Characterization of Wavelength Tunable Lasers For Use in Wavelength Packet Switched Networks

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A THESIS SUBMITTED FOR THE DEGREE OF

Master of Engineering

In the School of Electronic Engineering.

Dublin City University

Research Supervisor

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March 2005

Approval

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Degree: Master of Engineering

Title of Thesis: Characterization of Wavelength Tunable Lasers
For Use in Wavelength Packet Switched Networks

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I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Master in Engineering is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

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Abstract

The telecom industry's greatest challenge, and the optical systems and components vendors' biggest opportunity is enabling providers to expand their data services. The solution lies in making optical networks more responsive to customer needs, i.e., making them more rapidly adaptable. One possible technique to achieve this is to employ wavelength tunable optical transmitters. The importance of tunability grows greater every year, as the average number of channels deployed on DWDM platforms increases. By deploying tunable lasers it is much easier to facilitate forecasting, planning and last minute changes in the network. This technology provides with solution for inventory reduction. It also offers solution for fast switching at packet level.

The conducted research activities of the project was divided in two work packages:

1. Full static characterization-the laser used in the experiment was a butterfly-packaged Sampled Grating DBR laser with four electrically tunable sections. LabView programme was developed for distant control of the equipment and the laser itself. The parameters required for creating a look-up table with the exact currents for the four sections of the laser, namely wavelength, side mode suppression ratio and output power, were transferred to tables. Based on those tables the currents were defined for each of the 96 different accessible channels. The channel allocation is based on the 50 GHz spacing grid. A detailed analysis of the tuning mechanisms is provided.

2. Dynamic characterization and BER performance in wavelength packet switched WDM systems-a commercially available module was used supplied with the software package for controlling the wavelength channels and setting the laser to switch between any accessible channel. The laser is DBR laser without SOA integration so the dynamic tunability can be investigated. As the switching in the nanosecond regime is executed in the electrical domain, analysis of the switching parameters concerning the electrical circuit as well as laser structure is provided. The actual switching time was defined. The degradation in system performance due to spurious wavelength signals emitted from the tunable module during the switching event and their interference with other active channels was demonstrated by examining the presence of an error floor in the BER rate against received power measurements.

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Chapter 1

Optical Communication Networks

This chapter introduces the basic concepts of optical communication systems and details the advantages as well as the limitations of deploying optical systems. It also provides an insight into the present state and future prospects for telecommunication networks.

1.1The basics

The use of light as a medium for transmitting data is revolutionizing the speed and capacity of the Internet. The application of photonic technologies to the Internet backbone - the large data pipes that connect regional networks and provide the global linkage that gives the World Wide Web its name - has helped the Internet keep up with the exponential growth in traffic over the last decade [1]. As network designers look for greater speed and capacity, the use of optical technologies is growing, finding applications beyond the Internet backbone and closer to the end user.

The fundamental advantages of light pulses as carriers of digital data have made optical-fiber communications networks the dominant component of the worldwide communications infrastructure in general, and of its inner layers in particular. A comparison between optical fiber and its electronic counterpart can give an understanding of why eventually optical technologies will likely find a place in all kinds of networks, all the way down to local area networks (LANs).

Optical Fiber vs. Copper Wire

Over the past three decades fiber has become the transporting medium of choice for voice, video, and data, particularly for high-speed communications. Fiber is compact, low-loss, immune to electromagnetic interference, secure, non-corrosive, and has almost unlimited bandwidth. There are a few key characteristics.

- **Wide bandwidth**: Optical fiber has been proven to have the widest bandwidth compared to any other media known, including wireless, copper wire, sonar, and even free-space-optics. Tbit/s have been demonstrated by using the standard singlemode telecom fiber. As a comparison, the achieved rate over copper links is 1 Gbit deployed for Ethernet application. IEEE 802.3 Working Group formed two groups to pursue different approaches of achieving 10gGbit/s. One of them works toward a solution for getting that speed over unshielded CAT5 twisted pair for a distance up to 100m. The other addresses a shorter-range version using the cabling scheme with dual coax cables [2], [3]. Those rates still represent a small percent of the bandwidth supported by a single strand of fiber and the links are severely limited in length. As a result, a single strand of optical fiber can easily replace a large bundle of copper wires while significantly boosting system bandwidth.

- **Low loss**: Optical fiber poses far lower loss to signal than any other transmission media. The typical loss per kilometre in a singlemode fiber is around 0.4dB at any bit rate, making it possible to send signal over a much longer distance (more than 100km) without the need for repeaters or amplifiers. On the contrary, the typical loss figure for a coaxial copper cable is around 40dB/km at 10-100Mbps and grows linearly with bit rate [4].
- **High security**: Unlike its copper counterparts, an optical fiber does not emit electromagnetic waves and therefore is extremely difficult to tap into. Even if the fiber were tapped into, it would create enough disturbances in the system to be detected [5]. Therefore, optical fiber has been the most preferred transmission medium in secure systems worldwide, particularly military applications.
- **Increased safety**: Electrical current can be extremely harmful in an environment where flammable or explosive materials are used or stored. Optical fiber provides an ideal channel to collect useful information such as temperature, pressure, and humidity in these environments.

1.2 Optical Communication Systems

As any telecommunication system, an optical communication system has three main building blocks:

- The communication media, which is the optical fiber
- The passive and active components that interface with the fiber, such as transmitters, detectors, modulators and amplifiers

- The software based network management system and the protocols creating the communication environment

Figure 1.1 is a schematic diagram of a basic optical communication system.

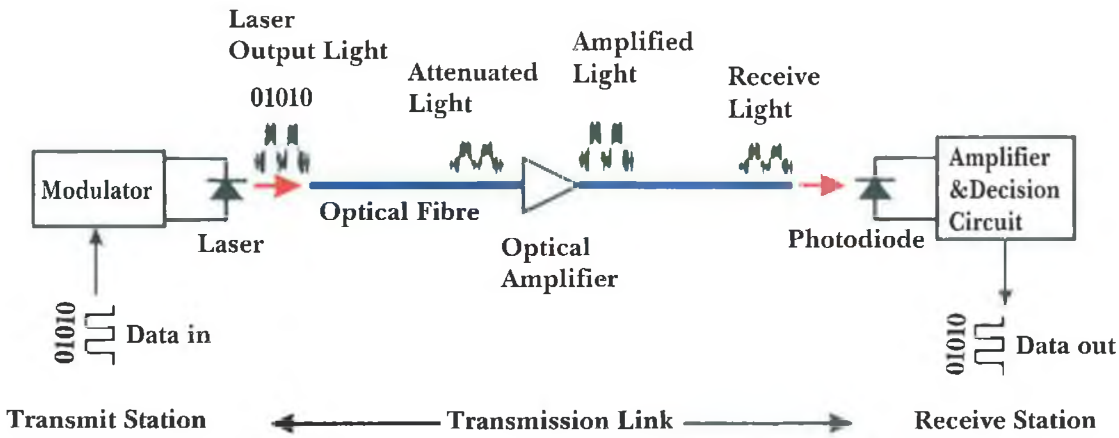

Figure 1.1-Basic Optical Communication System

The aim of the system is to transmit information using an optical carrier wave from a transmit station to a receive station over optical fibre. Electrical data usually represented as a series of '0's and '1's, modulates a semiconductor laser. The laser output is a series of light pulses representing the '0's and '1's {for digital information}. The modulated laser light is then sent down an optical fibre. At appropriate points in the transmission link, the light signal is either optically amplified or completely regenerated. Optical amplification is required to overcome the fibre loss. Regeneration means that the light signal is detected, reshaped, retimed and retransmitted. It is required when the light signal becomes distorted by the fibre (dispersion) or influenced by noise. At the receiver the light signal is detected, amplified and sent to a decision circuit. The decision circuit decides if a '0' or '1' bit has been received [6].

1.3 Bandwidth demand

Demand for network bandwidth has been increasing dramatically in recent years. Optical networks and the Wavelength-Division Multiplexing (WDM) technique that will be explained in more detail later are promising technologies for satisfying the explosive bandwidth demand. In addition, the wavelength conversion mechanism, which transforms an input wavelength to a desirable wavelength at conversion nodes, eliminates the wavelength continuity constraint, and increases the network efficiency significantly.

High capacity can be achieved in different ways. One of them is maintaining comparatively low channel rate while placing a large number of channels within the amplifier band [7]. Another way is supporting fewer channels that run at higher rates, from bandwidth perspective the two options are equally demanding, but there are fundamental differences concerning dispersion and nonlinearities.

As there are various applications and end users of the developed network there is a prerequisite that the service should be transparent, not obeying certain network protocol.

1.4 Limitations of fibre transmission

Physics play a crucial role in planning the network. With the increased channel bit rates, link lengths and launched powers in current systems, there are several optical phenomena that can result in the optical data transmission being impaired.

1.4.1 Nonlinear Effects

The response of any dielectric (such as optical fibre) to optical power is nonlinear. It is the dipole nature of the dielectric that interacts harmonically with light. When the optical power is low, it results in small oscillations. However when the power is large the nonlinear behaviour is significant. The reason nonlinear effects are becoming more prominent now is that with the advent of WDM systems and higher bit-rates being used, the amount of optical power within fibers is increasing. And it is at high optical powers that nonlinear effects start to become noticeable, whereas in systems where low optical powers are transmitted, they can often be ignored completely.

There are two categories of nonlinear effects: Kerr effects and scattering effects. The first consists of three phenomena. In an optical fiber the core in which the optical signals travel has a specific refractive index that determines how light travels through it. Depending upon the intensity of light travelling in the core, this refractive index can change. This intensity-dependence of refractive index is called the Kerr effect. It can cause "**self-phase modulation**" of a signal, whereby a wavelength channel can broaden out and interfere with adjacent wavelength channels [8]. It can also cause "**cross-phase modulation**" whereby several different wavelengths in a WDM system can cause each other to broaden [9]. Finally, it can result in "**four-wave mixing**" in which two or more signal wavelengths can interact to create a new wavelength signal [10]. The results of those nonlinear effects are:

1. Cross talk

2. Signal power depletion-as a result of power sharing among the contributing channels to the newly generated

3. Signal to nose degradation due to super position of noise and random data from the contributing frequencies.

There are two nonlinear scattering effects.

1.Stimulated Raman Scattering involves light losing energy to molecules in the fiber and being re-emitted at a longer wavelength (due to the loss of energy) [11].

2. Stimulated Brillouin Scattering light in the fiber can create acoustic waves, which then scatter light to different wavelengths [12].

As the thesis deals with DWDM system, which is described in details in the next chapter a short overview can be provided as to how the discussed nonlinearities affect the system. DWDM systems satisfy the constant increasing demand of capacity by allocating different channels close to each other. R&D activities are constantly challenging the relative space and constantly driving the channels closer. For the moment, the most widely used channel spacing is the 100 GHz margin but recent attempts have broken the barrier and experiment showed channel spacing of 25 and 10 GHz are possible. However XPM and FWM are the main obstacles to error free transmission as the channel spacing decreases. XPM can be divided in two categories: intensity distortion and timing jitter [13]. Different channels propagate at different group velocities so the overlap between the transmitted data patterns is changing along the fiber (an effect known as walkoff). Every transition in on the encoded channels introduces an optical frequency shift to the overlapped part of the other encoded channel.

Timing jitter accumulates until the frequency shift from the one edge in the interfering channel is cancelled by the following edge, since positive and negative transitions cause opposite frequency shifts. However because of imperfections the shift is never fully compensated and the jitter accumulates along the length.

So XPM contributes to both amplitude and timing distortions in the system.

There is a limiting combination of channel spacing, signal power and fiber chromatic dispersion. The influence of FWM has a great impact when the channels are densely spaced [14]. The effect of cross phase modulation can be neglected as they are approximately inversely proportional to the channel spacing and can be to great extent mitigated by appropriate dispersion compensation techniques.

1.4.2 Dispersion

Dispersion is the property of the fiber that can be attributed to the spreading of an optical pulse in time domain due to differences in the velocities of the various spectral components that are associated with the optical pulse. With optical networks moving to higher bit rates, the acceptable tolerance of dispersion drastically reduces. The tight tolerance margins of the networks mean that every source of pulse spreading should be addressed.

1.4.2.1 Chromatic dispersion

Material dispersion

Material dispersion is the phenomena whereby materials cause a "bundle" of light to spread out as it propagates. We know that a laser pulse, while almost monochromatic, actually contains a continuum of wavelengths in a small range. The index of refraction of a material is dependant on the wavelength, so each frequency component actually travels at a slightly different speed [15]. The following figure illustrates the refractive index as it changes with wavelength for silica material.

The refractive index of fiber decreases as wavelength increases, so longer wavelengths travel faster-*Figure 1.2*. The net result is that the received pulse is wider than the transmitted one, or more precisely, is a superposition of the variously delayed pulses at the different wavelengths. A further complication is that lasers, when they are being turned on, have a tendency to shift slightly in wavelength, effectively adding some frequency modulation to the signal. This effect, called "chirp" causes the directly modulated laser to have an even wider optical line width, then it would when operating under CW conditions.

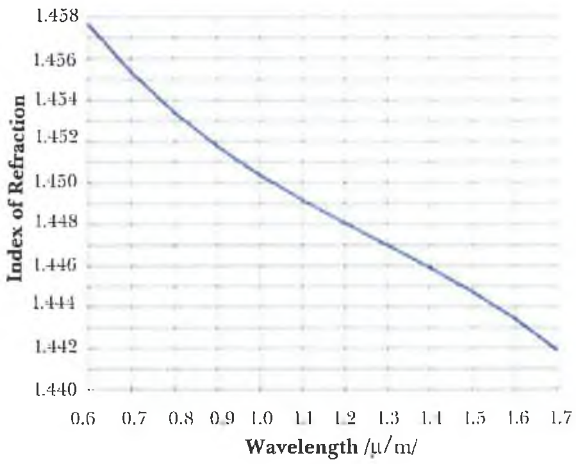

Figure 1. 2- Index of refraction against Wavelength

As the distance increases, the pulse becomes broader as a result. The *group delay* is an essential parameter. This is the time delay per unit length of energy propagating through a transmission system. It can be assumed that each spectral component travels independently and undergoes its own time delay,τ_g. The material dispersion parameter for different structures largely depends on the wavelength- *Figure 1.3.*

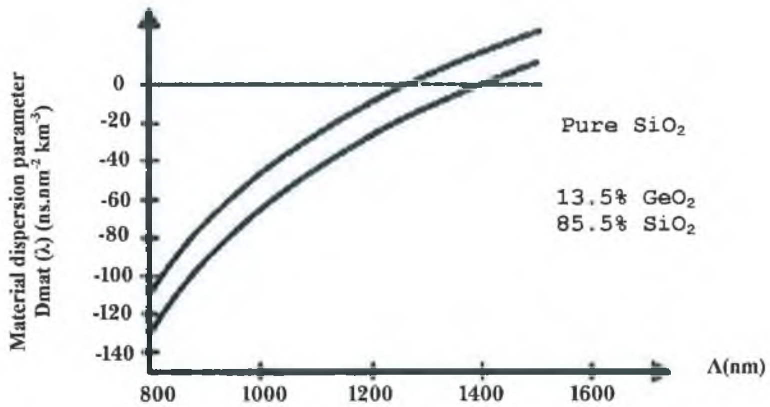

Figure 1. 3-Material Dispersion Parameter for different structures against wavelength

Waveguide dispersion

Optical fiber is composed of a core and a cladding, whose refractive indexes are different. This difference causes the light in the core travelling at slower rate, compared to the cladding, resulting in a spreading of the pulse [16].

1.4.2.2 Polarization mode dispersion

The fiber can be best described as an imperfect cylinder, whose physical dimensions are not constant. The refractive index of the optical fiber can have different values across the horizontal and vertical axis of the core. This variation results in two orthogonal states of polarization travelling at different speeds through the fiber-the effect is shown in *Figure 1.4*. The differential phase velocity in generally goes along with a differential group velocity for the two polarization modes [17]. This difference in group velocities broadens the pulses by introducing a differential group delay (DGD) between the modes. The DGD per unit length ($\Delta\tau / L$) is called the short-length or intrinsic PMD of a fiber and is usually expressed in units of picoseconds per kilometer. The linear length dependence is valid only for uniformly birefringent fibers.

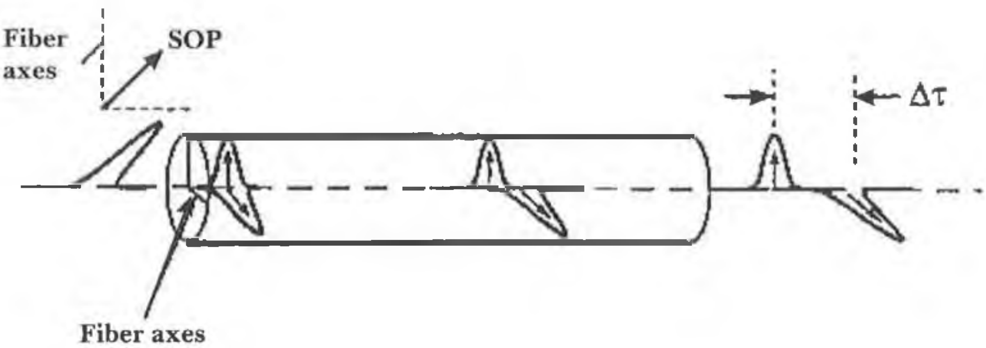

Figure 1.4-Orthogonal polarization states travelling at different speeds

1.4.2.3 Dispersion compensating methods

1. **Chromatic dispersion compensation**

Dispersion compensating fiber-DCF is a fiber with a refractive index profile with a dispersion parameter of the same magnitude but opposite in sign to the transmission fiber. Opposed to single mode fiber, which have a positive dispersion (longer wavelengths travel slower than shorter wavelengths). DCF is made with negative dispersion over a specific range of wavelengths [18].

2. **PMD compensation**

PMD becomes increasingly important as the bit rate goes higher. The fibers are specified by their average group delay/DGD/ in ps or a mean DGD coefficient in $ps/\sqrt{km}$:

Low PMD fiber-0.1 $ps/\sqrt{km}$

High PMD fiber-2 $ps/\sqrt{km}$

With the bit rate increasing, PMD compensation will improve the length of the fiber.
For now there are no easy and inexpensive solutions [19].

1.5 Multiplexing techniques for high capacity networks

The growth in data traffic leads to strong motivation and pressure to better utilise the enormous bandwidth of fibre optics networks. In a basic optical communication system comprising a transmitter, the capacity is limited by the speed at which the light can be modulated. To overcome this limitation it is necessary to use optical multiplexing techniques such as Wavelength Division Multiplexing and Optical Time Domain Multiplexing.

1.5.1 OTDM

Higher rate channels can be a combination of many lower-speed signals, since very few individual applications today utilize this high bandwidth. These lower-speed channels are multiplexed together in time to form a higher-speed channel-*Figure 1.5*. This time-division multiplexing (TDM) can be accomplished in the electrical or optical domain, with each lower-speed channel transmitting a bit (or allocation of bits known as a packet) in a given time slot and the waiting its turn to transmit another bit (or packet) after all the other channels have had their opportunity to transmit [20].

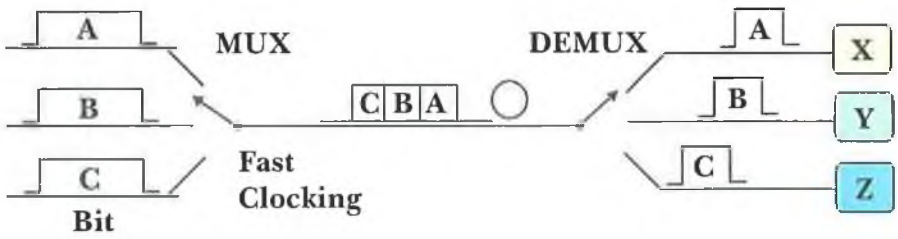

Figure 1. 5- Several TDM channels with bit interleaved multiplexing

1.5.2 WDM

One obvious choice for exploiting more of the fiber's THz bandwidth is WDM (wavelength division multiplexing), in which several baseband-modulated channels are transmitted along a single fiber but with each channel located at a different wavelength. Each of N different wavelength lasers is operating at the Gbps speeds, but the aggregate system is transmitting at N times the individual laser speed, providing a significant capacity enhancement-*Figure 1.6*. The WDM channels are separated in wavelength to avoid cross talk when they are (de) multiplexed by a non-ideal optical filter. The wavelengths can be individually routed through a network or individually recovered by wavelength-selective components. WDM allows us to use much of the fiber bandwidth, although various device, system, and network issues will limit the utilization of the full fiber bandwidth [21]. The concept and components used in the design of complete WDM systems will be described in more detail later in the thesis.

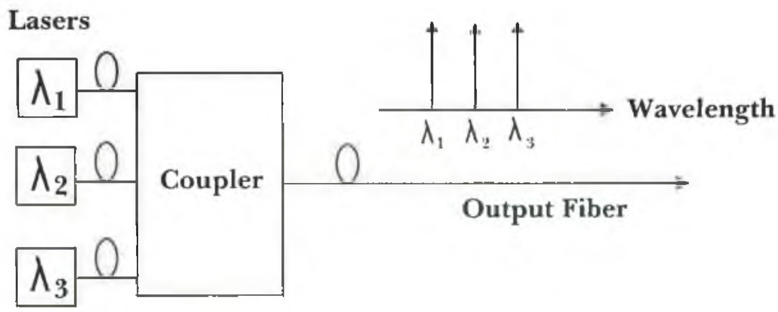

Figure 1. 6-Many WDM channels propagating in a single optical fiber

1.5.3 CDM

An additional multiplexing technology is code-division multiplexing (CDM). Instead of each channel occupying a given wavelength, frequency or time slot, each channel transmits its bits as a coded channel-specific sequence of pulses. This coded transmission typically is accomplished by transmitting a unique time-dependent series of short pulses. These short pulses are placed within chip times within the larger bit time. All channels, each with a different code, can be transmitted on the same fiber and asynchronously demultiplexed [23]. One effect of coding is that the frequency bandwidth of each channel is broadbanded, or "spread"- *Figure 1.7*. If ultra-short (<100 fs) optical pulses can be successfully generated and modulated, then a significant fraction of the fiber bandwidth can be used. Unfortunately, it is difficult for the entire system to operate at these speeds without incurring enormous cost and complexity.

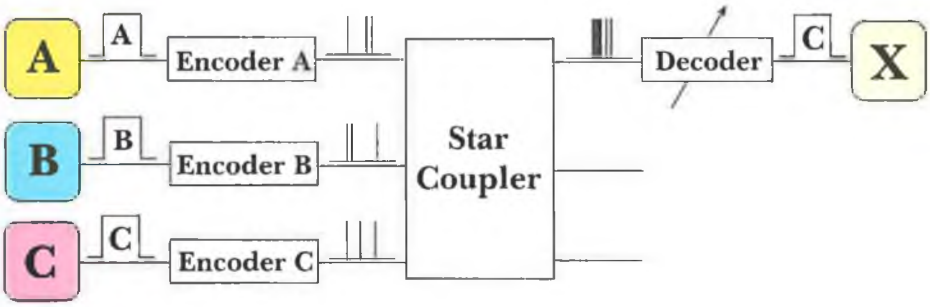

Figure 1.7-The basic concept of a coded pulse sequence for CDM, with each pulse located in a chip time and the entire code occupying a larger bit time slot

For different systems time and code division multiplexing are viewed as a favorable way to increase the channel number. OTDM is an option for increasing the channel number in simple fiber network structures with limited capacity. CDM techniques can be applied to more complex network architectures since some optical CDM approaches can be realized to support asynchronous operation of channels. Optical TDM typically can be applied to a limited part of the network usually in the access part, whereas in the MAN part of the network, both WDM and CDM techniques may be implemented as shown in *Figure 1.8*.

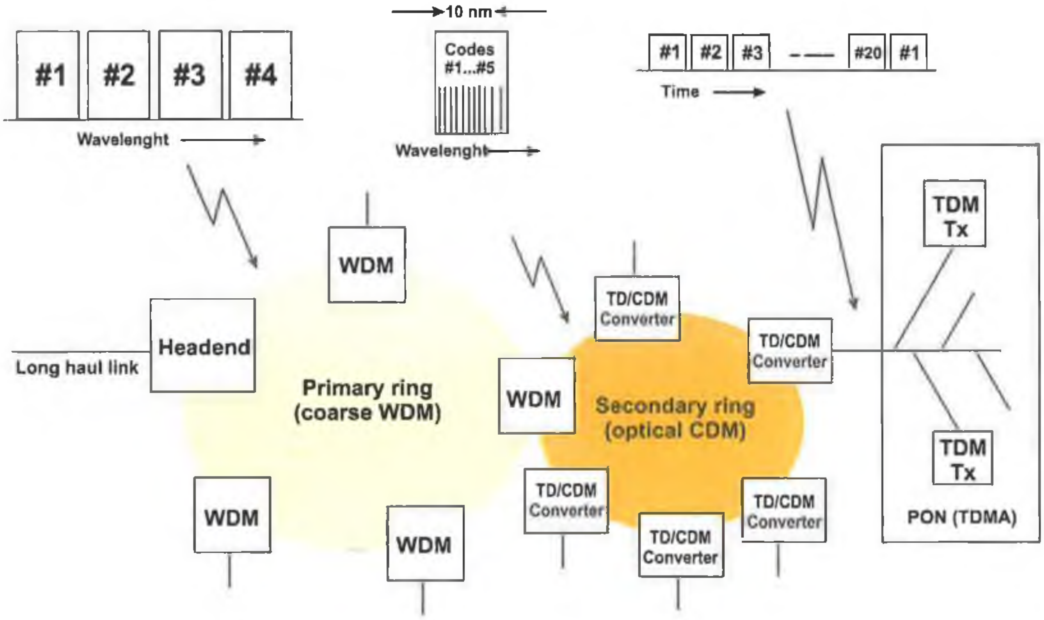

Figure 1.8-Network combining the three different multiplexing technologies

1.6 Emerging technologies

Telecommunications is currently undergoing a large-scale transformation. Multimedia services, HDTV and computer links are putting pressure on the telecom traffic, which will in turn demand deploying a network that can accommodate the entire traffic in cost effective matter. The efforts that are being made to utilize the new requirements comprise developing of new materials, components and structure of networks.

1.6.1 New Materials

New photonic materials are emerging with powerful properties and functionality. Research is under way of crystal like optical properties of synthetic materials [23] and artificially made photonic crystals [24]. New photopolymers have displayed interesting photonic characteristics [25]. Integration of many devices [26] requires advanced interconnection technology of nanowires and nanodevices [27].

1.6.2 Components

For successfully meeting future requirements several things are essential:

1. Wide spectral range and low cost tunable components operating at high bit rates (>>10 Gb/s), along with accurate wavelength converters for all optical network with dynamic wavelength assignment [28].
2. New fibers optimized for spectrally flat and low dispersion and extended linear behaviour, combined with dispersion compensation fibers for increase fiber span [29].
3. Ultra high level density in a single fiber-fibers specially designed to facilitate densely spaced channels

1.6.3 Systems and Networks

The "last-mile problem" is still present for delivering high quality broadband services. The high cost of extending the pipes to the residential places, branch office, or small-to-medium-sized business (SMB) has made broadband access sporadic at best. Customers were forced to choose between DSL and cable services, and both have a record of spotty availability and inconsistent service. Customer interest in greater bandwidth is real. Fiber To The Premises technology (FTTP) can easily manage 100Mbit/sec speeds, as opposed to ADSL, which typically achieves 1.5Mbits/sec downstream [30]. FTTP makes PC backup, telecommuting, and high-quality videoconferencing relatively simple, and can replace T1 or T3 PBX lines for larger branch sites. For very high speed services two different architectures have advantages.

FTTC-Fiber to the curb (FTTC) is a network technology that refers to the installation and use of optical fiber cable directly to the curbs near homes or any business environment in order to bring high-bandwidth services such as movies-on-demand and online multimedia applications to the customer. Coaxial cable or another medium might carry the signals the very short distance between the curb and the user inside the home or business [31]. Hybrid Fiber Coax (HFC) is one example of a distribution concept in which optical fiber is used as the backbone medium in a given environment and coaxial cable or some other medium is used between the backbone and individual users (such as those in a small corporation or a college environment). However there are limitations to that technology related to the inherent bandwidth limitations of the last mile access.

FTTH-Fiber to the home (FTTH) or Fiber to the User (FTTU) is a network technology that deploys fiber optic cable directly to the home or business to deliver voice, video and data services. By leveraging the extremely high bandwidth capacity of fiber, FTTH can deliver more bandwidth capacity than competing copper-based technologies such as twisted pair, HFC and xDSL [32]. It is considered to be completely future proof. It can support peak speeds of 1 Gbps and can be upgraded any time to higher bandwidths by replacing the electronics on either end of the system. The drawback of deploying a FTTH network is the high cost per home or business passed.

1.7 Conclusions

A fully intelligent optical network would incorporate the functionality to extend optical networks beyond point-to-point connections towards complex network architectures. A solution for flexible network is provided by DWDM. One advantage is that it would allow the preservation of the existing infrastructures and architectures, seamlessly upgrading, without disruption to existing processes. Another advantage is that it would allow different network components within the infrastructure to be managed from the same network management system. Just as important, the intelligent optical network enables operators to extend DWDM transmission beyond the backbone into the access ring environment as well. An overview of this network and its components is provided in the next chapter.

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Chapter 2

DWDM Networks

2.1 Overview

As outlined in *Chapter 1*, one of the major issues for optical systems is overcoming the electronic bottleneck in the optical systems, which highlights the necessity of using optical multiplexing techniques. It is possible to classify networks into three generations depending on the physical-level technology employed. First generation networks use copper-based or microwave technologies e.g. Ethernet, satellites etc. Second-generation networks comprise copper links or microwave links incorporated with optical fibers. However, these networks still perform the switching of data in the electronic domain though the transmission of data is done in the optical domain. Finally we have the third generation networks that employ Wavelength Division Multiplexing technology, for which the transmission and the switching of data is in the optical domain. This has resulted in the onset of tremendous amount of bandwidth availability

2.2 Dense Wavelength Division Multiplexing (DWDM)

DWDM is a technology that puts data from different sources and protocols together on an optical fiber with each signal carried on its own separate and private light wavelength. Using DWDM technology, up to 80 and, theoretically, more separate wavelengths of data can be multiplexed into a light stream transmitted on a single optical fiber. On the receiving side, each channel is then de-multiplexed back into the original source. A basic diagram of DWDM is shown in *Figure 2.1*.

DWDM is a very crucial component of optical networks that will allow the transmission of data: voice, video-IP, ATM and SONET/SDH respectively, over the optical layer. Hence with the development of DWDM technology, the optical layer provides the only means for carriers to integrate the diverse technologies of their existing networks into one physical infrastructure. For example, though a carrier might be operating both ATM and SONET networks, with the use of DWDM it is not necessary for the ATM signal to be multiplexed up to the SONET rate to be carried on the DWDM network. Carriers can quickly introduce ATM or IP without having to deploy an overlay network for multiplexing [1].

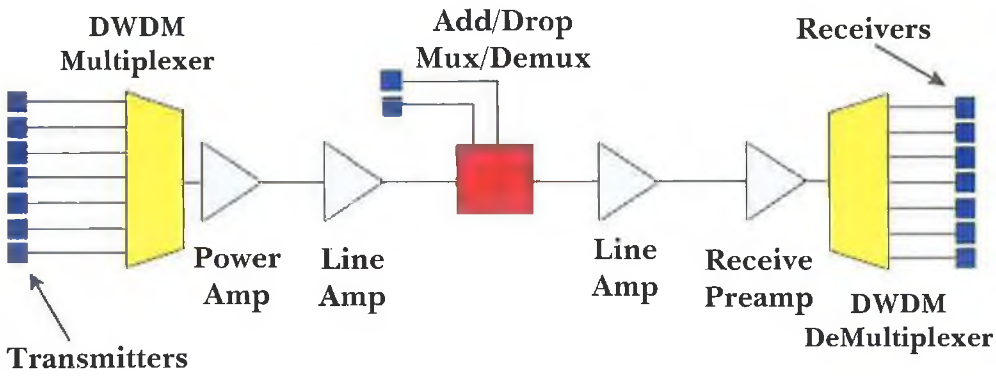

Figure 2.1-Basic DWDM configuration

2.3 Topologies

Different issues have to be addressed in the topology design of DWDM systems. The number of nodes, maximum traffic capacity, service restoration capability, fault resiliency and number of fiber links between the different nodes are part of the factors that can influence the decision of which topology to be deployed. The three main topologies will be described, outlining the advantages and disadvantages of their implementation.

2.3.1 Point to point

This topology enables aggregate traffic with many wavelengths to be transmitted over a single fiber, which is the most effective medium for transporting data, video, and voice traffic, and it offers virtually unlimited bandwidth. The DWDM point-to-point architecture shown in *Figure 2.2* is inherently simple to build and troubleshoot. But the cost of running fiber "point-to-point" to every customer location, installing active electronics at both ends of each fiber, and managing all of the fiber connections at the central point is prohibitive [2]. Optical add/drop multiplexing is not deployed because of the added insertion and fiber losses resulting in degraded optical signal.

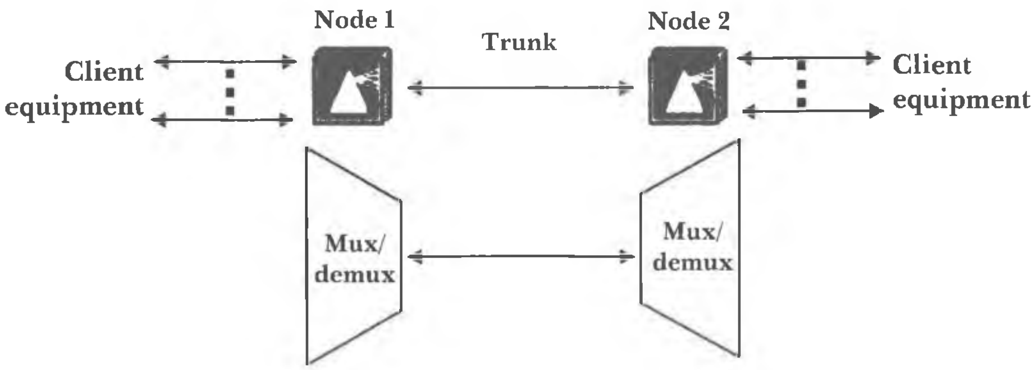

Figure 2.2-Point to point topology in DWDM networks

2.3.2 Ring topology

As the topology is embedded in SONET/SDH ring network and its performance is well known, it is one of the preferred. Every ring consists of optical add/drop multiplexers (OADM) and supervisory channel shared by all nodes performing flow control and management-*Figure 2.3*. The ring can be dual, which feature delivers protection [3].

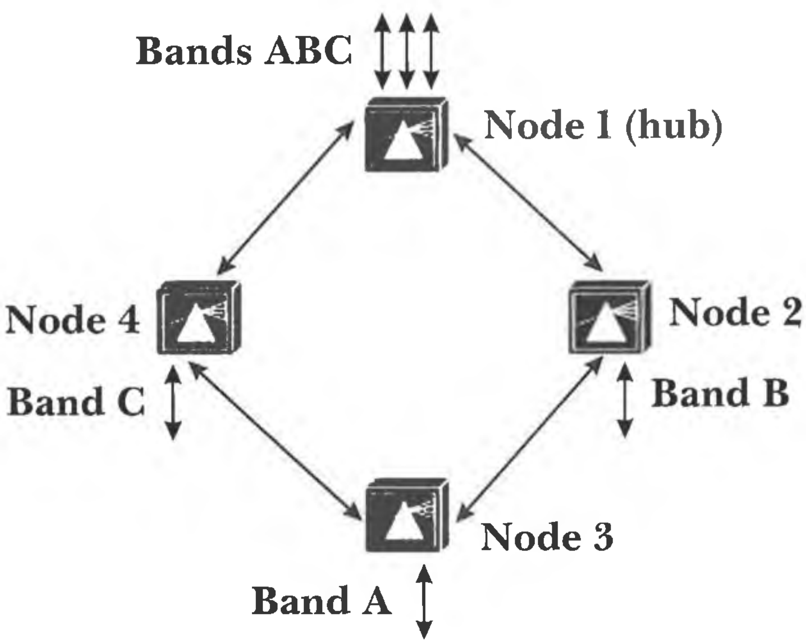

Figure 2.3-Ring topology in DWDM Networks

The hub node terminates all the DWDM channels. A channel can be provisioned to support protected traffic between the hub node and any node in the ring. Both working and protected traffic use the same wavelength on both sides of the ring. Protected traffic can also be provisioned between any pair of optical add/drop multiplexing (OADM) nodes, except that either the working or the protected path must be regenerated in the hub node.

2.3.3 Mesh topology

It utilizes full connectivity between different nodes- *Figure 2.4*. It is an ideal compliment to the high demand for data networking and packet-based transport. While telecommunications providers have typically built networks based on rings as a result of their self-healing and rerouting properties, data backbones have always been mesh designs. This is also partly a result of the complex interconnection of IP routers. Certainly, a mesh topology shared by both IP and transport networks provide an elegant solution [4]. Moreover, a mesh with optical routing can also provide self-healing capabilities without the complexity associated with ring software. Alternate routing through the mesh either by the router, switch, or optical network becomes an apparent solution.

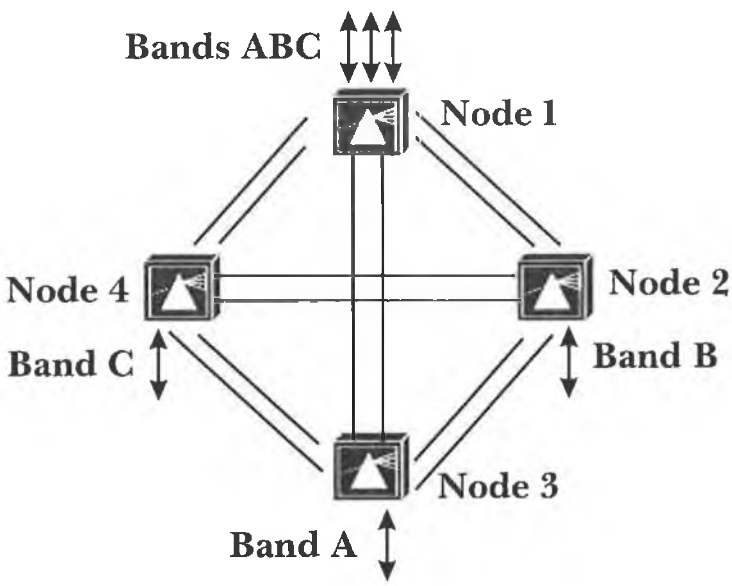

Figure 2.4-Mesh topology in DWDM Networks

Ring Topology vs. Mesh Topology

A ring topology is preferable owing to many of its capabilities. Unlike a mesh network, the expense of laying out the links is reduced in the ring, because the number of links increases only as a linear progression. The rings also have better resilience and restoration than meshes. The ring topology besides serving as a standby link helps share the load. The working segment and the protection segment of the fiber together handle the large data burst of the computer network. This reduces the load on the router and removes the need for buffering [5].

2.4 DWDM Key Building Blocks

In DWDM systems, data channels must be initially multiplexed in the wavelength domain, then transmitted through the optical network, and finally terminated at whatever destination the information channel is being sent to. These overall systems require a large number of electrical, opto-electronic, and optical components for correct operation. The various functions that need to be undertaken by the numerous components in a DWDM system include transmission, multiplexing, amplification, regeneration, and demultiplexing of the data. These functions are performed by various components, which are described in the following section that are used to develop a complete DWDM communication system. As a small part of the functions are performed in the electrical domain (laser drivers) only the components from optical domain will be analysed.

2.4.1 Transmitters

The light source is often the most costly element of an optical communication system. It has the following key operating characteristics: (a) peak wavelength, at which the source emits most of its optical power, (b) spectral width, (c) output power, (d) threshold current, (e) light vs. current linearity, (f) and a spectral emission pattern. These characteristics are key to system performance.

There are two types of light sources in widespread use: the Laser Diode (LD) and the Light Emitting Diode (LEDs). All semiconductor based light emitters that convert electrical current into light operate on the principle of the p-n semiconductor junction found in transistors. To achieve laser action a high concentrations of electrons and holes pairs are needed for recombination. This is achieved by high doping concentrations across the junction.

Historically, the first achievement of laser action in GaAs p-n junction was reported in 1962 [6]. Both LEDs and LDs use the same key materials: Gallium Aluminum Arsenide

(GaAIAs) for short-wavelength devices and Indium Gallium Arsenide Phosphide (InGaAsP) for long-wavelength devices.

The optical transmitters for DWDM systems are high resolution, precision narrow-band lasers. These lasers allow close channel spacing, which increases the number of wavelengths that can be used in the 1500 nm band while minimizing the effects of signal impairments such as dispersion. These lasers can use optical amplifiers that boost signal strength for extended distances and eliminate the electronic-amplifier need to regenerate individual optical signals. Most laser systems are designed to wavelength frequencies that follow the standards of International Telecommunication Union, which enables simplified interoperability and easier component selection [7].

2.4.2 Receivers

2.4.2.1 PIN

These types of receivers consist of an InGaAs photodiode connected to a pre-amplifier, usually fabricated with GaAs technology. InGaAs is the semiconductor material of choice for photodiodes used in optical communications, due to its spectral characteristic. The response of InGaAs matches the wavelength range from 1280 nm up to 1650 nm used in optical communications. The photodiode has a bias voltage and the amplifier may have an offset control and, additionally, a gain-control input. When it is reversed biased, its internal impedance is almost infinite and its output current is proportional to the input optical power. The photodiode and the amplifier can be either in different packages or they can be mounted in the same package [8].

2.4.2.2 APD

Because the optical signal for a DWDM receiver is perturbed by nonsymmetrical optical noise in addition to the fiber attenuation and dispersion, the input sensitivity should be increased. The avalanche photodiode (APD) multiplies electrons via a voltage-controlled avalanche breakdown during the conversion of photons into electrons. In order to achieve the multiplying effect, the APD must be reverse-biased (depending on type) up to 90V. The reverse bias for an APD must be tightly controlled to keep its multiplication factor (the gain factor "M") constant over temperature [9]. To maintain constant gain in an APD, it can be temperature-controlled with a Peltier element, or its reverse bias can be changed as a function of temperature.

2.4.3 Modulators

2.4.3.1 Direct or External Modulation

Modulation schemes can be divided into two main categories, namely, direct or external modulation. In direct modulation the electrical data signal (plus a dc bias current) is applied directly to the drive current of the laser diode to generate the optical data channel. The main problems associated with direct modulation are that the spectral output from the laser may be significantly broadened due to the direct modulation, and also the speed of the laser will limit the maximum data rate that can be achieved per optical channel [10]. The transitions of the voltage from high to low values and vice versa causes the optical parameters of the active region to vary and so does the tuning of the resonance ability of the cavity. Thus the optical pulse that is generated has a spectral frequency consisting of the centre wavelength plus shorter and longer wavelengths. This effect is known as chirping effect. In an external modulation scheme, the semiconductor laser is operating in a Continuous-Wave (CW) mode at a fixed operating point [11]. An electrical drive signal is applied to an optical modulator, which is external to the laser. Consequently, the applied drive signal modulates the laser output light on and off without affecting the laser operation.

A key component in optical signal generation is thus the external modulator, which impresses the high-speed data stream onto the optical carrier signal in TDM and WDM applications. Some materials exhibit properties that affect at least one of the characteristics of the light: frequency, polarization, phase or optic intensity. Such materials are used in optical modulator devices to affect traversing light in a controllable manner. The main types of modulators that are used are outlined below.

2.4.3.2 Mach Zehnder Modulators

Optical modulator devices with speeds greater than 1 GHz are typically fabricated from either the electro-optic crystal $LiNbO_3$ or III-V semiconductor compounds and multiple quantum wells such as GaAs/AlGaAs and InGaAsP-InP, which utilize the quantum confined Stark effect or the electro-absorption effect. Over the years, lithium niobate ($LiNbO_3$) has been and continues to be the material of choice for optical modulators at bit rates of 2.5 Gbits/sec and above, primarily due to its properties of enabling low-loss waveguides and its high electro-optic effect. $LiNbO_3$ travelling-wave modulators, based on a Mach-Zehnder (MZ) waveguide structure, are the most widespread modulators in deployed systems [12].

Light wave coupled into the MZI is split equally into the two arms, each of which may contain an active section, which converts an applied voltage into a small modification in the propagation velocity of light in the waveguide-*Figure 2.5*. Over the length of the active section(s), the velocity differences result in a phase difference in the two waves. Depending on the relative phase of the two waves after passing through the arms, the recombined wave will experience an intensity modulation. By using this technique, the electrical information applied to the modulator arms can be modulated onto an optical carrier.

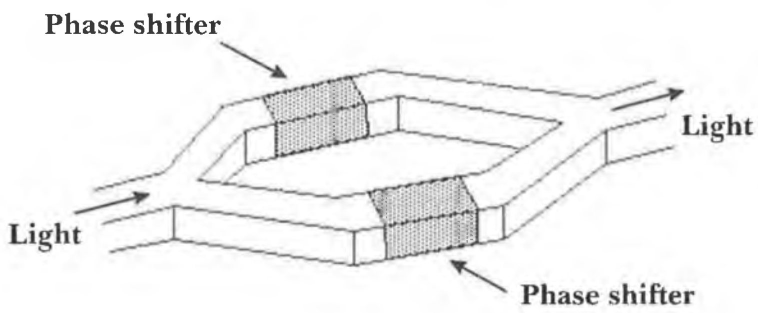

Figure 2.5-Schematic for the operational principle of MZ modulator

2.4.3.3 EA Modulators

Electroabsorption modulators are on-off devices made with InGaAsP and the percent of absorbed photons depends on the strength of the applied filed. EAs have an almost logarithmic attenuation of optical power that depends on a reverse voltage applied to them. They are transparent with no voltage applied, but provided voltage is applied the absorb light at the laser wavelength they are designed for. The electrical and optical properties of InP enable a large number of functions to be realized in one material system. The most obvious advantage of using InP as an EA modulator is that the device can be made relatively small. The bandgap energy of InP-based materials is close to the photon energies at telecoms wavelengths, so electro-optic and electroabsorption effects can be brought into play at low voltages and over short distances [13].

2.4.4 Multiplexing/ Demultiplexing

Mux/demux devices enable DWDM systems by combining (multiplexing) and separating (demultiplexing) the different wavelength channels at the terminals. The components require extremely high precision manufacturing techniques to route the channels with a minimum of loss and interference with other signals. An Add/Drop Multiplexer takes a single wavelength from a node, pulls the signal out, and allows a new signal at the same wavelength to be inserted into the node at (roughly) the same spot. All the other wavelengths pass through the add/drop mux with only a small loss of power (usually a few dB). So it can be said that precise filtering is the essential function to be performed.

Optical filters are frequently deployed in different systems to separate different wavelengths. They perform not only functions as filtering in multiplexers and demultiplexers, but also more complex functions as gain equalization, channel monitoring. There are many types of filters. Here a short description on the most important filters will be provided.

A **"Bragg Grating"** is a periodic or aperiodic perturbation of the effective absorption coefficient and/or the effective refractive index of an optical waveguide. Bragg Grating can reflect a predetermined narrow or broad range of wavelengths of light incident on the grating, while passing all other wavelengths of the light [14]. Any change to the spatial period of the grating, or index of refraction, will cause a proportional shift in the reflected and transmitted spectrum. Some of the characteristics are:

- Bragg Gratings have low insertion losses and are compatible with existing optical fibers used in telecommunication networks.
- Bragg Gratings allow low-cost manufacturing of very high quality wavelength-selective optical devices.
- Phase masks used to photo-imprint the Gratings allow manufacturing that is relatively simple, flexible, low-cost and large-volume.

Some of the optical filters are **interferometric devices** that rely on the amplitude and phase information carried by the signal and requires temporal and spatial coherence. Thus, the characteristic length or 'size' of the components must be much smaller than the coherence length or the signal delay time while travelling through the components must be much shorter than the coherence time. In the opposite case the phase information is lost and the device processes the intensity, rather than the amplitude of the signal.

The basic **M-Z interferometer** exploits the phase difference between two optical paths. Lets consider two wavelengths are propagating through a fiber. The optical power is then equally split and each half is coupled into two waveguides of unequal length and then recombined the effect will be that they will interfere constructively or destructively. Since the refractive index of the path can be controlled and thus the effective optical path or its physical length that means that at the recombination point different wavelengths can be selected [15].

Arrayed waveguide gratings (AWG) use silica waveguide structures to diffract light into individual output waveguides. AWGs are often designed to optimize one of the performance criteria (low loss, flat top,) and do not commonly offer all three features in a single device. For instance, to achieve a flat filter profile AWG-based MUX must insert another element into the waveguide design that generally adds 2-3 dB of insertion loss. As mentioned previously, AWGs use internal heaters to keep the waveguide chip at a constant temperature-typically 75C to function properly. Heaters introduce several cost and reliability issues. From a cost perspective, system designers using AWGs must add heater control circuitry that introduces cost, size and complexity in the system. From reliability standpoint a heater failure has a significant network impact since all wavelengths will be affected. Non-heated versions of AWGs are emerging, however, these devices typically have higher insertion losses than their heated counterparts [16].

Fabry Perot Tunable Filter- FP cavity is formed in a single mode low loss waveguide between two facets with high reflection coatings. The premise here is that the refractive index of the waveguide can be controlled and the effective optical path between the two mirrors also. The design involves a tradeoff between the desired free spectral range, which sets the limit on the number of channels that can be present if crosstalk from channels falling in adjacent FP transmission peaks is to be avoided, and the optical phase change that can be generated to tune the filter [17].

2.4.5 Amplifiers

Optical amplifiers have two great features for optical communications. They amplify the optical signals using only optical effects, and they exhibit full scalability in terms of communication speed and communication protocol.

2.4.5.1 Erbium-Doped Fiber Amplifiers

Erbium-doped fiber amplifiers (EDFA) use the quantum effect of stimulated emission into a three-level quantum system to amplify optical signals. In one quantum mechanism, pump radiation with wavelength of 980 nm brings the Erbium atoms from the ground energy band A to an intermediate energy band C. The atoms will stay in band C for about 10 μs, which is the lifetime of band C, and will leave this band through a non-radiative transition to the metastable band B, the upper level of the amplifying transition. The lifetime of Level B is quite long, about 10ms, which allows many Erbium atoms to be pumped into this level. The Erbium atoms leave level B by two quantum mechanisms:

- Transitions stimulated by an optical signal in the wavelength range 1500 nm to 1580 nm that amplifies the input optical signal
- Spontaneous transitions that generate optical noise.

One of the main drawbacks of EDFA is nonlinear gain in the optical region between 1530 nm and 1560 nm, but EDFAs can achieve gain in excess of 30dB over more than 50 nm with output powers up to 30dBm [18].

2.4.5.2 Semiconductor optical Amplifier

Semiconductor fiber optical amplifiers have been developed to serve not only as switching elements and nonlinear elements for optical signal processing systems, but also as in-line optical amplifiers for DWDM metropolitan transmission systems. SOA functions in a similar way to a basic laser. The same gain mechanism is used as in laser diodes but out of oscillation regime. The structure is much the same, with two specially designed slabs of semiconductor material on top of each other, with another material in between them forming the 'active layer': the active layer is sandwiched between a “p” region and “n” region. An electrical current is set running through the device in order to excite electrons, which can then fall back to the non-excited ground state. The recombination of electron-hole pairs generates more photons of the same wavelength as the optical signal and hence optical amplification is achieved [19]. The most important characteristics of the SOAs are as follows;

1. High gain (25-30dB)
2. Wide bandwidth
3. SOAs are made with InGaAsP, which makes them small, compact and easily integrable with other semiconductor components
4. Polarization dependency
5. Strong optical nonlinearity of the active gain medium which gives rise to some suitable performances as frequency transformation and multiplication but also to some parasitic effects as crosstalk
6. When the amplified optical signal is modulated in the gigabit per second range and SOA operates in gain saturated regime it gives rise saturation pattern effect.

SOA can be classified into two groups, Fabry-Perot Amplifiers (FPA) and Travelling Wave Amplifiers (TWA). The difference is the reflectivity coefficient value of both mirror surfaces.

2.5 Optical Switching

The most deployed network for transmitting Internet data is DWDM systems that carry 32-80 wavelengths modulated at 2.5Gb/s and/or 10 Gb/s per wavelength. Most networking equipment today is still based on electronic-signals, meaning that the optical signals have to be converted to electrical ones, to be amplified, regenerated or switched, and then reconverted to optical signals. This is generally referred to as an 'optical-to-electronic-to-optical' (OEO) conversion and is a significant bottleneck in transmission [20]. Huge amounts of information travelling around an optical network needs to be switched through various points known as nodes. Information arriving at a node will be forwarded on towards its final destination via the best possible path, which may be determined by such factors as distance, cost, and the reliability of specific routes. The conventional way to switch the information is to detect the light from the input optical fibers, convert it to an electrical signal, and then convert that back to a laser light signal, which is then sent down the fiber you want the information to go back out on.

The basic idea of Optical Switching is that by replacing existing electronic network switches with optical ones, the need for OEO conversions is removed. Clearly, the advantages of being able to avoid the OEO conversion stage are significant. Optical switching has long been proposed as a faster, less expensive, and more efficient alternative to electronic switching [21].

2.5.1 Optical Burst Switching

A potential disadvantage of optical circuit switching is that, once a wavelength has been assigned, it is used exclusively by the allocated source. If 100 percent of its capacity is not in use for 100 percent of the time, then clearly there is inefficiency in the network. One solution to this problem is to allocate the wavelength for the duration of the data burst being sent.

Optical burst switching is based on the separation of the control plane and the data plane. In optical burst switching data packets are aggregated into much larger bursts before transmission through the network. The burst is preceded in time by a control packet, which is sent on a separate control wavelength and requests resource allocation at each switch. When the control packet arrives at a core cross-connect (or switch) capacity is reserved in the cross-connect for the burst. If the required capacity can be reserved the burst can pass through the cross connect [22]. The burst has to be buffered by the OEO edge device while the wavelength is being set up, so the signalling has to be very fast.

The data plane is "service transparent." The control plane can operate at a much lower data rate, but must follow the path of the data plane (e.g. use optical supervisory channel).

There are lots of difficulties related to OBS such as creating a robust but simple out of band signalling system. But the benefits are very clear. By holding the label switched path (LSP) open only for the duration of the burst, we achieve a statistical multiplexing of the wavelength in the time domain. This should increase the efficiency of backbone utilization dramatically when compared to optical circuit switching.

2.5.2 Optical Packet Switching

An Optical Packet Switch (OPS) is the true, optical equivalent of an electronic packet switch involving reading an embedded label and making a switching decision using this information. It uses in band control information; the header follows the rest of the packet loosely, so there cannot be any reservation of resources. Reading and reinserting of packet headers with strict timing requirements are needed, due to the short packet duration-typically around 1 μs.

A key issue in OPS is whether to use synchronous or asynchronous transmission; the latter enables the use of variable length packets providing a close analogy to electronic IP packets. Asynchronous operation removes the requirement for synchronisers at the switch input, which can be costly to implement, however it is more demanding in terms of buffer control and utilisation. The implementation of OPS requires a packet labelling technique suitable to optical systems. Various schemes have been proposed and demonstrated, most of an opto-electronic nature, i.e. use optical detection and electronic processing rather than all optical processing. The optical packet switch must incorporate a number of functions, for example, label swapping, contention resolution and payload switching are key requirements; together with appropriate algorithms for scheduling packets through the switch [23].

A major advantage of optical packet switching lies in its bandwidth efficiency and ability to support diverse services, hence research is now growing on bringing the packet switching concept into the optical domain, that is optical packet switching. Until now work on this subject has focused on the synchronous container approach to networking. However, given the increasing dominance of the IP client signal, which presents variable packet lengths to the optical network, it is clear that the synchronous fixed length container approach may not be optimum.

Although current routers offer significant advancements over previous generations, they still cannot scale sufficiently to meet projected traffic demands, nor do they provide the very high level of availability required to run mission-critical traffic over IP networks. In addition, electrical switch fabrics have posed physical limitations that prevent routers from scaling sufficiently to avoid premature forklift upgrades.

All of this points to the need for a new kind of scalable router architecture that routes IP/MPLS packets electronically, but switches them optically. This combination of large port count with high speed switching (nanoseconds) is needed realize this next generation IP routing platform.

2.5.2.1 MPLS Overview

In traditional IP based networks, carriers use one IP network for data and a separate circuit-switched network for voice, but that distinction is increasingly breaking down. Routers work independently to determine the best next hop for packet forwarding. Robust interior gateway protocols consult a link state database to understand the entire network topology and choose the best next hop based on the lowest cost. As demand for "converged" network applications grows, carriers and corporations are eager to bridge the gap between diverse technologies to provide a seamless backend capable of supporting all of the latest applications and services. Ultimately, all lowest equal cost paths are selected and used to forward data [24]. The premise of multiprotocol label switching (MPLS) is to speed up packet forwarding and provide for traffic engineering in Internet protocol (IP) networks. MPLS alleviates many of the problems that arise in shifting applications that have traditionally run on circuit-switched networks to IP-based networks, such as the Internet. Because MPLS can handle any type of traffic, carriers can use it in their core infrastructure to converge traffic from all of its networks onto a single network, saving money in operational costs. To accomplish this, the connectionless operation of IP networks becomes more like a connection-oriented network where the path between the source and the destination is precalculated based on user specifics. To speed up the forwarding scheme, an MPLS device uses labels rather than address matching to determine the next hop for a received packet. Among the many positive attributes MPLS brings to internetworking is the ability to provide connection-oriented services to the inherently connectionless IP networks. The label switched path, or LSP, is the establishment of a unidirectional end-to-end path forwarding data based on fixed size labels.

2.5.2.2 Generalized MPLS (GMPLS)

GMPLS extends MPLS to provide the control plane (signalling and routing) for devices that switch in any of these domains: packet, time, wavelength, and fiber. This common control plane promises to simplify network operation and management by automating end-to-end provisioning of connections, managing network resources, and providing the level of QoS that is expected in the new, sophisticated applications.

2.5.2.3 Contention resolutions

With the exponential growth for Internet traffic next generation packet switched networks must provide extremely fast transmission rates as well as support for diverse quality of services [25]. In addition to bandwidth requirements, emerging packet switched networks are also expected to satisfy loss and delay requirements for different applications. In most packet switched networks, packet loss and end-to-end delay result from packet contention, which occurs when two or more incoming packets need to be forwarded to the same output at the same time. Approaches to resolving contention include finding a solution in one of the following domains:

- Wavelength domain-by means of wavelength conversion, a packet can be transmitted on a different wavelength channel of the designated output fibre. Provided that converters are employed, all wavelengths on a fiber can be considered a bundle of channels shared by all packets to be transmitted over this fibre. From the teletraffic theory it is well known that a bundle of ***n*** parallel servers each with capacity c have a smaller blocking capability compared to a single server of capacity ***nc***.
- Time domain-A packet can be delayed until the contention is resolved by applying a buffer. Fiber Delay Line (FDL) imitates conventional queuing by delaying packets that are forced to go through the optical fibre of a given length.
- Space domain-A packet is send to a different output fibre of the node, meaning on a different route to the destination node. An eventual outcome is that packets arrive at destination node out of order. Since FDLs give fixed delays, random access is not possible: in contrast to electronic memory, FDLs cannot provide access to a specific data packet at an arbitrary access time. As an alternative the use of simple electronic FIFO memory with few opto-electronic interfaces can be used.

2.6 Conclusion

Until now the technical obstacles to achieving an all-optical network were posing a problem. The fundamental issue was the inability to switch. Packet switching at gigabit speeds seemed impossible. Implementing more efficient bandwidth utilization in WDM networks by employing wavelength packet switching architectures is essential. In these networks, WDM optical packets are generated using fast tunable light sources, and then routed to specific nodes in the optical network by using optical filtering techniques. In the next chapter the different tuning mechanism and structures for the tunable light sources will be described in details.

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Chapter 3

Tunable Lasers

3.1 Overview

To meet the ever increasing traffic demands of cities and regions, metro network operators are turning to the same optical networking technologies that have relieved bottlenecks in core or long-haul networks. However, metro traffic is far less predictable than long-haul traffic: The traffic mix changes constantly as subscribers are added and removed, services are expanded, and providers scale up their bandwidth. DWDM systems promise to relieve metro providers, but extra channel capacity is only part of the solution. To deliver all the metro provisioning capacity that is promised with the flexibility to use it as market needs demand, vendors are now exploring the use of tunable lasers. In contrast to fixed-wavelength lasers, tunable lasers can tune to many different operational wavelengths, rather than just one. Metro carriers can substantially increase their DWDM systems' virtual channel capacity at initial deployment by using tunable lasers. Many DWDM systems featuring tunable optics are the ultimate choice.

3.2 Applications of Tunable Lasers

3.2.1 Network planning

Instead of the burdening process of forecasting lasers on a wavelength-by-wavelength basis optical networking companies can now reduce the amount of intricacy thanks to the advent of tunable technology. The expected outcome of this application is that there is an ease of forecasting and planning and last minute changes can be more easily accommodated resulting in fewer lost revenue opportunities [1].

3.2.2 Inventory reduction

In order to accommodate fluctuating demands the telecom operators needed to supply more units from the fixed wavelength sources resulting into huge expenses. Tunable lasers essentially remove the need to stock inventory at such massive levels. The new technology proves to be efficient for the vendors as well: vendors eventually need to manufacture a reduced number of part codes, which simplifies the process [2].

3.2.3 Sparing

Tunable lasers can be deployed in the event of a fixed wavelength laser failure. Thus instead of keeping an additional fixed wavelength laser to replace the already deployed one, tunable technology is used. This reduces the necessary planning, as there is a wide range of tunability. One tunable laser can easily substitute any of the transmitters [3].

3.2.4 Re-configurable Optical Add/Drop Multiplexer (R-OADM)

To date, deployment of Optical Add/Drop Multiplexers (OADM) has been somewhat hampered, either by the lack of flexibility offered by commercial solutions, or by the cost premium demanded for offering flexibility. There are many ways that a re-configurable OADM can be implemented - from a tunable filter approach to a back-to-back multiplexer with a switching fabric between. In either case the application demands tunable lasers. The benefit offered by a R-OADM is the ability to change the capacity being dropped and inserted at a remote site without the need for an expensive bandwidth manager. This results in major savings for the network provider. The impact of tunable lasers on this application is in the resolution of blocking scenarios without the need for a full complement of transponders. These savings mean that there is reduced price sensitivity for the tunable laser component in this case [4, 5].

3.2.5 Photonic cross connects

The function of the cross connection can be implemented using a photonic switch surrounded by transponders, the transponders are wavelength converters used to overcome wavelength blocking and provide SONET like performance monitoring. Most high-speed networking equipment uses multimode or single mode fiber optic interfaces, where the data is carried at 850nm, 1310nm or 1550nm. Since WDM systems need to multiplex different wavelengths together, these signals must all be converted to a particular wavelength that is suitable. If the photonic switch resides at a point in the network where two metro rings meet, tunable lasers can be used to enable traffic to transfer between rings without crossing an electrical switch [5].

3.2.6 Fast Packet Switching

One key feature of a solid-state tunable laser is that it can be switched from one wavelength to another is a few nano-seconds (ns). This enables wavelength switching at the packet level, which can then be used to route data traffic based on colour through a passive router such as a N x N arrayed waveguide grating (AWG) [6].

3.2.7 Wavelength converters

All optical wavelength converter devices capable of converting high-speed data rates are essential elements in DWDM networks. The ability of the wavelengths to be shifted leads to an efficient and easily managed network. One of the techniques used is an optically injected semiconductor tunable laser, where the laser oscillation is intensity modulated by the injection light with another wavelength. The data signal is transferred from the injection wavelength light to the laser oscillation wavelength.

From all the applications discussed above it is clear that tunable lasers are the future of optical networks not only from manufacturer's perspective. Given the variety of applications with differing needs, no tunable-laser technology is optimized for all of these DWDM requirements. The choice of laser technology will be determined by many factors, including output power, line width, relative intensity noise (RIN), tuning range, tuning time, and stability. It is important to understand the relative strengths and weaknesses of the different tunable-laser technologies against these requirements when considering what type of laser to implement for a given optical-network application [7].

Tunable lasers can be produced using a variety of laser structures, each with its own advantages and disadvantages. Five of the main basic laser structures are distributed feedback (DFB), distributed Bragg reflector (DBR), vertical-cavity surface-emitting laser (VCSEL), and external-cavity lasers (ECL), sampled-grating DBR (SGDBR)

These different laser structures use different tuning mechanism that partially or fully covers DWDM band. The categories in which those mechanisms can be divided are actually three:

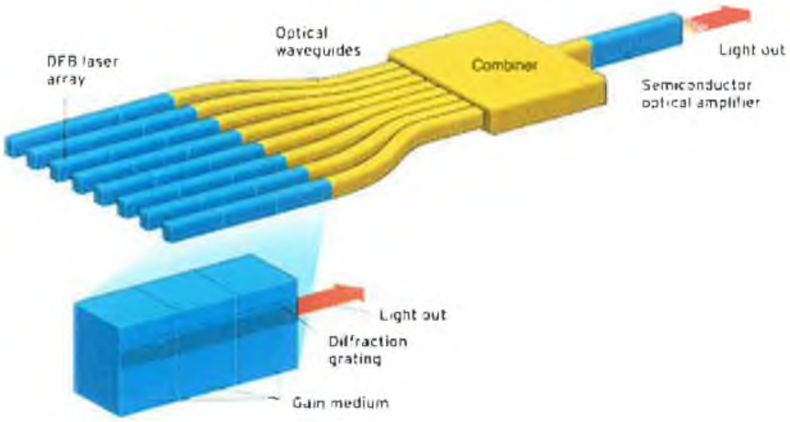
3.3 Thermal tuning

3.3.1 DFB

DFB lasers are simple structures that work by using an internal grating to change the wavelength of operation. The combination of its refractive index and the spacing of the corrugations serves to reflect only a specific wavelength of light. In this way the corrugations act as a grating, reflecting only a specific wavelength back into the cavity but allowing others to pass through. The desired wavelength is fed back into the cavity, and this is taking place over the whole length of the laser. The only laser light that builds up within the active layer is light of this specific wavelength, and so that is the only wavelength emitted from the laser. DFBs are tuned to Inter national Telecommunication Union (ITU) grid wavelengths by changing the temperature of the medium, either through drive-current changes or a temperature-controlled heat sink, which changes the refractive index of the internal waveguide. The thermally induced wavelength switching is slow (typically ≤ 0.5nm/s) that is the reason other types are preferred for deployment in DWDM networks. However extremely large mode hop free tuning ranges can be attained. The thermal tuning rate of the lasers amounts to 25-30 GHz/K (0.06 nm/K). DFB lasers use a thermo-electric cooler (TEC) to maintain wavelength accuracy. Changing the temperature of the DFB laser changes the wavelength. By taking advantage of this feature, with improvements in thermo-electric coolers, the temperature can be precisely controlled to produce a stable, well-defined output wavelength with an acceptable line width. In general, DFB lasers are well behaved and characterized and have proven reliable [8].

While DFBs offer some manufacturing, performance, and operational advantages, they have the disadvantages of low output power and very limited tuning range. Their effective tuning range tends to be limited because, as the tuning temperature increases, the efficiency and output power of the device decreases.

To extend the tuning range, these devices can be integrated into ensemble or side-by-side laser arrays of several lasers on one chip coupled into a single output as shown in *Figure 3.1*. One laser at a time is driven to select a wavelength [9,10].



[1]***Figure 3.1-DFB Laser Array***

There are, however, some limitations even to this design. This solution is not continuously tunable, the combining mechanism is optically inefficient, and the chip size leads to yield issues.

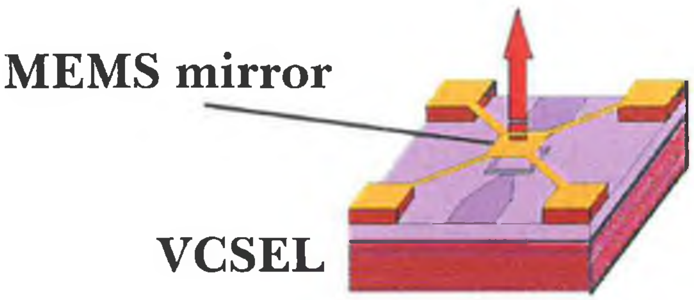
3.4 Mechanical and Micro Electrical Mechanisms

3.4.1 VCSEL

Conventional lasers are known as "edge emitters" because their laser light comes out from the edges. Also, their laser cavities run horizontally along their length. A vertical cavity surface-emitting laser, however, gives out laser light from its surface and has a laser cavity that is vertical. A typical VCSEL consists of an active region sandwiched between two oppositely doped distributed Bragg reflectors (DBRs) that form the optical cavity- in a VCSEL there are several layers of partially reflective mirrors above and below the active layer. Layers of semiconductor with differing compositions create these mirrors, and each mirror reflects a narrow range of wavelengths back into the cavity in order to cause light emission at just one wavelength. VCSELs have several advantages over edge-emitting lasers. A device generally supports a single Fabry-Perot (FP) wavelength within the gain spectrum, so the FP wavelength, and not the gain peak, determines the lasing wavelength. By changing the thickness of the optical cavity, it is possible to change the FP wavelength supported by the cavity. In other words, changing the thickness of the optical cavity changes the lasing wavelength of the device [11].

[1] The figure is taken from "Tunable lasers", Bruce E.

By integrating the top DBR of a VCSEL with a micro-electro-mechanical-systems (MEMS) cantilever, it is possible to precisely change the cavity thickness to achieve an electrically tunable device-see *Figure 3.2*. To tune the device, a reverse bias voltage is applied across the air gap between the top n-DBR and p-DBR. The resultant electrostatic force pulls the cantilever down toward the substrate, shortening the air gap to tune the laser output to a shorter wavelength. Because the movement is elastic, there is no hysteresis in the wavelength-tuning curve; when the voltage is removed, the cantilever returns to its original position. A simple and efficient process allows to monolithically integrate a high performance VCSEL with a micro-electro-mechanical system (MEMS) tuning structure that can be electrostatically activated at very low tuning voltage using standard low cost electronics [12,13].



[2]Figure 3.2-VCSEL with MEMS Tuning Structure

VCSEL lasers can be thermally tuned as well. The process of thermal tuning is slow and the range is limited. The speed depends on how quickly heat can be supplied and removed from the active region. For VCSELs this is an issue because their "pillar" structure leads to high thermal resistance. Some experiments show achieving 10.1nm by heating the active region.

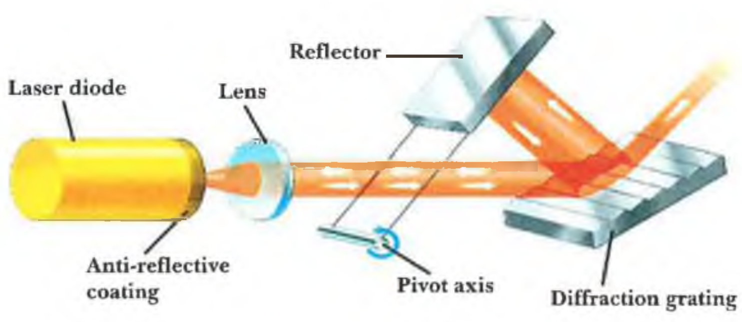
VCSELs are also more efficient than edge emitters and give out more light for the same electric current applied to them (they have a lower "threshold current"). Additionally, the light beam from VCSELs is narrower and more circular, making it easier to get the light into an optical fiber. Low-power VCSELs at 850nm are widely used for short-distance

[2] The figure is taken from "Tunable lasers", Bruce E.

networks, but high-power 1550nm products will be needed for widespread use in large-scale optical networks. Wavelength switching times of under 2 μs have been reported [14], [15]. Optimization of the mechanical design are being analyzed which can subsequently reduce the switching time.

3.4.2 ECL

External Cavity Lasers (ECL) uses a resonant cavity external to the active semiconductor section, which is typically a simple Fabry-Perot gain chip. ECLs provide high power, large tuning range, and narrow linewidth with high stability and low noise. The external-cavity approach alters the beam wavelength by mechanically adjusting the laser cavity, rather than through current or temperature changes applied to a semiconductor material, which causes delay in wavelength switching and prevents them from being used in fast packet switched networks. Furthermore, they provide continuous tuning through the entire spectrum of the gain medium, where other common laser technologies (like DBRs) exhibit mode hops between stable points in the spectrum. This laser consists of a separately fabricated gain medium (a simple Fabry-Perot laser diode) and an external cavity formed of separately fabricated optical structures (a diffraction grating and mirror) integrated at an assembly step. Generally the design of the ECL is based either on Littman-Metcalf or Littrow cavities.



[3]Figure 3.3-ECL based on Littman Cavity

[3] The figure is taken from "Tunable lasers", Bruce E.

The Littman cavity, *Figure 3.3*, uses a grating and tuning mirror in a patented configuration to deliver the highest level of side mode suppression (typically 60dB) with narrow linewidth (0.3-5MHz) [16].

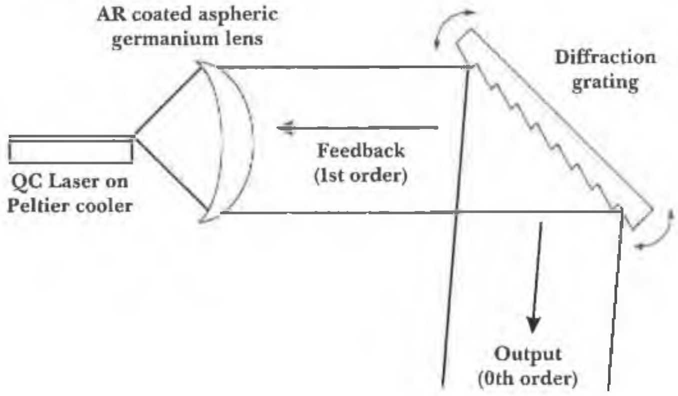
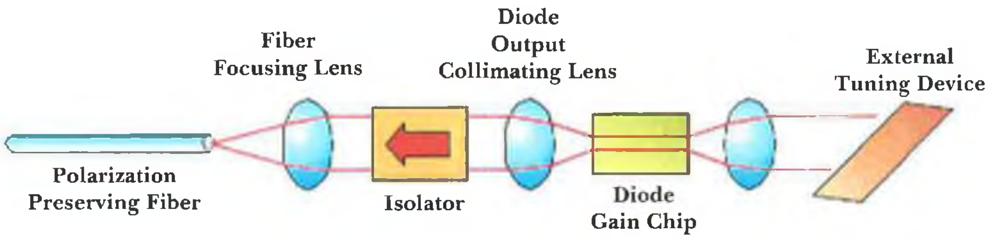


Figure 3.4-ECL based on Littrow Cavity

The Littrow cavity, Figure 3.4, simply uses a grating to deliver substantial increases in output power at the slight reduction in sidemode suppression (40dB) [17].

In an ECL tunable-laser design, some portion of the laser cavity resides off the laser chip, and the diode acts as a gain medium only. In some ECL source lasers, one facet of the laser diode is coated to act as a high reflector while the laser output and cavity tuning are provided on the other side of the chip.

Littman-Metcalf and Littrow cavity configurations are examples of such single-sided ECL sources in which gratings are used to provide optical feedback and tune wavelength. In a double-ended ECL *(Figure 3.5)* configuration one facet of the laser diode-uncoated or coated to be a partial reflector-acts as an output coupler. Light transmitted from the output-coupling facet is collimated, passed through a Faraday isolator, and focused into an output fiber [18].



[4]Figure 3. 5-Double Ended ECL Configuration

Recent technological advances have brought ECLs to the forefront of optical-networking component technology. In particular, the application of MEMS to optical-component designs produces high-performance micro-optics that readily fit on standard transmitter cards and can be manufactured at competitive costs in the optical-networking industry.

3.5 Electronic Wavelength tuning

Most continuously tunable lasers exploit the electronic refractive index change induced by the free carrier plasma effect for the tuning of the emission wavelength. Generally a p-I-n type double heterostructure junctions form a waveguide, where carriers are injected into the intrinsic region. However with increasing the current the recombination rate is also increased therefore, the excess carrier density saturates at high injection. The change of the refractive index is usually caused by injection of free carriers or by increasing the temperature or combination of both. The former leads to a decrease of the refractive index and thus to a decrease of the emission wavelength (blue shift), while the latter leads to a red shift and is usually unintentional. Here a Bragg grating reflectors are used such that the reflection spectrum represents a comb of peaks.

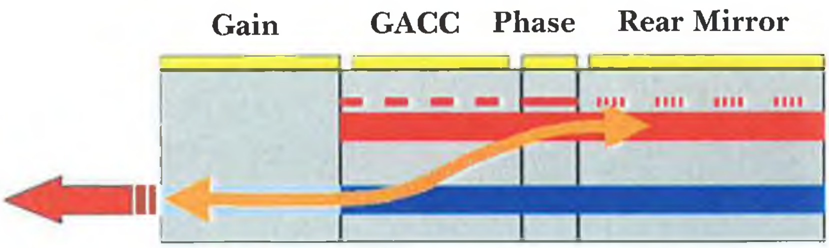
3.5.1 GCSR

Grating Assisted Codirectional Coupler with Sampled Reflector /GCSR/ lasers consist of four sections. The front one is a gain block, followed by a phase module used for fine-tuning the wavelength. Between the gain section and the phase section is the grating assisted codirectional coupler, which acts as a course tuner. GACC uses grating assisted wavelength

[4] The figure is taken from "Tunable lasers", Bruce E.

selective coupling between two forward propagating channel modes of directional coupler made of two parallel waveguides. As the waveguides are not synchronized /each one supports an optical mode with a different phase velocity/ those two modes can only couple energy with the assistance of the grating which provides the necessary phase matching [19, 20].

The structure of GCSR incorporates two waveguides -one that runs forward to the phase module and gain block, and another one, at a higher level, that runs backward into the last section, which is the Bragg grating-*Figure 3.6*.



[5]Figure 3.6-GCSR Structure

In this laser most of the light comes straight from the gain block out the front of the laser, to be sourced into a fiber. There is a small amount of reflected light at the front of the laser back into the laser and this will be bounced of the Bragg grating at the back of the laser if it is of the correct frequency, amplified by the gain section, and emitted from the front of the laser. Some of this is reflected back into the laser as before and the whole process can be repeated again and again.

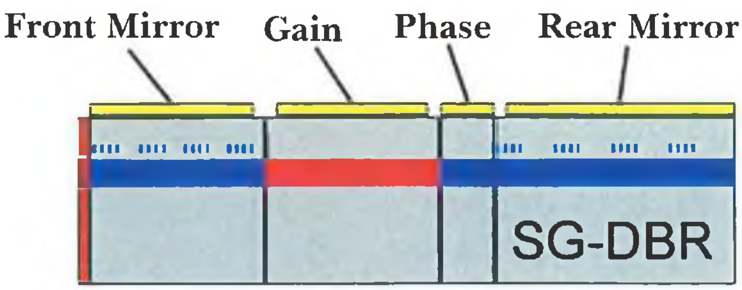
The combination of the sampled reflector section and the codirectional coupler section ensures lasing at only one cavity mode providing wavelength selective loss. The reflection peaks of the sampled reflector are about 4 nm apart. The coupler acts as a filter with about 8 nm bandwidth. The wavelength tuning is a response to the tuning signals. When those signals are changed, the carrier concentrations in each section change until it reaches the steady state value of the new operating point. During the tuning process the laser may hop

[5] The figure is taken from "Tunable Semiconductor Lasers", Coldren L. A.

between different peaks of the sampled reflector and different longitudinal cavity modes, which have spacing of usually 0.2 nm. During these transitions the laser frequency changes abruptly and large power variations occur. GCSR lasers are the first devices to reach commercialization after the development of the simple DBR laser. The tunability they provide is in the nanosecond range. It can be influenced depending on the switching technique that is being used. The usage of pre-distortion differentiated pulses drives the switching time down [21].

3.5.2 SG-DBR/SSG-DBR lasers

SG-DBR tunable lasers use-grating reflectors at either end of the cavity to produce a spectral comb response-*Figure 3.7*. The back and front sampled gratings have slightly different pitch so the resulting spectral combs have slightly different mode spacing. Tuning to a specific wavelength is achieved by controlling the current in the two grating sections so as to align the two combs at the chosen wavelength. The laser, therefore, "hops" between wavelengths. An additional contact is normally required to adjust the phase so an integral number of half-wavelengths exists. If this phase adjustment is not included, then mode stability can suffer and noise can increase [22]. While these types of lasers offer a wide tuning range, they suffer from low output power and broad line width. Furthermore, they have complex drive requirements when compared to other laser designs. They have more electrodes, and accurate wavelength selection requires matching of numerous input currents with the appropriate electrodes. Sampled gratings with grating-assisted co-directional coupler filters add a filter to select one of the sampled-grating peaks, making it easier and cleaner to select a wavelength but at the cost of additional manufacturing complexity. SG-DBRs also suffer from low output power, which can potentially be recovered with a semiconductor optical amplifier (SOA) [23]. However, SOAs are noisy devices and can cause other perturbations that will prevent them from meeting requirements of RIN and line width for 10-Gbit/sec narrow-wavelength-spacing extended-reach applications. Because SG-DBR devices are grown on indium phosphide wafers, the ability of the SG-DBR laser designs to meet all system noise, power, and tuning range requirements are limited to the physical characteristics that can be achieved by a single semiconductor system. In short, with all monolithic growth approaches, tradeoffs must be made between the material gain characteristics, electro-optical coefficients, and DBR current-tuning efficiencies. These devices can switch wavelength in nanoseconds. The SSG-DBR lasers add more complexity to the fabrication of the sampled gratings, which results in lower output power compared to SG-DBR at around 1mW, but at the same time have improved tuning range because of the phase modulated sampled gratings [24]. They also switch in the nanosecond region. The design of SSG-DBR lasers differs only in the design of the mirrors: the gratings in the mirrors are periodically chirped instead of sampled. The advantage of this approach is that the grating occupied the entire length of the mirror so that a much higher reflection can be achieved with a lower coupling constant in the grating. The other main advantage is that the reflectivity of the individual peaks can be tailored such that all the reflection peaks have the same magnitude.



[6]Figure 3.7-Schematic diagram of SG-DBR laser structure

While DWDM systems make the most of a network's configuration by carrying multiple channels along a single strand of fiber, the amount of supporting components needed-and the complexity of organizing them-almost diminishes the efficiency this technology is supposed to bring to telecom networks. Tunability eases quite a bit of this complexity by significantly reducing the number of necessary components in DWDM systems, making it an excellent facilitator for optical add/drop multiplexers (ADMs) and optical switching/routing. Tunability enables faster and more flexible network reconfiguration, which is one of the greater challenges to carriers, as their ability to meet customers' demands for effective bandwidth management is crucial to success in marketplace

[6] The figure is taken from "Tunable Semiconductor Lasers", Coldren L. A.

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Chapter 4

Complete Characterization of Wavelength Tuning in SG-DBR Laser

In the previous chapter some of the key advantages of the tunable laser technology were described and each of the designs was explained. In this chapter we will consider the experimented characterisation of one type of tunable laser –namely Sampled Grating DBR laser, detailed analysis of the operation and tuning aspects will be discussed. Here each section of the laser is analysed and its contribution to the overall tunability is explained.

SG-DBR laser deploys current injection in its active and passive section to tune to different wavelengths. An overview of the carrier induced index change due to the injected current is essential for further detail analysis of the tuning capabilities, schemes and parameters of the laser structure.

4.1 Carrier induced index change

Carrier injection is an efficient way to control electrically the index of refraction of a waveguide. The principle is simple: electrons and holes are created through forward biasing of a p-i-n structure of InGaAsP/InP. The carrier changes the refractive index, thus changing the propagation constant in the waveguide [1]. The waveguide uses a tuning region material with bandgap energy larger than the photon energy of the light through it. The smaller the bandgap of the material, the larger the tuning rate is: however the optical losses near the bandgap are high. It must be taken into account that a large rise in the temperature shrinks the bandgap. In addition with injecting carriers there is also a bandgap shrinkage that brings it closer to the working wavelength. For the active section this will not increase the absorption as the high carrier density implies population inversion, meaning gain for a particular mode and reduces absorption [2]. Having a small bandgap has another drawback: the noise due to the spontaneous emission will be difficult to be filtered out for high carrier densities and will degrade signal to noise ratio in the system.

There is a trade off between increasing injected current and thermal effects. With increased current, the carrier density increases, the refractive index decreases due to the carrier plasma effect [3]. For currents exceeding a given value, thermal effects will be predominant, which affects changing of the refractive index in the opposite direction [4]. It has to be noticed that the absorption also increases due to the free carrier and thus the amount of feedback to the active section.

4.2 Operational Principle

Wide tuning range can be achieved by using a tunable semiconductor laser based on DBR mirrors with comb-like reflection spectrum. Figure 4.1 depicts a typical structure of a buried hetereostructure laser. A typical SG-DBR laser consists of four sections: 2 multiwavelength DBR mirrors, active region and phase tuning region. The two DBR mirrors can be considered as an addition to the conventional Fabry Perot laser providing for a wide tuning range and high side mode suppression ratio.

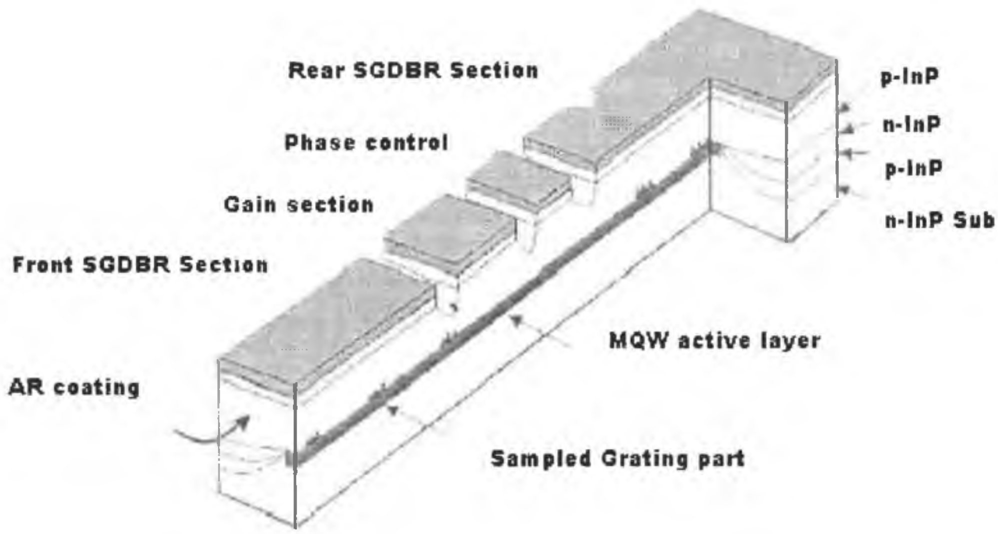

Figure 4.1-Schematic diagram of four section buried hetereostructure SG-DBR laser

4.2.1 Reflectivity spectrum of SG-DBR's gratings

The normal operation of this laser is based on the principal of Vernier. The idea is that if each end of the laser structure has a comb like reflection characteristics and the comb pitches are slightly different, the tuning range can be expanded [5]. The reflectivity spectrum of the front reflector consists of an array of peaks separated by $\Delta\lambda f$. The shift the injected current can cause is $D_f \geq \Delta\lambda_f$. The spectrum of the back reflector contains peaks and the difference between them is slightly different: $\Delta\lambda b$. For any given combination of currents I_f and I_b no more than one pair of peaks can coincide, though some pairs might partially overlap each other. The reflection combs of the two mirror section and the total reflection response due to the overlapping of the combs is shown in *Figure 4.2*.

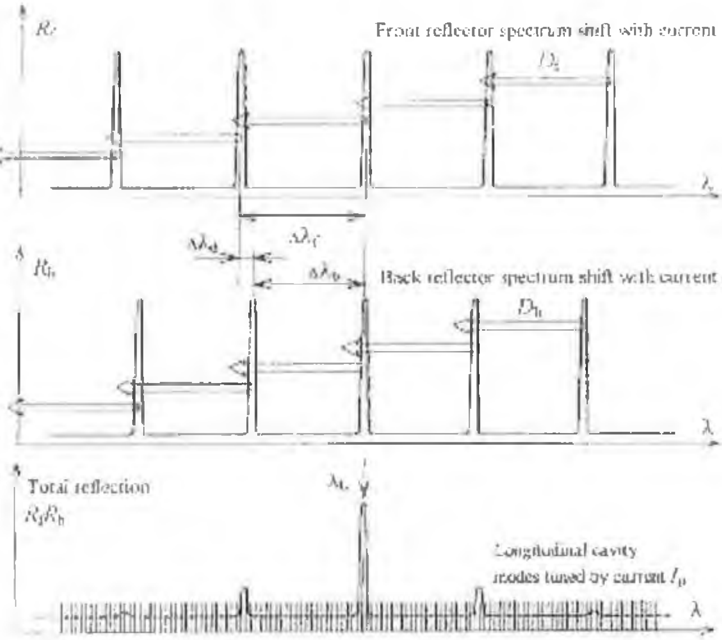

Figure 4.2-Operational principle of widely tunable SG-DBR laser
a) Reflectivity spectra of front and back reflectors
b) Total reflection product considering the overlap of the longitudinal and mirrors peaks

The width of the reflectance peak is defined by the coupling coefficient: for narrow peaks the prerequisite is long and weak grating. It is the period of modulation that determines the spectral separation between the peaks. The number of peaks is approximately equal to the inverse of the duty cycle:(a large number of peaks requires a small duty cycle). The relation between the actual number of reflection peaks and the length of the grating is expressed by *Equation 4.1.*

$$\left(\frac{k_0}{N}\right)L \approx 1$$ ***(Equation 4.1)***

k_0-coupling coefficient of the unremoved part of the grating

N-number of reflection peaks

L-the length of the grating

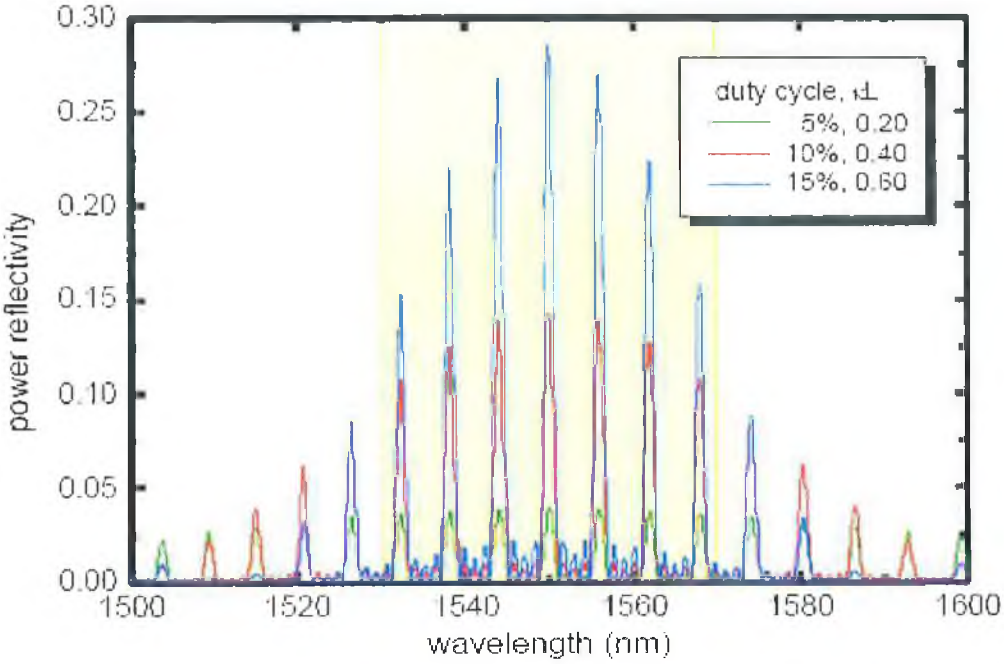

Figure 4.3-Reflection spectra of sampled gratings with various sampling duty cycles ranging from 5-15%

Sampled grating is constructed by multiplying a sampling function and a grating. In Fourier space this corresponds to convolving the spectrum of the grating with that of the sample function to obtain the Fourier component of the sampled grating. The strength of the reflection from the Fourier component n increases with the coupling strength, which is reflected by the coupling coefficient κ. The reflection spectrum of a sampled grating is not uniform and the reflection is decreasing with the wavelength deviating from the Bragg wavelength-*Figure 4.3*. Therefore reflection peaks that are too far away from the Bragg wavelength may not be usable due to too low reflectivity.

The amplitude of peaks in the Fourier spectrum is inversely proportional to their number. Usage of small duty cycle grating results in small reflection peak amplitude. The Fourier spectrum envelope of sampled gratings shapes like **sin (x)/x**: that means that the reflection peaks are of different amplitudes, so for the different ranges of tuning it will have different thresholds and efficiencies [6]. In the case of periodic index profile, the coupling constant is proportional to the Fourier component.

Every spatial Fourier component of the dielectric perturbation contributes a peak in the reflection spectrum. *Figure 4.4* shows a schematic of a sampled grating with regular dielectric perturbations [7].

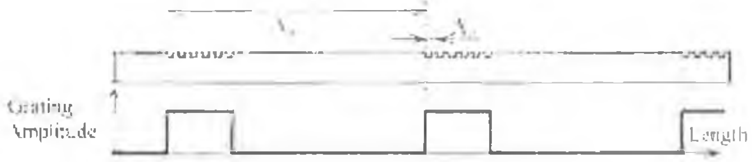

Figure 4.4-Sampled grating schematic

$$k = \frac{4\Pi}{\lambda}\frac{1}{\Lambda}\int n(x)\sin\left(\frac{2\Pi x}{\Lambda}\right)dx \qquad \textit{(Equation 4.2)}$$

Λ-Period of the grating

The periods of the two spectra are slightly mismatched and lasing occurs where the reflection maxima are aligned. The rule that applies is that there is a maximum in the reflection for the region that minimum occurs for the transmission spectrum. So if the SG-DBR laser is operated below threshold (the gain section is biased with current below the threshold I_a<37mA) it acts as a broadband LED and the transmission response of each of the two gratings can be taken [8]. Figure 4.5 shows the complex response of the mirror sections of the laser, where the peaks represent the reflection response of the back mirror and the dips represent the transmission response of the front mirror. The biasing currents of the mirror sections are not provided intentionally as the accent falls on the responses of the sections. By changing the biasing conditions the peaks and dips will be shifted thus changing the lasing wavelength if the current of the active section is to be biased above threshold.

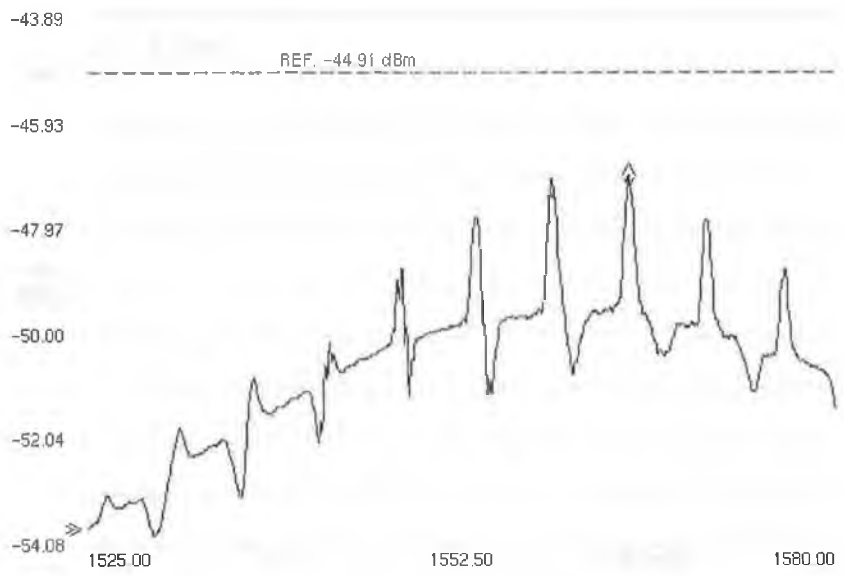

Figure 4.5- Subspectrum diagram

When both of the mirrors are unbiased alignment will happen at the Bragg wavelength, which is 1547.4nm-*Equation 4.3*.The overlap for that particular wavelength combined with cavity loss minimum allows a single mode operation.

Bragg frequency:

$$\omega_\beta = \omega_{\beta 0} - \Gamma \frac{\omega_{\beta 0}}{n_o} \frac{dn}{dN} N_m \qquad \textbf{(Equation 4.3)}$$

$\omega_{\beta 0}$-Bragg frequency without injection

Close examination of the spectrum diagrams can give an insight into what is the actual influence of the current on the transmission response of he mirrors. The back mirror section and the dips by the front mirror section contribute the peaks from the diagram. If the front mirror section current is fixed (I_f=25mA) and only the current for the back one is varied it can be noticed that the relative position of the dips on the wavelength scale does not change, while the peaks are shifted to shorter wavelengths-*Figure 4.6.* The first subspectrum diagram is taken at the following biasing conditions: I_a<37mA*;* I_f =25mA;I_b=16mA and the second one is taken at the following biasing conditions: I_a<37mA*;* I_f=25mA;I_b=92mA.

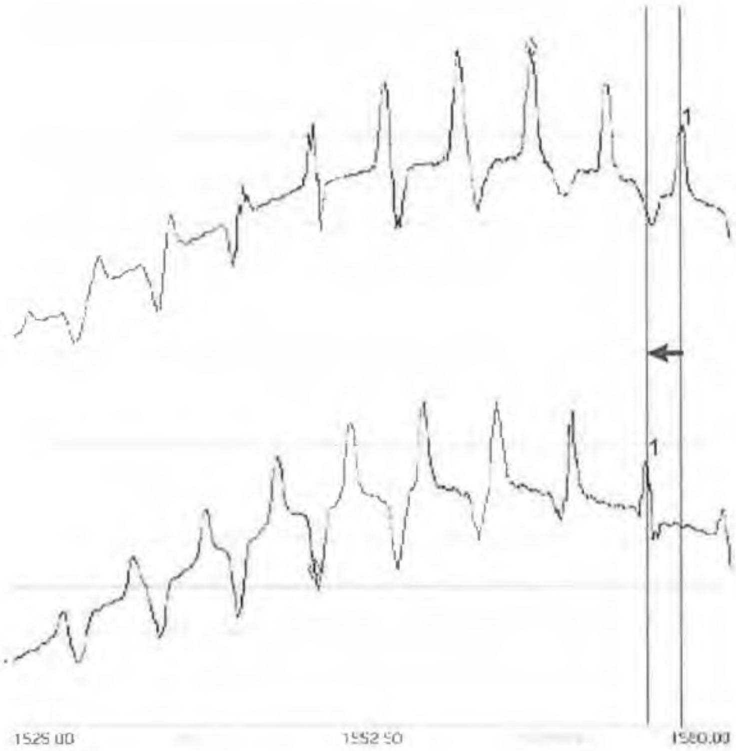

Figure 4.6 -Subspectrum diagrams showing the difference of the position of the peaks and dips while FM current is fixed.

SMSR is an essential parameter in DWDM networks as it determines the possible crosstalk and interference with other potential channels. It greatly depends on the overlap of the different peaks present. For precise tuning to one particular wavelength and achieving high SMSR, the currents I_b and I_f should be adjusted in such a manner that one of the reflectance peaks coincide with the desired wavelength [9]. Additionally the current for the phase section should be varied as well so only one of the longitudinal modes within the overlapping peaks of R_f and R_b is tuned.

If the changes in SMSR are examined, it can be deduced that the SMSR is 30-40 dB for 70 nm range and drops at the edges. As the reflection maxima of the mirrors align every 5-6nm, the lasing occurs at the alignment position with maximum gain. The tuning range of the combination of the two sampled gratings (*Figure 4.7*) is limited by the repeat mode spacing $\Delta\lambda_{rep}$, which is given by

$$\Delta\lambda_{rep} \cong \frac{P_{av}^2}{\Delta P} \qquad \textbf{(Equation 4.4)}$$

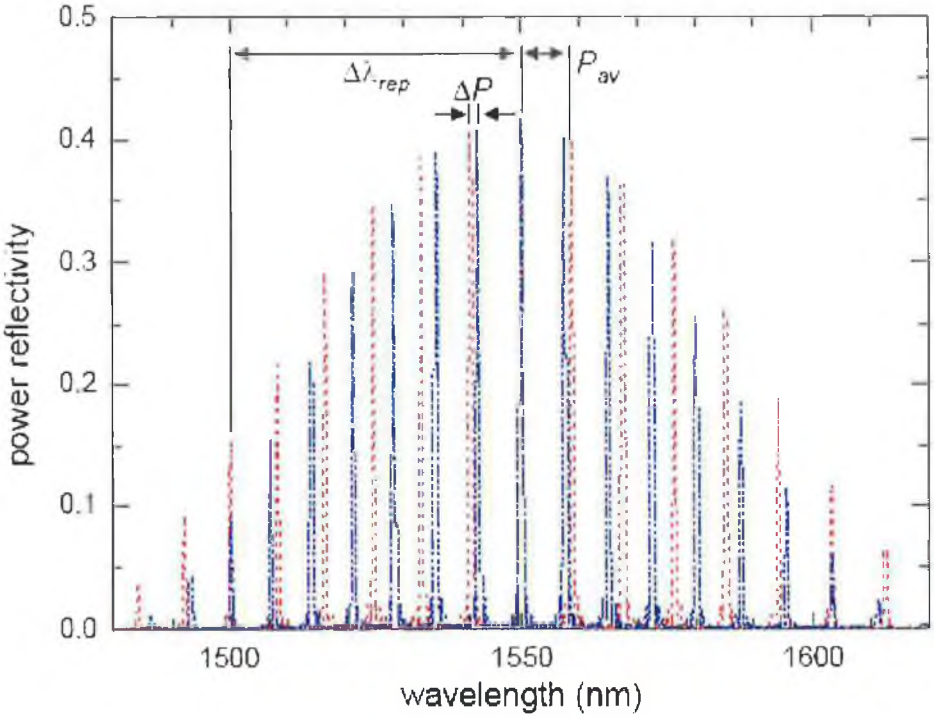

Figure 4.7-Power reflectivity against wavelength

Hence in order to achieve a large tuning range, a large peak spacing P_{av} and a small peak difference ΔP is desirable. Those two parameters are limited by the constraints of the actual structure. To be ensured large tuning range the average peak spacing has to be smaller than the continuous tuning range, by which the whole spectrum can be shifted. On the other hand the peak period difference should not be smaller than the width of the reflection peaks, otherwise the SMSR would become impaired.

The appearance of a repeat mode reduces greatly the SMSR along with the output power as the reflection maximum goes further from the Bragg wavelength. The mode hop occurs because the repeat mode at shorter wavelengths has more gain than the mirror band alignment position at the longer one, which is beyond the long wavelength falling edge of the quantum well gain spectrum [10]. The peak reflectivity product of the main wavelength decreases whenever it is tuned away from the zero bias point, due to the increased current induced losses. That rule is not applicable for the side mode reflectivity. Taking into consideration the increased threshold gain as well it can be concluded that with increasing current the SMSR deteriorates. Those side modes are called repeat modes.

2. Phase section control

The phase section alters the phase of the field reflected back to the active section. The injected current will reduce the effective refractive index through the plasma effect, which decreases cavity round trip time. For fixed DBR current that allows fine-tuning across the main lobe of the Bragg reflector. The longitudinal modes are defined by using the phase condition:

$$2\beta_a L_a + 2\beta_p L_p + \phi_f + \phi_b = 2m\Pi \qquad \textbf{\textit{(Equation 4.5)}}$$

$$\beta_a = 2\Pi n_a / \lambda;$$

$$\beta_p = 2\Pi n_p / \lambda;$$

β_a, β_b-Propagation constant of active and phase section

Φ_f, Φ_b -Reflections of front and back mirrors

The main mode should always be in reflectivity maximum by adjusting the phase current. For precise tuning detailed information of wavelengths and current refractive index shifts in the gratings are needed. As the reflectivity product of the mode varies in amplitude, the threshold carrier concentration and the indexes are changed. Tuning from one peak to another corresponds to different carrier concentrations, leading to different indexes of the active region.

4.3 Tuning schemes

As discussed in the previous section the lasing modes should satisfy the phase matching condition. Let's assume that the front mirror section current is fixed then changing the injected current densities into the phase and front mirror section will induce the adjustment of the wavelength. If the process is presented graphically-see *Figure 4.6*, then the crossings point between Φ_1 (phase curve for the Bragg reflector) and Φ_2+2mΠ(the phase lines) functions represent the possible lasing modes. With change of the phase current the lines that represent the phase function shift in a parallel fashion to each other. On the other hand the change of the current in the mirror section shifts the function to the left. The points those two functions cross each other are the possible lasing modes.

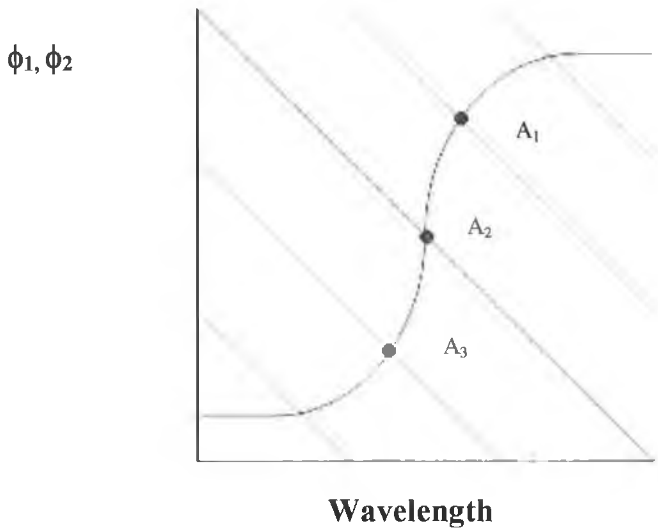

Figure 4.8: Defining lasing modes. Phases versus wavelength.

As the active section of a semiconductor laser has broad gain and loss spectra around the gain peak, it means that the mode with the lowest mirror loss as well as highest gain from all possible ones will prevail. That is the reason of the mirror loss to be monitored whenever the laser operating modes are defined.

The following expression defines the mirror loss:

$$\alpha_m = \frac{1}{2L}\ln\left(\frac{1}{rR}\right)$$ ***(Equation 4.6)***

L-total cavity length
r-Bragg section reflectivity
R-output facet reflectivity

The curve that is representing the mirror loss is included in the analysis of the wavelength control mechanisms in the following sections.

1. Bragg wavelength control

When only one of the two mirror sections is controlled the wavelength changes by jumping to another mode. With fixed phase and front mirror section current, the wavelength moves toward shorter wavelength.

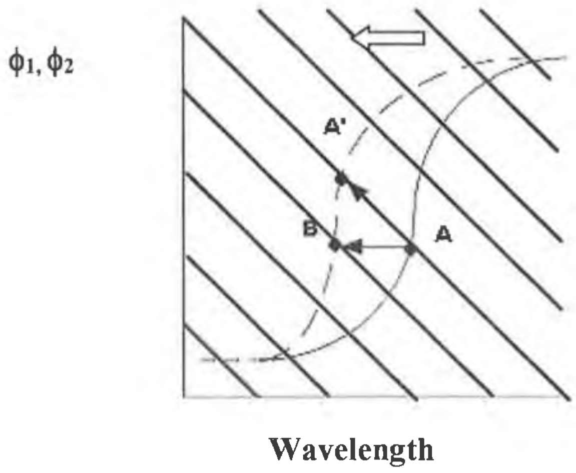

Figure 4.9: With the shift, the possible modes become A' and B. Since B has lower mirror losses it will become the predominant lasing mode.

So let's consider mode A on one of the many phase lines is the current mode as it has the lowest mirror loss and higher gain spectra. A change in the supplied current will cause a shift towards shorter wavelength on the same phase line that it resides towards A'. Another mode B residing on a different phase line has the same mode as A'. The two possible lasing modes are A' and B. At that point mode B has lower mirror loss compared to the initial lasing mode A as well as mode A' (refer to Section 2), which results in mode jumping. Thus B becomes the lasing wavelength. The steps are shown in *Figure 4.9.*

2. Phase control

The current applied to the phase section shifts the phase lines in parallel towards shorter wavelengths. The mirror loss curve for the Bragg reflector as well as the phase curve for the Bragg reflector don't change-*Figure 4.10(a)*.

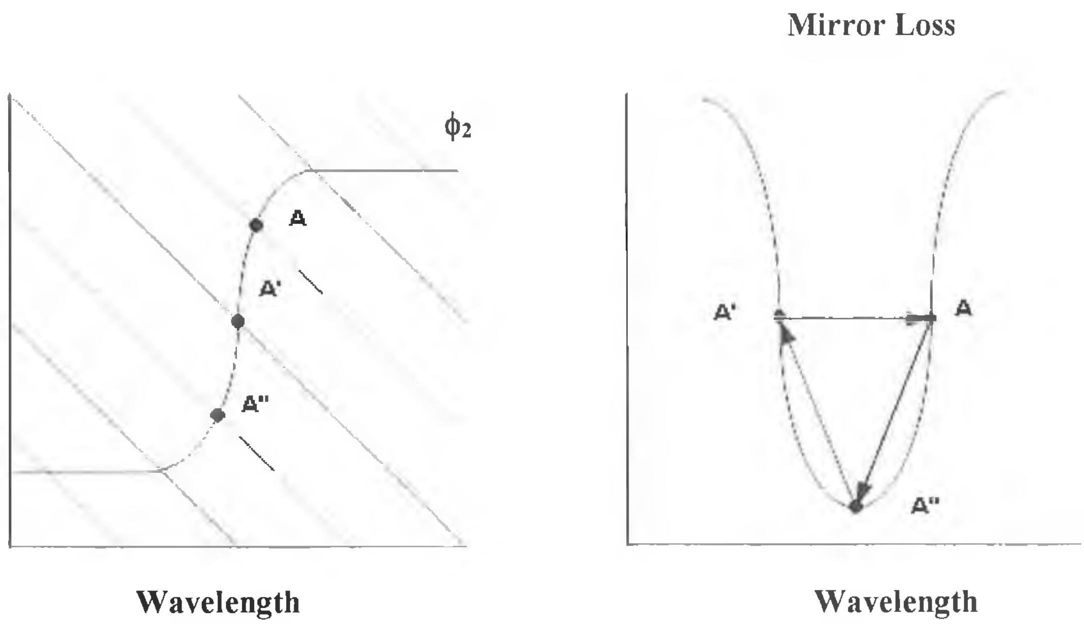

Figure 4.10: Change of lasing wavelength under the influence of the phase control section. A) Phases versus wavelength B) Mirror loss versus wavelength

With the increase of the current the lasing modes moves in a cyclic manner A-A"-A'. Therefore the induced change is limited to a certain value Δ. That is the reason why phase tuning is used for fine adjustments of the lasing wavelength only-see *Figure 4.10(b)* [12].

3. Simultaneous control of phase and front mirror section

Up till now an overview was made of how the separate changes in the current of the different sections affect the operating wavelength. It will be outlined briefly what happens when more than one sections are controlled simultaneously. The tuning mechanisms previously described are applicable, the difference is that an analysis of two simultaneously changing current should be made.

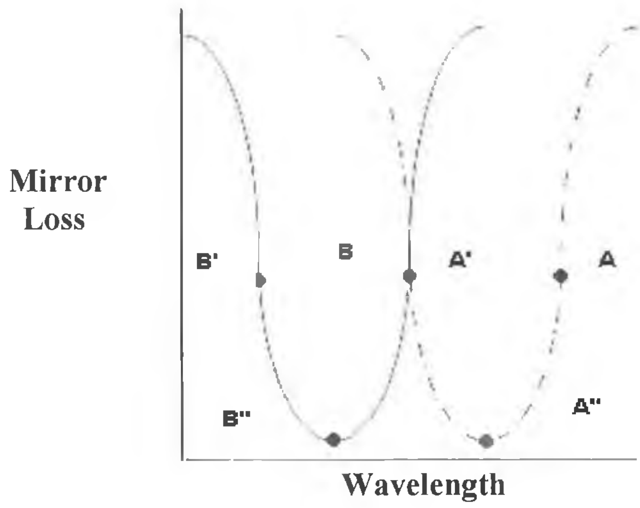

Figure 4.11-Mirror Loss against wavelength

A wide range of wavelengths is accessible without any overlapping, whenever two sections are controlled at the same time. This is achieved by changing the phase current repeatedly and the Bragg current in a step like manner. The phase current is changed so point A shifts to A' through A". Then the Bragg current is changed till mode B coincides with A'. By changing the phase again, mode B begins to lase and shifts to B' through B"-see *Figure 4.11*.

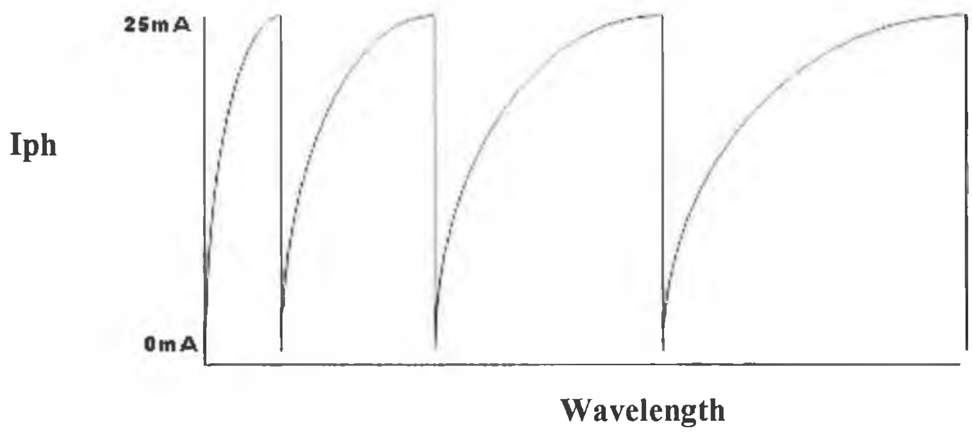

Figure 4.12: Wide wavelength tuning by applying phase control current in a repeated fashion.

A. Quasi-continuous tuning

The quasi-continuous tuning involves simultaneous control of all the tuning sections as described above. It provides complete wavelength coverage. The only factor that limits tuning capabilities is the threshold increase and power decreases caused by bigger losses due to the free carrier absorption and the heating with the injected current in the Bragg and phase section [13].

B. Continuous tuning

The aim with continuous tuning is maintaining the longitudinal mode, while changing in a certain way phase and front mirror sections simultaneously. The change in Bragg wavelength should equal that of the phase section so the wavelength can be changed without changing other wavelength conditions [14]. Assuming that the refractive index change is proportional to the square root of the injection current, the currents should satisfy the following condition:

$$\frac{I_f}{I_p} = \left(\frac{L_a}{L_a + L_b}\right)^2 \left(\frac{L_a}{L_b}\right) \quad \textit{(Equation 4.7)}$$

I_P, I_F-Currents of phase and front mirror section

L_a, L_b-Lengths of active and back mirror section

From the equation a suitable ratio for the currents can be derived. The advantage is that with one current supply, two of the sections can be controlled. The perfect alignment of the reflection peaks with the cavity mode corresponds to a minimum in threshold gain and carrier density. As the active section voltage for fixed bias current depends on the carrier density, it will also decrease.

Changing the currents for the mirror sections and the phase section induces shifts of the comb mode spectrums and the longitudinal mode. Super mode jumps range between 4-8nm (0.5-1.0 THz) and the longitudinal ones about 0.4nm(50GHz). The stable operating points are defined away from the boundaries.

With varying the currents the output power and SMSR will change along with the wavelength. When the wavelength is close to the Bragg region, the SMSR is maximum as the Bragg's section reflectivity is the highest for that region, so only a small fraction of light is transmitted through the mirror section.

4.4 Complete characterisation of wavelength tuning of SG-DBR laser

In order to completely characterise an SG-DBR laser we have used the experimental setup as shown in Figure 4.13. For initial characterization LabView is used. The PC and the device are connected through general-purpose interface bus. The programme is set to change the three currents, while recording the operating wavelength, the output power and SMSR.

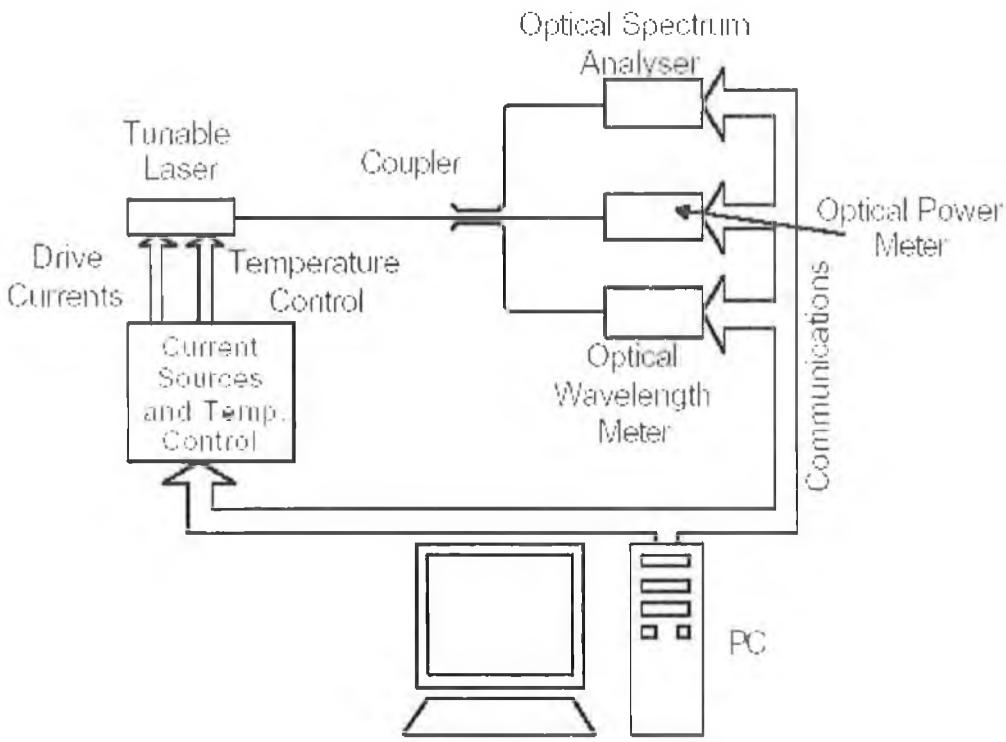

Figure 4.13-Set up for static characterisation of the SG-DBR laser

The programme is designed in such a way that currents are subsequently changed by the means of loops. The very first step is addressing all the devices-the process is called initialisation during which the distant response is checked as well the accessibility. Those devices include the spectrum analyzer, the temperature controller of the laser and current sources for the sections of the laser.

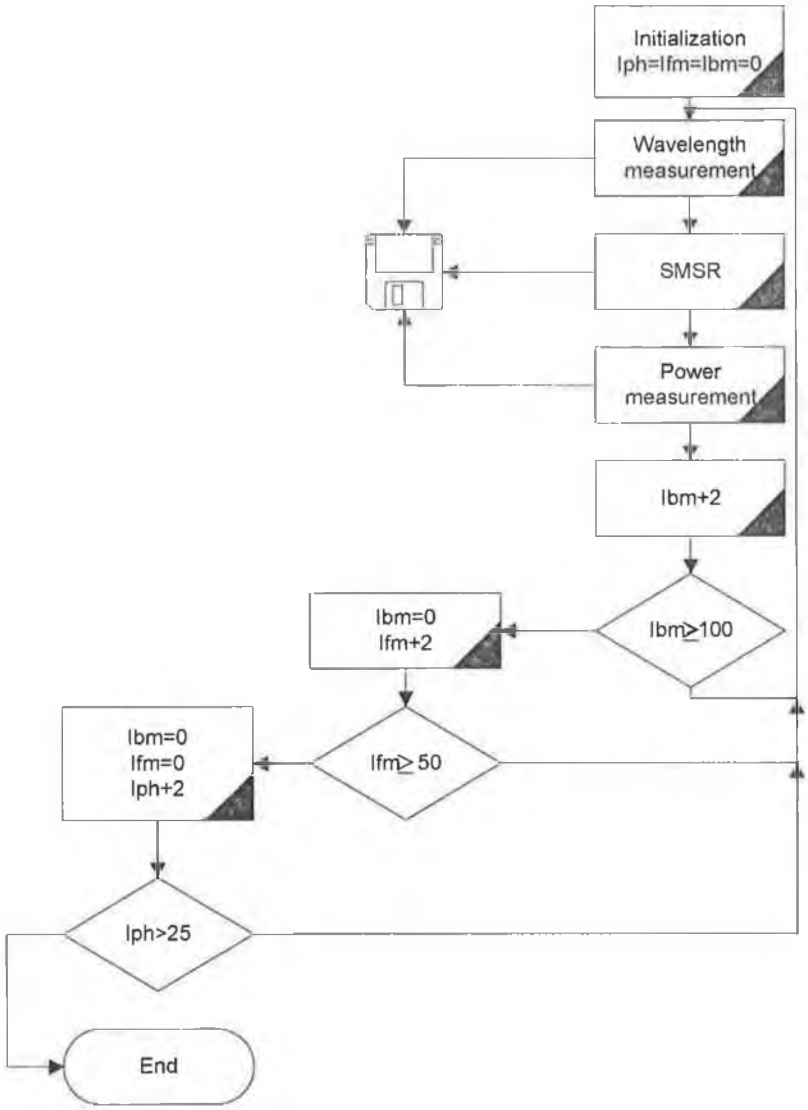

Figure 4.14- Flow chart. The building blocks of the programme

All the currents, except the gain section current, which is fixed at 147 mA, then are set to zero, which is the starting point of the characterisation. The first loop sets the required value for the current of the phase section. Immediately after setting value for it, the programme leads to the second loop, where a new value for the front mirror section is supplied. For those two fixed currents for the phase and front mirror section the third loop provides a complete sweep through the whole range of values for the back mirror section in steps of 2mA. For each current value the wavelength, output power and side mode suppression ratio is measured. After the limit is reached the third loop is exited. The programme leads again into the second one and change the value for the front mirror section after which the procedure with the third loop is repeated. Whenever the limit of the second loop is reached the programme jumps to the first one changes the value of the current for the phase section and goes again through the values of front and back mirror sections. This characterisation is very time consuming as that means that measurements for hundreds of particular values of the three currents have to be taken and summarised in a table. Figure 4.14 gives the flow of the different steps following different exit points of the loops.

After the required data is gathered an application in Matlab is created so the information can be visually displayed. All the information is divided in several phase planes. Thus in a single phase plane the variables are limited to two: front and back mirror currents, which can represent the X and Y axis of the plot, both of them representing a matrix z and the investigated behaviour of the wavelength, power and SMSR can be subsequently plotted using colour scale for the ranging values. A filled contour plot displays isolines calculated from matrix `Z` and fills the areas between the isolines using constant colours. The colour of the filled areas depends on the current figure's colourmap. The functions that can be used are `contourf (X,Y,Z)` and `contourf(X,Y,Z,n). They` produce contour plots of `Z` using `X` and `Y` to determine the *x*- and *y*-axis limits. X and Y are one-dimensional matrices that contain the values of the front and back mirror currents respectively and Z is a two-dimensional matrice that gives the value of the wavelength/output power or SMSR (depending on the purpose of the plot)."n" gives the number of different colours to be used in the plots. Those functions have been used for the wavelength areas against the changes of the back and front mirror currents. The plots should display the sampled grating mode hops as well as the longitudinal ones. The heavy black lines are outlining the borders between the super mode jumps of 4-8nm in wavelength and the light lines separate the regions of longitudinal mode hops of 0.4 nm. *Figure 4.15* depicts the wavelength borders between super mode jumps and longitudinal jumps.

Let's consider a scenario where the laser needs to be tuned from point A to B, corresponding to particular accessible wavelength modes. While sweeping through the currents of the front and back mirror sections the wavelength would experience several changes.

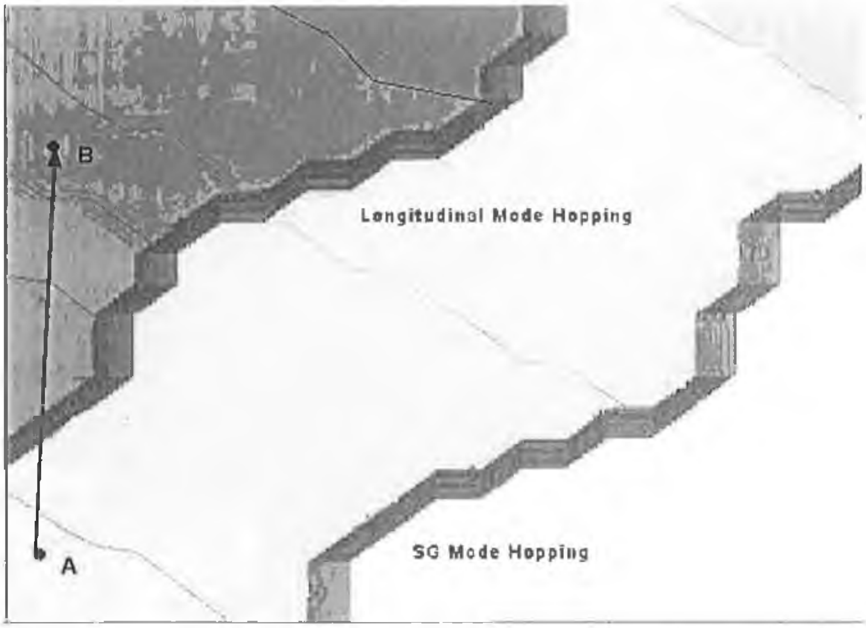

Figure 4.15-Plot of mode and longitudinal hopping against the front and back mirror currents

The first of them would be a longitudinal mode jump, followed by super mode jump, when it crosses the heavy black line to enter another wavelength region and the last transition is another two jumps caused by longitudinal mode hopping. The succession of the transition can be followed on the *Figure 4.16*.

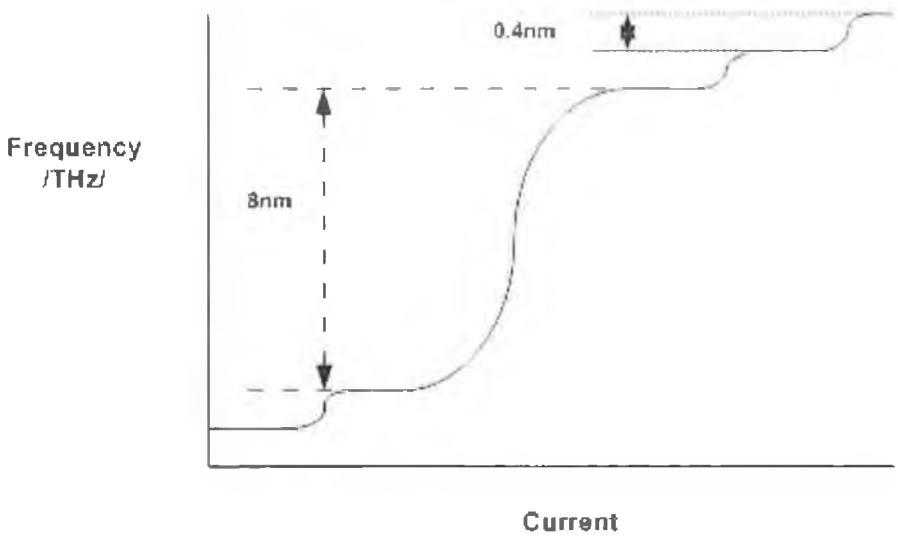

Figure 4.16- Frequency change with simultaneous control of front and back mirror section

As discussed above on the plot the different isolines form areas with different colour. The plot should be interpreted in the following manner: The tunable wavelength region from 1525 to 1575nm can be divided in several smaller ones comprising a small range of wavelengths. The boundaries of the super mode jumps produce a fan. The different regions from the fan stand for different wavelength changes between two consequent super mode jumps. Depending on the tuning currents of the back and front mirror sections different ranges are accessible. In the current limits of those two sections some of the ranges are repeated-see *Figure 4.17*. For best performance the actual applied current should be the lowest possible to achieve the required wavelength. This rule is important as one wavelength can be obtained by applying different combination of currents. Out of those combinations the lowest possible should be selected, as this would remove the problem with heating of the section and increasing the settling time. As the phase section control provides for fine-tuning, results are taken for several different phase planes. Interpolation between them provides look-up table currents.

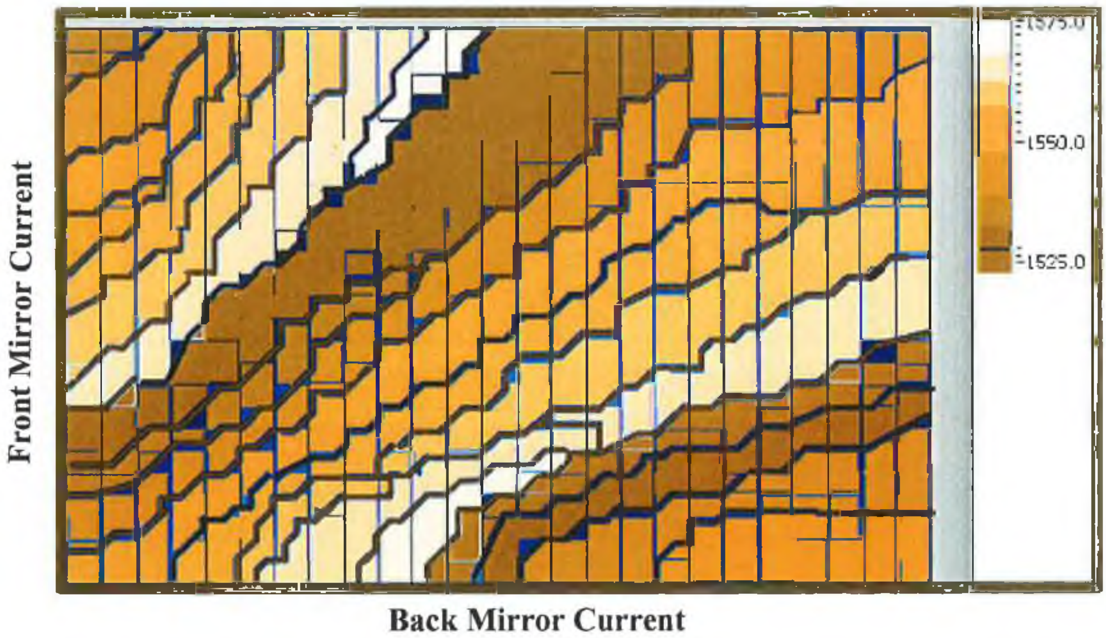

Figure 4.17-Contour map of the tuning wavelength regions for different front and back mirror currents

The longitudinal modes should be marked as well: regions within different super mode jumps have different green colour, opposed to longitudinal cavity jumps, which have different transverse shades of green. *Figure 4.18* represents an extraction from the above contour map. If the work wavelength region is within one of the presented super mode jumps, the change of the phase current shifts the wavelength slightly, providing fine-tuning of 0.4nm. That is the reason it is essential that the measurements are performed in more phase planes so at the wavelengths and the corresponding tuning currents are defined with high precision. If the channels are too close spaced relatively to each other the effect of the interference cannot be neglected.

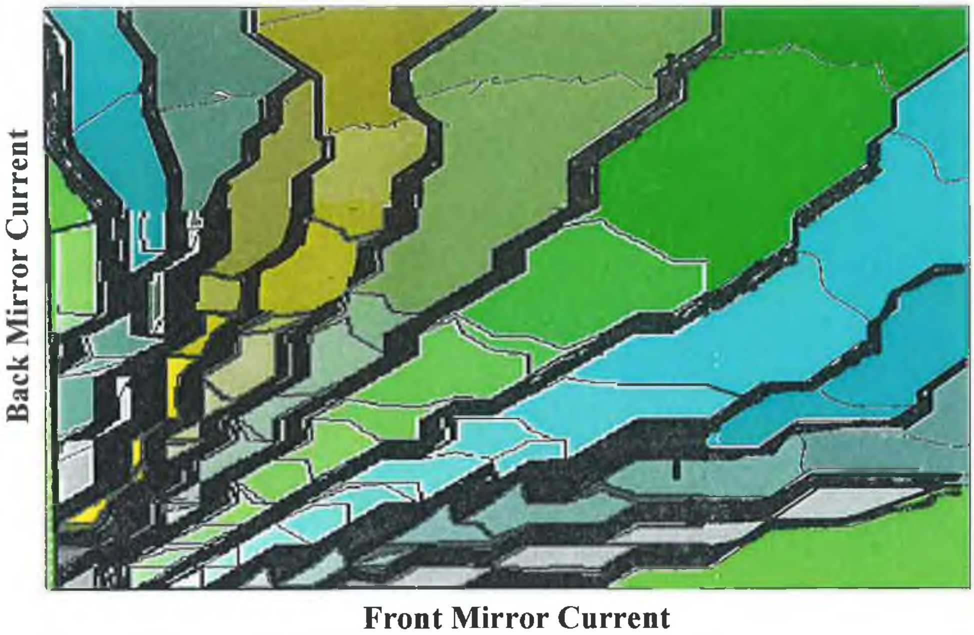

Figure 4.18-Contour map for different front and back mirror currents outlining the longitudinal modes

For achieving stable operation points the output power in addition to the emission wavelength, must be monitored. One and the same wavelength can be accessed through a various combinations of back and front mirror currents. The best way of deciding upon which pair of currents is to be selected for the particular wavelength is monitoring the output power. In *Figure 4.19* two plots for the output power are provided. One of them is for 5mA supplied phase current, the other for 20mA. Comparing the two plots it can be seen that there are more points in the lower current plane with high power. Partially the explanation for this is that with higher value of the currents the output power deteriorates because of the heating of the sections which causes changes in the bandgap structure of the laser-such as bandgap shrinkage. For an optimal decision different points need to be taken into account in various phase planes, that is why the current for the phase section has been changed in steps of two along with the two other sections.

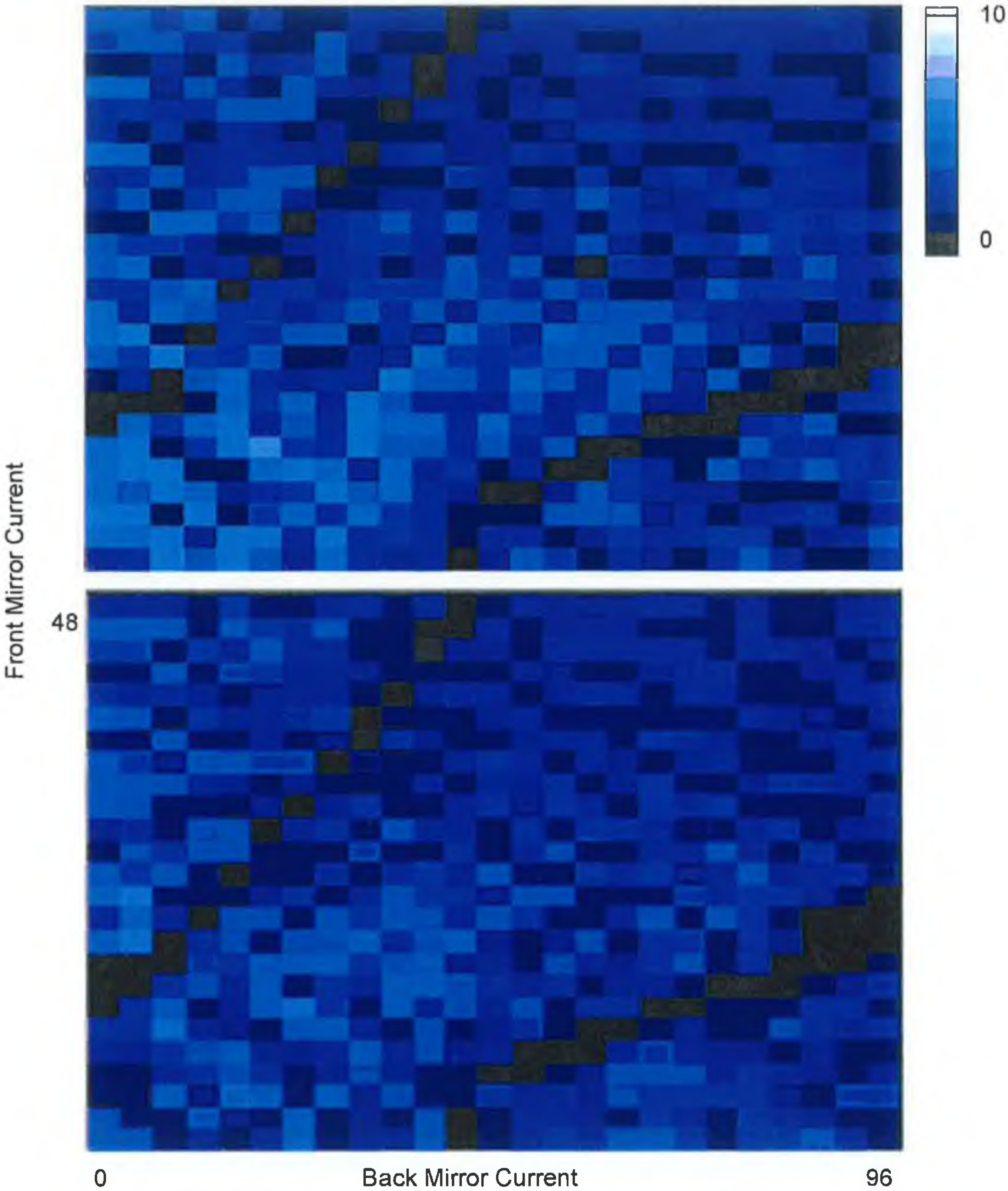

Figure 4.19- Output power for different back and front mirror mirrors in two different phase planes

If a particular region is taken under inspection and the colour coding is changed a better idea can be obtained for the variation of the power with the slightest changes in the applied currents. The output power is not related to the achieved wavelength but rather to the extent of alignment of the mirrors. The output power, which is measured with respect to the front and back mirror currents experience saddle points: a minimum with respect to the front mirror coincides with a maximum with respect to the back mirror-*Figure 4.20*.

In the absence of carrier induced absorption losses in the reflector, a saddle point would occur at the point where a peak of each reflector is exactly aligned with the same cavity mode. On *Figure 4.20* the saddle points appear as white spots that are standing for maximum output power.

The increase of the losses with the current causes the saddle point to shift towards lower rear and higher front DBR currents. For very high currents the saddle point can even disappear. The effect is largest for the front mirror as the output light passes through it twice.

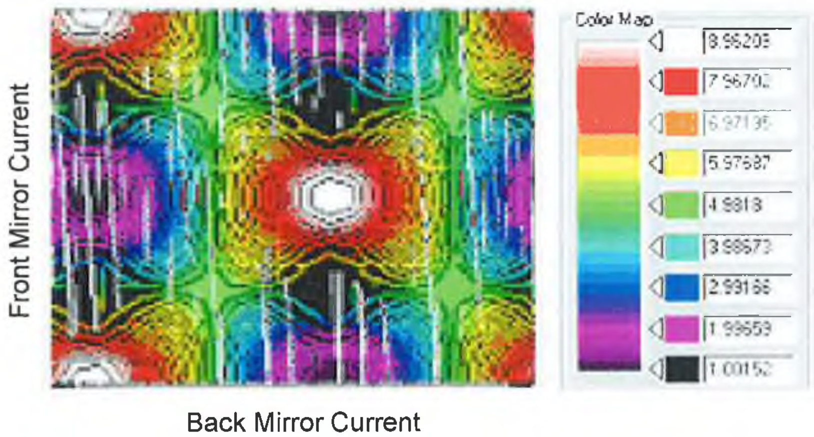

Figure 4.20-Colour grid for the output power

So far it has been shown that controlling the four section simultaneously for tuning to a particular wavelength is not an easy task. The wavelength accessibility is very important in addition to the precision of the tuning in order that interference be avoided. Any drift in the operating wavelength can cause interference between the channels. Many of the commercial tunable lasers have built in circuits for wavelength monitoring as well as control circuits for stabilizing the operating wavelength and protecting against drifts caused by overheating of the laser sections. In the following section some of these schemes will be reviewed.

4.5 Stabilization scheme

When an SG-DBR laser is deployed in a network, a control of the different parameters must be exerted, as well as a way of monitoring its behavior. Creating a look up table is an essential part of the process, as the most likely scheme of controlling the laser will be using a microprocessor to drive the current sources to the different sections. The data containing the appropriate values for the currents will be stored in a memory. The processor will read those values and the right currents will be injected.

Feedback control loops are required for achieving stable operating points. The channel currents must be adjusted based on the principle that the operating point should not reside near the mode boundaries. It is necessary not to jeopardize the modal stability, while maintaining the output frequency.

For that reason two different control loops are required. As the concept for the feedback control schemes are outside the scope of thesis work only a short outline of the each methods will be provided.

1.Frequency stabilization

High precision of the tuning can be achieved by changing the current of the phase section while the output wavelength is monitored using a wavelength meter or optical spectrum analyzer. The output from the meter may be used as external reference and according to their reading the current is appropriately adjusted [16].

2.Mode stabilization

By deploying only the frequency feedback loop there is no guarantee that high SMSR is maintained. A correlation between SMSR and variation of the output power has been reported. A high SMSR can be obtained by locking to a saddle point in the output power. The drawbacks of this approach are that other parameters like reflector losses with increased current are not taken into account and alignment between the longitudinal and reflector modes cannot be assured. Monitoring the active section voltage proves to be a solution [17]. The idea is that the voltage depends on the carrier density.

$$V = \frac{k_\beta T}{q}\left[\ln\left(\frac{N^2}{N_c N_v}\right) + \frac{N}{\sqrt{8}}\left(\frac{1}{N_c} + \frac{1}{N_v}\right)\right] + \frac{E_q}{q}$$ ***(Equation 4.8)***

N-carrier concentration
η-carrier confinement factor
I(t)-current
k_β-Boltzman constant
q-electorn charge
N_c, N_v-donor and acceptor concentrations of the N-type and P-type materials that make the junction of the active section

The voltage as it can be seen is assumed to follow the carrier concentration. The carrier density and the threshold gain have their minimums only for perfect alignment of the reflectivity peaks, thus providing for minimum voltage for the active section.

Monitoring the voltage and locking subsequently to the lowest level secures high SMSR and perfect alignment of the mirrors peaks.

4.6 Other parameters

The most important feature of tunable transmitters such as the tuning range and number of accessible channels was fully analyzed and explained earlier. For complete understanding of the Sampled Grating DBR lasers and their characterization some of the other important parameters have to be mentioned as well.

4.6.1 Spectral linewidth

Narrow spectral linewidth is fundamental for DWDM systems. The following expression gives the parameters that have influence on the overall spectral linewidth of the laser:

$$\Delta \nu = \frac{\nu^2{}_g h_\nu g \eta_{sp} \alpha_m}{8\Pi P}\left(1+\alpha^2\right)$$ ***(Equation 4.9)***

η_{sp} -spontaneous emission
h-Plank's constant
ν-optical frequency

P-light output
g-gain
α_m -mirror loss
v_g -group velocity
α-linewidth enhancement factor, where
α=(dn/dN)(dG/dN)
N-carrier density
n-refractive index

The linewidth of the SG-DBR laser is not constant: it varies widely. Values typically range between 3-10 MHz. There is a reported dependence on the tuning of the back, front mirror and phase section currents [18]. The largest broadening occurs with increasing the current of the phase section.
It is found that the linewidth is proportional to the square of the mode spacing. Thus a narrow linewidth requires a long cavity with small mode spacing, whereas a short cavity gives good SMSR. In a case of long cavity there are several modes within the main lobe of the Bragg reflector and the SMSR is rather poor. The oscillation in two or even more modes is likely to occur close to a mode jump causing large linewidth.

4.6.2 RIN

The relative intensity noise serves as a measuring tool of the noise characteristics of emitted optical power from the laser. The intensity fluctuations are usually characterized by RIN measurements. The relative intensity noise measurements are performed by analysing the electrical spectrum of the laser light at a fixed bias current converted by a high-speed photodiode. As the thermal and the shot noise in the photodetector contribute to the noise of the system for identifying the RIN of the laser, those terms should be subtracted.

$$RIN_{sys}=RIN_{laser}+RIN_{thermal}+RIN_{shot} \qquad \textbf{(Equation 4.10)}$$

$$RIN_{sys}=16\Gamma(\Delta v)_{st}\frac{1/\tau_{\Delta N}^{2}+w^{2}}{w_R^4}|H(w)|^2+\frac{2hv}{P_0}+\frac{2q}{\eta P_{fibre}}$$

$$RIN_{laser}=RIN_{sys}-\frac{N_{thermal}}{P_{el.ave}}-\frac{2qI_{dc}R_c}{I_{dc}^2R_L}$$

H(w)-modulation transfer function
w-electircal frequency

w_R-relaxation resonance frequency
h-Plank' constant
v-optical frequency
P_0-optical power
η-photodiode response
P_{fibre}-power coupled into fibre

Figure 4.21 shows the contribution of the different factors on the overall RIN

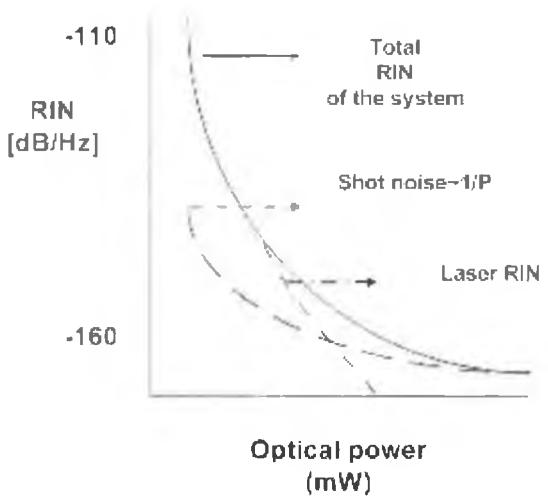

Figure 4.21-RIN versus frequency at different bias currents.

Figure 4.22 displays the RIN performance of the whole system for different active section currents.

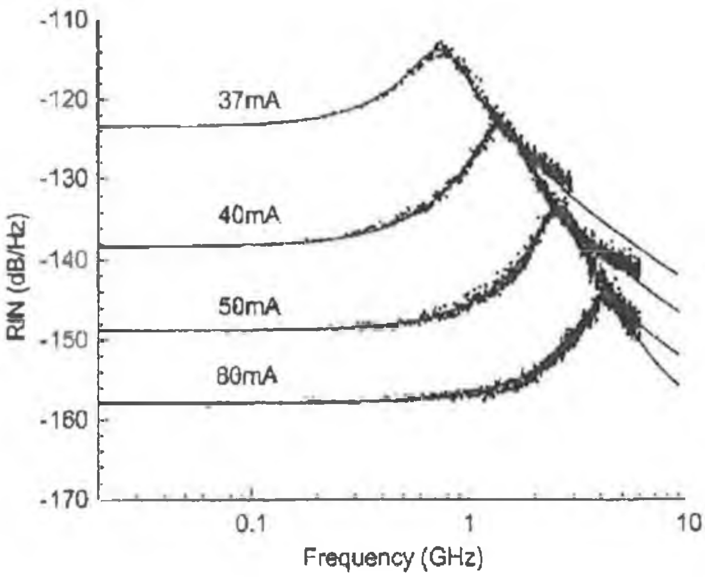

Figure 4.22- RIN versus fibre coupled power with active section biased

From the available information and graphs the resonance frequency can be extracted against the square root of optical power. The relaxation oscillation peaks at certain frequencies saturate due to the change of the gain slope dg/dN value at higher current because of a temperature increase in the gain section.

It has to be noticed that in SG-DBR lasers not only the gain section is biased. SG-DBR laser has different tuning regions that measurement will give different results as alignment of different reflection peaks of the two mirrors is performed. Different regions utilise different part on the material gain curve so it can be deduced that the output characteristics will differ. RIN measurements should be performed under different tuning schemes and the optimal points have to be allocated [19,20].

4.6.3 Direct modulation

The maximum achievable intensity modulation bandwidth is important in case direct modulation of the laser is deployed. The following equation gives the formulae for assessing the bandwidth:

$$f_{\max} = \frac{2\Pi\sqrt{2}}{K}$$ **(Equation 4.11)**

When analyzing the high speed properties of the laser, two parameters are important-K factor and the damping factor.

$$K = 2\Pi^2\left[\tau_p + \frac{\varepsilon}{v_g\frac{dG}{dN}}\right]$$ **(Equation 4.12)**

τ_p-photon lifetime
v_g-group velocity
ε-gain compression coefficient
dG/dN-rate of change of the material gain with respect to the carrier density

The intrinsic limits of the device performance can be determined by the damping factor as well. Theoretically the damping factor is proportional to the square of the resonance frequency. In fact it is calculated by the following formulae:

$$\gamma = Kf_R^2 + \gamma_0 \qquad \textbf{(Equation 4.13)}$$

For large resonance frequencies, the K factor describes the damping of the response, the damping factor offset γ_0 is important at low laser power when the relaxation oscillation frequency is small. So it can be summed up that K-factor is used to estimate the maximum intrinsic bandwidth (damping limited) in the absence of other limitations.

After having the two parameters the ultimate damping 3dB limited bandwidth can be calculated [21].

Most semiconductor lasers solve the light confinement problem by introducing a change in the refractive index in lateral direction. In strongly index guided lasers, the active region is buried on all sides by several layers of lower refractive index materials as the laser we were using. This structure is called buried heterostructure. A p-n-p-n thyristor blocking structure is often used to confine the current but it contributes to parasitic capacitance, which reduces the modulation performance of the laser.

4.7 Conclusions

Theoretical model for four-section SG-DBR laser static tuning was presented as well as a complete experimental characterisation of SG-DBR laser was undertaken to determine the tuning characteristics. The tuning properties were studied in terms of currents, linewidth, SMSR and output power. Regions of continuous tuning for the laser were presented and different limitations on the continuous tuning range were clarified. The last chapter will deal with the dynamic tuning of these types of lasers and the effect on the overall performance of the network provided more than one tunable module is functioning.

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Chapter 5

BER Performance in Wavelength Packet Switched WDM Systems During Nano-second Wavelength Switching Events

5.1 Introduction

In a complete WDM system that employs wavelength packet switching, each transmitter can tune its emission wavelength to transmit packets of information at a number of different wavelengths. The information from all the transmitters can then be multiplexed together and sent over optical fibre. The composite wavelength signal may then pass through an Array Waveguide Grating (AWG), which sends each of the incoming wavelengths to one specific output fibre port. In general it is possible to write the wavelength connectivity in form of a matrix. Thus by choosing an appropriate wavelength on the transmitter side, the laser selects the output port to which the information packet is sent. The tuneable transmitters, together with the optical coupler and the AWG, become a strictly non-blocking switch fabric with a switching speed equal to the tuning speed of the laser [1,2].

Clearly the key component for implementing such networks is the wavelength tuneable laser transmitter, as the overall design of the wavelength packet-switched WDM networks will be heavily dependent on the characteristics of these tuneable devices. The main characteristics that determine the usefulness of wavelength tuneable lasers in wavelength packet-switched systems are the wavelength tuning range, the side-mode suppression ratio (SMSR), the output power, and the speed at which the device can switch from one wavelength to another. Taking into account these characteristics, the most suitable tuneable lasers for use in wavelength packet-switched systems are electronically tuneable devices [3]. Typical examples of such devices are grating-assisted co-directional coupler with sampling grating reflector (GCSR) lasers [4,5], and super structure grating distributed Bragg reflector (SSG-DBR) lasers [6-9]. These devices can achieve tuning ranges in excess of 60 nm, SMSR's exceeding 30 dB, output powers above 10 dBm, and switching times in the order or 20-50 ns. Another important feature of these electronically tuneable lasers is that as the transmitter is being switched between a low and a high wavelength channel, it is possible that the device will emit intermediate wavelengths during the switching event. This effect may clearly cause serious problems in an overall wavelength packet-switched WDM network as the optical output from the tuneable laser, as it transitions between two specific wavelengths, may result in cross-channel interference on other wavelength channels in the WDM network. This may ultimately limit the Bit-Error-Rate (BER) performance of specific data channels in the network.

The work carried out in this chapter was undertaken using a nano-second wavelength switched laser module that uses DBR technology. The switching time of this module was initially being characterized by encoding a data packet onto the tuneable laser output, such that the data spans the transition period between two output wavelengths, and then examining the eye diagram of the resulting signal at both output wavelengths. From the experiment the switching time was determined. The output from the tuneable laser (TL) module was then multiplexed with a second laser transmitter (that is generating data at a wavelength channel that lies between the 2 wavelengths that the TL is switching between). From this work the degradation in system performance on the central data channel, due to the spurious wavelength signals emitted from the TL during the switching event, is confirmed by the presence of an error floor in the BER vs. received power measurements. Certain levels of attenuation are required at the output of the TL module such that BER's of 10^{-9} or better can be obtained for the data channel that lies between the two wavelengths that the TL module is switching between.

5.2 Switching time

Fast wavelength switching in the nanosecond regime combined with a wavelength selective device enables the routing of data packets. A critical requirement for an efficient optical fabric is that switching time between any channel combinations of the transmitter has to be short compared with the data packet length. The actual switching time depends on three parameters, namely:

1. Structure of the laser-the current settling times are highly dependant primarily on the laser chip capacitance and the dynamic resistance of the tuning section. Investigating carrier dynamics is a very complicated process, but it should be noted that for the most common deployed structures for those particular laser-buried heterostructure- there is so called p-n-p-n thyristor current blocking structure for current confinement, which yields high internal parasitic capacitance and thus hinders the switching performance [10].

2. Carrier lifetime-the typical carrier lifetime in semiconductor lasers, owing to the spontaneous emission is of order of several nanoseconds at threshold. The rate of spontaneous emission is very dependant on the carrier density [11]. It can be deduced that the switching will be greatly influenced be the injected current and different processes of recombination depending on the actual structure of the laser.

3. **Driver electronics**-even though the concept is simple: the current should be injected in the passive section in a square wave manner such that different levels correspond to certain injected electron density, which leads to carrier change and refractive index change, different parameters present an obstacle. Different approaches for developing high-speed circuits for fast wavelength switching can be adopted. One way is deploying a field programmable gate array with embedded microprocessor and a look up table. Every time a targeted channel is given the required currents are checked in the table and the tuning current are then processed by digital to analog converters, amplified to the required level and sent to the tuning sections [12]. Another approach is using an IC driver, mounted on an alumina substrate. To achieve fast switching times the driver uses GaAs depletion pseudomorphic high electron mobility transistor (P-HEMT) [13]. A relatively new approach is the optical printed circuit board-a platform towards VLSI Nano Photonics. The O-PCB is very much like that of electrical printed circuit board except that the former uses optical wires for optical signals [14].

CMOS IC laser drivers are potential choices for developing high-speed board [15]. The current going into the mirror section of the laser can be easily programmed, which respectively gives the option by changing the value to access different channels. Several issues should be dealt separately.

- Small changes in the bias voltage result in large changes in the supplied current, which accordingly causes switching of channels. Because of the required fast change in the current inductive voltage spikes are produced therefore the modulation current should be AC coupled [16].
- Damping resistor-connected in series with the laser section, which usually has resistance between 3-5 ohms (it varies with the current supplied), raises the load resistance, thus reduces the load frequency dependence [17]
- Taking into consideration that laser package series inductance cannot be eliminated completely, a compensation network should be designed in order to reduce it. The parasitic inductance and capacitance of the interconnect paths between packaged devices will cause severe ringing problems. No low loss impedance matching is possible for the laser interconnection as the laser impedance drops low with increasing drive current. That means the current must be fed into a variable and low dynamic impedance load. The load of the laser can be considered to be 4 ohms and 4nH,adding a damping resistor and a coupling capacitor, a R/C compensation network is recommended. It should be placed as close to the load as possible. Since the provided offset for the modulating current is attached directly, issues with he parasitic capacitance should be dealt with as well. Solution to the problem is adding R/L network in series [18].

Perfect impedance matching is very hard to be achieved. All the networks placed to compensate for different parasitic issues can operate properly only in a certain frequency region. Due to the parasitics and the not so sharp transition edges of the current steps different intermediary wavelength modes are aroused as it is shown on *Figure 5.1*.

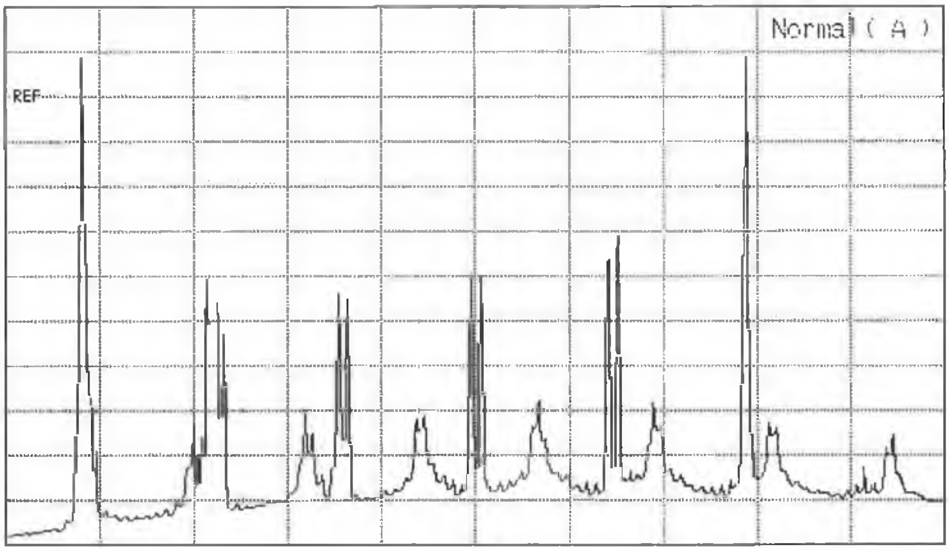

Figure 5.1- Intermediary modes caused by switching of tunable laser without attenuation or blanking of the output

Most of the recent developed tunable transmitters have integrated semiconductor optical amplifiers to achieve blanking (reverse biasing the SOA to achieve power shuttering during the switching event) of the output during the transition periods. Integrated SOA acts as a shutter during wavelength switching and an optional variable optical attenuator for pre emphasis of transmitted power levels to optimize link performance. The carrier lifetime is in order of nanosecond, which makes the integration suitable for supporting the blanking of the laser output in nanosecond switching. The gain of the SOA depends on the injected current, therefore as an amplifier and as an optical gate it can be controlled by current injection. The gain saturation induced nonlinearity generates crosstalk, which poses a severe limitation of the actual integration of the SOA. In contrast Gain Clamped SOA has a gain, which is constant with respect to input power variations, as long as the amplified signal power is less than the oscillating power, leading to a flat gain versus output power response [19]. The module that is used does not include that feature, as this will prevent an investigation of the dynamic tunability of the laser.

5.3 Determination of tunable laser switching time

To determine the switching time of the TL module we have employed the experimental test-bed as presented in *Figure 5.2*.

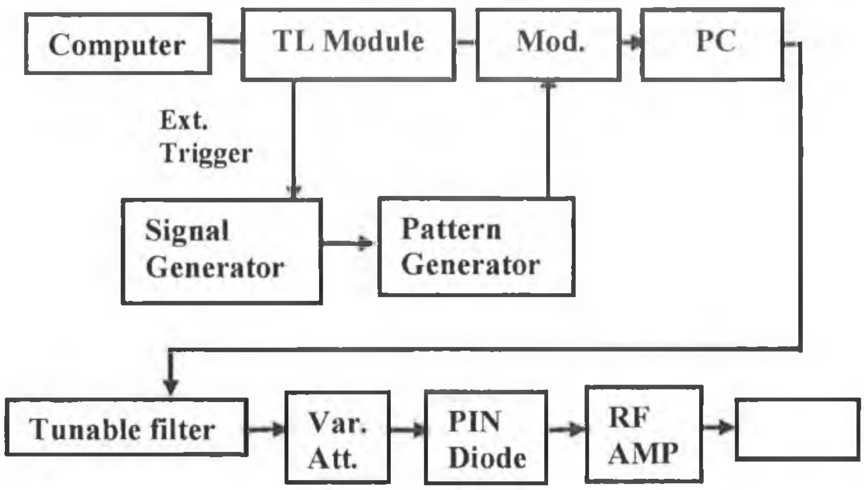

Figure 5.2-Experimental configuration to determine switching time of TL module

The module is controlled via a PC and can be set to transition between different wavelengths on the ITU grid. A trigger output from the wavelength tunable module is available to determine the timing of the transition between wavelengths from the TL. This trigger signal is then fed into a signal generator that can produce variable width pulses at the same repetition rate that the laser transitions from one wavelength to another. The output from this signal generator is subsequently fed into the Pattern Generator such that bursts of data, at a rate of 2.5 Gbit/s, can be applied to one specific wavelength channel, and the length of the burst and position of the burst relative to the laser transition time, can be varied using the signal generator.

The information is encoded onto the optical output from the TL using an external modulator with a bandwidth 8 GHz. A polarization controller (PC) is required before the modulator to ensure that the signal entering the PC has the correct polarization. The data signal from the pattern generator is fed directly into the RF port of the modulator while the bias port is connected to a voltage supply (this is optimized during the experiments to achieve the clearest eye opening). The optical data signal from the modulator is then amplified before an optical filter (bandwidth: 0.28 nm) is used to select out one specific wavelength channel. The optical data signal is then detected using a 50 GHz pin diode and can be displayed on an oscilloscope. The TL module is initially set to transition back and forth between 1533 nm and 1538 nm at a repetition rate of 50 kHz. Data bursts from the pattern generator are applied to the optical output from the tuneable laser as described above. By varying the relative delay between the data burst, and time the TL transitions between its two output channels, the information burst can be put on one of the two wavelengths, or set to sit across the transition between the two wavelengths. By triggering the oscilloscope on the burst signal we can view the data packets being generated at each wavelength

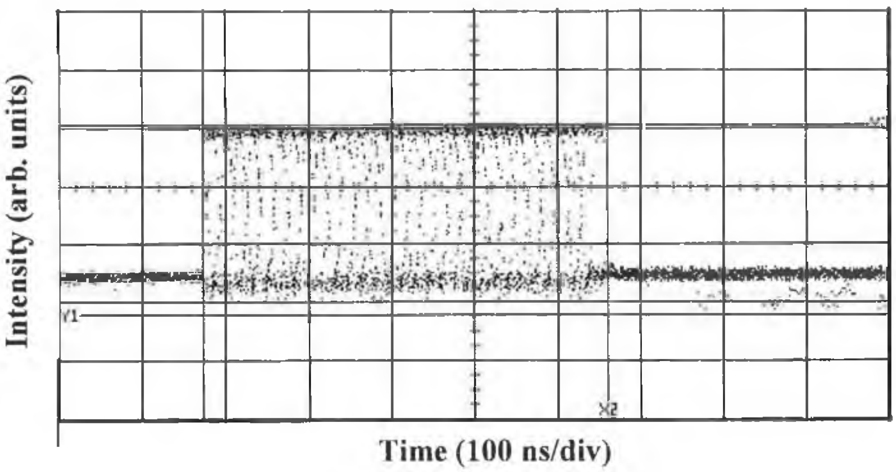

Figure 5.3-Data packet encoded onto transitioning TL module on wavelength channel at 1533 nm

. In the first case the data packet is applied to the TL output during the time it is emitting light at a wavelength of 1533 nm, and the resulting data packet is shown in *Figure 5.3*.

The packet length is measured to be 487 ns. We then moved the position of this packet such that it spans the transition from 1533 to 1538 nm, and examined the data output on both of the wavelength channels by tuning the optical filter between the two wavelengths. For the output at 1533 nm the initial bits of the data packet are clean, but as we approach the transition, and the output wavelength moves away from 1533 nm, the eye starts to close (as shown in *Figure 5.4*).

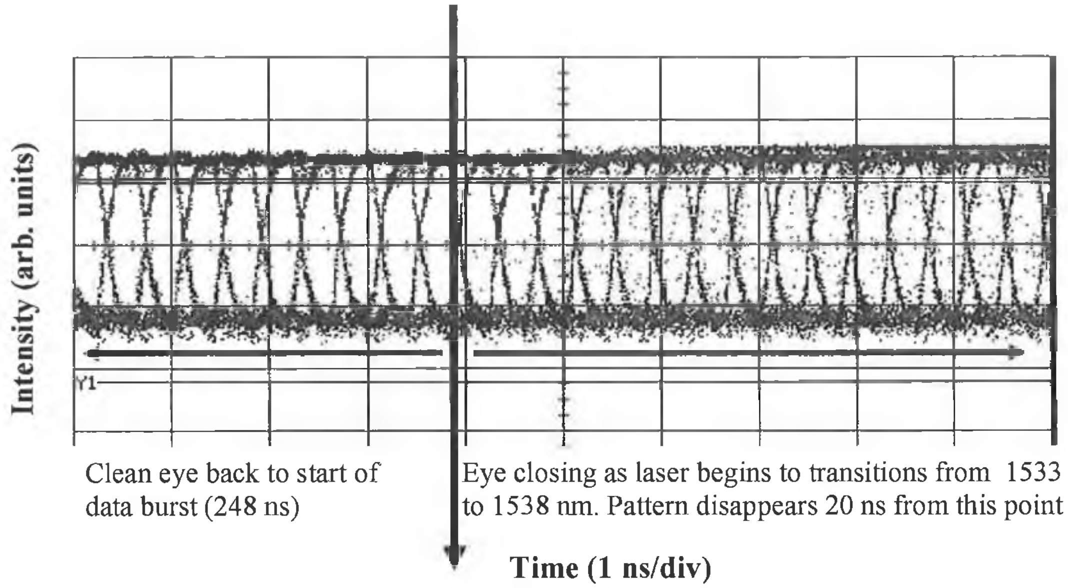

Figure 5.4-Portion of received data packet at 1533 nm with data encoded onto TL module such that it spans transition from 1533 to 1538 nm

The time interval for which the eye diagram is completely open and the TL can be used for error-free transmission at this wavelength is measured to be 248 ns. We then tuned the filter to select the output at 1538 nm, in this case the final bits of the data packet are clean, but the initial bits have closed eyes due to the fact the laser is in the process of transitioning to 1538 nm from 1533 nm (*Figure 5.5*).

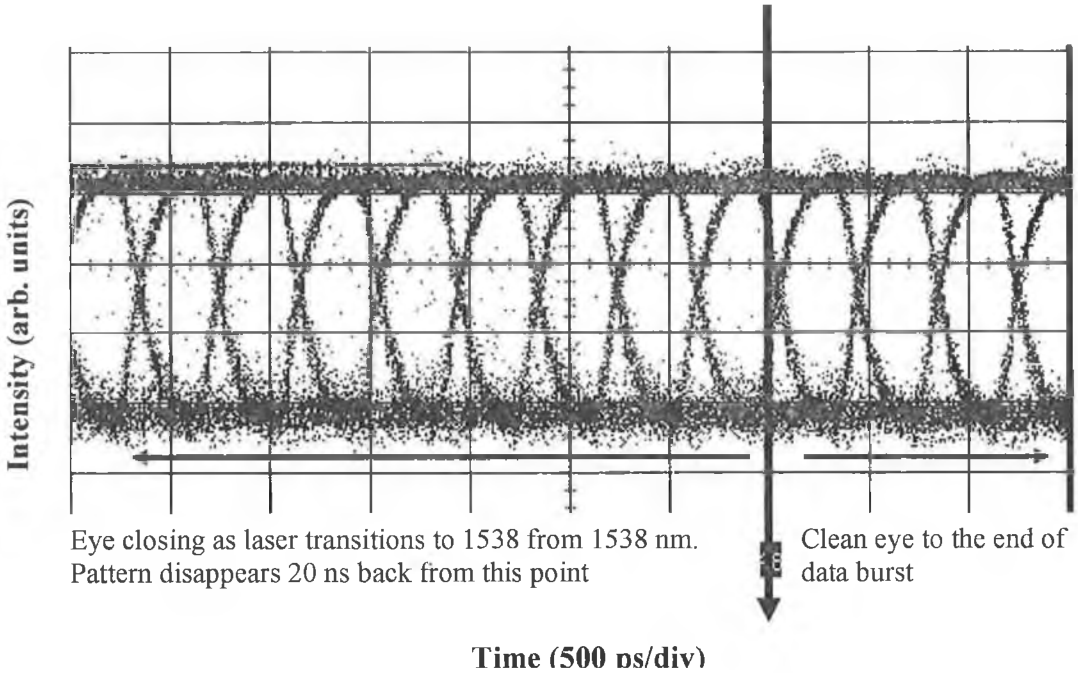

Figure 5.5-Portion of received data packet at 1538 nm with data encoded onto TL module such that it spans transition from 1533 to 1538 nm

The time interval for which the bits are clean and the TL can be used for error-free transmission at this wavelength is 202 ns. By adding up the time intervals for which the TL module can be used for error-free transmission at the two wavelengths it is transitioning between, we obtain a total of 449 ns. As the total length of the data bust is 487 ns, we can determine that the transition time (switching time) during which we are unable to transmit data error-free on either of the output wavelengths is 38 ns.

5.4 Effects of TL output during switching event

To investigate how the BER transmission performance of a WDM channel is affected by the output from the TL module that is transitioning between two wavelengths on either side of the data channel being monitored, we have used the experimental set-up shown in *Figure 5.6*.

In this case the TL module is once again set to transition back and forth between 1533 and 1538 nm at a repetition rate of 50 kHz. In addition to the TL we use a HP wavelength tunable external cavity laser (ECL) that can emit light from 1480 to 1570nm. 2.5 Gbit/s electrical data signal (2^{11}-1 PRBS) from the pattern generator is encoded onto the optical signal from the ECL laser using the external modulator, and this data signal is then coupled together with the output from the TL module. The data channel from the ECL can be set to any wavelength between the two output wavelengths from the TL module. A characteristic of this module is that as it transitions between two specific channels it may excite other wavelength channels that are being used for data transfer in an overall WDM network. The purpose of this set-up is to determine how this affect's the performance of information transfer in a WDM network.

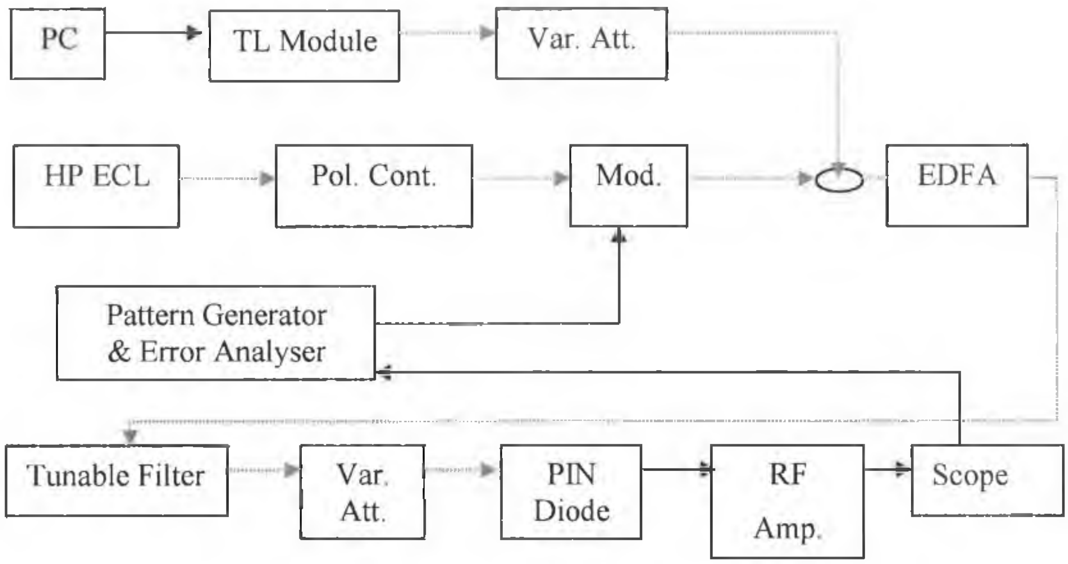

Figure 5.6-Experimental configuration to determine how the spurious wavelength signals emitted during switching of TL module effect multiplexed data channel lying between output wavelengths from TL

Figure 5.7 displays the composite wavelength signal after data channel from the ECL (which has been set to 1535.4 nm) is combined with the TL output. The power levels in the three wavelength signals have been equalized by attenuating the output of the TL module. The composite signal then passes through an optical filter, with a bandwidth of 0.28nm that selects the 1535.4 nm data channel. The optical data signal is then detected using a 50 GHz pin diode and displayed on an oscilloscope or inputted into the error analyzer to determine the BER of the received signal.

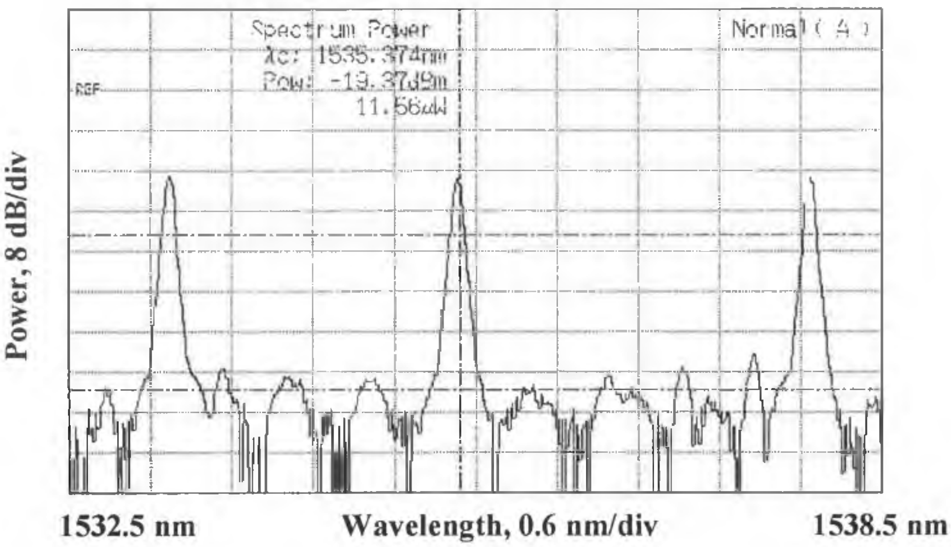

Figure 5.7-Composite wavelength signal after coupling together output from TL module (switching back and forth between 1533 and 1538 nm) and data channel from ECL at 1535.5 nm

To determine whether the signals excited by the tunable module (as it transitions between two wavelengths on either side of the data channel) affect the system performance, we must first of all plot the back to back performance of the 1535.4 nm data channel on it's own. The BER vs. received power for the back-to-back case is shown in *Figure 5.8*.

It should be noted that the low receiver sensitivities in this figure are as a result of the low receiver gain used in the present experiment. We then proceed to measure the BER vs. received power for the case when the data channel is coupled together with the TL module output before being filtered out (also shown in Fig. 7, 0 dB attenuation curve). In this case the power levels in the three wavelength signals have been equalized. The associated eye diagrams of the received data signals for the single channel case, and the case when the data channel is multiplexed with the tunable laser (that is switching between two wavelengths), before being filtered out and detected, are shown in *Figure 5.9*.

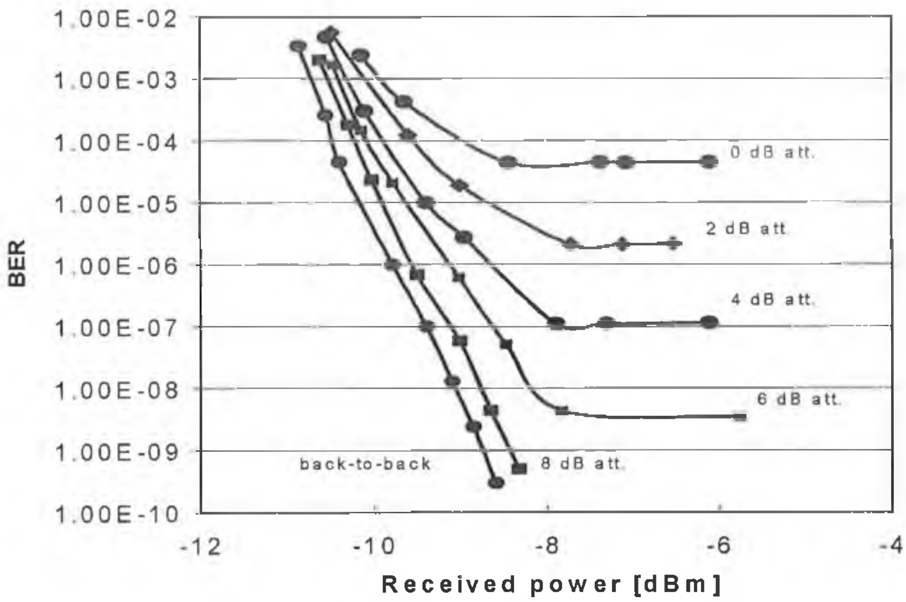

Figure 5.8-BER vs. received power for back-to-back case, and for case when the data channel is multiplexed with output from the TL Module (as a function of attenuation of the TL output)

From these eye diagrams we can clearly see the noise added to the data signal as a result of the TL laser generating a spurious wavelength output at the same wavelength as the monitored data channel, during its transition between two output wavelengths. The effect of this on the BER vs. received power curve is to place an error floor on the performance of the monitored data channel. The error floor is at 4 x 10^{-5} (as shown in *Figure 5.7*), and is a result of the TL generating light at intermediary wavelengths (including 1535.4 nm) for a small period of time during the transition from 1533 to 1538 nm. Similar error floors were obtained when the data channel was set to wavelengths corresponding to the other spurious wavelengths that are generated during the transition period of the TL module. *Figure 5.10* displays the BER vs. received power curves for the case when the ECL is tuned to three different wavelength channels (1534.2, 1535.4, and 1536.6 nm) between the output wavelengths being emitted from the TL.

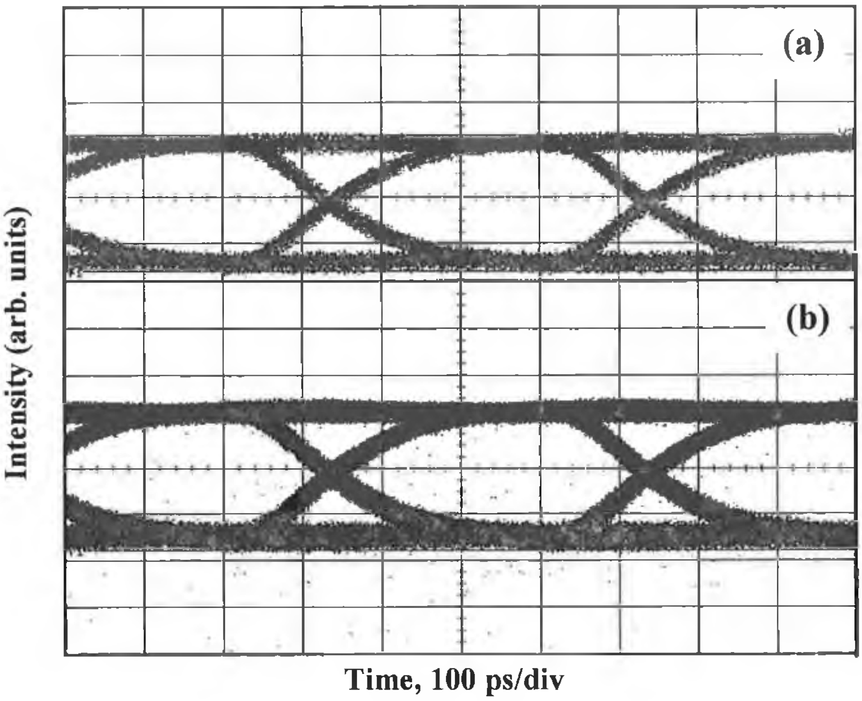

Figure 5.9-Received eye diagrams for the 1535.5 nm channel for (a) the back-to-back case, and (b) for the case when the data channel is multiplexed with the tunable laser output before being filtered out and detected

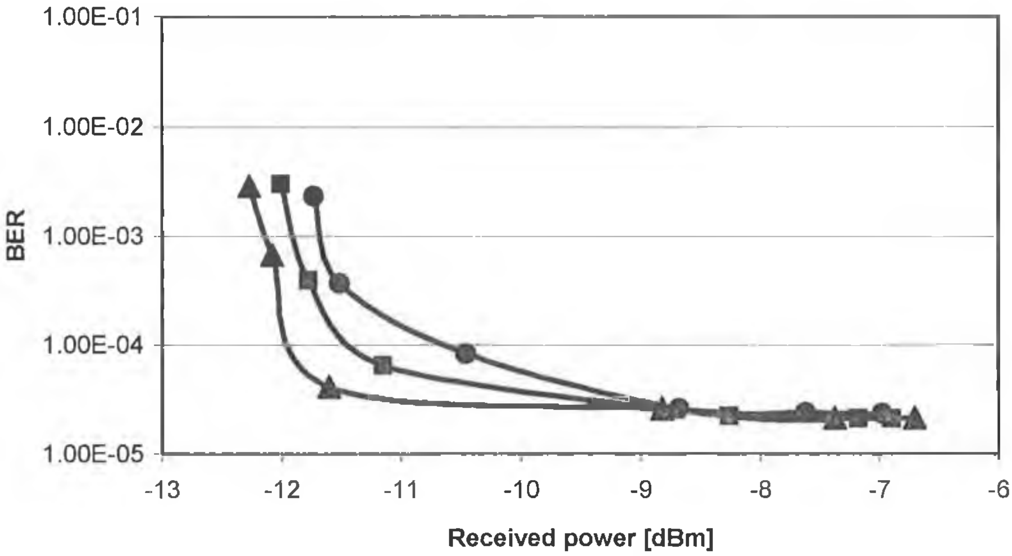

Figure 5.10-BER vs. received power when the data channel from ECL is tuned to three different wavelengths between output wavelengths from TL module (triangles : 1534.2 nm ; squares : 1535.4 nm ; circles : 1536.6 nm)

From the measured error-floor it is possible to estimate the length of time that the TL output is at the same wavelength as the monitored data channel, during its transition. This can be achieved in the following manner: the TL is transitioning between its two output wavelengths every 10 microseconds, and since we are sending information at 2.5 Gbit/s, in 10 microseconds we send approx. 25000 bits. With a BER of 4 x 10^{-5}, this means that 1 of the 25000 bits sent in 10 microseconds is received in error due to the excitation of the intermediary wavelength channel. However given that the signal generation from the tunable laser only gives an error for a sent "0", and given that we send unbiased data (equal number of "1's" and "0's"), we can assume that the intermediary wavelength is on for approx. 2 bit periods of the 2.5 Gbit/s data signal, or 800 ps.

The limitation on BER performance on the monitored data channel that we have investigated in this work (due to the spurious wavelength output from the TL module during it's transition period) is clearly a major issue for the development of large-scale WDM networks employing tunable lasers for wavelength packet-switched architectures. In order to overcome these limitations in real WDM communication systems using wavelength packet switching, it will be vital to extinguish the output from the TL as it transitions between specific wavelength channels. This will ensure that the spurious wavelengths emitted from the tunable laser as it transitions, do not limit system performance. To determine the required level of signal extinction at the TL module output, such that it will not affect system performance in a wavelength packet-switched WDM system, we have used the experimental arrangement described earlier. In this work we have examined how the BER floor on the filtered data channel (from the ECL), varies as the output of the TL module is attenuated. These results are shown in *Figure 5.8*. We can see that it is necessary to attenuate the output of the tunable laser module by 8 dB to ensure that the cross channel interference caused by the spurious wavelength signals (generated during a transition period), does not limit the BER of the received signal to worse than 10^{-9}. This result is for the case of one data channel being degraded by a single switching event (i.e. one tunable laser switching back and forth across the data channel). The TL attenuation requirements for the case when there is simultaneous switching of multiple TL modules, in a WDM packet switched system, will clearly exceed 8 dB in order to achieve error free performance on all wavelength channels. This area is currently under investigation.

As it was mentioned earlier there are commercially available laser modules with integrated gain clamped SOA. The SOA can be set up to blank the output during a wavelength transition. The measurements made with such a module for fixed length of blanking period is presented in *Figure 5.11*.

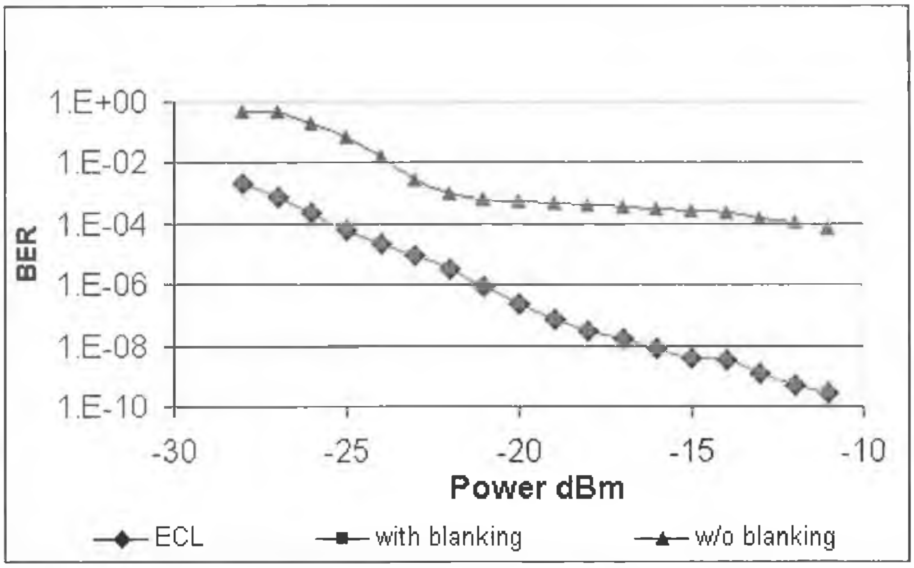

Figure5.11-BER performance with blanking the output of the TL using SOA

As the SOA blanking can be enabled or disabled a comparison can be made. With the SOA blanking not enabled and repeating the experiment as shown in *Figure 5.6*, an error floor of around 1×10^{-4} is obtained on the data channel, while with the blanking enabled the same performance as the back to back case is monitored. It can be seen that the switching of the tunable module does not affect adversely any other channel. The BER performance of the system when the ECL is working on its own is the same as the performance when the two lasers are working simultaneously: the ECL and the switching of the tunable laser with active blanking of the output.

5.5 Conclusions

Wavelength tunable lasers are becoming a mainstream component in photonic networks. In addition to providing cost saving for WDM networks with respect to inventory reduction, these tunable devices may also be used for implementing more efficient bandwidth utilization in WDM networks by employing wavelength packet switching architectures. In these networks, WDM optical packets are generated using fast tunable light sources, and then routed to specific nodes in the optical network by using optical filtering techniques. An important characteristic of electrically tunable laser devices, that may influence their operation in WDM packet-switched systems, is that as they transition between two output wavelengths they may generate light at intermediary wavelengths. This will clearly affect the performance of other data channels in the systems that are transmitting on the same wavelengths as those generated by a tunable transmitter during a switching event. In this work we have shown how this effect limits the performance of a data channel by placing an error floor on the BER vs. received power characteristic of that channel. To overcome these performance limitations, care must be taken to ensure adequate attenuation of the output of a laser transmitter under high speed switching operation. This will ensure that BER performance degradation due to the interference of wavelength signals produced during switching can be controlled. Ideally, the laser transmitter itself should perform the attenuation function and recent advances in integration technology are making this a cost-effective approach [20].

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Conclusion

The recent downturn in the telecom market has forced telecommunications carriers to put enormous pressure on equipment providers to reduce system costs in the core backbone, where DWDM transport systems are typically employed. As a result, equipment providers are beginning to outsource their line-side optics to transceiver vendors. Cost pressures will continue to push standardized transceiver-based solutions into next-generation products as the DWDM market continues to grow. However, standardizing DWDM line-side optics is very difficult given the very stringent and proprietary requirements specific to each system provider. OIF Tunable Laser MSA OIF Tunable Laser Implementation Agreement (IA) was endorsed by over 20 companies in Nov 2002. The benefits include assured supply of new technology from multiple vendors and support at component level of system architectures requiring tunability.

One question that is very important is why tunable laser technology should be used and what are the main highlights. If the roadmap of the development of the tunable laser technology is analyzed, an answer can be provided.

Revolutions in Fiber Optics – 1980s

- Point-point links
- Single-mode Fiber
- InP Lasers
- Enabled lower transmission cost

Revolutions in Fiber Optics – 1990s

- WDM point-to-point links
- EDFA
- DFB Lasers
- Optical Pump Lasers
- Increased capacity to reduce total network cost

Revolutions in Fiber Optics – Today

- Re-configurable Networks
- Tunable Lasers
- Tunable Filters
- Photonic Switching
- Reduce both Capital and Operational expenses and increase network flexibility

New developments have allowed tunable lasers to approach performance levels of fixed lasers. Tunable devices enable dynamic DWDM networks, flexible, remote service provisioning under software control, and integration of multiple technologies. Tunable lasers use a variety of structures and tuning methods and now they can offer a certain level of maturity that provides:

- Better or same optical performance as the fixed wavelength DFB's: Output Power, Linewidth, RIN, SMSR
- Meet requirements to support 99.999 network reliability
- 100% Locking
- Density
- Small form/factor
- Low power consumption
- Revenue Generating services
- Remote Provisioning and Bandwidth on demand
- Efficient network utilization
- Price-Same price as fixed wavelength DFB's

From network application point of view this technology avails of:

- Sparing /Inventory Mgmt
- Back-up laser that can replace any faulty laser in system
- Universal Line Card / Transponder
- Save inventory and production costs by designing "universal line card"

These applications reduce cost of operation of networks for Service Providers while enabling new revenue opportunities

- Dynamic Wavelength Management
- Fast Provisioning
- Wavelength Conversion
- Flexible OADM/OS
- Protection/Restoration
- Bandwidth on Demand
- Capex and Opex Savings -If demand set is known exactly, static transparency can produce lower network cost. In reality, to handle traffic variations, network price is more than doubled with static technology.

List of Publications

1.A. Dantcha, L. P. Barry, J. Murphy, J. Dunne, T. Mullane, D. McDonald, "BER Performance in Wavelength Packet Switched WDM Systems during Nano-second Wavelength Switching Events", European Conference on Optical Communication, Paper We4 P.146, 21-25 September, Rimini, Italy

2. A. Dantcha, L. P. Barry, J. Murphy, J. Dunne, T. Mullane, D. McDonald, "Developing Flexible WDM Networks using Wavelength Tunable Components", accepted for presentation at Information and Telecommunication Conference, Letterkenny, October 22-23,2003

3. A. Dantcha; L. P. Barry; J. Dunne, "BER Performance in Wavelength Packet Switched WDM Systems During Nano-second Wavelength Switching Events", Elsevier, 14 August 2004