized performance at high-speed networks, the laser must operate well above the threshold and well undersaturation (linear part of the power versus bias current curve) when applying modulation. Direct modulation is the most preferred technique due to its simplicity and effectiveness. The data signal is generated by supplying the optical signal from the VCSEL with an electrical bit-stream of “1”s and “0”s, with “1” standing for the highest power level and “0” the lowest. This is direct intensity modulation, which involves the turning on and off of the light signal with an electrical signal. When the driver current of the on-off modulation signal varies, the modulation depth changes so does the wavelength of the laser. This means that by changing the applied drive voltage of the programmable pattern generator (PPG) used to provide the non-return to zero modulation to the laser, we can increase the bias current. This changes the optical cavity length of the laser resulting in wavelength tunability, which in turn offers an additional degree of flexibility to the design of the network. Selecting the correct drive voltage related to the input power before the VCSEL is important since a high-power input signal causes VCSEL saturation. This would result in high levels of signal distortion at the output and potential of errors that are intolerable and would affect the quality of service.

We then measured the quality of an optical signal received from the transmitter as the extinction ratio. There is a lot of misconception around extinction ratio. Thus the common confusion with other parameters such as chirp, fibre dispersion, and self-phase modulation. Chirping is the instantaneous change of wavelength with optical power variation, resulting in time-dependent instantaneous frequency changes and consequently different group velocities. Dispersion influences how the optical spectrum of a laser under normal operation broadens as the signal propagates along the fibre during transmission. In this process, the direct intensity-modulated signal propagating through an optical fibre induces an index modulation of the fibre resulting in phase modulation of the signal which broadens the signal spectrum. This self-phase modulation is an optical fibre nonlinearity due to the nonlinear index of refraction, which varies with optical power levels resulting in frequency chirp. It relates the output optical power of a direct intensity-modulated laser to the chirp through the expression:

$$\Delta\nu(t) = \frac{\alpha}{4\pi}\left\{\frac{d}{dt}[\ln P(t)] + \kappa P(t)\right\} \qquad \text{Equation (4.1)}$$

Where α is the linewidth enhancement factor and κ the adiabatic chirp coefficient related to the geometry of the device and its non-linear gain. The first term is a structure independent transient chirp that relates to the time derivative of optical power, which has a significant value during relaxation oscillations. The second term is a structure-dependent adiabatic chirp related to relaxation oscillation damping due to instantaneous optical power. When viewed on an oscilloscope eye diagram analyser, more open the eye, the lower the likely-hood that the receiver in the transmission system may mistake steady-state “1” s and steady-state “0” s. The eye diagram of a transient-chirp dominated transmitter exhibits significantly more turn-on overshoot and ringing in output power and frequency deviation. The transient chirp component, which is always present has a relatively slight frequency difference between steady-state “1” and steady-state “0”. Adiabatic-chirp dominated transmitter exhibits damped oscillations and large frequency difference between steady-state “1”s and steady-state “0”s. Therefore, the extinction ratio of an eye diagram is an important parameter to specify a transmission system. The goal of any optical transport system is to transmit error-free data signals flexibly, reliably and economically from the transmitter to the receiver. We measure the probability of any received error bit in the data stream as a bit error ratio (BER) test performed using an error performance analyser, commonly referred to as a BER tester or BERT. Optical transmission system designers have over the years come up with techniques that correlate a particular shape that an eye diagram should have to achieve a good BER.

The common understanding of extinction ratio can be a great benefit for optical network designers, suppliers and users of transceivers, where the careful choice of component parameters improves the interoperability of complex devices such as the optimisation of an optical transmitter in short- and long-haul high-speed flexible spectrum network. We can achieve an ideal position to apply the drive current of modulation when the bias point VCSEL is at the midpoint of the linear region of the laser current-power characterisation curve. This is done to avoid under- and over-modulation of an optical transmitter that might cause electrical signal chirping. There is a trade-off between a chirp and the extinction ratio, which affects the system performance and other parameters. To state a minimum value for ER, the optical power levels of “0” and “1” need to be accurately determined. It typically expresses ER as:

$$ER = 10 \log \left(\frac{P_1(t)}{P_0(t)} \right) \qquad \text{Equation (4.2)}$$

where $P_1(t)$ is the average optical power level of the logic 1 and $P_0(t)$ is the average optical power level of the logic 0 levels. As the extinction ratio (ER) improves, the bit-error ratio (BER) improves, reducing the number of errors. When the “1” and “0” steady-state power levels are closer together than they would be for a cleaner wide-open eye diagram. The ER value is smaller, decreasing the BER, and diminishing the benefit of increased output power associated with increasing the bias and drive current. The eventual constraint is the reduction in receiver sensitivity as shown in figure 4.2. The figure shows the results of this effect at a fixed bias of 5 mA, while varying the modulation drive current from 1 mA to 6 mA in 1 mA increments.

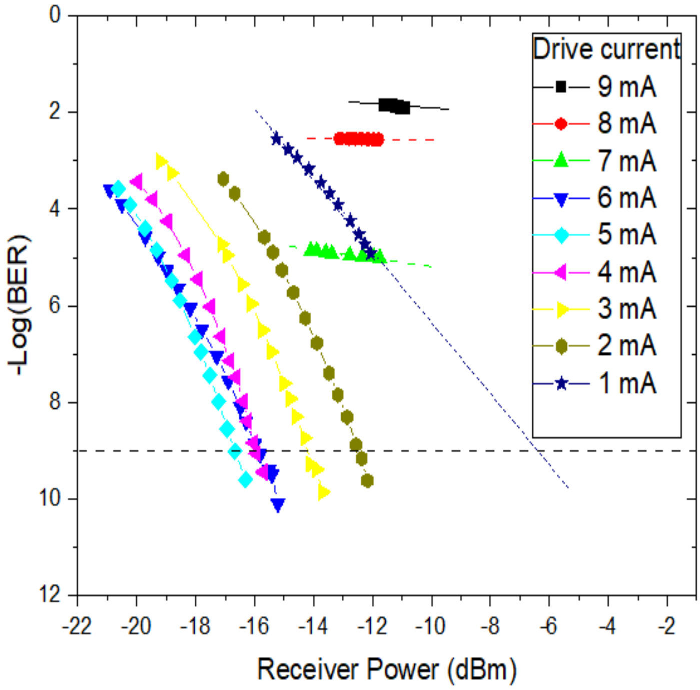


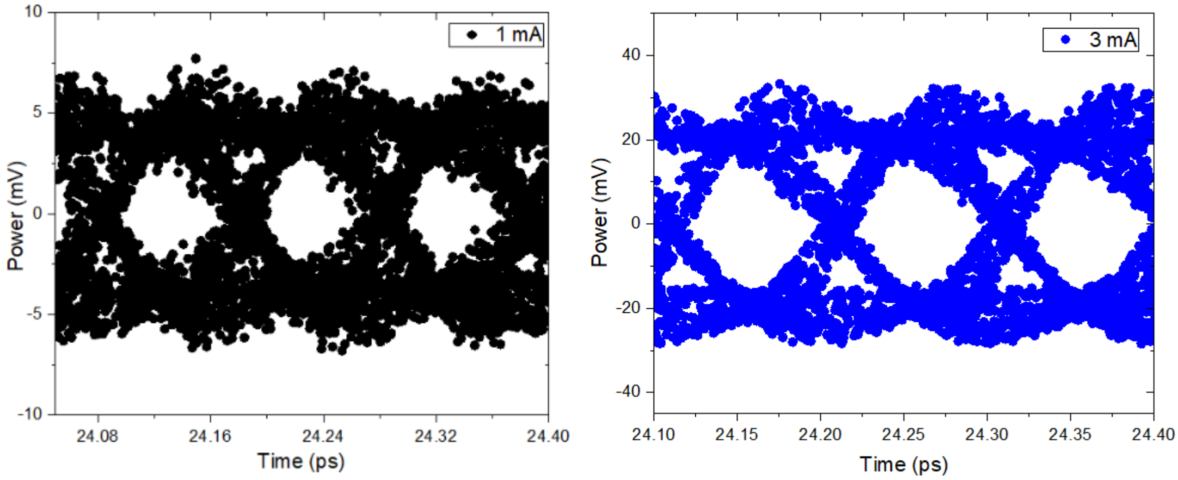
Figure 4.2: BER measurements showing receiver sensitivity at a bias of 5 mA and different modulation settings

The BER curve measurements were used to test the back-to-back transmission at ideal bias points under different drive currents of the input signal used for modulation. This was done to determine the receiver sensitivity level for optimised optical transport network performance. The BER curve measurements to optimise the modulation depth (drive current) demonstrate the best receiver sensitivity of -16.41 dBm at 5 mA drive current in the optimal modulation conditions. At drive currents higher than 6 mA the BER of the signal could not reach the error floor due to electrical signal chirping. Despite the high output power associated with high drive current and high modulation depth, it should match the swing current for better BER performance.

As network operators intend on transmitting higher data rates over an optical transport network, it increases the probability of receiving an error bit in the data stream. This results in the "0" and "1" power levels being closer together than they would be for a cleaner eye, resulting in lower ER values. This effect is known as a power penalty and can be expressed as:

$$P_{penalty} = -10\log\left[\frac{(ER-1)}{(ER+1)}\right] \qquad \text{Equation (4.3)}$$

Extinction ratio (ER) provides the optical signal with a common characterization metric for all users, basing it on the minimum value stated in the optical standards and recommendations, including ITU-T G.691, G.957, and G.959.1. These standards and recommendations control the characteristics of the optical transmitter signal as specified by the eye diagram shape such eye-opening, overshoot and undershoot limitations as to prevent excessive degradation of the receiver sensitivity. We define receiver sensitivity as the minimum acceptable value of average received power to achieve a 1×10^{-9} BER in back-to-back transmission configuration.The quality of the 10 Gb/s directly modulation data signal from the 1550 nm optical transmitter can be analysed using sampling oscilloscope to measure eye diagrams as shown in figure 4.3. The back-to-back error-free transmission at bias current 5 mA of the VCSEL for different drive currents corresponding to the receiver sensitivity on BER curve measurements. This allows for further characterization and optimisation of the VCSEL as an optical transmitter in high-speed transmission technology such as advanced modulation flexible spectrum optical transmission networks.



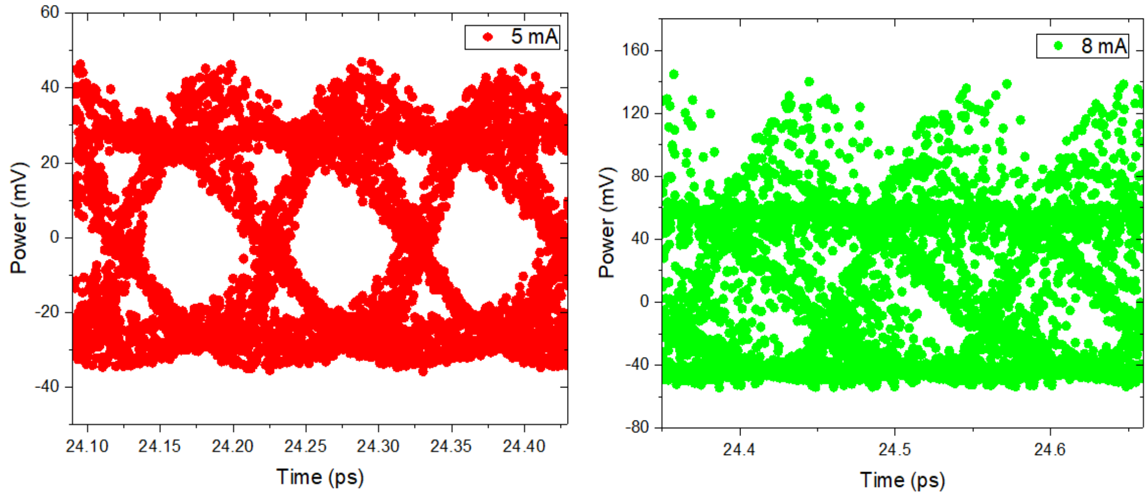


Figure 4.3: Eye diagrams for an optical signal with a bias current of 5 mA for different modulation drive currents, as marked. ***Note that the Power axes are plotted on different scales.***

At low driving current, the setup demonstrates clear, open and wide eye-diagrams meaning the receiver can distinguish between the 0 and 1 levels, although the extinction ratio is low. At a drive current of 1 mA the eye is slightly closed and a receiver sensitivity of -11.49 dBm was obtained; this corresponded to extinction ration of 1.109 dB. This value is below the acceptable power penalty which is in the 2 to 4 dB range, a typical margin according to the standards and recommendations for a beginning of-life, nominal temperature receiver and its end-of-life, worst-case counterpart.

As we increased the drive current to 3 mA, the eye diagram appears clearer with a receiver sensitivity of -13.91 dBm and an extinction ratio of 3.340 dB. At a drive current of 5 mA, the receiver sensitivity of -16.41 dBm was obtained this corresponded to an extinction ratio of 5.067 dB with a clear, open and wide eye-diagrams. As we increased the drive current to 8 mA, the eye diagram appears less clearer with a receiver sensitivity of -11.4 dBm. Though an extinction ratio of 9.136 dB was obtained the eye diagram is closed and there is an overshoot due to electrical signal chirping. At high drive current, the extinction ratio is high, but the eye is closed from received error-bits and there is an overshoot going above the 1 level, this means the power levels will not be distinguishable at the receiver end thus affecting how the system performs. A drive current of 5 mA the eye is open, and the extinction ratio is high, which implies that the modulation conditions are ideal for the system.

Furthermore, we conducted experiments to analyse the different bias and drive current combinations to establish the optimised receiver sensitivity as shown in figure 4.4. We performed this in a back-to-back (B2B) configuration using the VCSEL and at 25 km transmission over a G.655 optical fibre to analyse the effects of the lightpath impairments on the signal. A 3D surface was obtained and a domain that can be used to identify the region of optimum quality of service (receiver sensitivity) as a function of bias current of the signal carrier and the modulation conditions (drive current) of the data all to be transmitted.

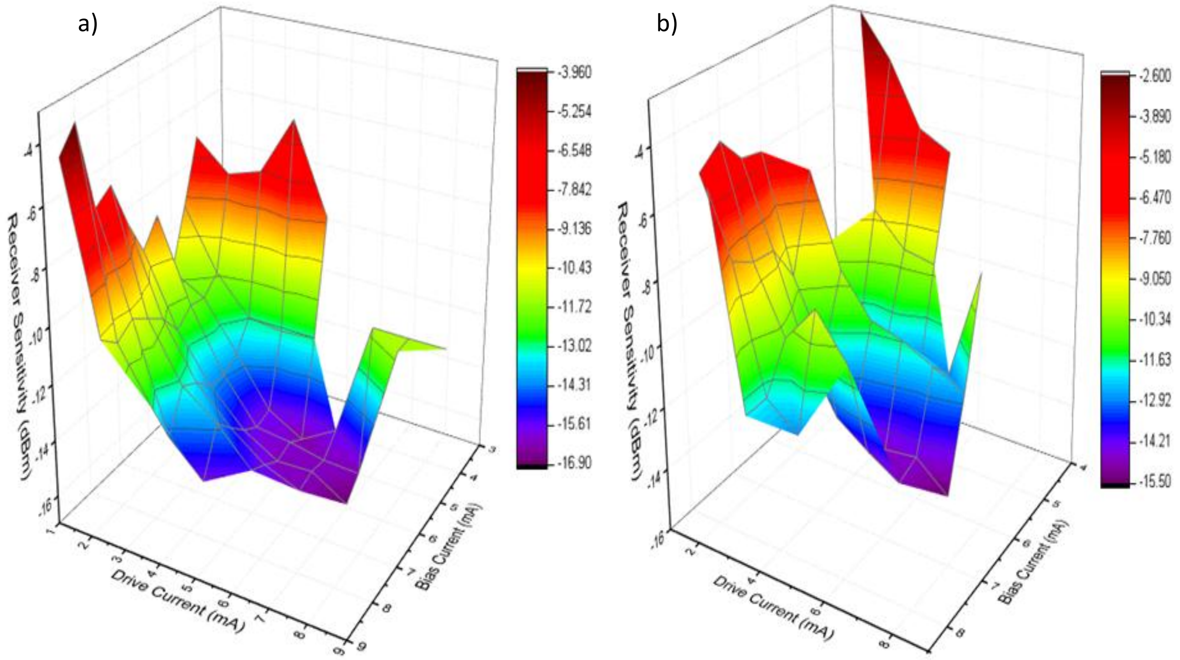


Figure 4.4: receiver sensitivity for VCSEL at different bias and drive currents a) back-to-back analysis and b) 25 km transmission

The laser exhibits linear optical power and bias current relationship for bias points after threshold and before saturation, this is the ideal region for operating for VCSEL. In this region, a finite range of bias and drive current combinations were used to investigate the receiver sensitivity producing a domain as a 3D surface map which can analyse how the system performs as shown in figure 4.4 (a). For bias points in the range 5-7 mA, bias current and modulation between 4-7 mA drive current the best receiver sensitivity was observed. The frequency difference between steady-state "1"s and steady-state "0"s power levels is relatively low and power ratio within in acceptable optical ITU-T G.691, G.957 and G.959.1 standards and recommendations there were obtained limiting VCSEL chirp, hence low penalties. The domain of the 3D colour Receiver Sensitivity surface map maintains the same shape upon 25 km transmission, with the reduced area due to the 5.8 ps/(nm.km) dispersion at the 1550 nm wavelength experienced by the signals that result in bit-errors as seen in figure 4.4 (b). At the extremities the system could not achieve error-free transmission and for known network reach the surface can work out the penalty for the transmission. For optical transmitter to exhibit signal a clear, wide and open eye diagram shape with reduced overshoot and undershoot the workable operating range for bias current and modulation drive current was limited to 5-7 mA and 4-7 mA respectively to prevent excessive degradation of the receiver sensitivity. For 25 km transmission over G.655 standard single-mode optical fibre, the power penalties were within the acceptable range in these optimum operating points, thus optimisation technique was successfully demonstrated experimentally.

To further analyse the optical transmitter, we measure eye diagrams at different bias and drive currents to examine the receiver capability to distinguish between the “0” and “1” levels for the back-to-back transmission, this was presented as extinction ratio as seen in figure 4.5(a). The domain of the 3D colour extinction ratio surface map reflects that there is a finite range of bias and drive currents within which the VCSEL can safely operate. As expected, a high drive current results in a high extinction ratio. At low driving current, the eye is open, meaning the receiver can easily distinguish between the 0 and 1 levels, although the extinction ratio is low. At high drive current, the extinction ratio is high, but the eye is closed and there is overshoot going above the 1 level. This is the effect due to chirp, where direct intensity modulation of high-speed lasers coupled to the phase variation through the linewidth enhancement factor induces a time variation in the lasing frequency. This instantaneous change of wavelength with optical power variation means the power levels will not be distinguishable at the receiver end. Thus affecting how the system performs, this performance degradation includes limitations to the transmission bit rate, transmission distance, and addition to the power penalty of the optical fibre transmission system. The points in the linear region of the laser current-power characterization curve produced clear and wide eye diagrams corresponding to high extinction ratio (above 4 dB).

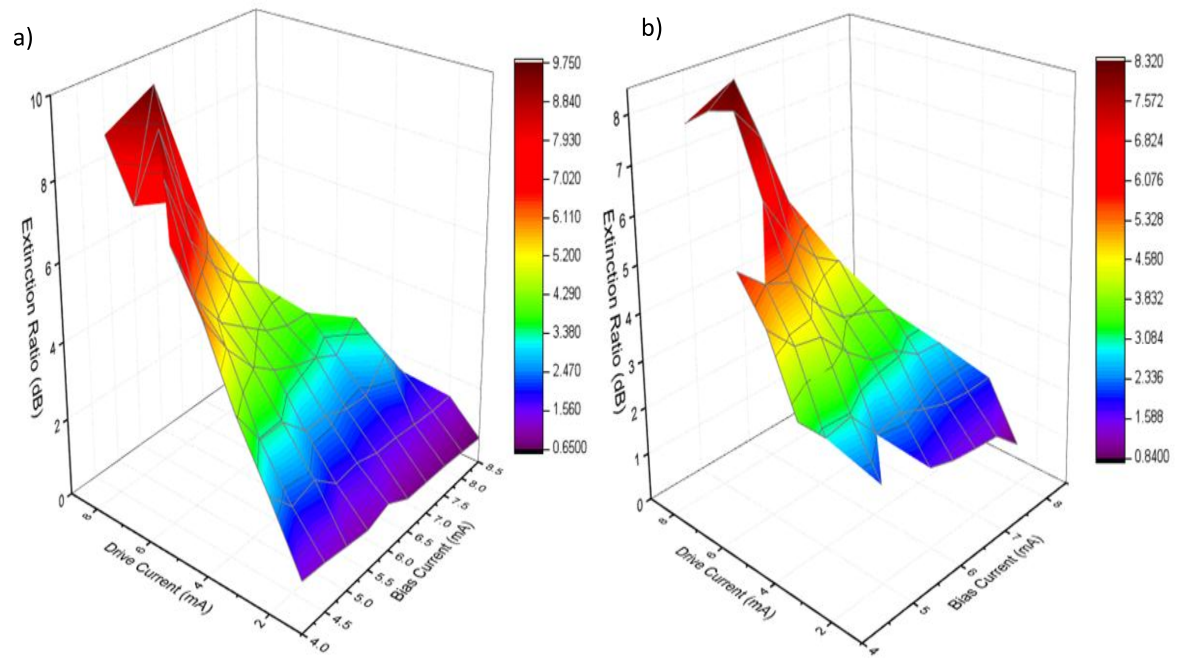


Figure 4.5: extinction ratio for laser at different bias current points as a function of drive voltage a) back-to-back and b) 25 km transmission

The domain of the 3D colour extinction ratio surface map maintains the same shape upon 25 km transmission, with reduced area as seen in figure 4.5 (b). This implied that the eye opening also reduced with a fibre transmission but remained clearly wide and open eye for successful error free at a communication threshold of BER 10^{-9} for the receiver to distinguish between the "0" and "1" levels. Therefore, error free transmission could not be achieved regardless of the high receiver sensitivity. Hence the extinction ratio can be used as an optimization technique thus it was also measured for both data back to back and 25 km transmission analyzing the Eye diagrams to qualitatively examine the VCSEL performance.

4.1.3 VCSEL Channel Switching and Wavelength Reassignment for efficient resource utilisation in flexible spectrum

Single mode operation of VCSEL technology make the optical transmitter an ideal candidate for advanced modulation flexible spectrum optical transmission networks. Since the transverse dimensions are larger than the effective cavity length in the longitudinal direction, standard design of a VCSEL leads to single mode operation with a side-mode. The output spectrum for VCSEL at stable single mode operation is shown in figure 4.6, demonstrating a >30 dB side-mode suppression ratio over the entire operating range of the VCSEL. As observed using an optical spectrum analyser where each coloured plot corresponds to a different bias point. The wavelength tunability of a VCSEL is exploited by varying the bias current, previously demonstrated in figure 4.1a) and b). The VCSEL lasing wavelength was tuned from 1548.5 to 1555.8 nm resulting in a 7.3 nm or 912.5 GHz spectral width by varying the bias current. A total of 9 continuous 50 GHz spaced WDM channels with non-overlapping nominal frequencies and uniform guard bands were generated.

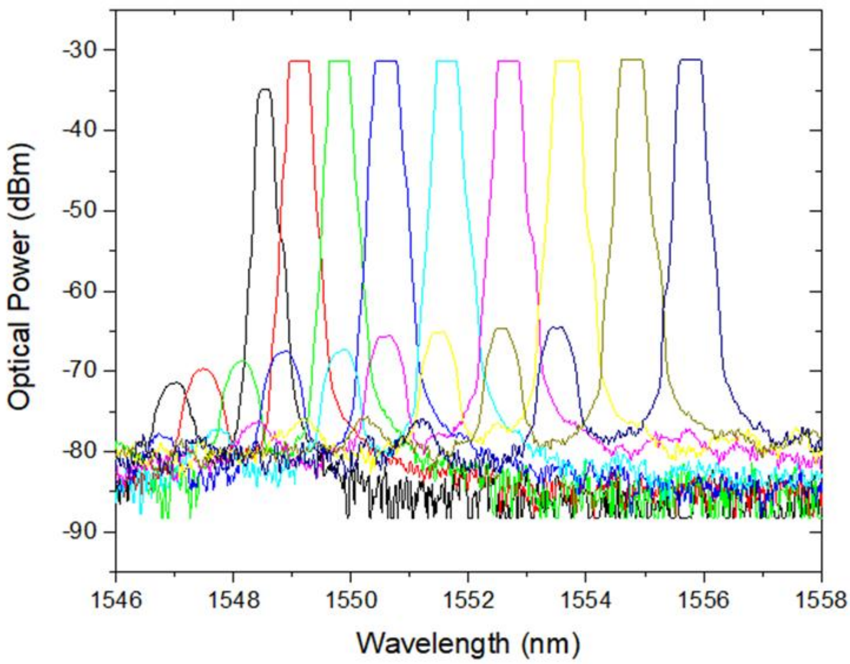


Figure 4.6: channel switching of VCSEL as a function of wavelength tunability

The VCSEL was biased at 6.5 mA with the dominant-mode seen to be at 1551.6 nm emitting an output power of -31.3 dBm and the side-mode at 1549.9 nm with -67.2 dBm output power. An inter-modal spacing of 1.7 nm (212.5 GHz) single-mode output power was observed with an SMSR of 36 dB without much change to the electrical properties of the device. The VCSEL laser cavity is current-driven and its wavelength can be tuned by using different drive currents. The two VCSELs exhibit similar characteristics emitting different wavelengths at different bias currents. We consider the wavelength tunability of two VCSELs at fixed channel spacing. Each VCSEL covers a finite wavelength band, with overlap of the two bands such that the wavelength coverage is continuous.

The lasers were selected such that the wavelength bands of the two VCSELs overlap so as to maximise the total spectral bandwidth. This improves network resource utilisation and resolves wavelength contention associated with flexible spectrum. The total continuous spectral bandwidth of the system consisting of the emission wavelengths achievable for the two VCSELs at different bias current points, was increased as shown in figure 4.7. The transmission performance of a VCSEL depends not only on its bias current, but the drive current/ modulation index is also a factor and should be considered. Despite wavelength tunability and increase spectral bandwidth of the VCSEL, certain operating points may give rise to unacceptable penalties. Hence, the quality of the signal was investigated at given bias points for different drive currents. This was done to quantify the extinction ratio and receiver sensitivity of the network for optimised transmission performance.

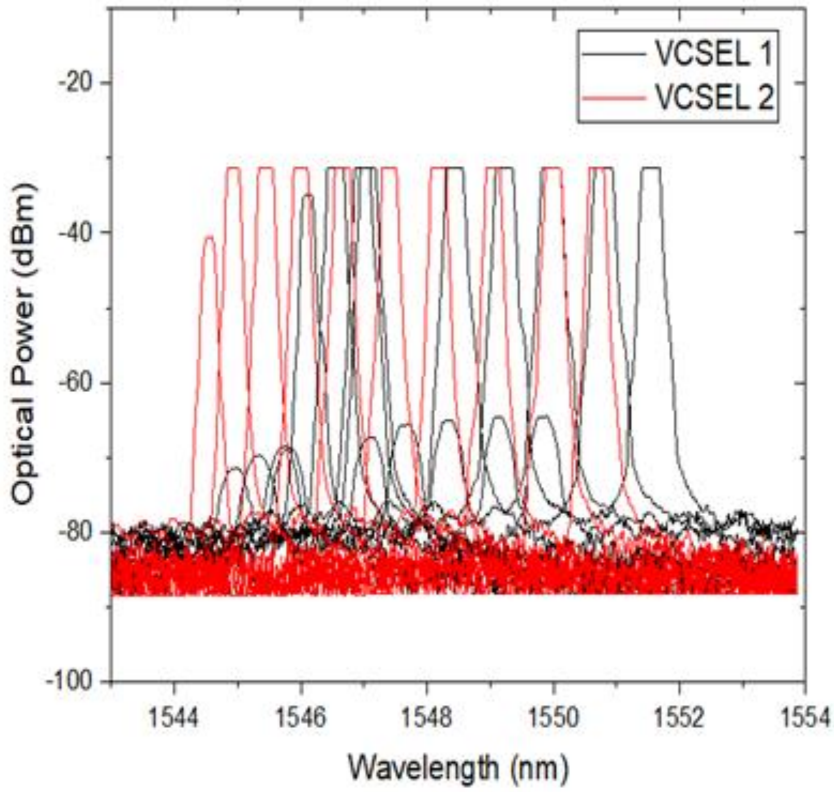


Figure 4.7: wavelength bands of the two VCSELs overlap so to maximise the total spectral bandwidth

Higher bias current implies high optical output power which corresponds to the longer wavelengths in the band achieved by biasing in the saturation regions of the current-output power characterization curve. This is detrimental for directly modulation flexible spectrum optical transmission networks to complete ON-OFF modulation swing to avoid signal distortion due to electrical signal chirping. Since the creation of non-uniform refractive index zones within the VCSEL optical cavity changes the effective optical path inside the cavity which manifests itself as undesired side-modes. An optical transmitter (master VCSEL) operating under optimal modulation conditions can be used to optically inject the side-mode of the laser (slave VCSEL) biased at the roll-over/saturation point. The optical power injection from the transmitted and received signal results in the energy transfer between the dominant modes and side-mode of the master and slave laser, causing data inversion on the transmission wavelength. This can transfer data signals with no demodulation, capitalisation on the power consumption and output (power budget) and efficiency on the resource utilisation as channel switching and wavelength reassignment for rerouting in flexible spectrum networks.

4.1.4 Experimental demonstration of VCSEL Channel Switching and Wavelength Reassignment for efficient resource utilisation in the flexible spectrum

In this section, we tuned the emission wavelength position of two VCSELs such that the bias points are in different conditions in the current-output power characterization curve. VCSEL 1 (master laser) was biased in the linear region such that upon being supplied with electrical bit stream it can complete ON-OFF modulation swing. It biased VCSEL 2 with a current that falls in the saturation region on the curve where high optical output power is expected at the expense of high signal distortion due to electrical signal chirping. The side-mode of the slave laser is within the optimised biasing and modulation condition for VCSEL 1 found between the two dotted green lines as shown in figure 4.8. In this region, the receiver sensitivity is high (between -16.41 to -11.39 dBm) and the extinction ratio is high (between 5.07 to 9.14 dB). These are ideal conditions for error-free transmission. For the channel switching to be successful and efficient wavelength reassignment to be achieved, the side-mode of the slave VCSEL and the dominant mode of the master VCSEL must be determined and be tuned to lase at the same wavelength for all-optical injection. This is to achieve wavelength switching from one channel to the next to satisfy the spectrum contiguity constraint associated with flexible spectrum networks for sufficient utilisation of spectral resources.

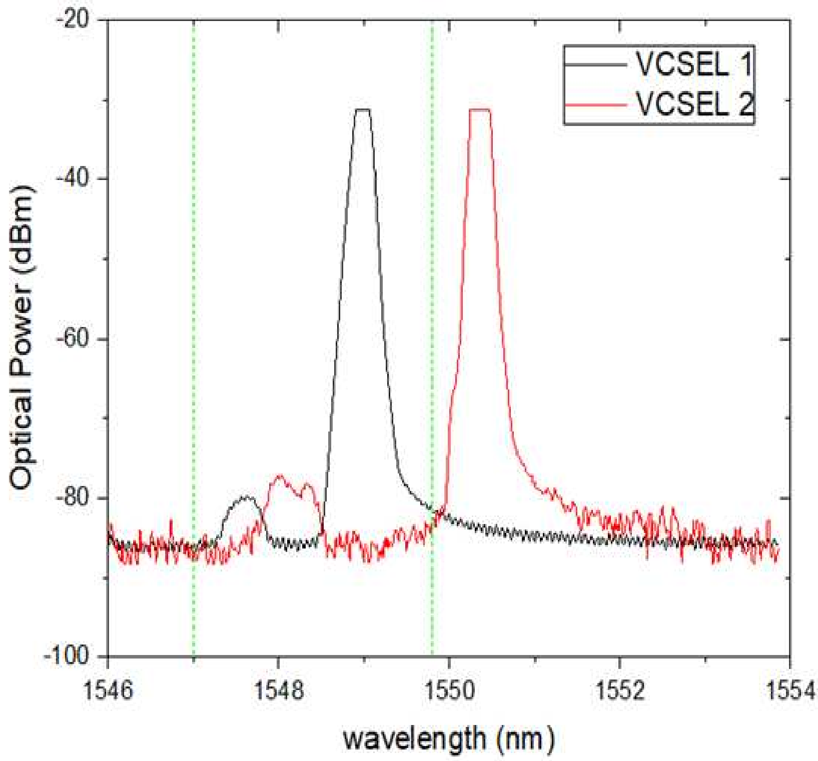


Figure 4.8: a) channel switching and b) band overlap of VCSEL as a function of wavelength tunability

In order to tune seamlessly across the combined spectral bandwidth of the two VCSELs, all-optical wavelength conversion through cross gain modulation can be performed. In this scenario, the intensity modulated master VCSEL is injected into the side-mode of a slave laser. As previously shown in figure 4.8, the normal operation lasing of the master VCSEL 1 was switched from a low side-mode and a high dominant mode, to a high side- and low dominant modes of slave VCSEL 2 due to the optical power injection. For direct intensity modulated laser the high dominant mode is the steady state "1" level while the steady state "0" is the low side-mode. VCSEL 1 at 5 mA bias current and VCSEL 2 was biased at 9.5 mA the saturation region, emitting a side-mode at 1548.17 mA which lines up with the dominant mode of the master laser. The intensity modulated signal carrying data (D) from the master laser changes the gain value of the semiconductor optical amplifier according to the gain saturation depending on the injection current applied. This configuration will function as an external modulator, optically stimulates the side-mode to oscillate within the fundamental gain medium transferring data signal to the side-mode of the slave VCSEL. Optical power is the injection from the master laser results in temporally switching "OFF" (suppression) of the dominant mode while the side-mode is switched "ON" (gain), and vice-versa. For sufficiently high optical power injection, the dominant mode is a "low" steady state "0" level and the side-mode is a "high" steady state "1" level. This results in an inverted data ($\overline{\mathrm{D}}$) replica of the input signal which is obtained at the target wave-length when data was used to modulate the master VCSEL. As a result, wavelength conversion takes place with the slave VCSEL transmitting the inverted data stream of the master VCSEL as will be elaborated in more detail in the following section.

With increased injection input power there is an energy transfer, the dominant mode of VCSEL 2 is suppressed and the wavelength conversion occurs with the data from VCSEL 1 transferred to the side-mode of slave laser. The quality of the VCSEL based optical injected converted data was determined using the BER measurements. At a bias current of 5 mA and drive current of 5 mV the intensity modulated VCSEL 1 dominant mode lases at 1548.20 nm and -3 dBm optical output power. This matches the side-mode wavelength of VCSEL 2 biased at 9.5 mA bias current with its dominant mode lasing at 1550.35 nm and an optical output power of -4.49 dBm. The dominant mode of VCSEL1 (master laser) carrying PRBS data from a PPG at 10 Gbps is optically injected to the side-mode of VCSEL 2. The BER curve measurements for the back-to-back transmission at these bias points was evaluated to determine the receiver sensitivity as seen in figure 4.9. Besides the optical output power of VCSEL 2 being higher than that of VCSEL 1, the receiver sensitivity is lower.

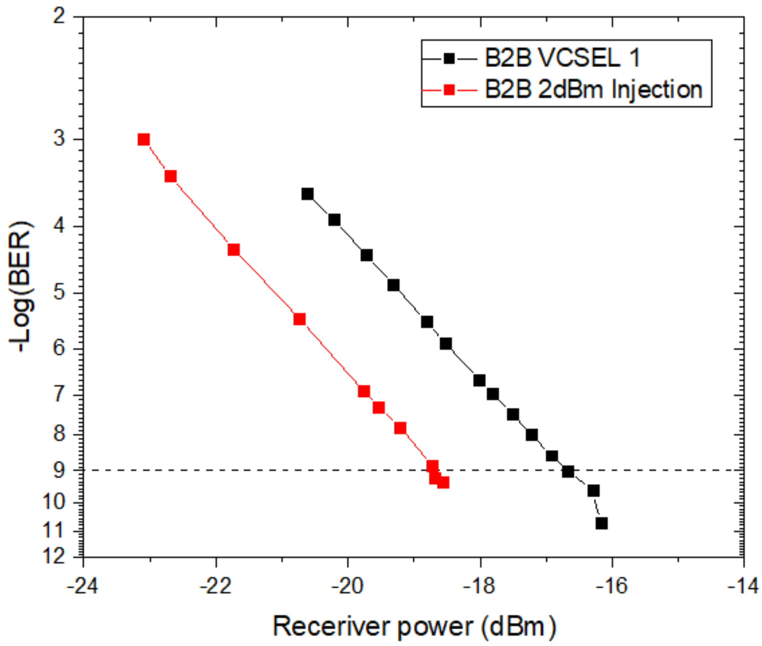


Figure 4.9: BER measurements showing receiver sensitivity before and after injection

To acquire the BER curve, we vary the optical power at the receiver end using a variable optical attenuator to match the optical loss that could be encountered in existing optical fibre transport network. The BER curve as the function of the decision threshold voltage is the ultimate performance measure of an optical transport network where a high-quality optical system with a large performance margin, the actual BER could be lower. The error-free receiver sensitivity at the BER threshold level for a VCSEL 1 was seen to be at -16.4 dBm while VCSEL 2 level had a -18.7 dBm for 2 dBm optical power injection was obtained experimentally for the back-to-back transmission. This is due to the applied current optimised on-off operation in the midpoint of current-output power characterization curve ability to complete swing that provides higher modulation index over VCSEL 2 biased at the saturation region. The receiver sensitivity of optical power injected VCSEL 2 for which the high side-mode represents steady-state “1” level inverted relative to the input signal provides 2.3 dB better quality of service compared to VCSEL 1 high dominant steady-state “1”.

The two binary levels of optical power used in optical transport networks to transmit data represent where the higher power level represents a steady-state “1” and the lower power level represents a steady-state “0”. At the receiver end, the optical power is converted to electrical current and then later to voltage, before it applies to the receiver decision circuit to determine the decision threshold. This is achieved by comparing the sampling voltage to a reference value say Vdt the decision threshold, thus if the sampling voltage is greater than Vdt steady-state “1” was sent if lower a steady-state “0” must have been sent. The decision-making threshold can be optimised for minimum BER, to take the optical signal-to-noise ratio to a useful form, thus attaining error-free signal transmission for a high-quality optical system with a large performance margin.

The BER as the function of decision threshold voltage measurement not only reveals the noise standard deviations associated with digital “0” and “1” as undershoot or overshoot; we can also identify eye closure penalty near the top and the bottom edges of the eye diagram. For an ideal clear, wide and open eye diagram the average power levels of steady-state “1” and “0” at the decision phase are equivalent to “1” and “0”, respectively. If a steady-state “1” is so distorted that the receiver at the far end of the optical transport network can misjudge it for steady-state “0”, it will be easy to discern this eye diagram. The respective back-to-back transmission eye diagram analysis for both VCSELs using the wide bandwidth oscilloscope was experimentally demonstrated as shown in figure 4.10. A clear, wide and open eye implies a successful error-free transmission. This also implies that the receiver could easily distinguish between the “1” and the “0” bits, therefore, minimising bit errors.

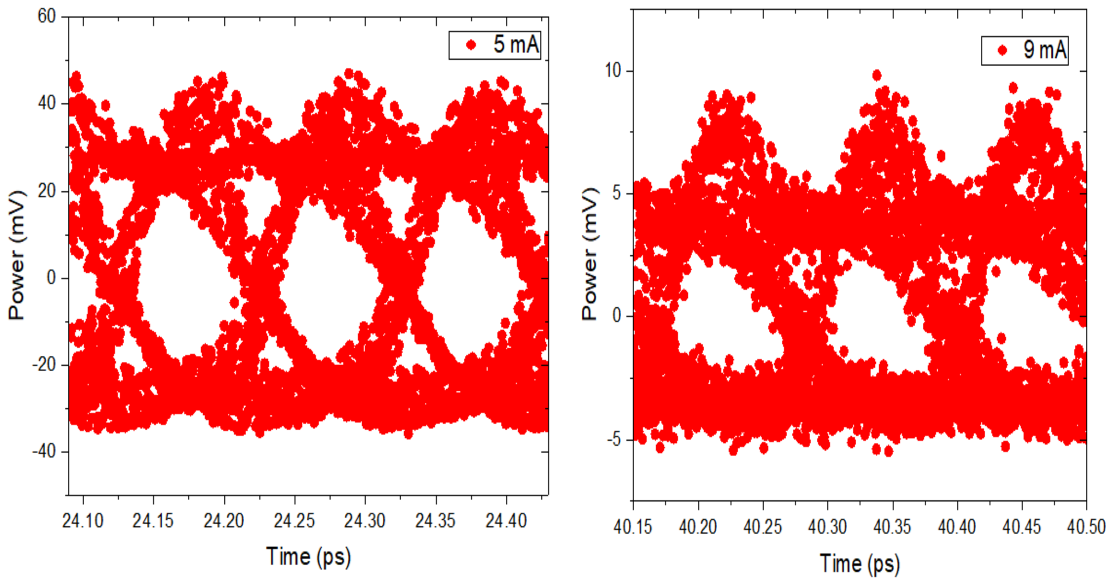


Figure 4.10: Eye diagrams for an optical signal modulated with a bias current of 5 mA VCSEL 1 and 2 dBm optical power injected VCSEL 2 at 9 mA

We conducted the measurements for the 10^{-9} BER threshold level for optical communication. For VCSEL 1 a clear, wide and open eye diagram is obtained, meaning the receiver can distinguish between the “0” and “1” levels with an extinction ratio of 9.136 dB. The decision threshold is sufficient for the receiver at the far end of the optical transmission network not to misjudge distorted and overshoot steady-state “1” for a steady-state “0” level, easily discerned from an eye diagram. For the inverted data back-to-back transmission from VCSEL 2, there is prominent overshoot going above the “1” level with 5.012 dB ER obtained, though power levels will be distinguishable at the receiver end the decision threshold was reduced as shown by the eye closure penalty and identified near the top edges of the eye diagram. At a reduced decision threshold, it increases the probability of making an incorrect decision in obtaining minimum BER, thus affecting how the system performs. A drive current of 5 mA the eye is open and the extinction ratio is high, which implies that the modulation conditions are ideal for the system. Small changes in extinction ratio can make a relatively large difference in the power required to maintain a constant bit error rate (BER), receiver sensitivity in the far end of the optical transport network. This application note shows how the optical extinction ratio is defined and demonstrates how variations in extinction ratio and receiver sensitivity affect the performance of optical communication systems, thus a domain was created as a 3-D surface for optimised low-cost directly modulated variable transceivers based on wavelength-tunable VCSEL as a function of modulation depth and bias current. The BER plot not only reveals the noise standard deviations associated with digital "0" and "1"; eye closure penalty can also be identified by looking at the BER curve near the top and the bottom edges of the eye diagram. Therefore, it can help to identify the sources of BER degradation in system design and development for application in high-speed next-generation WDM-PON based flexible spectrum networks.

4.2 Summary

The 3D surface colour map domain can be used to find the bias and drive current combinations for the VCSEL that will produce reasonably high extinction ratio, high receiver sensitivity and a wide-open eye. This we can use to control the modulation level of a channel to maximise the spectral bandwidth while maintaining the required quality of service as per end-user request. The optimisation method couples with the all-optical power injection wavelength conversion through cross gain modulation technique for efficient resource utilised. This customises bandwidth demand (as per end-user request) multi-node flexible spectrum network capable of wavelength reassignment and light path rerouting with consideration of the transmission impairments. The proposed wavelength conversion technique, with the VCSEL-to-VCSEL optical injection experimental demonstrations detailed discussion can be seen in the following section.

Chapter 5

5.0 All Optical side-mode Power Injection Based on Cross Gain Modulation for Wavelength Conversion application

The development of optical fibre communication systems architecture for long-distance data and signal transmission with large data capacity, high bit rate at low power consumption and cost-effective manner has become a necessary feature to transfer the exponentially growing volume of internet traffic. When planning transport systems, optical fibre network designers when planning transport system consider a high bit rate and long transmission distance without signal regeneration and efficient resource utilisation. Without necessarily converting to the electrical domain. However, this becomes problematic especially for directly modulated optical transmitters due to physical optics associated with lightpath impairments that result in signal distortion. The aim is to construct a cost-effective optical fibre network, using high-speed infrastructure, with VCSEL as the directly modulated data transmitter. This will operate within the low attenuation 1550 nm transmission window with flexibility degree of freedom, which is essential in the multi-node network. This can be achieved by considering the key elements of flexible spectrum which is the ability to dynamically assign transmission wavelengths for efficient utilisation of the spectrum and source to destination connection.

In this chapter, a novel technique for achieving purely all-optical side-mode power injection using a pair of directly modulated VCSELs operating at the low 1550 nm transmission window is developed. This will be used to achieve wavelength reassignment and routing, as some of the features of the flexible spectrum which are of crucial in reconfigurable multinode all-optical networks. In cross-gain modulation converters, the data can be transferred from one wavelength to another without optical-electrical-optical (OEO) conversion. The configuration for experimental demonstration of all optical wavelength conversion as performed in a laboratory test bed utilizes two tunable light sources. This was done to create transceivers capable of tracking each other for seamless wavelength switch and channel reassignment associated with flexible spectrum network. This makes the cross-gain modulation technique a simple and cost-effective all-optical conversion. In this work, the technique that was used for flexible spectrum optimization and wavelength switching as discussed below.

5.1 All Optical Power Injection Based on Cross Gain Modulation for Wavelength Conversion application

Optoelectrical converters are capable of achieving function by retransmitting incoming signals that have been detected onto a new wavelength. The major drawback of such devices is the large power consumption and electronic circuit complexity in high-speed networks operating at 10 Gbps and beyond. There are coherent converters that can handle all signal modulation formats such as four-wave mixing (FWM) using semiconductor optical amplifiers (SOA) which are dependent on the output wavelength of both the pump and input signal[21], [90]. However, wavelength converters based on FWM technologies have the ability to support all modulation formats contrary to other types which are only limited to intensity modulation. Moreover, FWM wavelength converters are ideal for ultrafast signal applications such as at bitrates above 100 Gbps. However, the main drawback of FWM wavelength converters is the dependency of the output wavelength on both the pump and signal wavelengths, so the pump must be tunable even with fixed output wavelengths. Consequently, two pumps are needed to ensure polarization insensitive operation. This therefore limits the network flexibility as well as its degree of freedom which is essential in a multimode network and a tunable pump will be required to even achieve wavelength conversion/reassignment at fixed output channels. In this section, a simpler all-optical wavelength conversion technique has been demonstrated in the NMU laboratory test bed. The conversion is performed by controlling a single master laser, launching its output signal into a tunable wavelength laser resulting in gain saturation used to manage the laser oscillation. The laser resonance frequency limits the speed and this is a major drawback for future optical networks expected to operate at speed beyond 10 Gbps.

In cross-phase and cross-gain modulation mode, semiconductor amplifiers are used as optically controlled gate converters[74], [91]. In cross-phase modulation (XPM), the converters the advantage is the dependency of the carrier density in the active region of the amplifier. The technique has drawbacks in systems needing intensity modulated output signals, which will require an interferometer as the output signal is phase modulated. In optical transport networks, to construct a cost-effective high-speed infrastructure, a directly-modulated semiconductor lasers, in this case, VCSELs, are deployed as data transmitters, which will generate optical data signals to be transmitted down a standard single-mode fibre. Due to chromatic dispersion and the signal chirping, the transmitted signal is prone to attenuation and distortion and by the time it reaches the receiver, it may have spread over several bit periods and causes detection errors. In this work we experimentally demonstrated a simple, cost-effective, and low power consumption technique to take the receiver signal and reuse the wavelength at a rerouted path without the need to modulate again, hence the technique that does not require optical-electrical-optical (OEO) conversion or any extra transceiver modules. The all-optical VCSEL-to-VCSEL wavelength conversion and transmission at the 1550 nm transmission window for high-speed optical NRZ modulated signals proposed does not only increase the total bandwidth, but it also changes the path of signal transmission which implies that the signal can be switched, wavelength reassigned or re-routed to a different path which is classed as efficient resource utilisation. This flexible spectrum functionality can be integrated to the 50 GHz fixed grid system high-speed optical devices to achieve better quality of service for 10 Gb/s data signals at the 1550 nm low attenuation transmission window.

All-optical wavelength conversion through cross gain modulation was used to seamlessly tune across the combined spectral bandwidth of the two VCSELs. The bands formed have the side-modes of slave laser wavelength overlaps with the dominant modes of the master laser. The intensity modulated master VCSEL is optically power injected to the side-mode of the slave VCSEL. This results in temporally switching “OFF” (suppressing) of the dominant mode while the side-mode is switched “ON” (gain), and vice-versa. As a result, wavelength conversion takes place with data transferred from one wavelength (already received optical signal upon transmission) to another wavelength (that was not being used awaiting modulation at the receiver end). The slave VCSEL transmits the inverted data stream of the master VCSEL. This allows for the converted data to be routed and the new wavelength be assigned to the next node for transmission in multinode flexible spectrum networks. In this way, a tunable transceiver is configured, capable of wavelength conversion, wavelength switching, wavelength reassignment and optical rerouting. To be implemented in a multimode optical system to support the dynamic traffic demands of next-generation flexible spectrum network based on wavelength division multiplex passive optical networks.

5.1.1 All Optical VCSEL-to-VCSEL Power Injection Cross Gain Modulation Based channel switching and Wavelength reassignment for Routing in Flexible Spectrum Network

All optical networks with routing and wavelength assignment capability have received extensive attention in flexible spectrum systems as they support dynamically varying traffic volume, managing the spectral resources efficiently[89], [92]. These networks have a centralized network management in a unified software-defined networking (SDN) controller platform. The SDN controller is responsible for channelization, bandwidth allocation, routing and wavelength assignment, end-to-end fibre connectivity and service restoration in case of fibre faults in any link. When planning the configuration for flexible spectrum network the designer must take topology, traffic matrix and physical layer models in to consideration as inputs. A typical multinode network consists of a transmitter/source (node 1) connected to the receiver/destination (node 3) via DWDM fibre links that propagate channels. The channel propagation occurs through colourless, directionless and contensionless reconfigurabilty links to route individual wavelengths from fibre to fibre across multiple nodes as shown in figure 5.1.

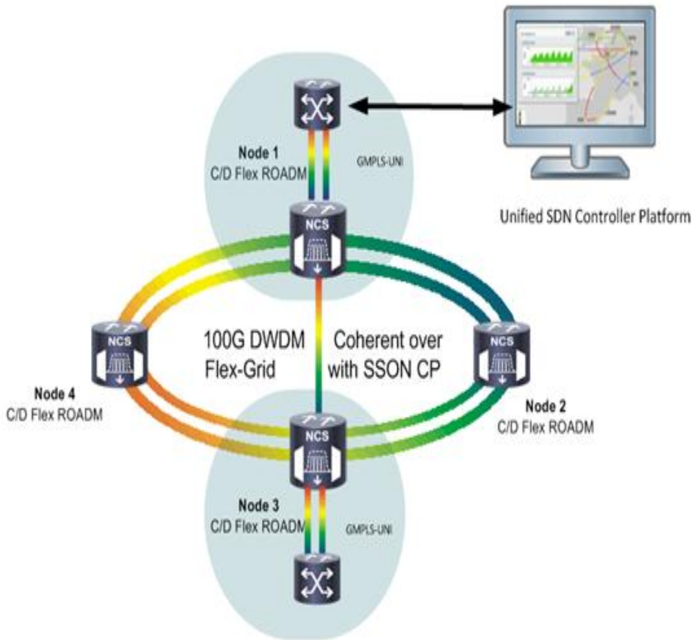


Figure 5.1: simple topology of the multinode network used for the experimental demonstration of bandwidth utilisation for the flexible bandwidth network [17].

These nodes have wavelength selective switch capability which can be used to convert optical signals from one wavelength to another for spectral efficiency and routing the user demands through spatial efficient lightpaths. This means that the multiple channels are transmitted using variable bandwidth transceivers through reach and capacity optimised links. The links accommodate each of the many arbitrary channels generated using one of the many possible modulation formats. Thus, the spectral and spatial flexibility in optical transport networks can be optimised in the network management system (SDN). This SDN controls the modulation level and modulation format of a channel according to maximise spectral efficiency while maintaining the required quality of service. Optical signals with high spectral efficiency are highly sensitive to physical layer impairments, this is seen as a bit error rate rise or degradation of the signal to noise ratio of the affected optical link.

5.1.2 Experimental Demonstration of All Optical VCSEL-to-VCSEL Power Injection Cross Gain Modulation Based Wavelength reassignment for Routing in Flexible Spectrum Network

Wavelength collision and fragmentation negatively affects the resource utilisation in flexible spectrum optical networks as it reduces the number of usable wavelength bands in the available spectral bandwidth. Various wavelength conversion techniques have been presented in WDM systems to effectively minimise this effect without assigning extra bandwidth by adding more components. The components includes devices such as flexible-rate transponder and a bandwidth-variable wavelength cross-connect made the optically routed transparent interconnected networks feasible without undergoing optical-electrical- optical (OEO) regeneration[74], [84]. The Centre for Broadband Communication research group at Nelson Mandela University, has experimentally demonstrated an all optical VCSEL-to-VCSEL wavelength conversion technique for transmission at low attenuation 1550nm window[6]. The technique was further studied and used to experimentally demonstrate all optical injection for spectral efficient utilisation through defragmentation and wavelength switching on a cascade of VCSEL successfully. This was explored further for transmission application in routing and wavelength reassignment capability in every node of an interconnected multi-node flexible networks as shown in figure 5.2.

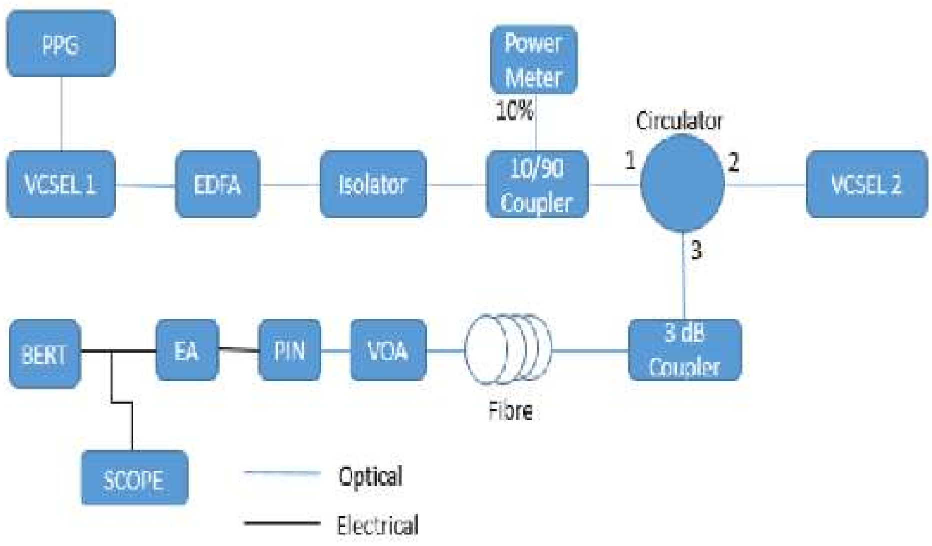


Figure 5.2: All optical VCSEL-to-VCSEL wavelength conversion scheme[6]

The all-optical VCSEL-to-VCSEL wavelength conversion technique was proposed by the Centre for Broadband Communication research group at Nelson Mandela University in a paper accepted for the International Photonic West SPIE OPTO Conference. This design was further developed and presented as a research article with Hindawi International Journal of

Optics [5], [6]. In this demonstration, a 10 Gbps 1550 nm single mode VCSEL 1 (node 1)with a wavelength tunability range of 5.2 nm was directly modulated at 8.5 Gbps by a non-return-to-zero (NRZ) pseudo-random binary sequence (PRBS $2^7 - 1$) from a programmable pattern generator (PPG). The PPG was used to vary the modulation conditions to match the desired drive current. Biased at 5 mA with a drive current of 5 mA lasing at 1548.20 nm wavelength with -3 dBm optical output power, the master laser was optically injected to the side-mode with similar wavelength of VCSEL 2 biased at 9.5 mA current with a dominant mode lasing at 1550.35 nm with an optical output power of -4.49 dBm.

To provide sufficient optical power for the gain saturation in the laser cavity of VCSEL 2, an Erbium-doped fibre amplifier (EDFA) was used to increase the injection power by amplifying the output power of the master laser. The wavelength conversion at 2 dBm optical power injection was considered. An optical isolator was used to prevent both the backscattered and back-reflection of the injected beam to protect the EDFA. For accurate power monitoring a 10/90 coupler was used, where 90 % of the optical power was directly injected to the 1548.20 nm side-mode of the slave VCSEL 2 through port 2 of the circulator and the 10% monitored via a power meter. The inverted data signal from VCSEL 2 (node 2) as a result of all optical injection routing and wavelength assignment is emitted through port 3 of the circulator for transmission over 25 km G.655 optical fibre. The destination (node 3) consist of a variable optical attenuator (VOA) which can be used to build a configuration representing the power loss of different fibre lightpaths similar to that of multi-node networks. A positive intrinsic negative (PIN) photodiode of known error free receiver sensitivity ~ -19 dBm at 10^{-9} BER threshold. An electrical amplifier (EA) was used to amplify the signal to meet the operation requirement of the measuring and analysing equipment. A bit error rate tester (BERT) was used to measure the extinction ratio (ER) and receiver sensitivity. This was used to analyse the quality of the data and inverted data signal at the given modulation measured as bit error rate (BER) curve and eye diagrams.

5.1.3 VCSEL-to-VCSEL channel switching and Wavelength reassignment for Efficient Resource Utilisation in Flexible Spectrum Network

To demonstrate the channel switching and wavelength reassignment within the 1550 nm transmission window, an incoming dominant mode of master VCSEL 1 was used to optically power inject the side-mode of the slave VCSEL 2. At the given wavelength, VCSEL 2 bias current was set at 9 mA, this is the point of high bias current and saturated output power region. The side-mode of VCSEL 2 lies in the optimised region of VCSEL 1, which can be tuned to lase at the same wavelength for all optical power injection. This is to achieve channel switching from one wavelength to the next to satisfy the spectrum contiguity constraint associated with flexible spectrum networks, wavelength reassignment and lightpath rerouting for sufficient utilisation of spectral resources.

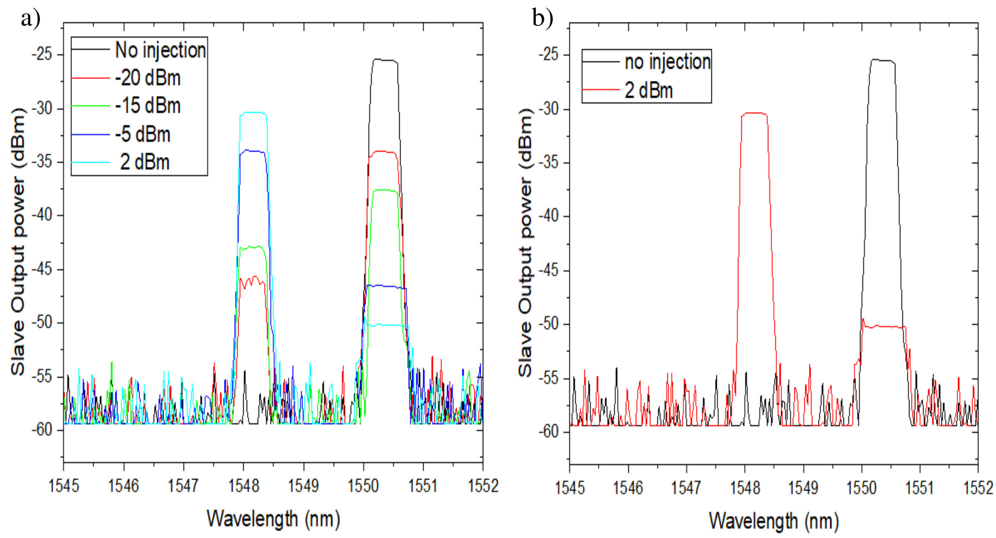


Figure 5.3: Dominant mode suppression at different optical power injections

At a bias of 5 mA and drive current of 5 mV the intensity modulated VCSEL 1 has a dominant mode that lases at 1548.20 nm with -3 dBm optical output power. This matches the side-mode wavelength of VCSEL 2 biased at 9.5 mA current with its dominant mode lasing at 1550.35 nm and an optical output power of -4.49 dBm. The dominant mode of VCSEL1 (master laser) carrying PRBS data from a PPG at 10 Gbps is optically injected to the side-mode of VCSEL 2. With increased injection input power there is an energy transfer as shown in figure 5.3a). The dominant mode of VCSEL 2 is suppressed and the wavelength conversion occurs with the data from VCSEL 1 transferred to the side-mode of slave laser. A sufficiently high optical power injection on to the side-mode of the slave VCSEL significantly suppresses the dominant mode as shown in figure 5.3b). This demonstrates the side and dominant mode of the slave VCSEL before and after the 2 dBm optical injection from the master VCSEL. The quality of service for the two VCSELs based optical injected data conversion was studied to further analyse the optical signal transmitters and transmission line performance, such as extinction ratio, dispersion, chirp, bit-error-rate, power penalty.

The dispersion induced optical signal distortion is the major impairment limiting the reach of transmission lines. In directly modulated laser this reach is ~ 100 km transmission distance in single mode fibre with a typical margin of >2 dB dispersion induced power penalty. In the previous chapters the effects of chirp on the optical signal propagations have been discussed, i.e. it is the instantaneous change of wavelength with optical power variation, resulting in time dependent instantaneous frequency changes and consequently different group velocities.

Thus the optical signal transmitted over single mode fibre broadens resulting in intersymbol interference and a significant chirp induced power penalty. The interaction of conventional standard single mode fibre positive dispersion with positive chirp present in directly intensity modulated lasers deteriorates the optical signal and sets a limit in the maximum achievable transmission distance. The bias current and drive current for the direct intensity modulated laser can be set to achieve positive chirp, this paired with negative dispersion can increase transmission distance relative to the single mode optical fibre.

A nonzero dispersion-shifted fibre (NZDSF) with negative dispersion was introduced to take advantage of the positive chirp characteristics of low-cost tunable transceiver configuration to be used in flexible spectrum with optimised transmission distance in optical transport networks. The NZDSF G.655 compliant fibre has an average dispersion of typically -3 and -8 ps/nm/km in the L and C band, respectively[90],[93], [94]. This dispersion-optimised optical fibre can eliminate the need for dispersion compensation and will enable the introduction of WDM-PON technologies as ideal solutions. This technology is implemented in elastic next-generation networks capable of handling extremely high data rates of the kind produced by MeerKAT and SKA in a flexible, adaptive and self-optimising manner. The result in this case will be, to some extent, signal restoration and significant transmission performance improvement is expected.

For the VCSEL to produce an ideal signal the drive current should be operated in the region just above threshold where the VCSEL starts lasing and just below saturation of the output power (roll over). For the given VCSEL, the optimal modulation conditions are seen at 5 mA bias and 5 mA drive current with receiver sensitivity of -16.41 dBm. This was used as the ideal modulation setting based on the desired quality of service (acceptable receiver sensitivity of the system) for lightpath rerouting and wavelength reassignment, for error free transmission measured at 10^{-9} BER threshold for data and the converted (inverted) data as shown in figure 5.4. The bit error rate measurements were performed for the slave VCSEL capability to transmit data upon the wavelength reassignment over 25 km G.655 optical fibre. This was compared to the original data from the master VCSEL transmitted over the same reach optical fibre link.

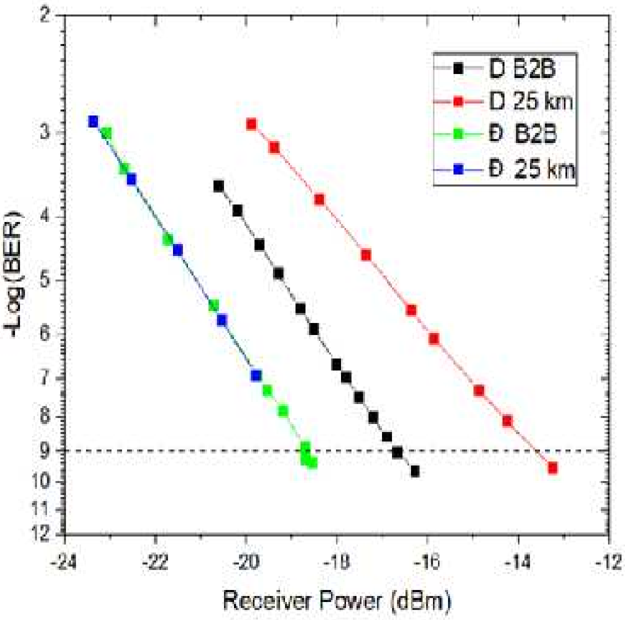


Figure 5.4: BER measurements showing receiver sensitivity for data (D) and inverted data (Ð) back-to-back and 25 km transmission

The BER measurements at a 10^{-9} threshold for the back-to-back analysis using VCSEL 1 is compared to the inverted data of VCSEL 2 after the wavelength conversion. For an optical injection power of 2 dBm, the wavelength converted receiver sensitivity was -18.71 dBm compared to the -16.41 dBm observed for the back-to-back data transmission of the master laser. As a result, optical injection not only switches the wavelengths but also improves the receiver sensitivity by 2.3 dB. For VCSEL 1, data carrier a receiver sensitivity of -9.19 dBm was measured for the back-to-back analysis and -11.39 dBm was measured for the 25 km fibre transmission resulting in a 2.2 dB power penalty. G.655 is a nonzero dispersion-shifted fibre (NZDSF) with negative dispersion that was paired with a direct intensity modulated optical fibre with positive chirp. Then the frequency components of the leading edge of the signal will be blue-shifted and the trailing edge red-shifted. The signals are transmitted over a negative dispersion fibre then the blue-shifted components of the signal will have a smaller group velocity and the red-shifted components will have a larger one.

Upon the all optical injection onto VCSEL 2 the inverted carrier demonstrated a receiver sensitivity of -18.71 for a back-to-back analysis at the threshold and no error free performance for 25 km inverted data transmission.

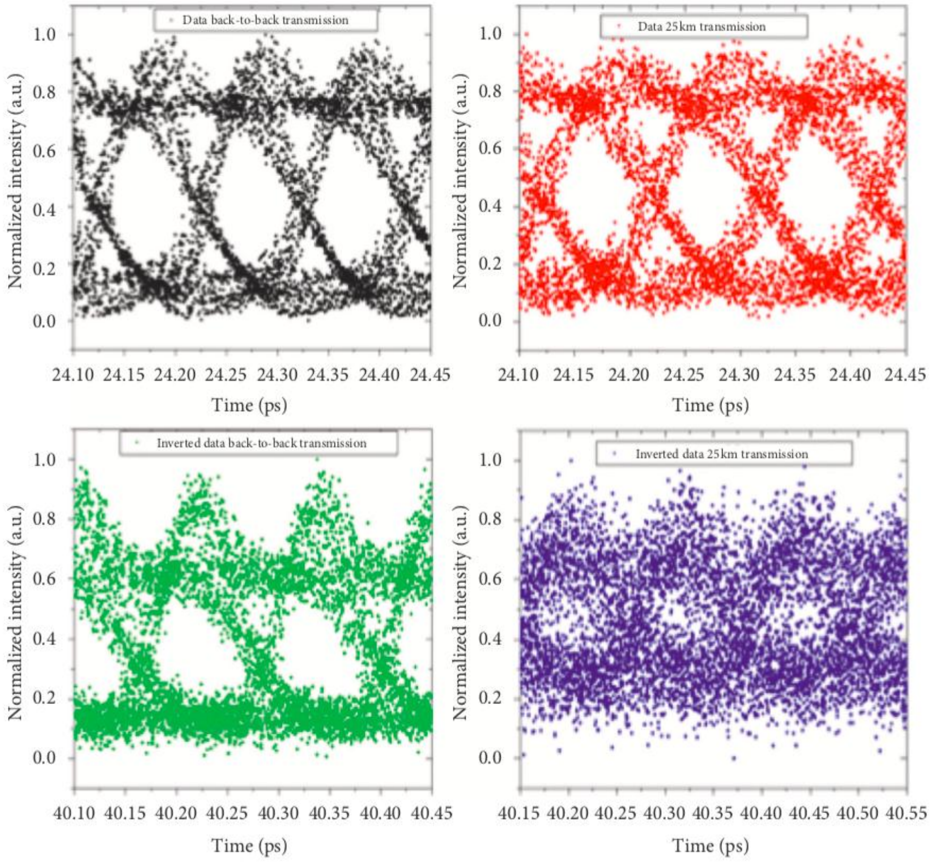


Figure 5.5: eye diagrams for each of the represented (BER) curves for data (D) and inverted data (Đ) back-to-back and 25 km transmission

For data transmission using VCSEL 1 without conversion and inversion the eye is open, meaning the receiver can distinguish between the "0" and "1" levels and extinction ratio of 9.136 dB obtained, as shown in figure 5.5. Upon 25 km transmission the eye was distorted and the extinction ratio reduced to 8.034 dB. Although power levels will be distinguishable at the receiver end, the decision threshold was reduced as shown by the eye closure penalty of the eye diagram. This implies that the eye diagram opening reduced with optical fibre transmission but remained clearly wide and open at Back-to-Back and after fibre transmission, an indication of successful error free transmission. For the inverted data back to back transmission from VCSEL 2 there is overshoot going above the "1" level with 5.012 dB ER obtained. This means the power levels will not be distinguishable at the receiver end thus affecting the performance of the system as the bit errors are maximised. Upon 25 km transmission the eye was highly distorted and closed with the extinction ratio reduced to 2.854 dB. At reduced decision threshold, probability of making an incorrect decision in obtaining minimum BER is increased thus affecting the performance of the system. Hence the extinction ratio can be used as an optimization technique thus it was also measured for both data back-to-back and 25 km G.655 optical fibre transmission analysing the Eye diagrams to qualitatively examine the VCSEL performance.

5.2 Summary

In this work, a novel experimental demonstration was performed at the CBC in NMU laboratory test bed to illustrate lightpath rerouting and wavelength reassignment based on all optical VCSEL-to-VCSEL Power Injection Cross Gain Modulation. This channel conversion and switching was demonstrated in the 1550 nm low attenuation transmission window using two low power consuming tunable VCSELS. The master laser, VCSEL 1 was biased and modulated in the ideal conditions to obtain a perfect swing. The slave laser, VCSEL 2 was poorly biased at the point of high bias current and saturated output power region. The incoming dominant side of the master VCSEL is optically power injected to the side-mode of the slave VCSEL. For all the incoming wavelengths, the dominant modes were suppressed while lasing the side-modes when the injection power was increased. A significant reduction in the output power of the dominant mode was observed after an injection power of 2 dBm. The data transmission of the incoming signal is received, transferred to the slave VCSEL resulting into data inversion which can be used for further transmission without the need of modulation. The PPG was used to vary the modulation conditions to match the desired drive current. In this way a bandwidth variable transceiver was simulated with the capability to adjust the transmission bitrates and modulation formats depending on the traffic demands. The bit error rate measurements were presented for the original 10 Gb/s signal data and the inverted data for back-to-back and 25 km G.655 optical fibre transmission. For Flexible spectrum with optimised transmission distance in optical transport networks (OTNs), adapting lightpath rerouting and wavelength reassignment techniques to attain realistic transmission distances with penalties at the acceptable bit error rate (BER) and minimizing the number of transceiver, thus achieving efficient utilisation of resources.

The next chapter expands on efficient utilisation of resources, introducing an intelligent way of wavelength management for WDM channels that can be implemented at the node of a flexible spectrum network made up of VCSEL transmitters. In a typical deployment, optical add and drop multiplexer (OADM) enable remote control of add and drop wavelengths at each node while ensuring that addition of any wavelengths does not affect the existing channels at that node. A Fibre Bragg Grating based OADM is presented, with details on the FBG inscription methods, operation principle, and current application.

Chapter 6

6.0 Introduction to Fibre Bragg Gratings

In recent years Fibre Bragg Gratings have generated great interest due to their many applications including structural health monitoring and optical transport network. These are based on the diffractive mechanism used as in-fibre filters for sensing and communication. The advancements of the Fibre Bragg Gratings have improved and reshaped the optical fibre technologies further revolutionizing the communication field making possible high quality, high capacity and long-distance optical transport networks through related components for better resource utilisation. Not only have there been improvements in optical fibre gratings manufacturing and advancements in the field in general, but has solved the challenge to integrate basic optical components such as mirrors, wavelength filters, and partial reflectors with optical fibre. This came with the ability to change the refractive index of core in a single-mode optical fibre by absorbing ultraviolet light. This fabrication of phase structures directly to the core of the photosensitive optical fibre is called Fibre Bragg Grating. This permanent change in the refractive index of the optical fibre has wavelength and intensity characteristics that depend on the material of the core. The Bragg gratings can be classified depending on their period as either short Bragg grating or long period grating relative to the operation, manufacturing and sensing characteristics depending on the refractive index. The main properties of the Fibre Bragg Grating; classification and the inscription methods will be thoroughly discussed. The Fibre Bragg Grating can perform many primary functions such as reflection and filtering, in a highly efficient, low loss manner. The main focus of this chapter is a comprehensive review of Fibre Bragg Gratings effect in an optical fibre as a passive component to provide channel management and efficient spectral utilisation in flexible spectrum optical transport network.

6.1 Classification of Fibre Bragg Grating for telecommunication

The Fibre Bragg Grating is made by engraving the optical fibre resulting in a change in the refractive index at these locations compared to the remaining silica glass. Fibre gratings refer to periodic structures that change according to the refractive index of the core of the photosensitive optical fibre. By controlling the engraving, a desired geometric pattern is produced and hence the desired refractive index for an individual grating is achieved. The diffraction gratings correspond to a periodic modulation that satisfies a phase-matching condition between a guided mode and the core, cladding or radiation modes[95]. This is to say that the modulation index of the Bragg grating has a physical spacing which has half the wavelength of the light propagating in the waveguide resulting in incoherent back reflection. The Fibre Bragg Grating permits the optical power transfer between these modes of the fibre.

The Fibre Bragg Grating has many advantages as it is simple, high wavelength selective and low insertion loss structure. It has been used in several applications which include telecommunications, sensing and structural health monitoring. This is due to the polarization insensitivity and full compatibility with general single-mode communication optical fibres[96]. Being an in-fibre component it makes it easy to integrate to other optical devices. The gratings are permanent after a proper annealing process, do not degrade the through traffic wavelength signals and the reflective spectrum is stable over time. It is a reflective type of filter in which the demanded wavelength is reflected instead of being transmitted. The bandwidth of the grating is typically 0.1 nm but can be tailored to more than tens of nanometres with a reflectivity approaching 100%[97], [98]. These characteristics allow the use of Bragg grating for reflection and filtering making it suitable for application in optical transportation networks.

Non-uniform Bragg gratings can expand or compress pulses, an important feature for high bit rate long haul telecommunication systems. To increase the transmission capacity and reach the dense wavelength division multiplexing that has been implemented in the optical transport networks, the technique is being developed to provide narrow channel spacing from 1.6 nm to 0.4 nm. This corresponds to 200 - 50 GHz bandwidth of C and L bands (1500 - 1600 nm), the appropriate bands available with optical amplification[99], [100]. DWDM system application requires low insertion low, highly selective, near-zero dispersion (de)multiplexers (optical filters). The uniform Fibre Bragg Grating can be tailored such that the phase response is linear so to correspond to a constant group delay and zero-dispersion, leading to low crosstalk and signal distortion. Uniform Fibre Bragg Grating can be considered as an important component for many applications in telecommunications, this is to introduce more advanced modulation formats to increase spectral efficiency[101]. The operational principles of uniform Fibre Bragg Grating are discussed in the section below.

6.1.1 Operation properties of Uniform Bragg Grating /Reflectivity

The uniform Fibre Bragg Grating is a device that has a grating period Λ, and the refractive index change n_{eff}, is constant over the whole length of the grating. It periodically modifies the phase or intensity of the propagating wave reflected on or transmitted through it. The wave is reflected when the wavelength is equal to the Bragg wavelength λ_B, else it is transmitted[97], [102]. The Bragg condition, the central wavelength of the FBG is described by the following equation:

$$\lambda_B = 2n_{eff}\,\Lambda \qquad \text{Equation (6.1)}$$

This equation relates the grating period of the index of modulation, effective index of the guided mode valid refractive index and the Bragg centre wavelength. The lightwave which satisfies the Bragg condition is reflected, whereas all the wavelengths that are out of phase have reflections that cancel each other out resulting in a high transmission[103]. The uniform Bragg grating is a spectral filter based on the principle of Bragg reflection, reflects a narrow wavelength λ_B from a broad input signal λ_{broad}, and transmits all other wavelengths output signals $\lambda_{broad} - \lambda_B$ as in indicated by the typical layout shown in figure 6.1.

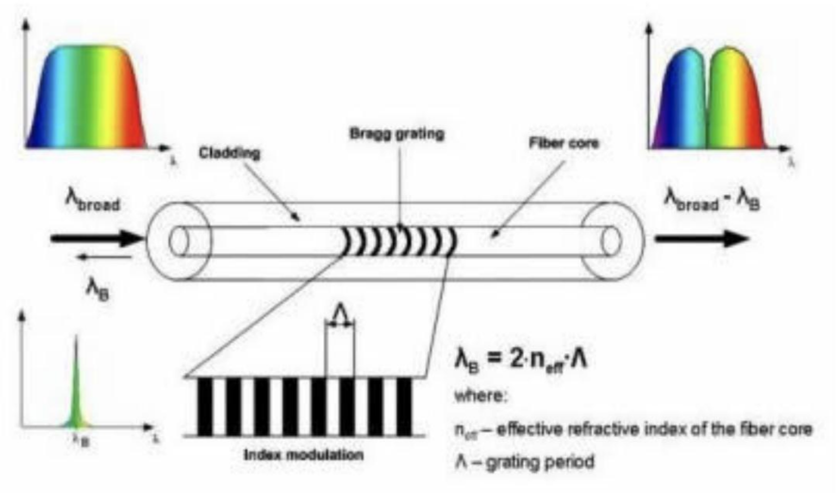


Figure 6.1: Operation of the Fibre Bragg Grating [104]

The fundamental building blocks of the uniform fibre grating is in the core of a single-mode fibre consisting of a periodic modulation of the refractive index. The grating planes have a constant period, where the phase fronts are perpendicular to the longitudinal axis of the single-mode optical fibre. Each of the grating planes backscatters light that is guided along with the core of the optical fibre. This is to say, when the Bragg condition is satisfied reflected light from each grating plane adds up constructively in the scattering to form a back-reflected peak with a centre wavelength, with a bandwidth measured at -3 dB of the maximum reflected signal as measured in nm[64]. The centre wavelength characteristics are governed by the grating parameters whose design can be controlled by the inscription method. The grating length and refractive index change are directly proportional to the reflectivity of the Fibre Bragg Grating[8]. The perturbation of the effective refractive of the guided mode is determined by the exposure power and time of the ultraviolet radiation of the single-mode fibre. In the next section, the inscription method is discussed in detail.

6.2 Methods for Fibre Bragg Grating inscription

The Fibre Bragg Grating inscription methods were made possible by the photosensitivity of optical fibres. This refers to the permanent change of the optical fibre core refractive index when exposed to the light of wavelength and intensity characteristics that depend on the core material. There is a variety of inscription methods that have been proposed, such as interferometric, point by point and phase mask. The effective and simple way of inscription using the phase mask makes it highly repeatable and critically important for Fibre Bragg Grating fabrication in high volumes. The production of refractive index gratings can be produced at any chosen wavelength, opening a door to an extensive area of research fields, including the interest in optical transport networks Bragg gratings integration to basic optical components that exist today. The Bragg gratings for this work are manufactured using phase mask inscription method, and hence the technique will be explained in more details.

6.2.1 Phase-mask technique for uniform Fibre Bragg Grating inscription

In the year 2018, the author undertook a three-month research visit as part of an academic collaboration made possible through funds provided by the Royal Academy of Engineering, UK. In this time work on designing, producing Fibre Bragg Gratings, a technology used in sensing reconfigurable optical switches for Flexible Spectrum networks was established under the supervision of Professor Kenneth Grattan, Dean of the City Graduate School at City University of London. A uniform Fibre Bragg Grating was fabricated at City, the University of London using the phase mask manufacturing setup as shown in figure 6.2. During the inscription process, a photosensitive optical fibre is placed directly behind the phase mask, a periodic corrugation silica substrate transparent to ultraviolet beams. In the method, Ultra Violet light is irradiated onto a phase mask obtaining specific period, which creates constructive and destructive interference in the core of the photosensitive optical fibre place in very close proximity to the corrugations of the phase mask to minimise the sensitivity to mechanical vibrations resolving the stability problem.

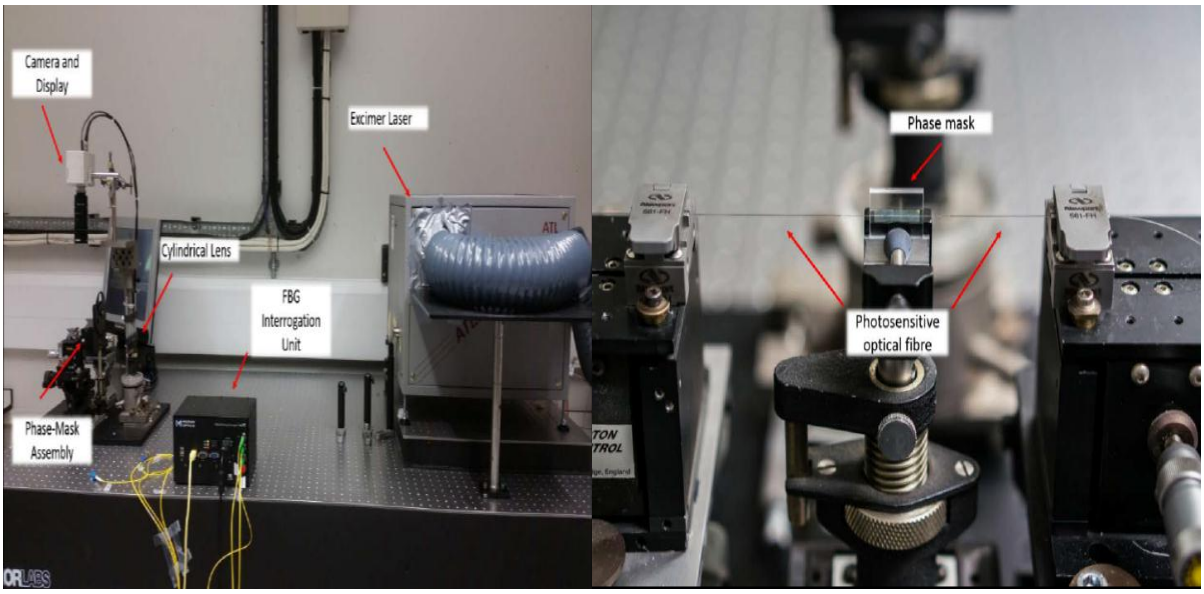


Figure 6.2: City, London university Phase-mask technique for Fibre Bragg Grating fabrication [12]

In the method Ultra Violet light is irradiated onto a phase mask obtaining specific period, which creates constructive and destructive interference in the core of the photosensitive optical fibre[105], [106]. Highly doped photosensitive fibres were used to imprint with an interference pattern created by a phase mask after exposure to krypton fluoride (KrF) excimer laser operating at 248 nm. The exposure produces a permanent increase in the refractive index of the fibre's core, creating a fixed index modulation related to the change in intensity of the exposure pattern. This fixed index modulation is called a grating, the periodic distribution[107]. The ultraviolet light that is incident passes through the phase musk in a normal direction such that it is diffracted by the corrugation in the 0, +1, and -1 orders as shown in figure 6.3. A simple schematic diagram is useful for understanding the significance of spatial coherence in the fabrication of Bragg gratings. The -1 and +1 transmitted orders interfere to form the fixed index modulation on the fibre derived from different parts of the mask separated by the distance that corresponds to the fibre grating period which is identical for the two interfering beams. Fibre gratings refer to periodic structures that change according to the refractive index of the core of photosensitive optical fibre[69], [108]. By controlling the engraving, a desired geometric pattern is produced and hence the desired refractive index for an individual grating is achieved. The exposure produces a permanent increase in the refractive index of the fibre's core, creating a fixed index modulation related to the change in intensity of the exposure pattern.

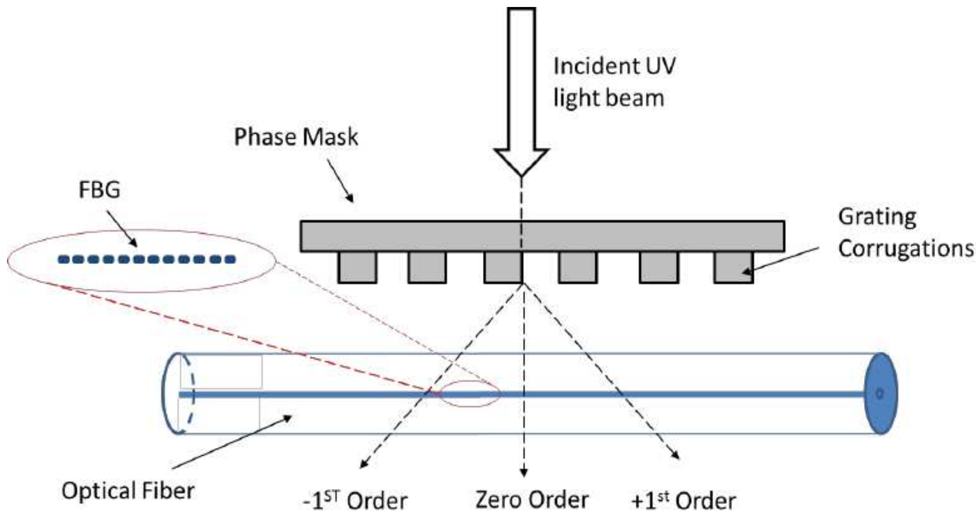


Figure 6.3: Bragg grating fabrication apparatus based on a zero order null diffraction phase mask [110]

The phase mask can be designed such that the diffracted orders +1 and -1 are maximised, while the diffraction into the 0 order is suppressed. This is achieved by controlling the depth of the corrugations in the phase mask creating an interferometric pattern along the optical fibre core from the interference of the +1 and -1 orders of the transmitted power [109], [110]. The grating period that corresponds to the period Λ from Eq. 6.1 is half a period of the phase mask. The selection of the phase mask to produce an FBG at a specific wavelength is independent of the wavelength of the UV laser, but the etch depth required to suppress the zero order is a function of wavelength and optical dispersion of the silica substrate used for the phase mask. A 10 mm uniform Fibre Bragg Grating was inscribed in a highly doped optical fibre to have a centre wavelength at 1554.7 nm by using a phase mask of 1074.16 nm period grating. This Bragg wavelength was shifted to 1554.2 nm due to the curing process.

6.4 The principle of operation in Fibre Bragg Grating

The refractive index and period of the Fibre Bragg Grating are sensitive to temperature and strain. The principle of operation consists of monitoring the shift in the Bragg wavelength reflected by the grating as a function of the ambient temperature and strain perturbation induced on the Fibre Bragg Grating. At the operating wavelength of 1550 nm in single mode fibres, the Fibre Bragg Grating sensitivity to temperature and strain was experimentally measured to be ~10pm/°C and ~1.2pm/ με respectively[111], [112]. Although being a simple demodulation technique, it presents some disadvantages: first, the commercial OSAs are heavy and expensive equipment, besides being inappropriate for field applications. Moreover, most of the spectrum analysers are limited to static measurements, so they don't have sufficient resolution concerning the response time when a number of sensors are being interrogated. A conventional OSA will present an accuracy of about ±50 pm, which would produce errors of about ±4°C and ±60 με [111]. Hence, most Fibre Bragg Grating sensors are designed to suit interrogation devices which are widely available at low-cost in the telecommunications C-band range. Therefore, the Bragg wavelength can be actuated by varying the effective refractive index of the optical fibre core or the grating period. When a broadband light source is launched into an FBG, a specific Bragg wavelength will be reflected with a reflectance that depends on the strength of the Fibre Bragg Grating.

6.4.1 FBG sensitivity to external physical perturbation

The wavelength shift of an FBG dependence to strain was experimentally demonstrated and measured at room temperature. The FBG was placed at a fixed distance between the stages of a micrometre screw gauge. The one side is the fixed stage and the other side is the movable stage and strain is applied by varying the micrometre as shown in figure 6.4. A broadband light source was launched into Fibre Bragg Grating travelled to the detector and the detected by optical spectrum analyser with Bragg wavelength changing by varying the distance between the two stages of the micrometre screw gauge.

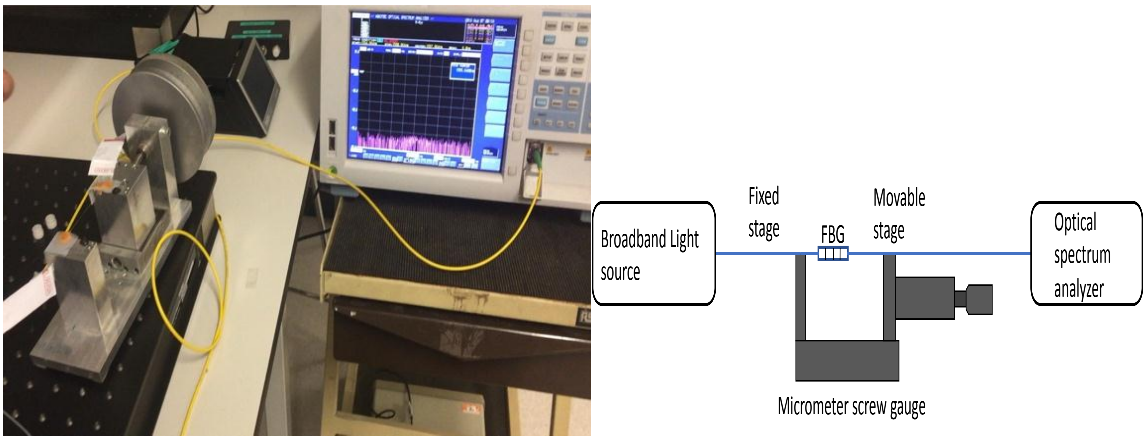


Figure 6.4: Bragg wavelength shift due to strain applied by varying the micrometre

A broadband light source was used to characterize a Fibre Bragg grating fabricated using the phase mask technique. The EXFO FLS- 2300B ASE source covering the C and L bands (1530-1600 nm) was incident into port one of the circulator. The circulator was connected to the 10 mm FBG with 1547 nm Bragg wavelength via port two and port three used to emit the reflected signal. The spectrum of the incident, transmitted and reflected spectrum was measured using an Agilent 86142B optical spectrum analyser and are shown in Figure 6.5.

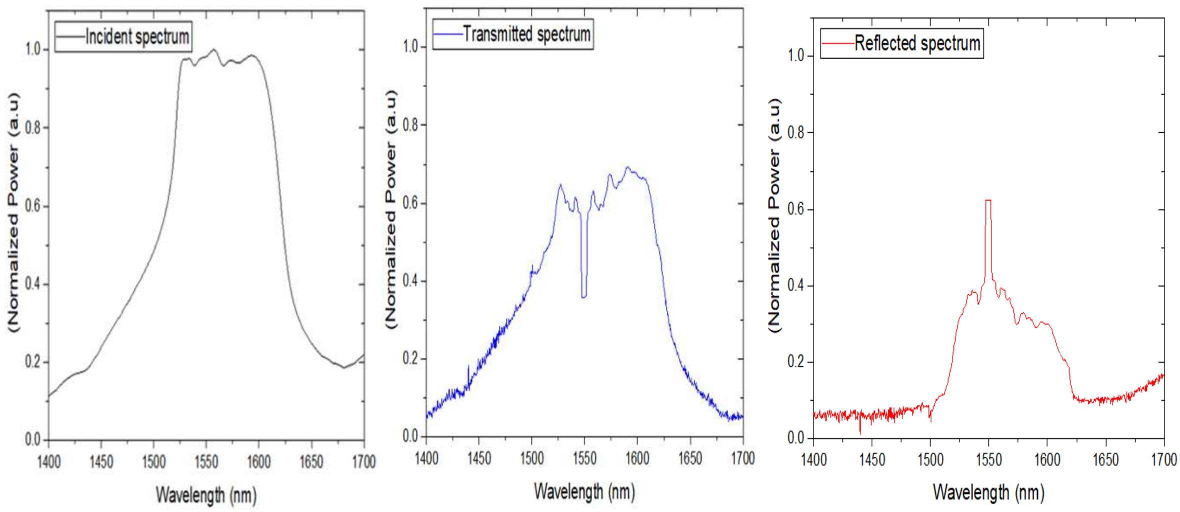


Figure 6.5: Fibre Bragg Grating characterization using broadband light source and circulator configuration

The FBG used for reflecting the channel to be reserved has a central reflective wavelength of 1547 nm, with 0.1 nm as the - 3 dB bandwidth. The FBG acts as a narrow band filter with 34.1% reflectivity with a 0.1 nm bandwidth. This element can be used to configure a passive optical Add/Drop multiplexer for WDM system. Due to its feature to filter, it could compensate for the chirp associated with modulation which results in a chromatic dispersion penalty for optical fibre transmitted signals. If strain is applied to the fibre the grating period changes. If under strain the fibre length L changes by ΔL then the relative strain can be described as ΔL/L. and since the FBG is on the fibre the Bragg displacement extension is equal to that of the grating period.

Under variable strain from 6,30 to 13,46 % relative to the original length of the FBG at a constant temperature of 25 °C, have a shift in the Bragg wavelength from 0,02 to 6,58 nm as a function of applied strain stretching a 1547 nm grating as shown in figure 6.6. The wavelength shift in 1.2 nm increments is represented. In the 1550 nm transmission window, 1.2 nm wavelength change linewidth is equivalent to 149.7 GHz [113]. This was in line with reducing the channel spacing from 1.6 nm (200 GHz) to eventually narrower 0.4 nm (50 GHz) as a mean to increase the transmission capacity and reach in the WDM-PON to meet the increasing wavelength demand of applications as especially in the C and L bands (1500 - 1600 nm). From the results it can be observed that the wavelength of the Fibre Bragg Grating increases, shifting with applied strain. This relation can be used to tune the FBG to a certain Bragg wavelength corresponding to a certain longitudinal strength from the original length of the grating by applying a percentage strain.

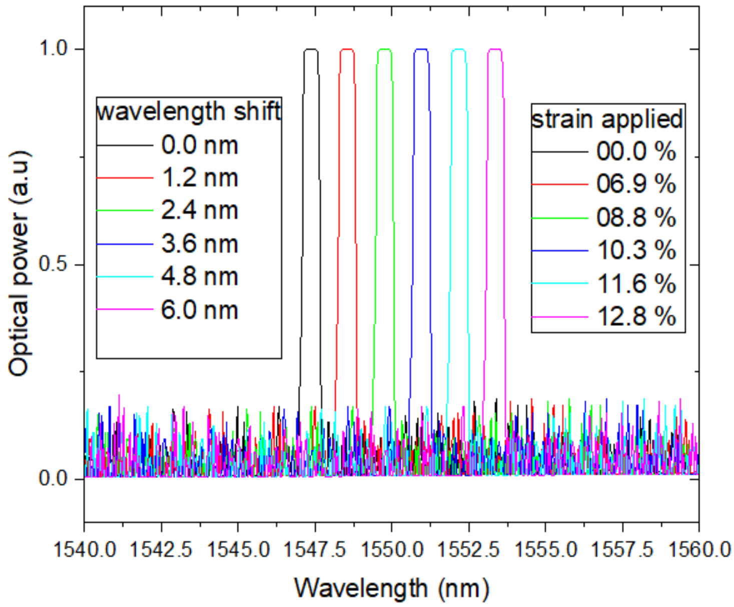


Figure 6.6: Wavelength shift spectra for the reflected signal under different longitudinal stretch

The good linear relationship between strain and Bragg wavelength as shown in figure 6.6, has the potential of using the Fibre Bragg Grating as a sensing device, with widespread use in structural health monitoring applications. FBGs have many advantages compared to conventional electrical sensors due to their corrosion resistance, immunity to electromagnetic interference (EMI), light weight and small physical dimensions allowing embedded deployment of FBGs into structures for long-term strain monitoring purposes.

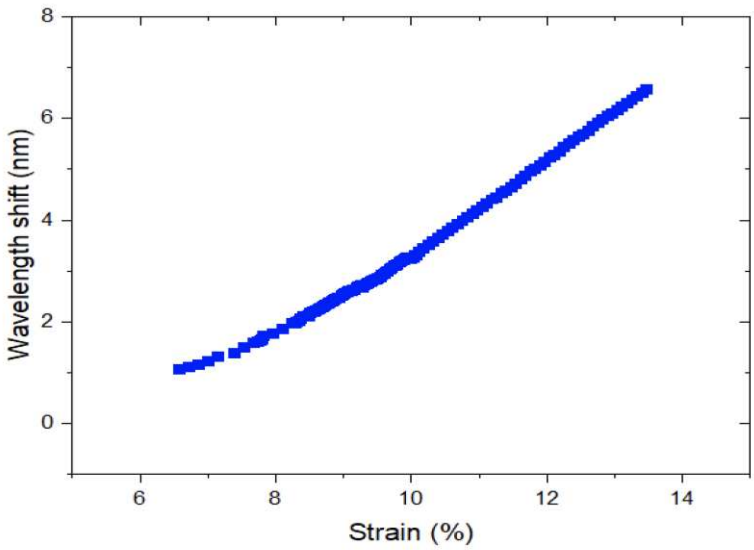


Figure 6.7: wavelength shift of an FBG dependence to strain

The reflected spectrum of the FBG has a relationship with the shift in Bragg wavelength due to strain-induced to the optical fibre. This corresponds to the change in the grating period and the refractive index of the optical fibre core. This can be described by an equation:

$$\Delta\lambda = 0.8534 \times S_{app} - 5.0932 \qquad \text{Equation (6.2)}$$

Where $\Delta\lambda$ is the wavelength shift and S_{app} the applied strain percentage on the FBG longitudinal stretch. The gradient of this equation can be compared to the Fibre Bragg Grating sensitivity to strain of ~1.2pm/ με as previously mentioned. The phase mask inscription method is relatively easy, cost-efficient and repeatable which is ideal for mass volume production, fabricating core gratings an ideal candidate for use in telecommunication application. The uniform Fibre Bragg Gratings for optical communication network can be easily implemented to existing systems for signal filtering, gain flatness to increase the capacity and performance of the system, as will be thoroughly discussed in the following section.

6.5 Current Applications of FBG

The uniform Fibre Bragg Grating has several applications especially in sensing and optical communication networks. It is the unique features of FBGS that allowed the FBG based sensors to be deployed in various sensing application such as biomedical sensors and e-health enablers in medical devices and structural health monitoring in civil structures such as bridge condition monitoring for cracks, vibration, strain and or temperature variation. The sensing principle is that the grating period and the optical fibre core index of refraction changes with the applied vibration, strain and or temperature resulting in a change in the reflection wavelength of an FBG, Bragg wavelength shift. The Fibre Bragg Grating-based sensors have many advantages over conventional sensors including immunity to electromagnetic interference/radio-frequency interference (EMI/RFI), inherent insensitivity to environmental induced drift, completely passive operation, high sensitivity, compact size, and low-cost. Moreover, as the FBGs are only a few millimetres long, a number of gratings can be inscribed along the same optical fibre core, allowing to multiplex a diverse network of sensing points.

In optical telecommunication systems the Fibre Bragg Gratings can be used for dispersion compensation, gain flattering for optical amplifiers, wavelength selective filters and as add/drop multiplexers. Current efforts of research and development are aiming at increasing the total capacity of optical fibre as a medium and improving long haul optical transmission systems using new innovative technologies such as dense wavelength division multiplexing (DWDM). As optical transport networks move toward highly dynamic mesh-based topologies it is evident that the demand for communication systems require a large bandwidth, high data and high-speed to some destination amongst the flexible optical node in the network. The use of add/drop multiplexers based on the narrowband FBGs for wavelength selective filtering which help extracting a single wavelength from a number of multiplexed channels in an optical fibre without disturbing other wavelengths, thus can achieve high optical data rates. The application of Fibre Bragg Gratings in optical transport networks will be thoroughly discussed in the following section.

6.5.1 FBG in Optical transportation networks

The basic optical transportation network consists of three basic elements which are transmitters as an input converting an electric signal to the optical domain, medium an optical fibre for the transmission of the wavelength channels and a receiver converting the optical signal into an electrical domain at the output. The FBG can be added to the design of the optical transport network with the gratings placed in line with the optical fibre, in the transmission channel. Due to their intrinsic integration with the optical fibre and having an ideal spectral for multiplexing and demultiplexing, the FBG have revolutionized optical communication systems. The FBG is a key component in optical transport net as it is passive, linear, and compact and can facilitate a large number of device functionalities. These include optical amplifier gain flattening, inline optical filtering and chromatic dispersion compensator. As a dispersion compensator, the FBG is used to improve the non-linear signal distortion that results from optical power variations in the optical transport system for both the reflected and transmitted signals.

The advancement of optical transport has long haul communication system as one of the important requirements. Optical fibre amplifiers such as Erbium-Doped Fibre Amplifier (EDFA) have enabled a wide range of Dense Wavelength Division Multiplexing (DWDM) networks deployment and have enabled longer optical fibre links between signal regenerators, which impose a significant cost and complexities on the network. The length of the optical fibre and the attenuation coefficient are directly proportional to the noise figure, which is a measure of how much noise the optical fibre adds to the signal[40]. It is, therefore, necessary to mitigate the optical signal-to-noise and non-linear effects for optical amplifiers in DWDM networks, achieved through an appropriate gain flattening filter based on fibre grating with a spectral response matched to the inverse gain profile of amplifier[114]. The distinguishing feature of FBG based filter is the relatively narrow linewidth of its reflection spectrum. As a result, the FBG can be used as very simple, low-cost and spectrally extremely wavelength selective filter, filtering with high efficiency and low loss to improve the quality of service in a DWDM system[30]. This ability to optically add and drop wavelengths at intermediate points in the optical transport network of different architectures is the key function of FBG based Optical add/drop multiplexers (OADM) as will be discussed in detail in the following section.

6.5.1.1 Fibre Bragg Grating in Passive optical networks

The Fibre Bragg Grating has been proposed as an efficient monitoring method, giving information of temperature at any place of the network at a very short measurement time (a few seconds)[40]. It is capable of distinguishing the monitoring reflection peaks from two nearly located optical network terminations even if the branches are of equal length. This is an easy way of determining a fault in a branch, as the system measures the temperature in the individual optical network units, optical network terminations, fibre distribution hub, or network access terminals[63], [69]. These measurements are realized by the FBG spectrum places inside an interferometer unit, creating a peak to check the integrity of the corresponding branch. Each interferometer unit contains a uniform FBG that creates a beat term on the Optical Time Domain Reflectometry trace allowing for easy branch fault distinction after the splitter. This is since in passive optical network the whole traffic to a remote node is carried by a single optical fibre, and it gets split into separate fibres that run to the individual optical network units. By applying simple signal processing steps on the beat term from the OFDR trace, it is possible to deduce the Bragg wavelength shift of each FBG located in each IF unit therefore foreseeing environmental condition that could create severe damage to the network[115]. This physical layer monitoring method can therefore be viable and easily integrated to the Network Management System enabling preventive countermeasures such as protection, restoration and isolation of attacking port.

6.5.1.2 Fibre Bragg Grating in Metro access networks for flexible spectrum

A metro access network containing either point to point (P2P) or point to multipoint (P2MP) for the single or multi-wavelength distribution system, creating the foundations for the Optical Transport Network. This requires routing and spectrum assignment (RSA), channel collisions and switching and real-time fault detection and repairs. This is to restore the signal continuity constraint for fixed DWDM systems. As a result, an OADM can be used to effectively reconfigure an access network from the control plane located at the central office of a passive optical network[116]. This can be used to provide optimised transmission with a trade-off between capacity, optical fibre reach and quality of service. Hence resource utilisation and signal assignment of the different requests can, therefore, be effectively monitored[117]. A long-haul DWDM signal entering a metro-access network where an OADM controls the incoming and the outcoming wavelengths at a network node while ensuring that spectrum efficiency and self-healing network is realized[118], [119]. Optical add-drop multiplexers (OADM) are the simplest, cost-efficient elements to introduce for wavelength management capabilities by enabling the selective insertion (add) and removal (drop) of optical channels. OADM has been demonstrated using an FBG to increase spectrum capacity by providing wavelength add/drop and channel reassignment whilst attaining an optimised trade-off between capacity and reach[120]. A wavelength-tunable OADM, giving access to all the wavelengths of the WDM signals provides more flexibility to satisfy reconfiguration requirements and to enhance network protection. The wavelength selective switching capability of the OADM based on the spectral characteristics of FBG is used to drop wavelengths at intermediate points in an Optical Transport Network, because it is more economical and allows a better performance in the bandwidth utilisation[119][116].

6.6 Summary

The FBG is made by engraving the optical fibre resulting in a change in the refractive index at these locations compared to the remaining silica glass. There is a number of methods currently used to produce FBGs, with the interferometric and phase mask methods being the most common. In this work we used the Phase mask setup for FBG manufacturing process at City, University of London. The optical component was characterized to understand the refractive index conditions that result in the Bragg wavelength and analysing linewidth and other inherent features such as narrow band filtering. The response to external parameters such as strain sensitivity was investigated to further understand the Bragg conditions and relations between change in the refractive index, grating period and the wavelength shift. The FBG wavelength was specially designed such that the grating is suited for OADM application flexible spectrum channel reservation to minimise optical crosstalk in WDM optical communication networks as will be discussed in chapter 7. Wavelength Division Multiplexing refers to the transmission of multiple optical fibre wavelengths within a single optical fibre. Flexible spectrum refers to the fact that the channel wavelength assignment is not statically fixed, but is dynamically optimised in real-time to ensure optimum network performance at all times. In order for these networks to function optimally, novel hardware and dynamic algorithms need to be identified and developed to perform critical tasks. Such tasks include wavelength assignment, signal routing, network restoration and network protection. The objective is to design and build an experimental lab testbed reflecting a full flexible spectrum DWDM network architecture based on the conventional WDM-PON able to be integrated into the next-generation technology capable of handling extremely high data rates of the kind produced by MeerKAT and SKA. Concepts were proposed, experimental designs made, setups built in Nelson Mandela University Lab which featured multiple WDM channels, channel tunability, wavelength conversion and performance optimization across bias and modulation depth and experimental data collected. A highlight of the results was VCSEL tunability and wavelength channel conversion through side-mode injection. This lead to development of a novel defragmentation approach for flexible spectrum networks based on the design, production and characterization of uniform Fibre Bragg Gratings. These are vital components for use in reconfigurable optical Add/Drop multiplexers (ROADMs).

Chapter 7

7.0 Fibre Bragg Grating Based All Optical Add and Drop Multiplexer

To achieve greater spectral efficiency, greater capacity and to minimise the performance degradation caused by transmission impairments, system investigation and advancement are crucial. Therefore, it is important to test and develop wavelength division multiplexing optical networks. By implementing direct systems parameters with currently available and reasonably priced optical components. In a WDM optical network system, it is necessary to add or drop different wavelengths to enable greater connectivity and flexibility of the network, for channel reservation, channel switching, wavelength reassignment and lightpath rerouting as a mechanism to reduce optical crosstalk. A cost-effective way to limit the crosstalk effect is the efficient spectrum resource utilisation. In this chapter, we report a uniform Fibre Bragg Grating (FBG) based Add and Drop Multiplexer (OADM) with optical circulators configuration. This was done by performing an experimental demonstration of a 20 Gbps high data speed signal to study the effect of inter-channel crosstalk on flexible spectrum networks. The configuration multiplexes two 1550 nm VCSELs which were direct intensity-modulated using a 10 Gb/s NRZ PRBS (2^7-1) as optical transmitters with one of the emission wavelength that matches the Bragg condition. The system considers VCSEL 1 as the main signal carrier while it regarded VCSEL 2 as the interfering channel, with a wavelength tunability range of 5 nm used to demonstrate inter-channel crosstalk.

We propose a FBG based OADM for channel reservation in a multiplexed network, dropping optical carrier signals from the system if not in use and adding the wavelength signals upon request to support dynamically varying traffic demands. The OADM introduces wavelength management capabilities by enabling selective removal of one or more wavelength channels by rerouting its data to another lightpath. The primary function of an OADM is to drop or add an optical carrier signal in a fibre optic communication network. An important technical issue for OADM design is to reduce crosstalk, which can severely degrade system performance. Therefore, analysing the quality of service of the systems back-to-back and 25 km standard single-mode fibre transmission, evaluated in terms of BER and eye diagram measurements this was all done upon characterising the FBG to obtain the reflectivity.

7.1 Flexible Spectrum integration to existing 50 GHz WDM Optical Communication Networks

The enormous growth in the demand of bandwidth is pushing the utilisation of existing fibre infrastructures to their limits. The aim of this section is to develop the already deployed optical network layer with a flexible, bidirectional, contentionless and colourless standardised protocols that transfer multiple digital bit streams synchronously over optical fibre using lasers. This is more economical and allows better performance in the bandwidth utilisation. To fulfil this requirement, the constant technology evolution has substituted the actual single wavelength systems connected in a point-to-point topology by wavelength division multiplexing (WDM) systems, creating the foundations for the Optical Transport Network (OTN). Wavelength division multiplexing (WDM) optical networks are state-of-the-art systems in optical bidirectional communications. In an ideal WDM system, the signals travel down the standard single-mode fibre (SSMF) and separate at the end of the transmission lightpath with no interference. In reality, the multiplexer and fibre are not perfect and some interference occurs between the channels, this known as crosstalk. The presence of optical crosstalk in a WDM optical channel can degrade the quality of the received signal, increasing the bit error rate. An optical add-drop multiplexer (OADM) is the simplest element used in WDM systems for channel reservation, channel switching, wavelength assignment and lightpath routing into or out of an SSMF. This device introduces allocation of bandwidth, channels switching, and lightpath routing and wavelength assignment/management capabilities by enabling the selective add and drop of optical channels the key features of an optical node in flexible spectrum network. The OADM based on FBG will provide the Flexible Spectrum integration to existing 50 GHz WDM Optical Communication Networks at a reliable, cost-effective and scalable manner. This means that an economical and efficient spectral and resource utilisation flexible network can be achieved, as the configuration is based on low-loss, low-cost passive devices and does not need any power supply.

7.1.1 FBG and OADM Implementation

The Optical Add and Drop Multiplexer (OADM) introduces wavelength management capabilities by enabling selective removal of one or more wavelength channels by rerouting its data to another lightpath. The primary function of an OADM is to drop or add an optical carrier signal in a fibre optic communication network. Optical add/drop refers to the ability of the multiplexer and demultiplexer technology to drop (reflect wavelength) a single of multiple data signals from existing WDM system while transmitting the other signal. The system can later add the reflected signal to a different lightpath of the network and receive it in an alternative optical node. An important technical issue for OADM design is to reduce crosstalk, which can severely degrade system performance. In the past, there have been several OADM configurations proposals for various optical communication systems. These include OADM configurations based on Fibre Bragg Gratings (FBG) with two optical circulators, integrated planar arrayed waveguide gratings (AWG) and thin-film filter (TFF) as shown in figure 7.1. There is a variety of techniques used to achieve the add/drop selective switching functionality, these include manual fibre patch panel, micro-electromechanical systems, liquid crystal and thermo-optic switches in planar waveguide circuits.

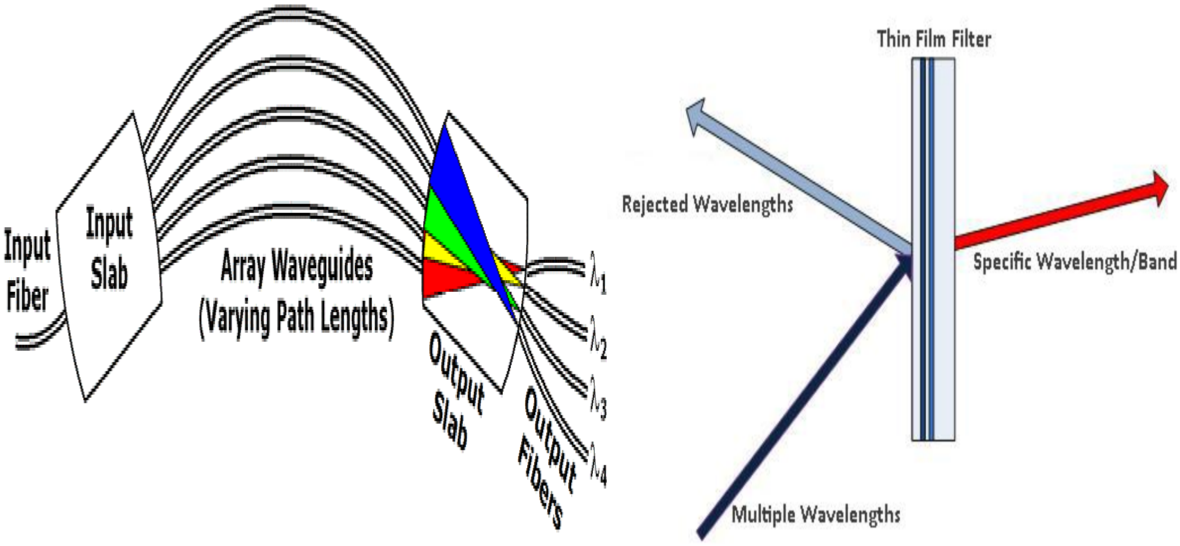


Figure 7.1: Optical Add and Drop Multiplexer configuration based on a) Integrated planar Array Waveguides b) Thin Film Filter[121]

We commonly use integrated planar AWG as optical multiplexers/demultiplexers in WDM systems. These devices can multiplex many wavelengths into a single strand of optical fibre, enabling increased transmission capacity in optical communication networks. Each signal wavelength coupled to the grating waveguides undergoes a constant change in its phase due to the constant length increment in grating waveguides. Light diffracted from each waveguide of the grating interferes constructively and gets refocused at the output waveguides the different wavelengths will follow the design on a different channel to reach as shown in Figure 7.1a) and thus achieve OADM function. The major disadvantage of the technique is that it forms the output channels, being wavelength dependent on the array phase shift. In the case of OADM configuration design with TFF, an optical carrier signal drops from wavelength-multiplexed signals using a narrow band-pass filter (BPF) as shown in Figure 7.1b), only transmitting the desired signal wavelength while it reflects other wavelengths. Wavelength-multiplexed signals add Optical carrier signals using a narrow BPF, whereby the desired signal being transmitted combines with the reflected signal wavelengths[122]. The major drawback of the technique is that in order to enable add/drop of multiple signals, the signals need to adjacently fit in the filter's bandwidth.

More economical and transparent OADM configuration based on Fibre Bragg Gratings (FBG) with two optical circulators have been proposed[97], [123]. The basic architecture of the OADM optical node presented comprises an FBG fitted between two optical circulators, where port 3 of the first circulator reflects/drops signal. The system can later add the reflected signal through port 1 of the second optical circulator as shown in figure 7.2. At first, N multiplexed wavelength optical carrier signals propagate to the Fibre Bragg Grating through port 1 of the first optical circulator, reflecting only the signal with a wavelength matching the Bragg period engraved on the fibre core while it transmits others..

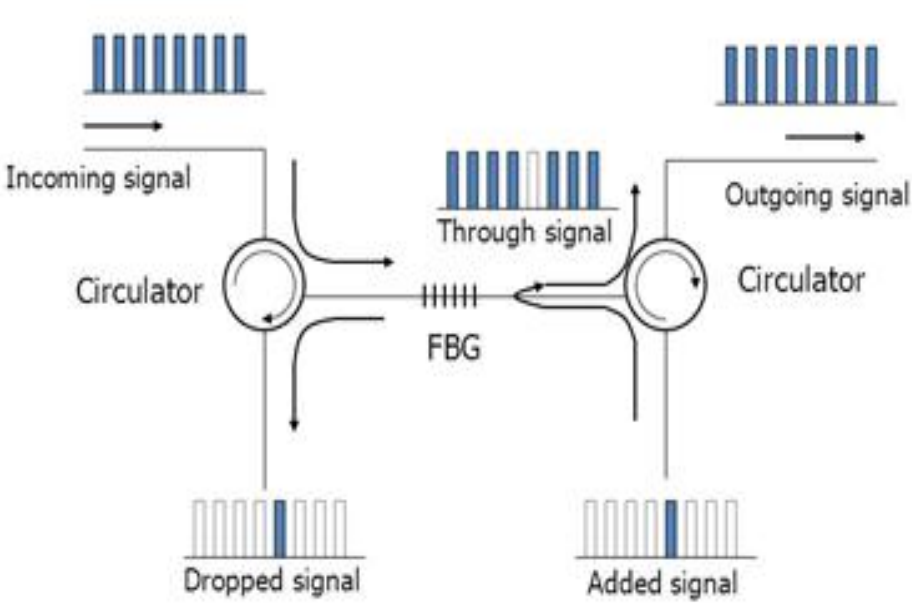


Figure 7.2: Optical Add and Drop Multiplexer configuration based on FBG for WDM networks[97], [121]

It transmits the remaining signals through the FBG passing to the receiver end via port 3 of the second optical circulator. The reflected/dropped signal couples back to the original multiplexed wavelength optical carrier signals, added through port 1 of the second optical circulator being transmitted on a different lightpath and possibly carrying a different modulation format for improved spectral utilisation. The Bragg wavelength tunes over a range of wavelengths to add/drop the desired signal from the wavelength-multiplexed signals or engrave the FBG with several Bragg periods distributed along with the fibre. This enables it to drop/add over one signal. This means that the system can add and/or drop any wavelengths of optical carrier signals from the WDM channel from an OTN with no optical-electrical-optical conversion. Of all the currently available techniques, this inherent WSS makes the FBG configured OADM the most popular and most used, as it allows more flexible channel bandwidth in dynamic optical communication networks. The Fibre Bragg

Grating (FBG) based optical add-drop multiplexer (OADM) is thus a key device, as it supports the ability for configuring remote switching traffic for WDM system at the wavelength layer. In Flexible Spectrum WDM, optical communication networks this channel reservation technique can minimise optical crosstalk, quality of service measured as Bit Error Rate (BER).

7.1.2 Characterisation of FBG reflectivity using VCSEL

Optical Fibre Bragg Gratings have perfect spectral characteristics for adding -dropping data signals in a WDM introducing cost-effective wavelength management capabilities of flexible spectrum in dynamic optical communication networks. Since they are an inherently low loss, spectrally extremely selective narrow-band filtering, and low-cost passive devices and do not need any power supply. In this section, we characterize the Fibre Bragg Grating, to experimentally demonstrating the Bragg grating effect by launching signal from an optical transmitter into the FBG to determine the Bragg wavelength λ_B, bandwidth and reflectivity.

In this study, VCSELs lasing in the 1550 nm windows, produced and commercialised from Raycan Company transmitters were used. The material composition of these VCSELs is InAlGaAs, InGaAs and InAlAs which offers the VCSEL high reliability, reflectivity, low-loss current confinement, reduced thermal impedance and low series resistance for long-wavelength emissions[124], [125]. The emission wavelength of the Raycan VCSEL adjusts by varying the drive-in bias currents. The Raycan VCSEL, bias and temperature control and electrical radio frequency (RF) input signal shown in figure 7.3. The VCSEL was used to characterize a Fibre Bragg grating fabricated using the phase mask technique. During fabrication the desired Bragg wavelength might experience a slight shift, resulting in a unique value than expected determined as half phase might period, thus the need to characterize so identify the exact wavelength.

In this experimental demonstration and report, we achieve the Bragg wavelength match due to the VCSEL biasing and the ability to tune the emission wavelengths as reported in previous chapters. In correlation with the output power of the VCSEL that was measured as a function of bias current increases from 0 mA to 9.8 mA, with the threshold current of the VCSEL noted to be at 0.9 mA while the saturation current was 8 mA. The technique connected the circulator to the 10 mm FBG to determine Bragg wavelength via port 2 and reflectivity via port three used to emit the reflected signal. Circulators are non-reciprocal optical devices allowing for the routing of light from one fibre to another, based on providing direction for light propagation. These are used to separate forward and backwards propagating signals and are essential components of dynamic optical communication networks. Normal use of circulators is in applications such as fibre optic sensors, optical amplifiers, dense wavelength division multiplexing (DWDM) networks and optical add-drop multiplexer (OADM).

The spectrum of the incident (incoming), transmitted (through) and reflected (dropped) signal was measured using an Agilent 86142B optical spectrum analyser are shown in figure 7.3. The Optical Spectrum Analyser (OSA) analyses the power output as a function of wavelength. The observed spectra of the three signals in the 1550 nm transmission window supplied on the OSA, as shown below with their spectral output identified as incident, reflected and transmitted signal. The spectral width characteristics of the signals get changed upon interacting with FBG. Determine their spectral width s using the OSA. We define the spectral width as the full-width half-maximum of a peak (i.e. width at 50% (3 dB) of peak maximum).

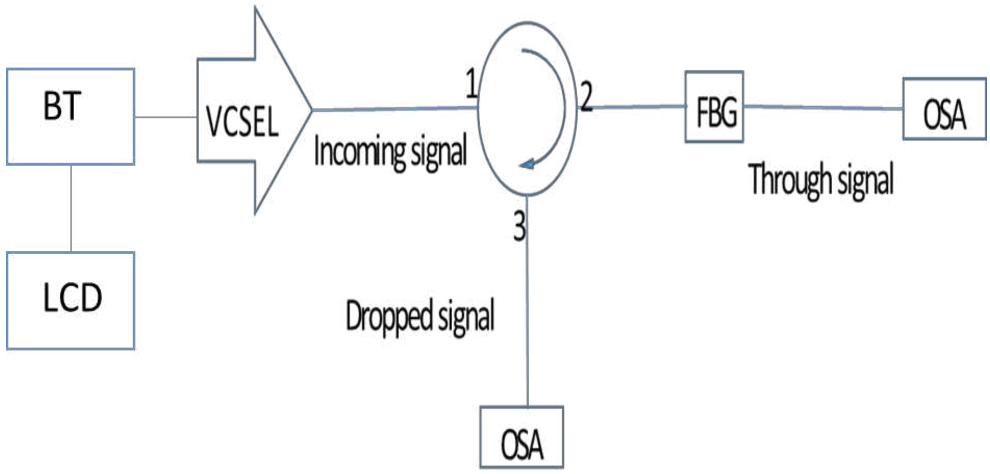


Figure 7.3: experimental demonstration of Optical Add and Drop Multiplexer configuration based on FBG for Bragg wavelength characterization

The setup directed the incoming signal from the broadband light source laser into and from the FBG via an optical circulator. Thereafter, an optical spectrum analyser (OSA) was used to measure the optical spectrum of the transmitted and reflected light beams. In the experiment, we observe maximum reflection at a wavelength that matched with the output optical spectrum connected to port 3 of the optical circulator. The configuration transmits wavelengths that do not satisfy the Bragg grating condition, measuring optical spectrum of the through signal using the optical spectrum analyser. The optical spectrums of the incoming dropped and through signals are shown in figure 7.4. The VCSEL with a bias current of 5.99 mA lasing at 1547.28 nm was the incident signal incoming into the circulator via port 1.

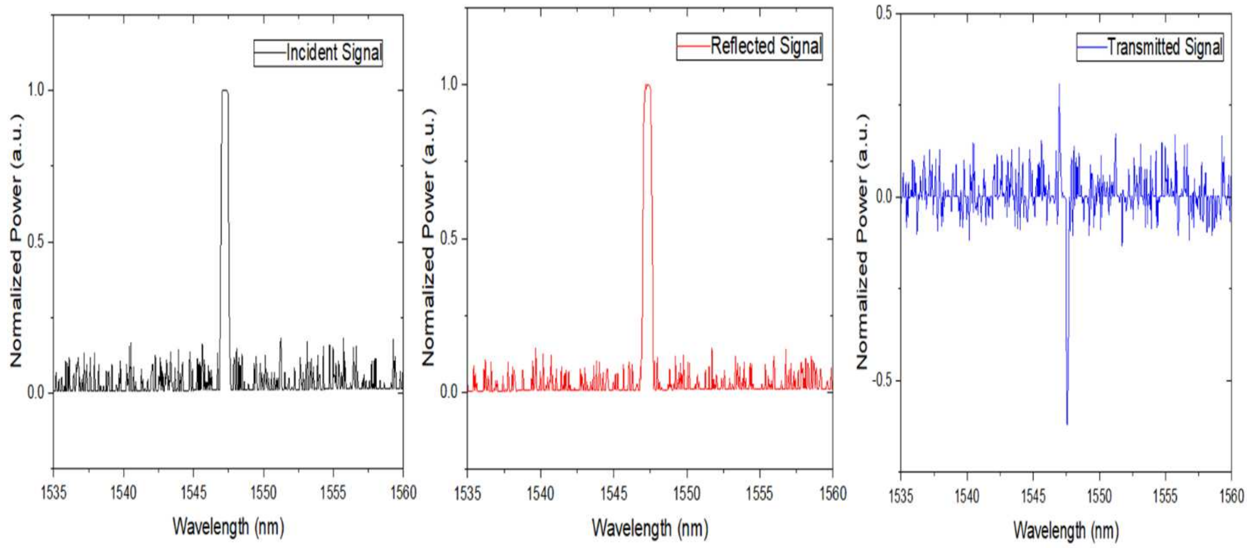


Figure 7.4: Characterization Bragg wavelength and FBG reflectivity using narrow linewidth VCSEL

ASE light source is one type of optical light sources, generating the emission by Amplified Spontaneous Emission covering the C and L bands (1530-1600 nm). This light source offers a fast and reliable characterization of passive components such as thin-film filters, arrayed waveguides and Fibre Bragg Gratings. There is no need to refer at every measurement and the light source has a high spectral density of –8 dBm/nm without gain flattening and spectral resolution bandwidth of 0.15nm. The single-mode 1550 nm VCSEL not only provides a reliable long-wavelength solution with 2.5 Gbps, 4.25 Gbps and 10 Gbps capability at 25 ^{o}C temperature operations but also has a narrow spectral resolution bandwidth/ RMS spectral width of 0.85 nm[124]–[126].

The FBG acted as a narrow band filter with ~ 100% reflectivity and 0.1 nm bandwidth, dropping a signal at 1547 nm out of port 3 of the optical circulator. This is the wavelength that matched the Bragg wavelength of the Fibre Bragg Grating FBG. The FBG has multiple uses in optical transportation networks. These include filters, multiplexers, dispersion compensation, wavelength lockers, etc. It functions as an optical reflector and filter, reflecting the wavelength that fulfils the Bragg condition while transmitting the rest. The FBG is a periodic variation of the refractive index of the fibre core along the length of the fibre. It reflects light in a narrow bandwidth centred about the Bragg wavelength. This element can configure a passive optical Add/Drop multiplexer for WDM system. Due to its feature to filter, it could compensate for the chirp associated with modulation, which results in a chromatic dispersion penalty for optical fibre transmitted signals. Thus the extension of the experiment to a WDM system comprising two directly modulated VCSELs to further analyse the effects of FBG based OADM for channel reservation to minimise crosstalk in an optical transport network.

In WDM optical transportation networks, inter-channel crosstalk significantly limits the spectral resource utilisation and quality of service (QoS) for closely spaced channels. The factor that affect the levels of crosstalk are the signal optical power, bitrates, channel spacing, a distance of transmission and the filtering properties of the multiplexers and demultiplexers (in the strong grating, this wavelength spacing is a limitation). As we extend the signal transmission to higher bitrates, adjacent inter-channel crosstalk becomes detrimental to the quality of the signal (QoS). The optical communication networks are therefore optimised to achieve a trade-off between channel spacing to operate within a minimum acceptable crosstalk penalty as discussed in the following section.

7.1.3 Experimental demonstration of FBG based OADM in a 2 signal WDM optical transmission network.

The constant technology evolution has substituted the actual single wavelength systems connected in a point-to-point topology by wavelength division multiplexing (WDM) systems, creating the foundations for the Optical Transport Network (OTN). Wavelength division multiplexing (WDM) optical networks are state-of-the-art systems in optical bidirectional communications. Wavelength division multiplexing is a technology that combines several optical carrier signals at different wavelengths onto a single optical fibre. In an ideal WDM system, the signals travel down the fibre and separate at the end with no interference. In reality, the multiplexer and fibre are not perfect and some interference occurs between the channels, this known as crosstalk. Existence of optical crosstalk in a WDM optical channel can degrade the quality of the received signal, increasing the bit error rate.

We demonstrate the functionality of the FGB based OADM configuration using the experimental network in Figure 7.5. The FBG used for reflecting the channel reserves a central reflective wavelength of 1547 nm, with 0.1 nm as the - 3 dB bandwidth. Two vertical-cavity surface-emitting lasers (VCSEL) based at the ITU grid of 50 GHz (~0.4 nm) channel spacing, 1547.28 nm (dropped channel) and 1548.27 nm were used. The directly modulated VCSELs with a programmable pattern generator (PPG), through a bias tee intensity modulator, at 10 Gb/s with a non-return to zero (NRZ) 27–1 pseudo-random bit sequence (PRBS). We then decorrelated the Data patterns using different lengths of RF cables to introduce random time delays. Thus, experimentally demonstrating a 20 Gb/s system comprising of two VCSELs WDM optical network (each channel at 10 Gb/s).

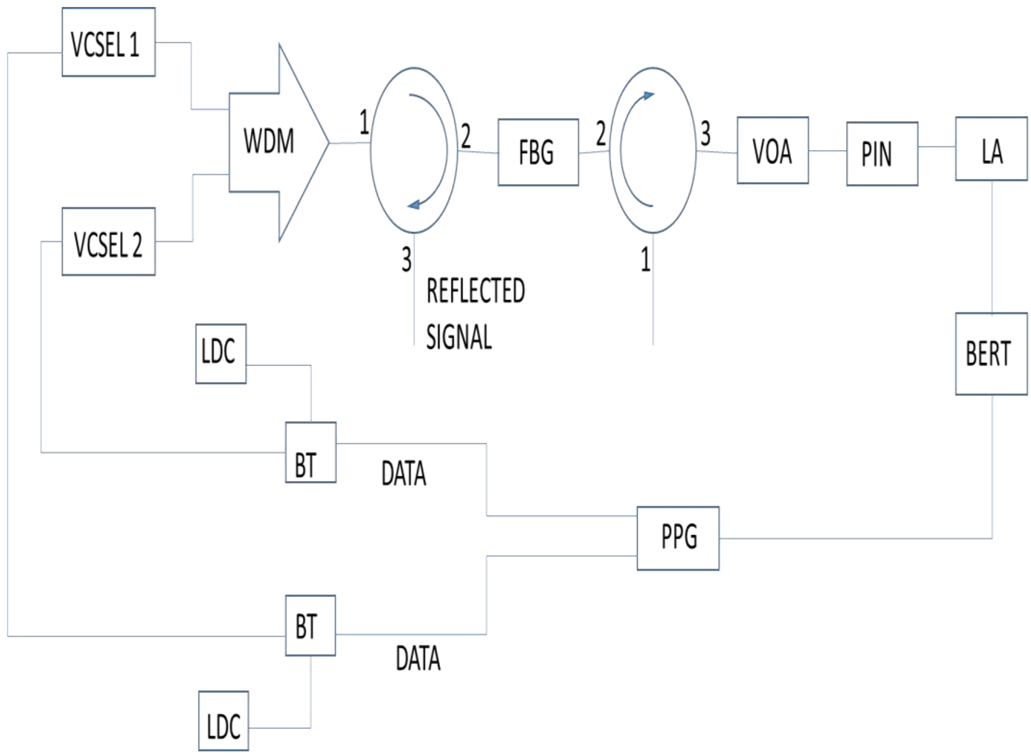


Figure 7.5: The functionality of the FGB based OADM configuration in WDM network

We consider two separate scenarios, for scenario 1 detunes the wavelength of VCSEL 2 to not match the Bragg condition. The two signals from VCSEL 1 and 2 are simultaneously incident on the photodiode, this results in errors as the receiver cannot distinguish the two signals. For scenario 2, we tune VCSEL 2 to match the Bragg condition. The resultant filtering/wavelength reservation avoids traffic collision and improves the quality of service. The system with two multiplexed signals leads the wavelengths to the Fibre Bragg Grating through an optical circulator, then reflects the optical carrier signal satisfying the Bragg condition and sends it back to the optical circulator where it drops.

The system reserved this channel as it does not form part of the bandwidth request. We analyse the output optical signal from drop port of the circulator using an optical spectrum analyser. A power meter (PM) is used to measure the attenuated power, while the oscilloscope (SCOPE) is used to observe the pattern sequence and eye-diagrams of the signal. An on-off keying (OOK) direct detection receiver was used to determine and analyse bit error rate (BER) using a numerical analyser (NA) used to calculate the power penalty. The system can add the reflected signal to the reserved channel combining with the transmitted signal forming the two-channel multiplexed network at different channel spacing and modulation format for efficient resource utilisation. We analysed the crosstalk due to the FBG network and compared it to the back-to-back signal transmission of the WDM system with no channel reservation as a technique to improve quality of service of the network as presented in the following section.

7.2 Effect of crosstalk on Channel Reservation in FBG based OADM

In WDM and flexible spectrum networks, having closer channel spacing increases the spectrum efficiency. The crosstalk can however degrade the system performance from neighbouring signals. This is the fundamental difficulty associated with flexible spectrum networks capable of wavelength assignment and routing. Due to crosstalk, the network directs a small portion of the power of one optical carrier signal to another optical carrier signal and becomes noise. If the received signal is not within the receiver sensitivity, detecting the optical carrier signal incorrectly. Therefore, we must consider the trade-off between channel spacing and crosstalk . The effects of crosstalk are inter-symbol interference (ISI) resulting in error-bits. This means that the receiver struggles in distinguishing the received bits in high-speed modulated signals. The receiver requires additional optical power to maintain a Bit Error Rate (BER), crosstalk is a measure of this power penalty. Adjacent channel interaction is a common phenomenon optical communication network known as inter-channel crosstalk.

7.2.1 Description reflected and transmitted signals of the WDM system

The system multiplexes two directly modulated vertical-cavity surface-emitting laser (VCSEL) to form a WDM system for the experimental demonstration of the FBG based OADM as previously characterized. Reflectivity nearly reaches 100 % and the 3-dB bandwidth is about 0.4 nm for the FBG was achieved using a more narrow-band source (VCSEL) compared to the 34.1 % obtained using a broadband source. The system performance depends on the signal wavelength, thus to achieve optimal performance requires fine adjustments of signal wavelength. VCSEL 1 lasing at 1548.27 nm biased at 5.00 mA was modulated with a drive voltage of 1.4 V achieved an extinction ratio of 4.61 dB. VCSEL 2 lasing at 1547.28 nm biased at 5.99 mA was modulated with a drive voltage of 1.4 V achieved an extinction ratio of 3.17 dB as measured and analyser from eye diagram. Upon modulation, the 1550 nm VCSELs with a linewidth of 0.4 nm exhibit a shifted wavelength with improved channel conditions to match the grating plane improving the reflectivity. Because FBG is narrow-band, it limits the passband compared to the wideband device, thus narrowing available bandwidth. The spectrum of the WDM system was measured and analysed as shown in Figure 7.6. Directly modulated lasers have a positive chirp parameter, which affects the signal propagation by causing the leading and trailing edges of the signal to have slightly different frequencies and consequently different group velocities. Concerning the major portion of the signal, the leading and trailing edge will be blue-shifted and red-shifted, respectively. This effect will cause optical signal spreading (green dotted circle for VCSEL 2) and inter-symbol interference will occur. Reflectivity and group delay varies with the refractive modulation index change related to the FBG ideal spectral response. Therefore, varying chirp parameter will change both available reflectivity FWHM bandwidth, and group delay associated with the optical signal. However, minimising group delay results in the loss of reflectivity bandwidth.

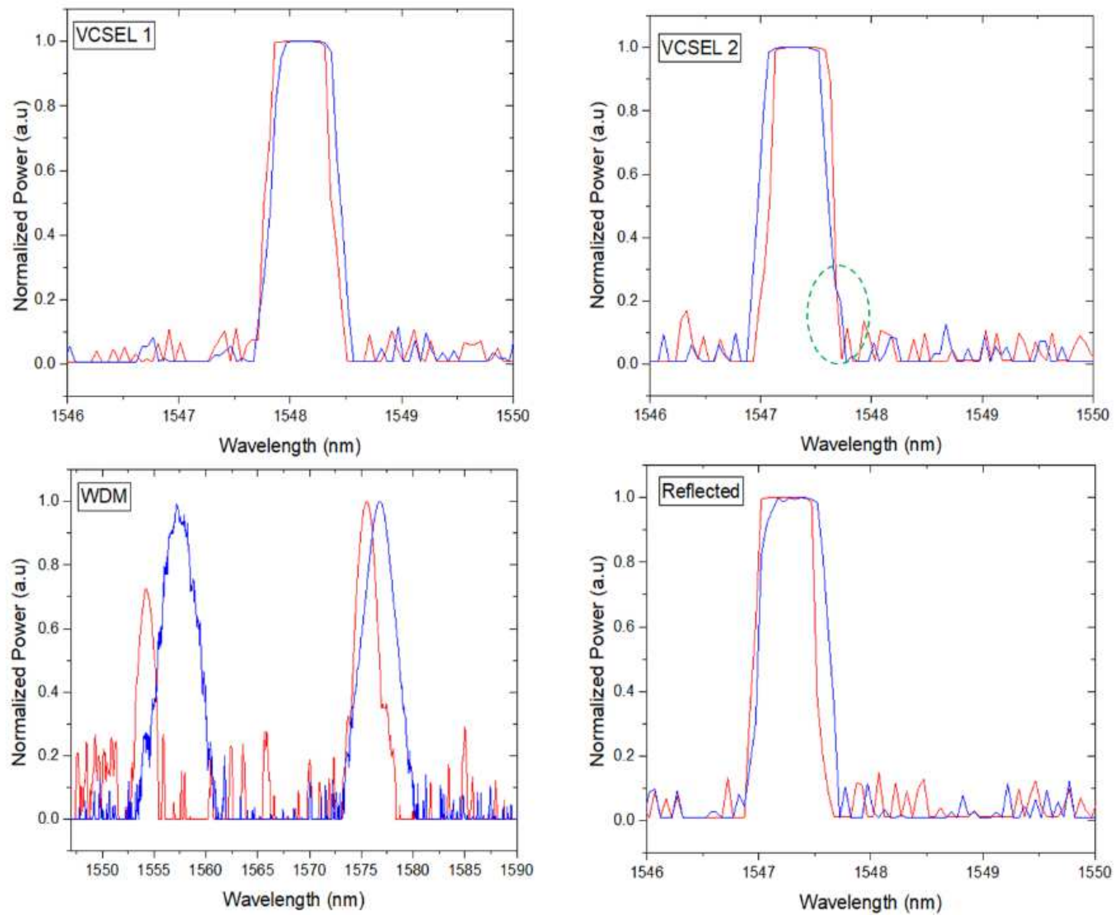


Figure 7.6: WDM optical communication network spectrum for both scenarios (Red: no modulation, Blue: modulated)

The spectra of both VCSELs change wavelength slightly when modulation is added, due to the changing carrier dynamics in the device. For VCSELs there is chirping as highlighted by the green circle, the peak is not smooth as shown in the WDM spectrum. The chirp manifests as a split of the “one” and “zero” level in the wavelength domain. This essentially broadens the spectrum and introduces a penalty through the positive dispersion of the fibre. This is due to the blue-shifted components of the signal having a larger group velocity than the red-shifted components. This results in signal broadening and significant chirp-induced power penalty due to inter-symbol interference. The spectrum of the optical signal is first flattened over the desired bandwidth by the appropriately designed FBG as discussed in chapter 6. The signal spectral shaping filter changes the spectrum according to the grating spectral response and index modulation chirp. We model Bragg Gratings as a narrow pass filter for optical signal shaping applications. The design process is widely simplified because it directly relates the corresponding reflection temporal spectral response to the apodization profile used to get the optimised reflection. The reflected peak is smooth and not chirped, allowing the FBG to be a narrow band filter and uses it for spectral shaping to compensate for such effects and minimise crosstalk in WDM systems by dropping specific signals for correction and later adding for improved quality of service.

7.2.2 Performance Improvement with FBG based OADM in High-speed signal transmission

The eye diagrams of both VCSELs (scenario 2), WDM system (scenario 1), Reflected (dropped signal) and Transmitted (passing) peak was a measure to further analyse the signal quality and the power needed for the receiver to distinguish between the "zero" and "one" level, these areas shown in Figure 7.7. The shape of the received eye diagrams can infer the chirp characteristics of the transmitted optical data signals. The chirp effect and power levels of the steady-state "0" and "1" for the direct intensity-modulated optical transmitters (VCSEL 1 and VCSEL 2) and the WDM system are shown in a simplified way.

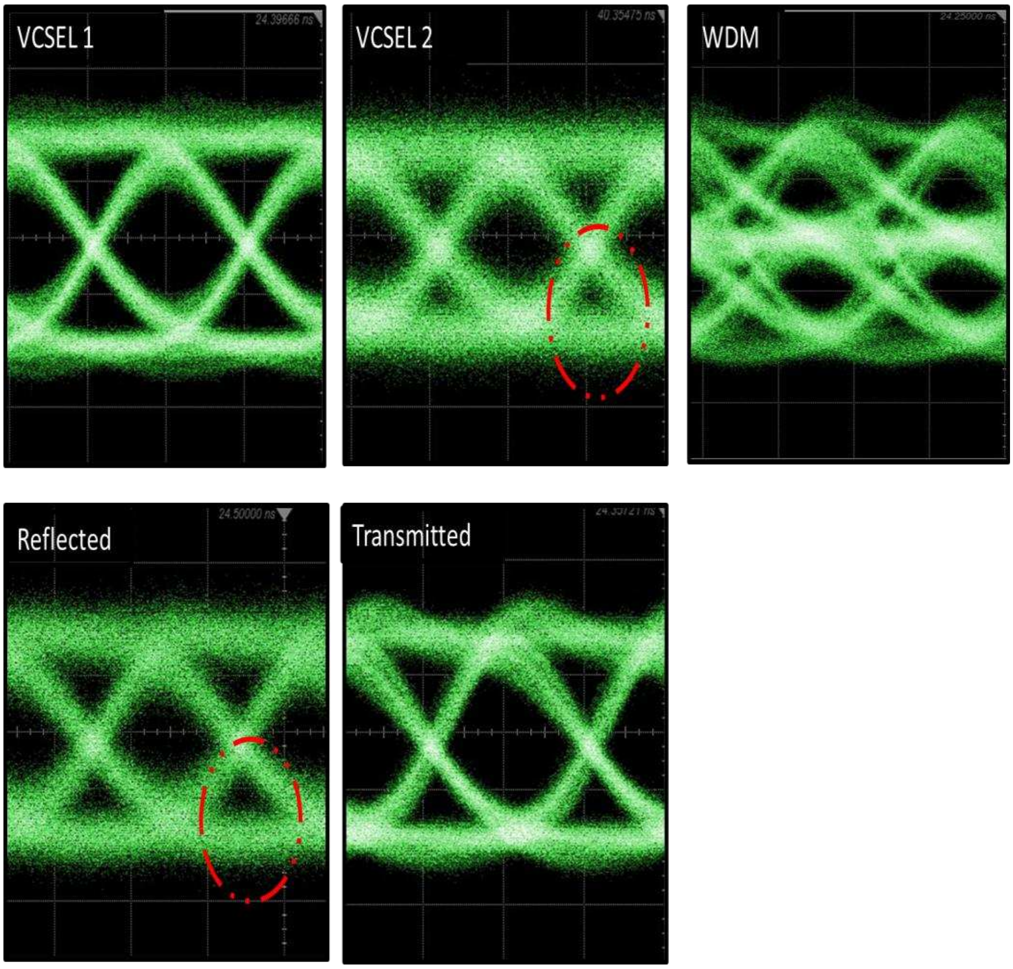


Figure 7.7: Eye diagram for WDM optical network modulated at 10 Gb/s

VCSEL 1 with extinction ratio 4.61 dB has an open eye, with no overshooting above the “one” level. The difference between the “zero” and “one” level (eye amplitude) is high, thus the receiver would require less power to distinguish between the two levels. The incoming signal from VCSEL 1 has a wavelength that does not satisfy the Bragg grating condition of the FBG, thus it is the through signal labelled as transmitted. The inherent narrow-band filter and spectral shaping features of the FBG resulted in a wider and clearer open eye diagram for the transmitted diagram. Also, the leading edge of the signal has a slightly higher steady-state “1” power level distortion (overshoot) than the major portion of the signal. VCSEL 2 with extinction ratio 3.17 dB eye diagram is less open, which reflects amplitude (noise) and phase (timing) errors. When the chirp effect is present, different dispersion sign associated with optical fibre transmission will affect the asymmetry of the eye diagram and influence reduces decision threshold, signal dispersion and power penalties. This distortion in the rise and fall time is a problem in high data signals. In the experimental demonstration, we observed maximum reflection at a wavelength that matched with the output optical spectrum by connected to port 3 of the optical circulator. The system dropped VCSEL 2 signal using an FBG of matching wavelength and we measured the reflected signal eye diagram. The inherent narrow-band filter and spectral shaping features of the FBG resulted in a wider and clearer open eye diagram for the reflected diagram. We observed the eye diagram to have less jitter and more open with better eye-crossing percentage as shown by the red circles.

In the WDM system (scenario 1) there is a crossover between the “zero” power level of one transmitter optical signal and the “one” level of the other. The optical spreading of each signal will cause inter-channel crosstalk and inter-symbol interference will occur. As a result, the eye diagram is severely closed and affects the asymmetry of the eye diagram. This means that the receiver cannot distinguish between the two levels, resulting in eminent power penalty regardless of the high extinction ratio recorded of 5.72 dB. The inherent narrow-band filter and spectral shaping features of the FBG mismatches the chirp parameters for each WDM channel. This issue guarantees that only one WDM channel will have exact compensation.

In evaluating the quality of the incoming signal from both VCSELs and the WDM system, performed BER measurements for FBG based optical add and drop multiplexer configuration. We measured the receiver sensitivity at a bit-error-rate (BER) of the threshold for the different systems. For back-to-back transmission we present the plots as a function of chirp and spectral shaping effect introduced narrow band filtering of FBG as shown in Figure 7.8. For the first optical signal transmitter, VCSEL 1 represents the original data from the PP, while transmitted represents the pass through signal. The receiver sensitivity for an error-free wavelength not satisfying the Bragg condition was seen to be -17.6 dBm and upon going through the FBG we saw it to be -17.3 dBm. For the second optical signal transmitted, VCSEL 2 represents the original data from the PPG while reflected represents the dropped signal. The receiver sensitivity for an error-free wavelength drop was seen to be -17.6 dBm and -17.3 dBm respectively. The high-speed signals that affected the Bragg grating period and increased optical resonations at the Bragg wavelength are analysed on the BER curve.

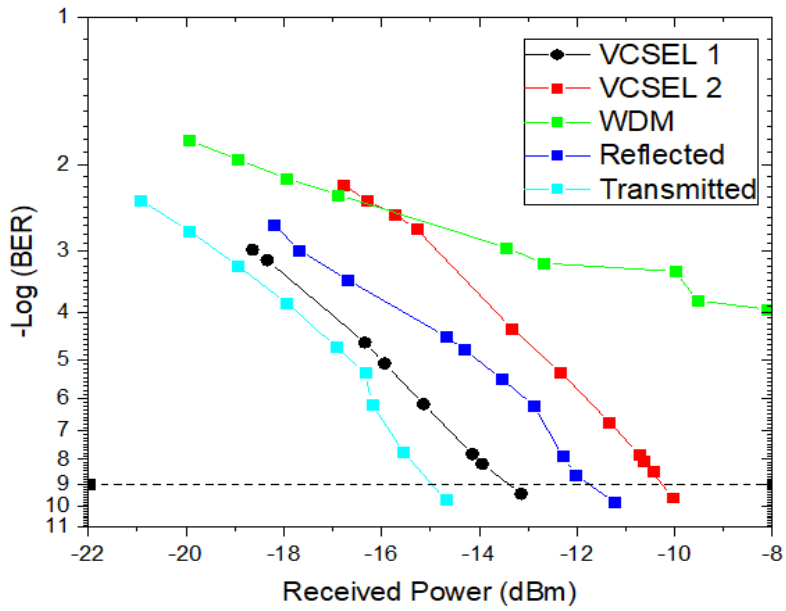


Figure 7.8: BER measurements demonstrating improved crosstalk due to FBG based OADM

Due to inter-channel crosstalk present in the optical communication network from the adjacent channel interaction, inter-symbol interference was present resulting in error-bits, not achieving error-free transmission for the WDM system. We plot the results at different extinction ratios for each laser and the bit rate per wavelength being 10 Gb/s.

The choice of the optical transmitter and its associated chirp characteristics will determine the maximum distance that it can transmit the signal. Depending on the per wavelength bit rate, we consider different optical transmitters concerning the power penalties accumulated during transmission. VCSEL 1 transmission has a higher receiver sensitivity compared to VCSEL 2, as it had a higher extinction ratio and clear open eye diagram. There was improvement of the receiver sensitivity of both VCSEL 1 and VCSEL 2 upon passing through the FBG as demonstrated by the transmitted and reflected signals, respectively. The transmission after passing the FBG improved the receiver sensitivity of the VCSEL 1 signal by 1.58 dB. The reflection after the FBG filtering improved the receiver sensitivity of the VCSEL 2 signal by 1.51 dB. The inherent narrow-band filter and spectral shaping features of the FBG can compensate for the chirp parameters associated with directly modulated optical signal transmitters increasing the decision threshold and improving the receiver sensitivity of the system. This performance enhancement depends on the extinction ratio. Hence the FBG narrow band filter to minimise crosstalk and improve the quality of service in WDM optical communication networks. The proposed all-optical add and drop multiplexer based on FBG proved to be far more sensitive to equipment costs, requiring the use of low-cost optical components. Depending on the choice of the optical transmitter and consequently its frequency chirp characteristics, signal distortion can be deleterious even for the back-to-back signal transmission.

7.3 Summary

A cost-effective way to limit the crosstalk effect is the efficient spectrum resource utilisation, which is precisely the focus of this work. We proposed FBG based OADM for channel reservation in a multiplexed network, dropping optical carrier signals from the system if not in use and adding the wavelength signals upon request to effectively support dynamically varying traffic demands. FBG was a narrow band filter to minimise crosstalk and improve the quality of service in WDM optical communication networks. There is improvement of the receiver sensitivity of both VCSEL 1 and VCSEL 2, upon passing through the FBG as demonstrated by the transmitted and reflected signals, respectively. The transmission after passing the FBG improved the receiver sensitivity of the VCSEL 1 signal by 1.58 dB at BER threshold. The reflection after the FBG filtering improved the receiver sensitivity of the VCSEL 2 signal by 1.51 dB at the BER threshold. The system can later add the reflected signal to the reserved channel combining with the transmitted signal forming the two-channel multiplexed network at different channel spacing and modulation format for efficient resource utilisation.

Chapter 8

8.0 Reconfigurable Optical Add/Drop Multiplexer

A ROADM is an all-optical subsystem that enables remote configuration of wavelengths at any node of given degree (switching direction) associated with a transmission fibre pair. The cost of each node increases linearly as the direction switched increases due to each degree requiring an extra wavelength switching element. In this work, we proposed and experimentally demonstrated a novel uniform Fibre Bragg Grating based reconfigurable optical add/drop multiplexer through optically tuning the periodic modulation of the refraction index. Index modulation variation plays an important role as it decides the centre wavelength of the Bragg grating so that a network operator can choose whether to add, drop or pass a wavelength through wavelength a node. The all-optical FBG based ROADM is a cost-effective and efficient resource utilisation technique for increasing spectrum capacity through wavelength add/drop for channel reservation. This is due to FBG's being relatively simple to manufacture as they are small-dimension, low-cost devices that exhibit good immunity from the electromagnetic radiation. We investigate the sensitivity of Fibre Bragg Gratings, FBGs, to the modulation depth of input signals. Obtaining a tuning range of up to 10 nm in a prototype based on directly modulated tunable vertical-cavity surface-emitting laser by controlling the bias current and drive current of the transmitter. Preliminary results show great potential for telecommunication applications, optical tunable Fibre Bragg Gratings have perfect spectral characteristics for channel reservation in a flexible spectrum network. The bandwidth of the FBG can fit a 6.25 GHz channel with the spectral range of 3 nm, accommodating 30 channels to choose from such that the nominal central frequency does not overlap. We have analysed the Bragg wavelength tuning positions in an error-free 10 Gb/s transmission along 25 km non-zero dispersion-shifted, NZD, fibre, showing negligible power penalty and bit error rate variation.

8.1 All-optical Tunable Fibre Bragg Grating

A conventional optical add/drop multiplexer comprises three stages; optical multiplexer, lightpath route reconfiguring technique, and an optical demultiplexer. The (de)multiplexer comprises a set of ports for removing/adding signals. The reconfiguration technique available at the nodes of the optical transport network should have the wavelength selective switch capability that can route lightpaths and assign channels to the relevant ports [127]. For FBG based OADM configuration, the multiplexed wavelength signal enters the FBG through port 2 of the circulator as previously illustrated in figure 7.3. The wavelength signal matching the Bragg condition is back-reflected while it transmits the other data signals on the output of the FBG. It drops the reflected optical carrier out of port 3 of the circulator [128], [129]. Addition of a second circulator extends the configuration, allowing the reflected signals to be wavelength-multiplexed signals that the FBG transmits through. The technology can engrave several FBGs onto one fibre core with different Bragg periods cascaded along the medium which can drop/add over one signal. To increase the degree of each node, we can tune the Bragg wavelength covering a range of wavelengths to drop the desired wavelength from the multiplexed signals. This means that it can add/drop any wavelength of optical data signals to the optical transport network with no Opto-electro-Opto conversion on all the wavelength division multiplexer channels [130]. This allows more flexible channel bandwidth in dynamic optical communication networks. For these reasons the FBG based OADM configuration is the most popular and most used wavelength selective switching technique. The FBGs are compact, low-cost passive devices, do not need any power supply, have low insertion loss and provide a fast switching speed to support existing optical transport at 10 Gb/s and beyond. This makes the FBG based OADM configuration a reliable, scalable, energy and cost-efficient solution for future flexible spectrum networks in the optical domain with a minimum number of electrical devices [131]. In this work, we proposed a reconfigurable optical add-drop multiplexer (ROADM) based on the optical tunability of Fibre Bragg Gratings. We discuss the principle of operation in the section below.

8.1.1 FBG based ROADM principle of operation.

Optical transport network with flexible spectrum provisioning offers plenty of advantages over the WDM systems with rigid spectrum assignment and coarse granularity of bandwidth resulting in inefficient utilisation of the resources. For traffic demands that require multiple wavelengths, this problem becomes more significant as there is no way to eliminate the spectral gaps between any adjacent wavelengths[132]. The OTN with flexible spectrum can support heterogeneous bandwidth demands as it accommodates super wavelength traffic, reaching high spectrum efficiency and scalability through an additional networking level. To achieve this, we introduce dynamic routing, wavelength assignment and adaptive allocation of custom-sized optical bandwidth to an end-to-end elastic spectrum optical path not limited to linear or ring configurations[133]–[135]. By introducing a colourless, directionless, and contentionless ROADM in the network's node, removing the constraints on wavelength assignment from the add/drop structure. Wavelength assignment constraints still exist at the network level, restricting two channels with the same wavelength on the same optical fibre link connecting any two nodes[89], [136]. ROADM design removes wavelength assignment constraints from the add/drop portion of the ROADM node so it can assign a transmitter to any wavelength as long as the number of channels with the same wavelength is not more than the number of degrees in the node. Wavelength channels can reach any adjacent node in the network with each degree representing a direction in which the node connects to another node. A network operator can flexibly add and drop the optical channel under software control through the switching function built into the transport node, adding wavelength switching into the optical transport network that allows the wavelength management. The ROADM required manual reconfiguration to change channel add/drop locations[74], [137]. In this work, we propose an all-optical reconfiguration able to select whether to transmit, add or drop a channel at a node, as will be discussed in the following sections.

8.1.2 VCSEL direct modulation response effect on FBG based ROADM.

To achieve the desired low-cost and power consumption target, the use of vertical-cavity surface-emitting lasers as directly modulated transceivers for optical Add/Drop multiplexing in the nodes of a flexible spectrum network is promising. It can modulate the VCSEL at gigahertz rates while manufactured at very low-cost wafer-scale method, in which VCSELS undergo complete testing and burned-in while still in wafer form resulting in increased manufacturing yield[138]. Also, the laser has low power consumption due to small threshold current applied, moreover the availability of multiple wavelengths at different bias current points[139]–[141]. The low modulation bandwidth (1- 10 Gbps) of VCSEL in the 1550 nm transmission window is a significant disadvantage, which is easy to manipulate through channel reservation for spectral efficiency based on OADM by exploiting wavelength tunability of the laser[42], [124], [142].

The optical cavity length is used to determine the lasing wavelength of a VCSEL, controlling it by varying the bias current which results in changes in output power and wavelength as shown in chapter 4. For the performance at high-speed networks, operators apply modulation to the laser operating well above the threshold and well undersaturation (linear part of the power versus bias current curve). We supply it with an electrical bit stream of "1"s and "0"s, with "1" standing for the highest power level and "0" the lowest. Varying the driver voltage of the on-off modulation signal, changes the modulation depth and the wavelength of the laser. This means that changing the applied drive voltage of the programmable pattern generator used to provide the non-return to zero modulation to the laser, increases the bias current which changes the optical cavity length resulting in wavelength tunability offering an additional degree of design flexibility to the network. The correct drive voltage related input power before the VCSEL is important, since a high-power input signal causes VCSEL saturation, resulting in high levels of signal distortion at the output and potential of errors that are intolerable affecting the quality of service [143], [144].

The modulation representing the digital “1”s and “0”s typically has a bit rate of > 10 Gbps for systems operating 1530-1610 nm (C-L band), with a channel spacing of 50 to 100 GHz. To provide a very high capacity link, we combine multiple transmitter channels into a single strand of optical fibre since it has very large bandwidth [145]. This technique uses wavelength division multiplexing (WDM) for the combination of channels and wavelength selective multiplexer such as Fibre Bragg Grating. In this chapter, we use two low-cost 1550 nm directly modulated VCSELs with high-speed NRZ to create a WDM system with reconfigurable OADM. Varying the modulation depth of input signal to maximise the data rates of OOK signal in the channel conditions, changes the cavity length and laser emission wavelength of the signal to drop/add for channel reservation in flexible spectrum network. Variation of the refractive index plays an important role in deciding the Bragg wavelength, so if finding the modulation conditions to match the grating plane in the constructive interference pattern for the reflection of the desired wavelength as shown in figure 8.1. We used a 20 Gbps WDM system to demonstrate the functionality of a reconfigurable OADM based on FBG using tunable laser sources as transceivers at a node of a flexible spectrum network.

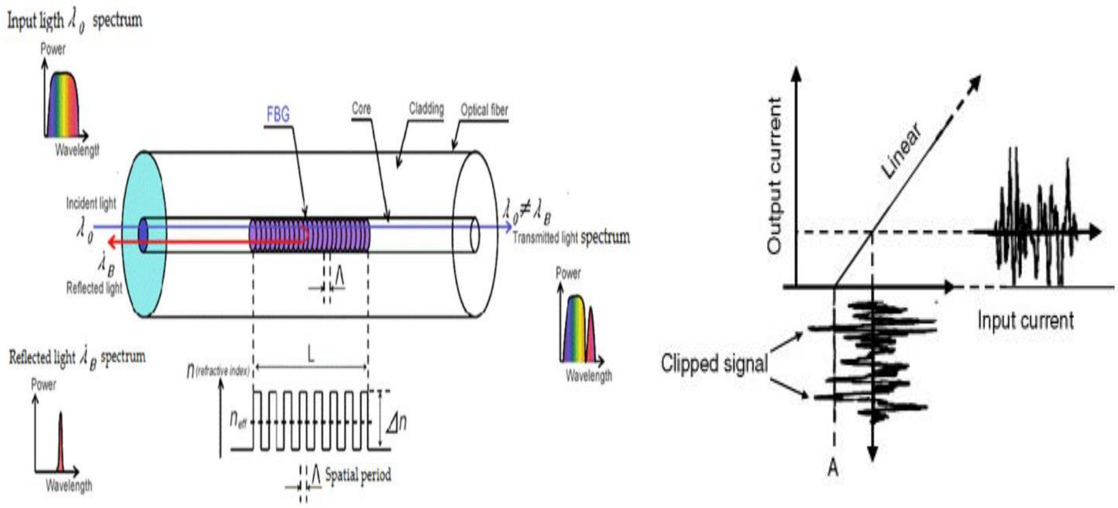


Figure 8.1: FBG based ROADM as a function of VCSEL tunability a) Fibre Bragg Grating used as an inline optical filter to block certain wavelengths b) characterization of a directly modulated VCSEL[146], [147]

FBGs operate on the principle of Bragg reflection. FBG reconfigurable Add/Drop multiplexers are then because the Bragg wavelength changes with a change in the grating's pitch and the change in the refractive index. The major drawback is that modulation of the device current leads simultaneously to phase or frequency modulation (FM) through carrier-induced refractive index changes and lattice heating[148]. The constantly increasing demand for bandwidth requires faster lasers. It is of the utmost importance to understand the mechanisms occurring in a laser under modulation, to identify the limiting factors and ultimately to minimise them. The different longitudinal modes is a term that refers to the resonant wavelengths that correspond to unique solutions of the phase conditions [141]. Because the material gain and sometimes the optical losses highly depend on wavelength, the laser will only emit light at one or a few discreet wavelengths for which the gain is maximum.

A laser oscillating at only one wavelength is, a single-mode laser. The gain-cavity detuning is defined by the respective alignment of the cavity resonance and the gain peak wavelength and is of crucial importance for the VCSEL performance[149]. Therefore, the output power and threshold current will highly depend on the gain-cavity detuning and therefore on the temperature and drive current at which the VCSEL is operated, as shown in the figure 8.1. Under direct intensity modulation it is thus crucial to consider drive that will not lead to severe distortion such as undesired frequency chirping and signal clipping as shown in the figure, but yet still obtain the desired carrier concentration variation for the intended change in the refracted index to match the desired modulation index tunability of the FBG.

8.1.3 Experimental demonstration of Bragg wavelength tunability as an effect of modulation depth

Bragg Gratings have proven attractive in a variety of optical fibre applications, such as Narrow-band and broadband tunable filters. The periodic modulation of the refractive index in the optical fibre core acts as a selective mirror for the Bragg wavelength of the structure. The grating periodically changes the phase or intensity as a light wave reflected on or transmitted through it. In reflection grating; coupling occurs between modes travelling in the opposite direction, while in transmission grating; coupling occurs between modes travelling in the same direction. This experiment considers the effect of changing the refractive index based on the numerical solution of the coupled-mode.

Analysing the spectral response of the uniform FBG to the different modulation depth from a tunable laser by varying the drive voltage as shown in figure 8.2. This was done to move optical transport networks toward highly dynamic mesh-based topologies, with flexible optical node architecture to optimise network operation by providing automated wavelength provisioning and lightpath restoration. A tunable laser (VCSEL) has many beneficial features such as low power consumption, low threshold current, low-cost, on-wafer testing capability, and high bandwidth and can be directly modulated. According to the light-current characteristic of 1550 nm VCSEL operates at different bias conditions exhibits different modes. where the y polarization (YP) mode defines the polarization mode of a VCSEL with a shorter wavelength , while the x polarization (XP) mode defines the longer wavelength [150], [151]. After introducing a FBG to provide wavelength-selective feedback, multiple dominant polarization mode switching will occur when the bias current or the drive voltage varies, as these result in wavelength tuning.

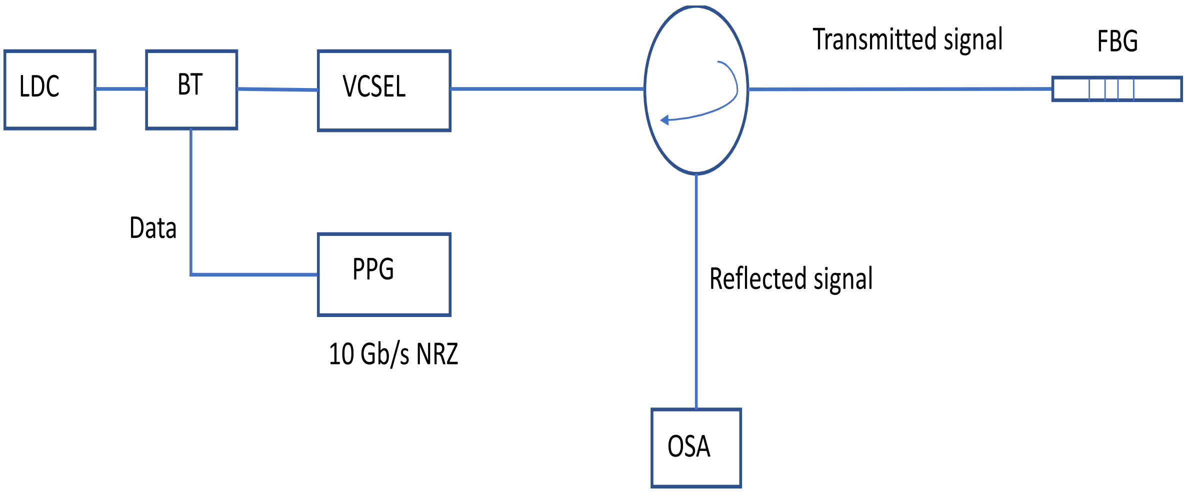


Figure 8.2: experimental setup for characterization of a directly modulated VCSEL for FBG based ROADM response to modulation depth variation

We conducted an experiment to investigate the wavelength variation of a 10 mm Phase mask manufactured by Fibre Bragg Grating to analyse the reflectivity, resolution and the wavelength shift range. We used a tunable laser source (VCSEL) fixed at a specific bias point and characterized the FBG tunability as a function of drive voltage (modulation depth). The 10 Gb/s 1550 nm VCSEL in this section was biased by setting the current using a laser diode controller (LDC). It biased the VCSEL above the threshold current. We performed direct modulation of the VCSEL with a 10 Gb/s non-return-zero (NRZ) pseudo-random binary sequence (PRBS 27-1) from a programmable pattern generator (PPG) via a bias-tee (BT). The modulated signal from the VCSEL was then incident on to port one of the circulator over to the FBG via port two. Measuring the reflected signal using an optical spectrum analyser connected to port three of the optical circulator. We characterized the Bragg wavelength of the FBG to be 1547.5 nm which corresponds to the wavelength emitted by the VCSEL at 4.30 mA bias current under no modulation (0 mV) drive voltage.

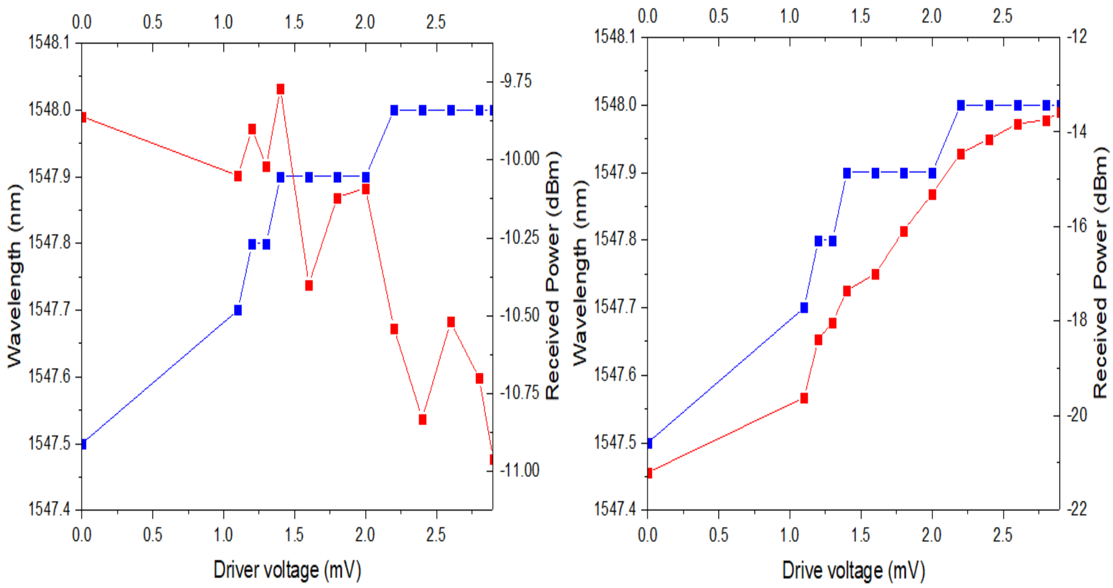


Figure 8.3: VCSEL fixed at a specific bias point and characterized the FBG tunability as a function of modulation depth for: a) reflected signal b) transmitted signal (Blue: wavelength, red: received power)

The measurements wavelength and the power of the reflected (dropped) and the transmitted (pass-through) signals are shown in figure 8.3 a) and figure 8.3b), respectively. The received power of the transmitted signal as emitted through port 2 of the Circulator pass the FBG increases linearly with drive current. This corresponds with the wavelength change ranging from 1547.5 nm to 1548 nm, 0.5 nm wavelength shift. The reflectivity changed from partial reflection to a percentage approaching zero at 2.9 mV, with the reflected signal completely diminishing meaning it transmitted the signal.

We measured FBG reflectivity of 92 % for a VCSEL at 4.30 mA bias current under no modulation and bandwidth of 0.1 nm at full-width half-maximum. The experienced changes in scale of drive voltage resulted in a 0.5 nm wavelength shift as shown in figure 8.4.

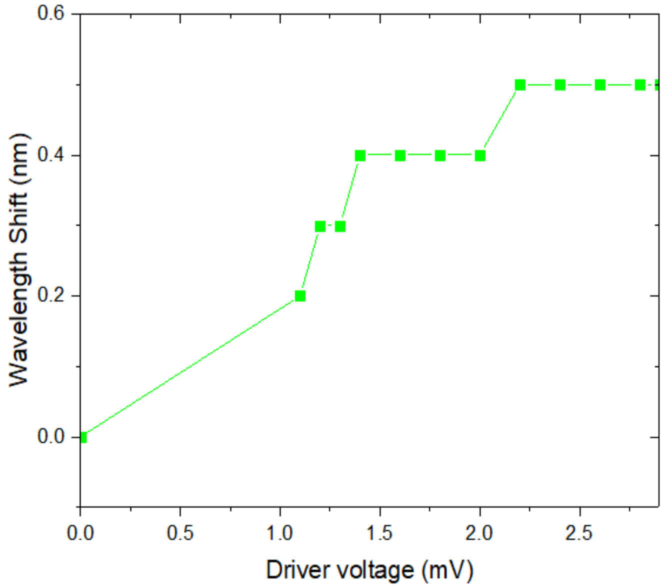


Figure 8.4: The wavelength shift of the reflected signal was observed with drive voltage variation

This characteristic was true for both the transmitted and reflected signal, though the power differs since the FBG acts a narrow filter. This means that the network has 62.4 GHz total spectral bandwidth, hence it can accommodate 5 channels of 12.5 GHz channel spacing. From this, we can drop a desired wavelength carrier signal from the channel by varying the drive voltage. Achieving successful experimental demonstration of flexible spectrum network optical reconfigurable Add/Drop multiplexer based on FBG response to tunable laser modulation depth variation.

8.2 Experimental demonstration of Channel Reservation in Flexible Spectrum Network for improved quality of service in optical transport networks

Wavelength collision negatively affects the quality of service and resource utilisation in flexible spectrum optical network as it reduces the number of usable wavelength bands in the available spectral bandwidth. This requires more components such as bandwidth variable transceiver and reconfigurable OADM for implementation in each node of the optical transmission network, which increases the overall cost and power consumption of the system. We have presented various wavelength conversion techniques in WDM systems to effectively minimise this effect, without assigning extra bandwidth by adding more components. The Centre for Broadband Communication research group at Nelson Mandela University has experimentally demonstrated an all-optical VCSEL-to-VCSEL wavelength conversion technique for transmission at low attenuation 1550 nm window[152]. The technique was further studied and used for experimental demonstrations of all-optical injection for spectral efficient utilisation through defragmentation and wavelength switching on a cascade of vertical-cavity surface-emitting lasers successfully. We further explored this technique for application in all-optical channel reservation capable node in multi-node flexible networks ROADM based on wavelength tunability of VCSEL and modulation depth variation of FBG as shown in figure 8.5.

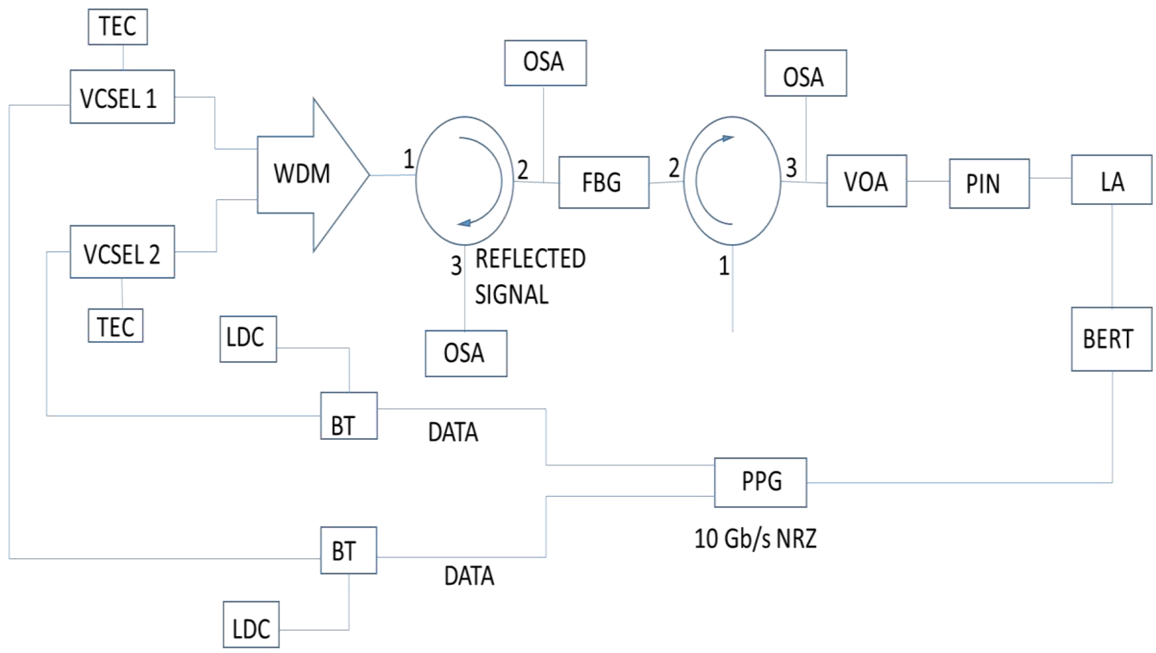


Figure 8.5: The set-up of the FGB based reconfigurable OADM configuration in WDM network using directly modulated VCSELs

Current variation of VCSELs controls the biasing and operation temperature (maintained at 25 °C) using a laser diode controller (LDC) and the thermo-electric controller (TEC), respectively. A 10 Gb/s non-return-zero (NRZ) pseudo-random binary sequence (PRBS 27-1) drive current applied to the VCSELS via a bias-tee (BT) for direct modulation. The pattern generation occurs at the bit-error-rate tester (BERT) with a variable modulation depth (drive peak-to-peak voltage) at bias points above threshold current and below saturation (linear regime of the power-current characterization curve). We combined the two VCSEL incoming transmission signal carriers wavelengths using a 50 GHz multiplexer to form wavelength division multiplexer (WDM) system. The multiplexed incoming wavelengths from both VCSELS both carrying 10 Gb/s PRBS data pattern from a PPG launches into the passive optical circulator through port 1. The optical circulator directs the signal to the FBG through port 2, which reflects a portion of the signal that (drops from the WDM system) for redirection through port 3. The signal that passes through the FBG (transmitted signal) launches into a variable optical attenuator (VOA) used to vary the optical signal power into the receiver to match the typical lightpath impairments. The receiver comprises a positive intrinsic negative (PIN) photodiode to convert the optical to an electrical signal and a linear amplifier (LA) used to amplify the electrical signal to meet the operational requirements of the BERT which compares the transmitted sequence to the received sequence on a bit to bit bases. The optical spectrum analyser (OSA) was used to observe the output optical spectrum of the multiplexed, transmitted and reflected signals.

8.2.1 20 Gbps WDM-PON data signal transmission Optimization without adjacent channel

The modulation index (grating planes) of the FBG changes with the varying drive voltage, this results to Bragg wavelength shift, hence the tuning of the reflected signal to any desired wavelength data signal. The received power increased with increasing drive voltage, which is the same effect observed with multiple multiplexed signals. The more signals are in the WDM system, the higher the received power. To analyse the sensitivity and wavelength variation resolution in a multiplexed optical transport network, we had to conduct an additional experiment as shown in figure 8.6.

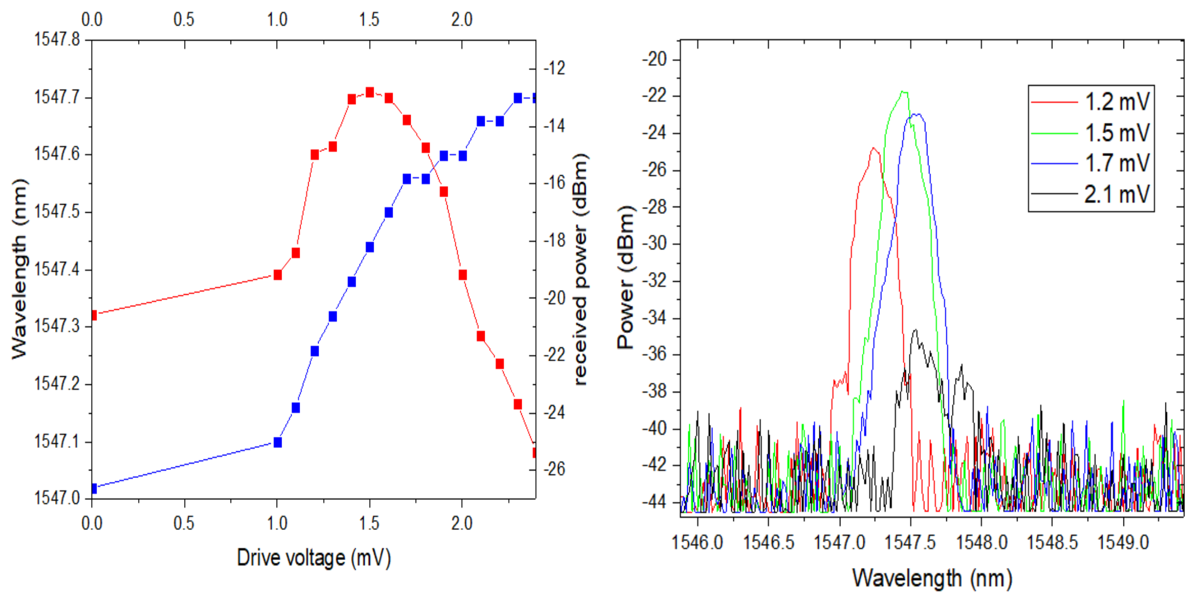


Figure 8.6: VCSEL fixed at a specific bias point and characterized the FBG tunability as a function of modulation depth a) reflected signal in a WDM system (Blue: wavelength , red: received power) b) output optical spectrum wavelength shift with varying modulation depth

The wavelength of the reflected signal changes with varying drive voltage as shown in figure

8.6a). The received power of the reflected wavelength signal drops drastically between 2.0 to 2.4 mV drive voltages. This is due to the FBG covering a range of wavelength limited to the grating planes perturbation that matches Bragg conditions, out of these limits no reflection of signal but a transmission of all the data carrier wavelengths. The wavelength shift of the reflected signal in the WDM system and the received peak power increase of the transmitted optical transport network is as shown in figure 8.7a) and 8.7b) respectively.

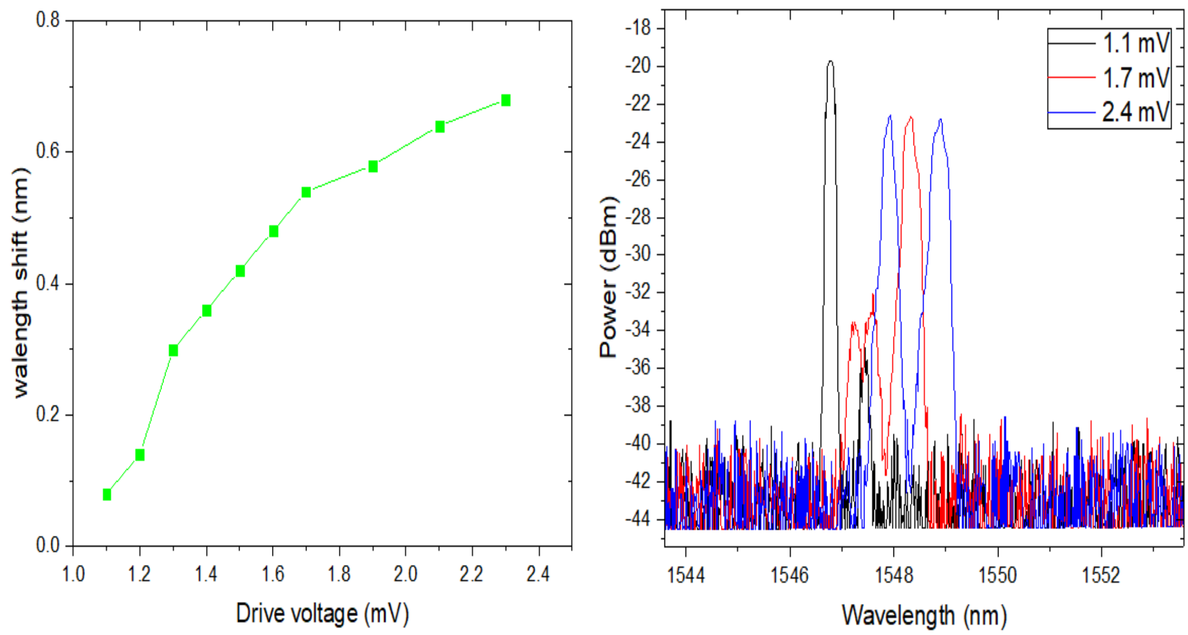


Figure 8.7: VCSEL fixed at a specific bias point and characterized the FBG tunability as a function of modulation depth a) reflected signal in a WDM system (Blue: wavelength , red: received power) b) Transmitted output optical spectrum wavelength shift with varying modulation depth

We achieved a maximum wavelength shift of 0.7 nm, which is equivalent to 87.3 GHz spectral bandwidth in the 1550 nm transmission window. This means that the network can accommodate 7 channels of 12.5 GHz channel spacing/granularity each with a full width half maximum bandwidth of 0.1 nm. Using figure 8.7a) we can predict the wavelength shift (Dl) in nm as a function of direct modulation peak-to-peak drive voltage (Vpp) from pattern generator into the VCSEL. In the WDM system, figure 8.7b) is used to test and analyse the effect of FBG tuning as it shows the wavelength of the transmitted data signals and the relative power.

8.4 Summary

The exponentially increasing demand for bandwidth by emerging cloud-based applications which leads to ever-growing data traffic volumes, stretching the limits of hardware requirements in existing optical transportation networks. The flexible spectrum network formed can obtain a high quality of service by avoiding wavelength collision through wavelength switching, lightpath routing and wavelength reassignment. We can achieve this by implementing the optical add and drop multiplexer in each node of the network for channel reservation. The wavelength division multiplexing (WDM) PON configuration combines wavelength selective multiplexer such as Fibre Bragg Grating. In this chapter, we directly modulated two low-cost 1550 nm VCSELs with high-speed NRZ creating a WDM system with reconfigurable OADM. Where the variation of input signal modulation depth to maximise the data rates of OOK signal in the channel conditions, changes the cavity length and laser emission wavelength of the signal to drop/add for channel reservation in flexible spectrum network. Direct modulation of VCSEL for wavelength tunability and FBG based ROADM development of flexible nodes, as they feature a fine spectrum granularity that enables the implementation of highly customisable band-reject filter or band-pass filter with variable bandwidth. The reflectivity increases with the increase of modulation depth so do bandwidth of the WDM system. From the present work, optimisation and improvement of the WDM system by commercially available low-cost components to achieve the degree of freedoms required for next-generation flexible spectrum network. There are studies to further develop FBGs with long period grating as the new applications demanding further refinement and control of the grating planes. Continued work on the different optical tuning of FBG modulation index techniques will open for an ever wider range of application areas with flexible, efficient and powerful optical components which eliminate the need of costly conversions from optical to electrical signal and back. As capacity demands continue to increase, flexible channel bandwidth will be needed to optimise reach for channels with data rates beyond 100 Gb/s. Thus, having a flexible spectrum ROADMs can improve spectral efficiency. Further, since the sub-carriers are fully tunable to any wavelength at bias points above threshold current and below the saturation point. We can simply tune the sub-carries to any existing 50 GHz fixed grid spectrum, allowing full backward compatibility with existing ROADM networks.

Chapter 9

9.0 Conclusions and recommendations

MeerKAT and SKA rely on optical fibre communication technology for transporting tremendous amounts of data. The dishes of the SKA and aperture arrays as a collective will produce 110 times the current global Internet traffic. Optical networks rely on complex technologies to meet the requirements of traffic demand requests. The networks comprise several components such as transceivers, routers, wavelength selected reconfigurable add-drop multiplexers, optical amplifiers distributed within optical networks spanning thousands of kilometres. The underpinning technologies and control algorithms for real-time dynamic operation of these networks in terms of operations such as wavelength assignment, wavelength routing, network restoration and protection are still under construction (not fully developed nor implemented). Flexible Spectrum Dense Wavelength Division Multiplexed (DWDM) optical fibre networks are next-generation technology for handling extremely high data rates of the kind produced by MeerKAT and SKA. Wavelength Division Multiplexing transmits multiple optical fibre wavelengths within a single optical fibre. Optimization of Flexible spectrum is dynamic, so to offer real-time channel wavelength assignment to make sure the network always performs at its best. For these networks to function optimally, identification and development of novel hardware and dynamic algorithms are necessary to do critical tasks. Such tasks include wavelength assignment, signal routing, network restoration and network protection. This project focuses on developing, implementing and testing modulation formats, hardware technologies and algorithms for optimising operation of such networks.

9.1 The planned objectives of the thesis

Upon summing up the aforementioned facts, the Doctoral Thesis proposal aims to: Develop a high-speed optical transport network based on the Advanced Modulation Flexible Spectrum Technology for MeerKAT and SKA telescope Data Transport over Optical Fibre. Through the development of next-generation system implementation on the existing WDM-PON infrastructure, to do critical tasks such as wavelength assignment, signal routing, network restoration and network protection.

To achieve the aim set, it is necessary to perform the following key tasks:

1. Background study on theory and operation of network components (reconfigurable optical Add/Drop multiplexers, wavelength selective switches, optical

transceivers etc.) and modulation formats (NRZ-OOK, QPSK, DPQPSK, QAM etc.) These are key elements of state-of-the-art time division multiplexed (TDM) and wavelength division multiplexed (WDM) passive optical networks.

2. Background study on software-defined optical fibre transport network architectures (cloud-based), specifically on DWDM flexible spectrum for the next-generation passive optical networks. This includes experimental work to gain expertise with equipment in NMU lab testbed for Clear formulation of the control plane and hardware requirements as relating.
3. Identify and improve the best technologies from 1) and topologies from 2) most suited to the problem. This features proposing a novel and dynamic solutions to design and build an experimental demonstration in the lab testbed reflecting a full high-speed flexible spectrum for the next-generation system based on DWDM PON architecture such as MeerKAT and SKA.
4. Assess the factor that affects the quality of service of a network such as polarization mode dispersion, chromatic dispersion, nonlinear effects, optical noise, crosstalk, inter-symbol interference and fragmentation due to the limit of spectrum continuity constraints and other concepts.

We have proposed novel all-optical FBG based ROADM design through the development and testing using tunable lasers and direct modulation to control bandwidth variable transceivers for next-generation flexible spectrum optical transport networks. Developing an electro-optical spectrum sliced transceiver for transmitting and receiving high-speed optical signals by implementing 10 Gbps NRZ-OOK electrical signal slicing for transmission over 25 km standard single-mode optical fibre reach, and to assess its performance based on receiver sensitivity, bit error rates, extinction ratio, eye diagrams and power penalties. We also applied wavelength multiplexing to increase the capacity of the system, whilst investigating effects of crosstalk and analysing the add/drop multiplexing and signal reshaping effects of FBG narrow filter on signals transmitted on the developed optical transport system.

9.2 Research Results and Scientific Novelty

Novel achievements of the Doctoral Thesis are:

1. We proposed a solution for WDM-PON through the development and testing of novel next-generation high-speed VCSEL based flexible transceivers for future flexible spectrum optical transmission systems, by using the electrical and optical-electrical components in the existing optical transport network. These WDM-PON have

wavelength assignment, channel switching and routing capabilities for a restricted frequency throughput bandwidth, to transmit higher-bitrate signals. The network achieves these functionalities through the wavelength tunability of the VCSEL with a response to the bias current, drive modulation depth effect optimisation for efficient resource utilisation. The optimisation helps characterise the VCSEL as an ideal bandwidth variable transceiver, in terms of receiver sensitivity and extinction ratio, producing a domain as a 3D surface map which can analyse the performance of the system and predict the quality of service of a network for known transmission impairments and intended reach.

2. All-optical spectral efficient VCSEL-based technique for routing and spectrum assignment in optical networks. Exploiting all-optical VCSEL-to-VCSEL injection to attain cross gain modulation, optimising the optical transmitter for optical transmission paths to assure the quality of service by overcoming blockage for differentiated bandwidth demands during network congestion incidences. These characteristics and advantages of VCSEL technology for high-speed signal transmissions such as central nominal wavelength tunability and the ability for direct modulation and detection for optimised flexible spectrum technology leading to a novel demonstration spectrum allocation, channel switching, and wavelength reassignment. This technique uses cross gain modulation where semiconductor optical amplifier re-modulate a signal in the receiver end through the saturation gain of EDFA, resulting in wavelength reassignment, channel switching and lightpath rerouting in flexible spectrum based on WDM-PON.
3. In collaboration with the City University of London optical fibre laboratories through the Royal Academy of Engineering research funding, the design, manufacturing and production of uniform Fibre Bragg Gratings were achieved. The uniform FBGs were used to develop and implement reconfigurable optical switches for Flexible Spectrum networks. Though the main application of FBG technology is sensing such as structural health monitoring and e-health. In this work, we experimentally demonstrate a novel passive FBG based OADM configuration for defragmentation approach in flexible spectrum networks. we achieved signal reshaping due to the chirp effect and dispersion effect trade-off in directly modulated systems. Utilizing FBG based OADM for wavelength switching and lightpath routing implemented to 10 Gbps NRZ-OOK electrical signal slicing for transmission over 25 km standard single-mode optical fibre reach, and to assess its performance based on receiver sensitivity, bit error rates, extinction ratio, eye diagrams and power penalties.
4. NMU Centre for Broadband Communication laboratory testbed experimental demonstrates the use of vertical-cavity surface-emitting lasers as directly modulated transceivers for optical Add/Drop multiplexing in the nodes of a flexible spectrum

network. We did this to reduce wavelength collision, which negatively affects the quality of service and resource utilisation in flexible spectrum optical network, as it reduces the number of usable wavelengths in the available spectral bandwidth. This requires the implementation of components such as bandwidth variable transceiver and ROADMs (configured in 2.) in each node of the optical transmission network, which increases the overall cost and power consumption of the system. An all-optical ROADM design demonstration will be realised through the development and testing of novel control using tunable lasers and direct modulation to design bandwidth variable transceivers for next-generation flexible spectrum optical transport networks. Optically reconfiguring/tuning the OADM over a range of wavelengths by varying the Bragg conditions as a response to the refractive index to the modulation depth/drive current.

5. We have tested the application of the ROADM, increasing the data transmission speed from 10 Gbps to 20 Gbps in two-channel spectrum sliced WDM-PON systems, to investigate the effect of crosstalk and inter-symbol interference as a function of channel spacing. The inherent narrow band filtering characteristics of passive FBG, the signal chirp of directly modulated transmitters, and experimental demonstrations of dispersion matching to achieve high-speed data transmission. using the existing transmission WDM-PON infrastructure for further developed enabling fully integrated into the next-generation high-speed flexible spectrum networks.

9.3 Future work

The following main conclusions and future work of the doctoral thesis study:

Flexible spectrum systems based on the dense wavelength division multiplexed demonstration using passive optical network implementation for the next-generation technology capable of handling the extremely high data rates of the kind produced by MeerKAT and SKA. The Wavelength Division Multiplexing refers to the transmission of multiple optical fibre wavelengths within a single optical fibre. Flexible spectrum refers to the channel wavelength assignment and is dynamically optimised in real-time to ensure optimum network performance. For these networks to function optimally, novel hardware and dynamic algorithms need to be identified and developed to perform critical tasks. Such tasks include wavelength assignment, signal routing, network restoration and network protection. This project focuses on developing, implementing and testing modulation formats, hardware technologies and algorithms for optimising the operation of such networks. The optical layer has been designed, developed and implemented to the existing WDM-PON infrastructure, optimising the hardware technology such as the transceivers and switches through ROADM in the nodes of the system. In the future, the project identifies and researches dynamic optimisation control algorithms with a dense wavelength division multiplex (DMDM) flexible spectrum network architecture as a solution. Algorithms under consideration include genetic algorithms, evolutionary algorithms, particle swarm optimisation, ant colony optimisation, etc. A further research consideration is whether the control plane performs best through a centralised or distributed network implementation. Such algorithms and control plane offer the power and flexibility for real-time implementation. The underpinning control algorithms for real-time dynamic operation of these networks in terms of operations such as wavelength assignment, wavelength routing, network restoration, protection and shortest path rerouting have not yet been fully developed or implemented.

Appendix A

Research outputs in journals, peer reviewed conferences, collaborations and other reports

Published/accepted/ presented articles

Journal publications:

1) G. M. Isoe, **P. P. Dlamini**, and T. B. Gibbon, "Real-time wavelength reuse based on Bragg trans-reflection for dynamic reference frequency and data transfer in Datacom," J. Mod. Opt., vol. 66, no. 16, pp. 1631–1636, Sep. 2019.

2) **P. P. Dlamini**, G. M. Isoe, D. Kiboi Boiyo, A. W. R. Leitch, and T. B. Gibbon, "All-Optical VCSEL-to-VCSEL Injection Based on Cross Gain Modulation for Routing in Multinode Flexible Spectrum Optimization in Optical Fibre Transmission Links," Int. J. Opt., vol. 2019, p. 2987652, 2019.

International collaborations:

3) During the second semester, Miss Dlamini undertook a three-month Research visit at the City University of London. She spent time with the Research group of Professor Kenneth Grattan. Prof Grattan is Dean of the City Graduate School at City University of London. He has over 40 years in the field of lasers, fibre optics, sensors and measurement and have published over 1300 papers in key international journals and

at major Conferences during that time. With her visit to the UK, Miss Dlamini benefited through use of equipment from the recent £2M investment in the optical fibre laboratories by City University of London. She worked on designing, producing Fibre Bragg Gratings, a technology used in sensing reconfigurable optical switches for Flexible Spectrum networks. The research visit was funded by the Royal Academy of Engineering, UK. This lead to development of a novel defragmentation approach for flexible spectrum networks. Miss Dlamini also spent three months in the UK designing, producing and characterizing Bragg gratings. These are vital components for use in reconfigurable optical Add/Drop multiplexers (ROADMs). Miss Dlamini returned from the UK with the Bragg gratings that she manufactured and she will work further with them in her research.

International Conferences:

4) **P. P. Dlamini**, G. M. Isoe, D. K. Boiyo, A. W. R. Leitch, and T. B. Gibbon, "Cascaded VCSEL-to-VCSEL all-optical injection for spectral defragmentation and switching using optical transmitter cross gain modulation," in Proc. SPIE OPTO, vol. 10946 2019, San Francisco, California, United States, 2019

5) **P.P. Dlamini**, R.R.G. Gamatham, A.W.R. Leitch, and T.B. Gibbon, "Stability Budget of Optical Clock Signal Stability Transmitted over Single Mode Optical Fibre," The annual 2017 Southern African Telecommunication Networks and Application Conference (SATNAC) 3rd – 10th September 2017 on the Freedom of the Seas Cruise Liner, Royal Caribbean International, Barcelona, Spain.

Local conferences:

6) **P. P. Dlamini**, G. M. Isoe, D. K. Boiyo, A. W. R. Leitch, and T. B. Gibbon, "Fibre Bragg Grating Based All Optical OADM for Flexible Spectrum Channel Reservation to Minimise Optical Crosstalk in WDM Optical Communication Networks", Proceedings of Southern African Telecommunication Networks and Application Conference (SATNAC), Fairmont Zimbali Resort in Ballito, KwaZulu-Natal, South Africa (1-4 September 2019)

7) **P.P. Dlamini**, G. M. Isoe, D. K. Boiyo, A. W. R. Leitch, and T. B. Gibbon,

"Reconfigurable optical add/drop multiplexer for channel reservation in flexible spectrum networks for the SKA", SARAO Postgraduate Scholarship Conference, Southern Sun, Elangeni | Maharani Hotel Durban, 2-6 Dec 2019.

8) **P.P. Dlamini**, R.R.G. Gamatham, A.W.R. Leitch, and T.B. Gibbon, "Ant Colony Optimization for IPoDWDM Flexible Spectrum Optical Fibre Networks", SKA Student Conference, Cape Town, 27 Nov -1 Dec 2017.

9) **P. P. Dlamini**, G Isoe, RRG Gamatham, AWR Leitch, TB Gibbon, "VCSEL-based Wavelength Allocation and Defragmentation Technique for Next-Generation Flexible Spectrum Networks", Proceedings of Southern African Telecommunication Networks and Application Conference (SATNAC), Hermanus, South Africa (2-5 September 2018), pp. 98-103.

10) **P. P. Dlamini**, GM Isoe, RRG Gamatham, AWR Leitch, TB Gibbon, "Spectral Resource Management based on VCSEL Wavelength Switching and Allocation", 63rd Annual Conference of the South Africa Institute of Physics (SAIP), University of Free State, 25-29 June 2018.

11) **P.P. Dlamini,** R.R.G. Gamatham, T.B. Gibbon and A.W.R. Leitch, " Short-Term Stability of RF Clock Signal Distribution System Over Different Optical Fibres," the 62nd annual conference of the South Africa Institute of Physics (SAIP), Stellenbosch University, 3rd – 7th July 2017.

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