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Dynamic Wavelength Routing in
Packet-Oriented WDM Optical Networks

Sadegh Abbasi Shahkooh

A dissertation submitted to the University of Bristol in accordance with the requirements of the degree of Doctor of Philosophy in the Department of Electrical and Electronic Engineering, Faculty of Engineering.

April 2003

40500 words
Abstract

The work in this thesis investigates a dynamic wavelength routing switch which is suitable for packet-based WDM optical networks. This switch involves a tuneable wavelength converter combined with a passive wavelength router such as Arrayed-Waveguide Grating (AWG). The first part of the work is focused on the performance of AWGs. The results of measurements of the amplitude and phase response as well as link performance of a 16x16 AWG for data rates up to 10Gb/s is demonstrated. A novel non-destructive phase measurement technique is described in order to resolve the phase changes across each AWG channel. Also the short pulse and spectral response of another AWG interleaver has been measured. A model has been developed in MATLAB in order to investigate the performance limitations of AWGs. By using this model, we have investigated the relations between the performance characteristics of an AWG and its structural parameters to find out the causes of its performance limitations. From this model we were able to predict, for the first time, the short pulse response of an AWG which has led us to the short pulse measurement of the AWG interleaver. The input-output pulse-width relation of an AWG has also been calculated to assess the ultimate data rate limit of the AWG.

We then used a simulation based on VPI TransmissionMaker software to investigate in detail a wavelength converter and all-optical regenerator based on cross-gain modulation in an integrated DFB laser and semiconductor optical amplifier (SOA). The advantages of the integrated component over single devices are highlighted. It is shown that for otherwise similar components, the Q factor of the converted signals are much higher in the case of the integrated device at bit rates of up to 10Gb/s, than those found in the single DFB laser and SOA. In addition, the integrated device improves not only conversion range and sensitivity, but also gives good regeneration with a considerable dynamic range. It has also been shown that using an SOA before DFB/SOA improves the sensitivity and gives better performance for very low input powers.

Finally, we demonstrated the results of a system test to prototype a dynamic and regenerative wavelength router based on a SG-DBR laser as a tuneable wavelength converter combined with an AWG as wavelength router. A CW signal is externally modulated with data rates up to 5Gb/s limited by the speed of SG-DBR laser, and then propagated along 80km of conventional single mode fibre. The received data is coupled into a SG-DBR laser generating a different wavelength, determined by a particular setting of bias currents of the laser sections. The output signal is then applied to one of the inputs of a 16x16 AWG, the wavelength causing the signal to be routed to a certain output. Varying the tuneable laser wavelength allows routing to different outputs of the AWG. The switch shows an improvement of Q^2 value up to 9.5dB even for very low input signal Q factors.
Dynamic Wavelength Routing in Packet-Oriented WDM Optical Networks

To Kolsoom, Amir and Sara
Dynamic Wavelength Routing in Packet-Oriented WDM Optical Networks

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Dynamic Wavelength Routing in Packet-Oriented WDM Optical Networks

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Department of Electrical and Electronic Engineering
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April 2003

Author's declaration

I declare that the work in this dissertation was carried out in accordance with the Regulations of the University of Bristol. The work is original, except where indicated by special reference in the text, and no part of the dissertation has been submitted for any other academic award. Any views expressed in the dissertation are those of the author.

SIGNED: ........................... DATE: 17/09/03
A list of publications arising from the work in this thesis is presented below:


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CHAPTER 1

Packet-Oriented WDM Networks

The work in this thesis investigates dynamic optical signal routing by using a wavelength-routed switch. Such a switch involves a wavelength switching device combined with a passive fixed wavelength router. In order to provide a context for the router, this chapter gives a brief overview of the development of optical communication. Special attention is paid to the evolution of wavelength division multiplexing from point-to-point links to optical networks and optical packet switching systems. The requirements of future WDM packet-oriented networks are discussed in terms of system performance and the components and functionality that will be required to achieve this. It is shown that two key devices and subsystems for such networks are AWGs and wavelength converters.

1.1. Optical Communications Review

The demand for the internet and multimedia interactive bandwidth-hungry applications has become the driving force pushing forward many optical communication developments in recent years. If we consider that the traffic volume transported by most long distance operators is doubling every 6-12 months [1], it is understandable that substantial advances are required in a short period of time to meet this growth.

The first speculation of the potential for using light as a carrier for telecommunication applications began in 1960 after the invention of the laser. It was recognised that the amount of information that can be modulated on a carrier frequency is roughly proportional to the frequency, and as optical frequencies are 100000 times larger than their microwave counterparts, much larger transmission rates could be achieved [2]. However a major problem was the transmission medium. The real idea of transmission of information via an optical medium was initiated in 1966 [3] but it was from 1970, after the development of optical fibre with losses reduced from
1000dB/km to 20dB/km, when this new transmission medium attracted the world's notice and became viable [4].

Early optical fibre transmission systems used multi-mode optical fibre and Fabry-Perot (FP) lasers operating in the 850nm window. The loss of around 2 dB/km [5] in these systems limited the transmission link length to 10km and the modal dispersion limited the data rate to 100Mb/s [6]. Also, due to the lack of optical amplifiers, there was a need for electronic repeaters every 5-10km. The next step happened after the development of InGaAsP based lasers operating at 1300nm. According to figure 1.1, the loss of fibre at this wavelength is about 0.5dB/km which allows the link span of up to 50km. Also, the use of single mode fibre removed the modal dispersion and allowed data rates up to 2.5Gb/s.

The main goal of researchers at this point was to move to the lowest loss window of optical fibre which was around 1550nm. According to figure 1.1, the loss at this wavelength range is about 0.2dB/km and allowed a repeater spacing of 100km. But the fibre was optimized for the 1300nm window and at the 1550nm window, the fibre does not have zero dispersion as seen in figure 1.2 and this therefore sets a limitation on the bit rate. Also, the poor linewidth of FP lasers is another limiting factor.

![Figure 1.1 Typical single-mode fibre loss vs. wavelength](7)
There were two major technological developments to overcome the above limitations. The first was the realisation of Dispersion Shifted Fibre (DSF) which was formed by a change in geometry of optical fibre to allow the zero dispersion point to be shifted from the 1300nm window to the 1550nm wavelength window [9]. However since most of the installed fibre was standard single mode fibre the cost of re-installing DSF was not favourable for network providers. In addition there existed another problem in the application of DSF to Wavelength Division Multiplexing (WDM) systems. Although the lower fibre dispersion allowed the signal to travel further without distortion, when applied to WDM, signals around the zero dispersion point had a greater chance of interfering and mixing with other signals by phenomena known as Four Wave Mixing (FWM). To avoid this unwanted effect, which was due to fibre non-linearity near the zero dispersion point, Non-Zero Dispersion Shifted Fibre (NZ-DSF) had been developed with a small dispersion in the 1550nm window allowing WDM applications with minimum FWM [10].

The second and more significant technological development arose from improved source design by the introduction of the Distributed Feedback (DFB) and Distributed Bragg Reflector (DBR) lasers [11, 12]. Since the FP cavity laser used mirrors to create a simple cavity no special preference was given to a particular optical mode. The development of the DFB and DBR allowed the use of periodic structures to create wavelength selective feedback and this made possible the development of highly
wavelength selective devices, capable of lasing in a single longitudinal mode with a lower linewidths.

Research then focused on the removal of the electronic "bottleneck" imposed by electronic regeneration. The optical-electronic-optical conversion process involved with standard electronic regenerators imposed a limit on the maximum bit rate of future systems and also any future upgrades for these complex pieces of equipment would be very costly. The need for an all-optical method of regeneration eventually led to the development of the Erbium Doped Fibre Amplifier (EDFA) in 1987 [13]. The EDFA was constructed of an erbium doped optical fibre which is optically pumped by a semiconductor laser at 980nm or 1480nm. EDFAs typically amplify optical signals in the 1555nm window in the range of 1525-1565nm (C band) allowing a typical optical gain of 30dB. Another important consideration was the transparency that EDFAs provided to systems with respect to the multiplexing and modulation format used in existing and even future systems. The arrival of the EDFA was really a critical breakthrough. Additionally it was ideal for the implementation of Wavelength Division Multiplexing (WDM) since the EDFA could amplify more than one wavelength at a time thereby replacing one regenerator for each channel [14].

The EDFA is now the effective limiting device for the available bandwidth in many single mode fibre systems. As the removal of the OH absorption peak has already been achieved in Lucent's Allwave optical fibre [15], the potential bandwidth of a single mode optical fibre is between 1250nm and 1620nm, i.e., equal to 370nm which corresponds to 55000GHz. Currently, only about 5000 GHz of this bandwidth is available, this being determined by the bandwidth of EDFA which is normally between 1525nm to 1565nm.

Research has therefore focused on developing optical amplifiers which can amplify these huge bandwidths. Fortunately, in recent years a new type of amplifier named Distributed Raman Amplifier was introduced which can cover all this bandwidth subject to available pump lasers [16]. Also, the use of other rare-earth atoms has been shown to be a solution for making amplifiers similar to the EDFA but covering other bands. For example the Thulium-Doped Fibre Amplifier (TDFA) has been used for the 1470nm window. It is possible to use all above amplifiers in a parallel...
configuration by using an EDFA in the range of 1528nm-1610nm, TDFA for 1420nm-1520nm, and a Raman amplifier for the rest of band to achieve a record bandwidth of 17.7THz (1297nm-1605nm) with a conventional single-mode fibre [17].

1.2. Multiplexing Techniques

The ultimate performance figure of merit of any optical communications network is its cost per bit per kilometre [18]. When applied to the physical layer, this leads to either longer distances or higher bit rates. In addition to the efforts to enable long-haul transmission systems, a challenging task in optical communications research is finding ways to exploit most of the available bandwidth. The ratio of modulation bandwidth in a system to the available bandwidth is defined as the spectral efficiency of that system, and this can ideally be 1, although in practice it is normally less than 1. To maximize the transmission spectral efficiency, we need to multiplex data as effectively as possible. In a similar manner to electronics communications, multiplexing can be performed in time, wavelength, and code domains, or a combination of them.

1.2.1. Optical Time Division Multiplexing (OTDM)

In OTDM, each channel has its own time slot to carry information. Different time slots are interleaved between each other. The electronic version of this multiplexing technique has been used in digital communication systems for some time. However, the speed of electronic circuits currently limits the possible TDM data rate to about 40Gb/s (OC-768) which is being planned for installation, so optical techniques have to be applied to achieve higher aggregate data rates [19]. Higher OTDM bit rate results in increasing the bit rate per wavelength. This allows less number of wavelengths and is of interest as it is believed that systems with a modest number of wavelength channels are potentially easier to manage compared to those with large number of lower data rate WDM channels.

Optical time division multiplexing can be performed by splitting a pulse stream optically and modulating each portion using devices such as electroabsorption modulators. Each modulated channel may then be interleaved in time by delaying each channel by the appropriate amount before transmitting the interleaved signal.
down the same fibre. The channels may then be decoded by incorporating clock recovery and a synchronised receiver. Any timing error (jitter) between successive pulses can have a severe effect on the performance of such links. Therefore much interest has been shown in the development of low pulse width, low jitter sources for OTDM applications. The key technology for OTDM is a stable and reliable pulse source that generates narrow pulses. For example, pulsewidth for 160Gb/s OTDM should be as short as 2.5ps. For 640Gb/s or Tbit/s one needs to create pulses in the 300-600 femtosecond (fs) regime [20]. In addition to high extinction ratio and low insertion loss, the pulse source must provide high signal to noise ratio (SNR), well-controlled repetition frequency and wavelength.

However, OTDM systems have key disadvantages. For example, they are not scalable, i.e., the bit rate can not gradually be increased in line with the demand. Also, with OTDM, removing and replacing (Add-Drop) of single channels of information is a difficult task, where potentially the whole data stream has to be decoded and re-coded to provide access to the individual channel.

1.2.2. Optical Code Division Multiplexing (OCDM)

OCDM is of interest for possible application in future high-speed optical fibre networks. The main attractive feature of OCDM is that the same time slot and the same wavelength are shared by many channels. In an OCDM system, each data bit is coded with a code that is unique to a particular user [21]. Several different optical CDMA schemes have been proposed, based on different choices of sources, coding schemes and detection. Optical CDMA schemes may be classified according to the choice of coherent versus incoherent processing, coherent (modelocked pulses) versus incoherent (e.g., Amplified Spontaneous Emission or LED) broadband optical sources, and encoding methods for example time-domain versus frequency-domain and amplitude versus phase [22, 23, 24, 25, 26, 27]. Schemes based on incoherent processing and broadband incoherent sources are generally the easiest to implement. However, coherent processing based on manipulation of optical fields, which can be made to sum to zero, is needed for good suppression of multiple-access interference in higher performance systems.
The selection of the desired signal from among all of the other signals on the channel is based on matched-filtering, followed by thresholding. The output of the optical decoder is the correlation between the input signal and the matched filter. In general, in order to maintain a good signal-to-interference ratio (SIR), the signature codes must be mutually orthogonal and the optical code length must be sufficiently long [28]. Encoding and decoding of optical pulses can be performed in the spectral domain using a diffraction grating pair [29] and in the time domain using optical transversal filters [30]. Also, spectral encoding with an AWG-based encoder has been reported [31].

When combined with other multiplexing methods, OCDM provides an additional mean of achieving high optical channel counts, making it possible to reach the non-linearity-limited fibre capacity without resorting to expensive ultra-narrow WDM channels. The technique provides enhanced network versatility and is a potential solution for the future wavelength resource problem. There is also the possibility of increasing communication security. Also, OCDM is suited for bursty network environments, and the asynchronous nature of the data transmission can simplify network management and control. For example, OCDM can be potentially used for packet addressing. In this application, the IP address is mapped onto an optical code and then recognized by performing optical correlation in the time domain in a parallel manner. It uses optical processing to perform certain network applications such as addressing and routing.

OCDM systems are basically more complex than WDM and OTDM systems, and as they cannot support high data rates with the current technology, they are not suitable for core networks. It is expected that OCDM may be suitable for the LAN or access networks with higher number of users and lower bit rates per user.

1.2.3. Wavelength Division Multiplexing (WDM)

Wavelength Division Multiplexing (WDM) is a simple and effective way of exploiting the large bandwidth of optical fibres. WDM can maximize the use of installed fibre cable and allows new services to be quickly and easily provisioned over the existing infrastructure. Flexible add/drop modules allow individual channels to be
dropped and inserted along a route. The information content of individual electrical channels which may already be time multiplexed electronically, are transmitted on different wavelengths within the available bandwidth of the system. These are passively combined using a multiplexer and coupled onto optical fibre. At the receiver a demultiplexer which is normally the same as the multiplexer can separate the different wavelengths. An important parameter in a WDM system is the channel spacing which is the optical frequency difference between adjacent wavelengths. The maximum number of WDM channels can be simply derived by dividing the available bandwidth by the channel spacing. WDM systems with small channel spacing are called Dense WDM or DWDM.

The ultimate limit for channel spacing is determined by the individual channel bit rate, but in practice due to crosstalk between adjacent channels, the channel spacing is greater than this. By improving laser sources and reducing nonlinear effects in optical fibres it is possible to reduce the channel spacing. Therefore, there are trade-offs between channel spacing, number of wavelength channels, bit rate per each individual channel and link length.

A Channel in a WDM system consists of a band centred on one of the optical frequencies known as the channel centre wavelength which is a wavelength that is selected from a set of standard wavelengths suggested by International Telecommunications Union (ITU). This set which is known as ITU "grid" wavelengths, based on 100GHz spacing from a reference frequency of 193.1THz equivalent to 1552.52nm and a number of wavelengths are listed in table 1.1. The channel spacing and the wavelengths used need to conform to this standard to ensure compatibility between different vendor equipment. Each channel can support a single optical wavelength, which can carry an individual data stream, for example OC192 at 10Gb/s.
Early WDM systems consisted of simple point-to-point long haul systems as shown in figure 1.3. In this system a number of wavelength channels are multiplexed, propagated through an optical fibre and amplified by EDFA where needed. At the receiver end, the data on each wavelength is decoded after demultiplexing the wavelengths. Between two nodes, where needed, an add-drop operation can be carried out in order to extract the data to and replace the data from that point. The add and drop is simply performed by demultiplexing the wavelengths, dropping the wanted wavelength and re-multiplexing the other wavelengths with the new one.
Research into WDM is currently carried out to increase the number of wavelengths, the bit rate per wavelength and the distance in order to achieve higher spectral efficiency and cost per bit per kilometre. Transmission of 80 wavelength channels each carrying 10.66Gbit/s over 3200 km of Non-Zero Dispersion Shifted Fibre (NZ-DSF) with 50GHz channel spacing[33] and 128 channels with 40Gbit/s per channel, reaching a total throughput of 5.12Tbit/s (5120Gbit/s) over 300 km [34] has been demonstrated. Also, a channel spacing of as low as 3.125GHz has been realized by Essex corporation Hyperfine WDM technology [35].

One potential benefit of WDM, apart from the increased bandwidth, is the use of multiple wavelengths as a network “tool” [36]. Wavelength can be used to perform functions such as routing and switching. These benefits are not used in a point-to-point system but rather in WDM networks. There are several architectures to transfer data using WDM systems. Among them the most important ones can be summarized in 3 categories: broadcast and select, wavelength routing and optical packet switching [37]. There are three main categories for broadcast and select networks: they are the star, bus and ring configuration. The basic operation is the same but usually the star configuration is more suitable for access networks and ring networks are more popular in metro networks. Figure 1.4 shows a ring network. Here each node sends its traffic into the ring and every other node can receive all traffic but it only filters out and receives its own incoming traffic and replaces its ongoing traffic to the network. Several ring networks can be connected by optical cross-connects.
This thesis however will focus on the wavelength routing WDM network. A basic general network configuration which takes the advantage of WDM and uses the wavelength as a tool is shown in figure 1.5.

In this network each node is connected to the network hub by two fibres and transmitters and receivers. At the network hub the incoming wavelengths are separated and rearranged to be routed to their destination nodes. For a completely nonblocking routing network we need $N^2$ different wavelengths but it is known that
$N$ wavelengths are sufficient [38] if the wavelengths are chosen according to following rules:

1- $\lambda_q$ carries the traffic from transmitter node $i$ to receiver node $j$.

2- $\lambda_q = \lambda_{(i+1)(j-1)}$ if $0 < i < N$ and $1 < j < N + 1$

3- $\lambda_{ij} = \lambda_{(i-1)(j)}$ if $1 < j < N + 1$

4- $\lambda_i = \lambda_{(i+1)N}$ if $0 < i < N$

As a result each wavelength is being used for $N$ different routes. This is called wavelength reuse. The number of supported nodes is limited by the crosstalk level of router. As any wavelength is used $N$ times in the network, the main limitation is the crosstalk of same wavelength sources which is not removable by filtering.

In the network hub of figure 1.5 a huge number of multi/demultiplexers and optical fibres are being used which increases rapidly when the number of nodes increases. It is therefore desirable to use compact devices to replace this. The device is an arrayed-waveguide router which is the subject of following chapters.

1.3. Optical Networks and Switching

To date, most applications have been based on optical point-to-point links as transmission media. Current research however is now engaged the development of components and sub-systems that will enable the construction of scaleable, modular, re-arrangable and transparent all-optical networks [39]. These networks generally consist of three sub-networks: core, metropolitan, and access [40].

The core network consists of all trunk lines between the major central offices in the larger cities including transoceanic submarine links and long-haul terrestrial links, all operating over single mode fibre at the 1550nm wavelength window. These routes are high speed and have simplified routing operations at each node mainly to add and drop wavelength channels.

Connected to the core network are metropolitan networks. They consist of rings connecting major customers such as businesses in the regions near large cities. Distances at the metropolitan level are shorter than that of the core level but demands on routing are higher due to the need to deliver a broader range of services and to
easily add new customers to the network. An advantage of such ring architecture is that data can be sent in the opposite direction around the link if a break in the fibre cable should occur. Presently most long-haul core networks and metro backbone links are implemented with Synchronous Optical NETwork (SONET) and Synchronous Digital Hierarchy (SDH) systems which are standards for physical layer and optical data transport.

The lowest level is the *access network* where the network is connected from the telephone company central office switch to and from the end-user. The local access level can be sub-divided into two levels namely Local Area Networks (LANs) and residential services. LANs normally exist in the business or academic users offices. LANs within business and academic environments may be classed as data communication networks and use 1300nm and short wavelength lasers operating around 850nm on multi-mode fibre.

The basic requirements of the future optical networks are the development of highly functional components to allow the construction of network nodes with the following main characteristics [41]:

- **Enormous aggregate capacity**: easily growing to the tens of Tb/s.
- **Scalability**: the property of always being able to add more nodes. By deploying more copies of the same equipment the network can handle an increasing number of users located over an enlarging service region while offering higher capacity. Scalability can be affected by any transmission limitations such as noise, crosstalk, dispersion and nonlinearity [42].
- **Modularity**: the property of being able to add only the desired number of new nodes and updating the logical connectivity diagram to include these new nodes.
- **Enhanced reliability**: the failure of an access node affects only the users connected via that node; the failed node is then bypassed by changing the connection diagram thereby preserving all other real and virtual connections.
- **Integration of circuit and packet switching**.
- **Integration of services** such as analogue, digital, voice, ATM, IP, video, etc.
Furthermore the network must be dynamically re-arrangeable in response to changing user-to-user traffic patterns and be fault tolerant. A critical factor in achieving these network benefits is the realisation of functional components for switching, routing, and wavelength translation [43].

The main part of any network is its switching fabric. Unlike a point-to-point system in which the transmitted signal has only one destination and route, in a network with $N$ different users, any user at any time may send data to any other user therefore the switching fabric should be able to establish a route between any 2 users upon request. There are 3 main categories of switching: circuit, packet and burst-switching.

1.3.1. Circuit-Switching Networks

In this method which is now happening in conventional telephone networks, a link or circuit will be established between two users when they request it and it will be assigned to this particular connection as long as they did not disconnect it. If two users have to send information continuously, this circuit will be used efficiently but if during the connection time there is no traffic between nodes, the resource will be wasted. A typical configuration is shown in figure 1.6. This system much reliable and presents better quality of service. This type of switching is suitable when the traffic is voice, but data traffic is now dominant. Data traffic is bursty in nature. This means in some occasions, large levels of traffic may occur and other times there may be no data transmitted. Also, in an optical network where each circuit is capable of transporting large amounts of data, a circuit-switched network is not desirable in terms of granularity. This implies that to access a very low data rate in each node, one needs to process a high data rate channel.
1.3.2. Optical Packet-Switching

For data communications, a network capable of packet switching is desirable to support packet-based applications such as Internet Protocol (IP) and Asynchronous Transfer Mode (ATM). Electronic packet switching is currently being used. Any conversion of the optical signal to an electronic one causes a "bottleneck" which doesn't allow the efficient use of available bandwidth of optical fibre and restricts transparency. As a result, there is much interest in handling optical signals at the packet level. The optical packet switched layer can be laid between the electronically switched layer and optical transport layer. The optical packet network layer may be configured so that it can support both ATM cells and IP packets as well as SDH frames [44]. Although it is unlikely that all-optical packet switching will happen in the near future because at least the control stages will be electronic, but even the routing and switching stages which have to work in packet rate requires far more functionality for optical systems than they provide now.

The Internet Protocol (IP) is the network protocol of most data applications, and optimising the network for IP traffic has to be in the mind of all providers. As a result, finding the most cost effective way to transport IP traffic over optical networks, with a large potential for scalability, is likely a key factor in the future competition between network providers. This will add the intelligence of IP networks to the nearly
unlimited bandwidth of optical systems to fulfil the requirements of increasing demands of high bit rates.

The current WDM-based IP-backbone is provided by SONET/SDH and supported by the point-to-point WDM links, denoted as IP-over-WDM [45]. Although the systems are packet-based in the electronic layers, they are circuit switched from the optical layer point of view. IP may be directly mapped into a digital frame based on the optical path (OP) payload without SONET/SDH multiplexing, this is denoted as photonic IP network [46].

Packet switching allows several different packets intended for different destinations to use the same wavelength. Therefore when there is no data for one destination, that wavelength can be used to carry information for another destination. However the order of information may change and delay may be introduced for some packets due to buffering.

An optical packet switch like its electronic counterpart has three principal functions: switching, buffering and header recognition. Switching ensures that each packet arrives at the correct destination, depending on the information contained in the packet header. Even if the packets arriving at the inputs are synchronized, there is no coordination between packet streams arriving on different inputs. Hence one or more packets may arrive during the same timeslot on different inputs wishing to go to the same output. For this reason, buffering is required and all but one packet is held up, and subsequently transmitted to the output. Header recognition is needed to provide control signals for switching to send information to the appropriate outputs or buffers. Various solutions to optical packet switching networks have been proposed mainly dictated by buffering strategy [47].

Although different architectures have been proposed for a packet switched node, figure 1.7 shows a generic configuration which is common to many proposed architectures. This configuration is based on WDM and includes buffers and tuneable wavelength conversion (TWC) for dynamic routing or deflection routing where needed. The control unit which is an electronic circuit to extract the header
information and control the switching and routing process is not shown in this figure because it is not in the scope of this thesis.

![Diagram](image.png)

*Figure 1.7. A generic configuration for WDM packet switch [48]*.

Wavelength routing networks allow wavelength reuse and packet switching allows even more reuse at the packet level. It is reasonable to think of networks taking advantage of both. This will be possible by using an arrayed-waveguide grating (AWG) router combined with tuneable wavelength conversion instead of space switch in the figure 1.7. This configuration of switch is the main switching scheme studied in this thesis. Here we will briefly describe some important aspects of a packet-based network, i.e., packet format, header structure and buffering.

**Packet format**

Two main approaches exist for realising optical packet formats. One is the ATM approach in which the number of bits in each packet is constant (48 bytes for payload and 5 bytes for header). Therefore as the bit rate increases, the packet duration decreases. This means that for link speeds up to 40Gb/s and beyond, the cell duration is so short that cell processing in the switches becomes difficult, even with very advanced electronics. Also this approach is not scalable and transparent as all the
system depends on the bit rate. Consequently, the ATM approach does not seem to be able to follow the huge increase of bandwidth made available by optical technology.

Several alternative packet-switched approaches have been developed to overcome this problem. One such technique was introduced in a project called KEOPS [49, 50]. Here fixed duration packets are utilized where both the header and its attached payload are encoded on the same wavelength carrier. Routing information is derived from the packet header after optoelectronic conversion. The header is encoded at a low fixed bit rate, e.g., 622 Mb/s, to allow the utilization of standard electronic processing. In order to realize a network insensitive to the load bit rate, the payload duration is fixed whatever its content, the data volume is proportional to the user-defined bit rate. In this case the total time of each packet is constant and all the optical components are based on this. By increasing the bit rate the only parameter which changes is the number of bytes in each packet. For higher bit rates, the information content of each packet is higher. In the KEOPS proposal, the payload duration is 1350ns which is equivalent to 1687bytes at 10Gb/s. The guard time is 116ns which is fixed by the processing time of the devices. The header time slot is 180ns which is equivalent to 14bytes at 622Mb/s. It has to be noted that any optical packet may contain a huge number of IP packets or ATM cells. For instance, the KEOPS packet contains the equivalent payload of 35 ATM cells.

The choice of a packet of fixed length in time and not in bits has several advantages. Firstly, it allows for the use of the same switching infrastructure whatever the user bit rate. Secondly, it allows for the scalability of link speed without affecting the optical switches. As a result, the processing speed of the logic in the nodes is independent of the link speed. Finally, the buffering space in the switching nodes, which is realized by means of fibre delay lines whose length is proportional to the time length of the packet to be stored, is independent of the link speed. In this method, packet delineation is very important and has to be carried out to detect the header and payload boundaries. This is a key function for header reading, packet synchronization and possibly header rewriting.

There is no standard at the moment, but when considering the packet size, it should be long enough to have a higher efficiency, i.e., the ratio between payload and size of packet is higher, on the other hand it should be short enough to achieve more
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flexibility and granularity to allow the use of transmission capacity more efficiently [51].

**Header Structure**

In a packet-switched network, each packet must contain its own routing information which is normally stored in the header of the packet. Switches determine where to send the packet based on this information. Ideally, the switches in the network only need to look at the header information. Any other information, such as the payload, does not need to be processed by the switches.

In terms of the position of header and payload there are two types of packet structures, namely, serial and parallel which is shown in figure 1.8. To implement these structures, there are three common ways as follows [52]:

1- **Subcarrier Multiplexing (SCM):** In this option which is a parallel method, a low-bandwidth header is modulated on an electrical subcarrier above the baseband frequencies of the packet payload. Both payload and header are transmitted on a same time slot. Within the switching node the optical packet is converted to the electrical domain, and the header is removed by high pass filtering. The header is processed electrically, and there is no processing of the payload. A routing decision can only be made after an entire packet time slot has arrived. As a result, the delay introduced in the node is equal to the packet duration plus the header processing time.

2- **Transmitting the header on a separate wavelength (parallel method):** Here the header is transmitted on a different wavelength. The process of extracting the header is very simple, but each node needs delay compensation to realign the header and payload. Also, an additional laser is required for each data channel. In a similar manner to SCM, the payload and header are transmitted simultaneously.

3- **Transmission of the header before payload:** In this option which is a serial method, a time slot is allocated to header before the payload time slot. Therefore a portion of bandwidth is effectively used for header, but header removal and insertion are very easy. In addition, there is no interaction between header and payload causing crosstalk. The switching delay introduced in this method is equal to the header length plus the processing time. If the header length can be minimized, the processing time
can fall within the time gap and switch can be set to the correct route when the payload arrived.

![Packet structure](image)

Figure 1.8. Packet structure for: (a) Serial header (b) Parallel header

One commonly used method of header recognition is to tap off a small portion of the signal and electronically detect the header bits, but this approach is likely not to be suitable for future high-bit-rate packets for which electronic techniques are too difficult. A potentially faster approach is to decode the header bits optically so that a given routing decision can be made on-the-fly [53]. For example, a photonic IP router has been proposed in which the IP address, mapped onto an optical code, is recognized by performing optical correlation in the time domain in a parallel manner [54].

**Buffering**

A key problem when designing packet switches of any kind is contention resolution, because multiple packets may arrive asynchronously within a single packet period and
destined for to the same output. Buffering is often employed to solve this problem. Since optical Random Access Memory (RAM) does not exist, delay lines (usually made of optical fibre) must be used to store optical packets and implement buffering.

For high loads or burstiness, the number of delay lines may increase resulting in a very complex system. However, by using wavelength conversion it has been shown that the number of delay lines can be decreased [55]. Here, for a system where two packets (P1, P2) with the same wavelength arrive simultaneously at a switch, one is converted to another wavelength and stored on the same delay line. By this scheme, with more wavelengths, more packets can be stored on each delay-line.

There are different buffering strategies which give different levels of packet loss and packet delay depending on the bit error rate. In terms of position of buffer in the switch there are 4 different buffering approaches: Input, shared, re-circulating and output buffering. Output buffering is more common and beneficial in optical packet switching proposals [56, 57, 58, 59].

In terms of buffer size it is best to use large buffers where possible for highly bursty traffic which can occasionally lead to strong contentions. The other solution uses small buffers or even no buffers by employing deflection routing. In this case when multiple packets arrive destined for a given output, all but one are deflected to other outputs or in the case of multi-wavelength system it is possible to convert the data to other available wavelengths, to find their way to destination by another route through the network. This solution reduces the number of required buffers and hence complexity of the system, but each packet transmitted from a node may be routed across a different path to the same destination. Some packets may wander in the network and waste bandwidth. Also, each packet will experience different propagation delays, and the traffic may not arrive at the destination node in sequence. There is a compromising solution using a small amount of buffering with deflection routing or wavelength conversion [60].

Currently available buffers in optical systems use fibre delay lines whose length have to be an integer multiple of the packet duration. The holding time or the total available delay is determined by dividing the length of delay line by the speed of light in
medium. The memory size which is the number of memory positions is determined by multiplying the holding time by the bit rate. As we can see these two main parameters of the buffers are intimately related. As a result they are degenerate [61] and this limits the flexibility of system design.

1.3.3. Optical Burst Switching
Optical packet switching networks will need tuneable lasers with the switching time in order of nanoseconds which is currently a challenging technology. However it is possible to define a transition method which achieves most of the benefits of a packet switching system by using mature and available technologies. As a result optical burst switching method which is a compromise between circuit and packet switching has been proposed [62]. It can be considered as a packet-switched system with longer and variable length payload, which is called data burst. A control packet which acts as header is sent before data by considering a variable time offset. The control packet contains information required to route the data burst through the optical transmission core, the length of corresponding data burst and the amount of time offset. It may also be sent on a different out-of-band wavelength. In the switch the control packet is processed electronically and based on its information a circuit will be reserved for the coming data burst. When the data burst arrives it passes through the reserved circuit without any processing. A remarkable difference of burst-switched system with packet-switched system is the possibility of supporting different quality of services by defining different time offset between control packet and data burst. Although, there is no standard definition for optical burst switching, its main characteristics can be highlighted as follows compared to a packet-switched system [63]:

1- **Burst size granularity** which lies between packet and circuit switching. Although this results in less spectral efficiency compared to packet switching, but the longer payloads require longer switching time for lasers and other components which make it cheaper and easier to implement. The switching time can be in order of microsecond rather than nanosecond In terms of network architecture there is no difference with packet networks.

2- **Separation of control information and data**: the control information here is sent on an independent packet on a different wavelength.
3- Reservation scheme: This is very similar to table reservation in a restaurant where the earlier reservation results in better positions and higher priority. In burst switching system, the longer time offset means the earlier reservation and results in higher quality circuit and priority for the coming data burst. This allows supporting different quality of services.

4- Variable payload length compared to fixed-packet length in proposed optical packets.

5- Lower or even no optical buffering: as a result of reservation scheme, the possibility of collision and therefore the needs for buffering is very small.

A packet-switched system can be basically considered as a burst-switched system with small and fixed data burst and a time offset as short as the guard time. As the technology advances, it is possible to reduce the size of data burst and the time offset in a burst-switched system to implement a packet-switched system.

1.4. Optical Routing Requirements

In the future packet-based systems, optical routers capable of processing headers and forward packets to another router or its final destination are essential components. They have to be able to replace packet headers in real time for label swapping, perform packet rate wavelength conversion and regenerate both payload and header information to overcome the losses caused by cascading many nodes [64, 65].

The main difference between a packet switched node with a circuit-switched optical cross-connect is the ability to perform dynamic switching and routing [66]. As the successive packets may be destined for different nodes, the routing has to be dynamic, i.e., it should be able to reroute the incoming signal quickly. The routing node can be based on space switches consisting of either couplers or gates. Also, it is possible to use wavelength routing devices to perform the same function. The key requirement in a packet switch which is not necessary in conventional cross-connect is the ability to dynamically route the signal. If a wavelength router is used, it has to be dynamic. We call the resultant node a dynamic wavelength router. Another requirement of a packet switched network is regeneration. Regeneration is needed in any long distance system to overcome noise and distortions, but is particularly important in wavelength routed...
networks as the path length is likely to be different for different packets in the network.

This thesis will report the use of an AWG with specific characteristics as a complete wavelength router. The router is made dynamic by adding a tunable wavelength to its input. This tunable conversion can be achieved using a tunable laser. Also, this converter shows the regeneration property required for this switch. The switching time needed for the wavelength change in the converter based on the packet header has to be in the order of ns.

1.5. Scope of this Thesis

In conclusion, a brief introduction to the evolution of optical communications and more specifically the wavelength division multiplexing has been given. Also, a brief description of optical packet switching and its main requirements has been investigated. The role of the dynamic routing in a WDM-based optical packet switches has been discussed. It can be concluded that there is a distinct role for a dynamic wavelength routing subsystem allowing the future realisation of highly functional packet-based WDM networks. Chapter 2 will discuss the advantages that a dynamic wavelength router offers and particularly a dynamic router based on AWG and wavelength conversion will be discussed. A review of the current router and wavelength conversion technologies and their requirements will be given. Chapter 3 will be focusing on the analysis and structure of AWG and the result of performance measurements made on two different AWGs will be demonstrated. The description of a model developed in this thesis to assess the limitation of AWG and the result of the model for two AWGs will be investigated in chapter 4. Also, the short pulse behaviour of AWG will be discussed which is useful in the assessment of its ultimate speed limit. Chapters 5 will be about wavelength conversion and the result of the modelling on the different structures involving a DFB laser and SOA based on VPI software will be given. The integrated SOA distributed feedback laser is then shown to provide excellent regeneration properties to overcome degradation due to fibre dispersion limitations and system noises. Finally, chapter 6 demonstrates the aim of this thesis to build a regenerative router. The system test is based on dynamic
wavelength routing using a 16×16 AWG and a tuneable SG-DBR laser. This switch shows promise for use in future photonic packet switching architectures.

Conclusions and suggestions for future work will follow in Chapter 7.

1.6. References


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CHAPTER 2

Components for Dynamic Wavelength Routing

This chapter considers the concept of optical routing. We investigate different methods of optical routing and then focus on wavelength routing. As mentioned in the previous chapter, dynamic routing is an essential part of modern packet-based optical networks. Consequently dynamic wavelength routing is discussed and its requirements in terms of performance are studied. Finally, the advantages of using an AWG and tuneable wavelength conversion for construction of a dynamic wavelength router are highlighted, as this is the subject of the following chapters. This system can also provide regeneration which is very important in such networks.

2.1. Optical Routing Techniques

One of the main task in any network is "routing", a key process quite different from switching. Routing is the process of finding a specific route from the transmitter to receiver in a network. This involves not only the switching of signals but also the interpretation and setting of control information to configure the switches. It is possible to route signals by optoelectronic conversion. At the moment, for example, large scale routings are performed electronically up to 2.5Gb/s. However it is desirable to have all optical routing for future networks. As a result there is much interest in optical routers which are scalable, compact, high speed and low loss.

Scalability is very important as network providers want to start with small number of users and are interested in expanding their network according to demands smoothly and economically. Scalability in the component level depends on various parameters particularly insertion loss and crosstalk. In a router, non-blocking operation and switching control are also important [1]. Additionally, in packet switching applications, dynamic operation is desirable as consecutive packets may have different destinations. There are different technologies to perform optical routing and they can be divided into two main categories: space switch based routers and wavelength routers.
2.1.1. Space Switching

The function of a space switch is to switch all the data of an incoming fiber to an outgoing fiber as shown schematically in figure 2.1. This is in function similar to the switches available in public telephone switching centers.

The main requirements for a space switch are: low fiber to fiber loss, polarization insensitivity, WDM compatibility, high speed operation, controllability (electronically or optically), low drive power, low noise, low crosstalk, reliability, large channel count, scalability, lower complexity and compactness [2].

![Space Switch Diagram](image)

*Figure 2.1. A schematic diagram of space switch*

There are different approaches performing space switching. They can be categorized according to their speed. Mechanical switches are basically slow with the switching times in order of milliseconds. Switches based on nonlinear optics are faster with the switching time as low as a few nanoseconds. Space switch fabrics can be constructed using multi-stage architectures based on 2x2 or 1x2 couplers as their building blocks. These couplers are basically configured to construct a cascade of asymmetric Mach-Zehnder interferometers with a refractive index controllable material in one arm. This material can be Lithium Niobate (LiNbO3) which works using the electro-optic effect or silica-based materials which use the thermo-optic effect [3, 4].

Space switches based on a combination of SOA gates have also been reported [5]. This is likely to be the main approach to achieve reasonable scalability. SOA based gates offer some advantages such as providing gain, short switching time, on/off ratios of more than 40dB and possibility for integration. However they have some
disadvantages as they have high noise figure, saturation power and limited input power dynamic range (IPDR) [6].

As another approach, a high-speed, compact 4×4 cross-point space switch array has been developed at Bristol University on InP substrates as shown in figure 2.2. The array is based on an orthogonal optical bus architecture which is believed to offer excellent scalability. In this architecture, input and output optical signals are carried by two groups of passive optical waveguides perpendicular to each other. At each intersection, a switch unit employs carrier-induced refractive index and gain change in the vertical directional couplers as the switching mechanism and a total internal reflection mirror (TIR) to steer the beam. The use of vertical couplers allows very compact device size of 250×250 μm/switch. Carrier injection allows a switching time of less than 1.5ns, and the high gain to loss contrast suppresses crosstalk to a very low level of <-50dB and gives rise the possibility of loss-less switching. The optical bandwidth of the switches is about 40nm [7]. If a train of packets are applied to this switch, data will be steered to the perpendicular output when the current pulse is applied. When no current is applied, the packets travel through the switch unit.

![Figure 2.2. A 4×4 cross-point space switch array [7]](image)

All the above switches are electronically controlled and the light travels in waveguides. On the other hand, optical switches can use mechanical routing of free space propagation of light. Here as the mechanical movement of parts are involved, switching is inherently slow. However, certain types of mechanical switches,
particularly those using MEMS (Micro Electro Mechanical Systems) seem to be readily scalable to large switches (more than $100 \times 100$) [8]. They are basically bit rate, wavelength and protocol transparent. Also, they are polarization independent and future proof. This technology is definitely suitable for the protection switching and for the large scale circuit switches but it is very unlikely to be suitable for the packet switching applications.

2.1.2. Wavelength Routing

Wavelength routing is defined to be the selective routing of optical signals according to their wavelength as they travel through the network elements between source and destination [9]. Wavelength routing determines the path taken by the optical signal. Therefore as each signal is restricted to a particular path it is possible to have each wavelength reused many times on different paths throughout the network as long as the paths do not try to co-exist on the same fibre link.

It is believed that possible DWDM network architectures will be based on the use of wavelength to route the signal to its intended destination in the network. This will be possible by using wavelength selective switches along with translation of signals from one wavelength to another via wavelength translation where needed.

A great advantage of WDM is achieved by implementing wavelength-routing, enabling the routing of high-capacity optical signals according to their wavelength. Here the wavelength acts as the address information of signal. This provides a network with simplified management and processing [10]. Wavelength routing enables the system to use the wavelength of a channel in a WDM system as a network tool to assist in adding functionality to the network. Fixed wavelength routing uses WDM multiplexers and cross-connects. Networks with full wavelength conversion have been proposed for wavelength routing and re-use in the network [11] and can achieve higher capacity than networks without it.

The core of any wavelength routing node is a wavelength selective switch. There are different technologies to implement this. Among them is the AWG which offers a route to high port count scaling. For example, a $256 \times 256$ multiplexer has been
realized by NTT [12]. Complexity, polarization sensitivity and crosstalk are potentially low.

### 2.2. Dynamic Wavelength Routing

As a result of the increasing traffic in wide area networks (WAN), routers throughputs are expected to increase from hundreds of gigabits per second currently to several terabits per second in the near future. Although static wavelength-routed optical networks (WRONs) are relatively simple to analyze and design, they may not be sufficiently flexible in responding to dynamically varying and bursty traffic loads and service diversity in the future [13].

As stated before, in wavelength routing, the operation is based on the signal wavelength so that the signal path is determined uniquely by the source wavelength. This fixed version is suitable for a circuit switched system. A packet-based system, however, should be able to re-route the signal whenever a collision happens. This ability to change the path of the signal according to system conditions is called "dynamic routing". If the dynamic routing is based on wavelength, it can be called "dynamic wavelength routing". As a result, a wavelength router is needed along with a tuneable wavelength converter. A generic architecture of a dynamic router is shown in figure 2.3, which is based on the combination of tuneable wavelength converters and AWG as the wavelength selective switch. This architecture is the basis of this thesis.

![Figure 2.3. A dynamic wavelength router.](image_url)
In conclusion, for a dynamic wavelength router, two components are needed. One is a wavelength router which carries out a fixed routing operation. The second is a tunable wavelength converter which gives the possibility of dynamic operation by changing the wavelength of incoming data. Here we describe briefly the technology and requirements of these two components.

2.3. Wavelength Selective Switch Technologies

The function of a wavelength selective switch is to switch any input to any output according to the wavelength of the signal. Basically, the wavelength selective switches can be classified in two categories, all based on optical filter technology. The first category is the discrete switches which are made of a number of filters in a specific configuration. The second category is integrated switches which can be designed to have the same functionality by a single device.

2.3.1. Discrete Components

A wavelength selective switch can be constructed by cascading a number of discrete filters similar to a demultiplexer configuration as shown in figure 2.4. According to this figure, \( N - 1 \) filters are needed to construct a \( 1 \times N \) demultiplexer. Basically a \( N \times N \) switch can be constructed by \( N \) multiplexers and \( N \) demultiplexers. As a result a \( N \times N \) switch needs \( 2N \times (N - 1) \) discrete filters. In this approach the building block is an optical filter. There are three main technologies for the optical filters which will briefly be described.

\[ \lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_N \]

*Figure 2.4. A cascaded configuration of optical filters as a demultiplexer.*

**Thin-film interference filters**

The structure of the thin-film filter is based on that of the Fabry-Perot (F-P) etalon, which is composed of a cavity and mirrors. The centre wavelength of the passband is determined by the cavity length. A signal at the passband wavelength passes through the filter and signals at other wavelengths are reflected with a very high reflectivity. A
narrow band thin-film interference filter consists of more than two F-P cavities separated by dielectric reflection layers and each cavity contains a multilayer structure with more than 50 layers [14]. By using multiple phase shifted cavities, it is possible to change the filter response shape such that the passband becomes flatter and the sides of the wavelength response become steeper yielding an effective component with losses less than 0.5dB. The characteristics of a demultiplexer made of thin film filters are low loss, low crosstalk, wide passband and low polarisation dependence.

The thin film based filter is currently a mature technology and 16 channel 100GHz spaced components are commercially available [15]. With their low temperature sensitivity and good adjacent channel isolation, they are a cost effective solution for many current low channel count WDM systems. Thin film technology for high channel count DWDM applications would be unfeasible due to the serial nature of the device which leads to high last-channel loss and high channel dependent loss. Additionally there would be a prohibitively high cost per channel due to complexity of assembly for more than approximately 16 wavelengths.

**Fibre Bragg Gratings**

A fibre Bragg grating (FBG) is a periodic perturbation of the refractive index along a length of fibre. The FBG's most prominent feature is its ability to act as a stopband filter. A narrow band of incident light is reflected backward due to successive coherent scattering by the grating.

Fibre gratings are devices that can be used for a variety of applications including filtering, add and drop functions and for dispersion compensation in the system. Their main advantages are low loss, ease of coupling, polarisation insensitivity and simple packaging. Fibre Bragg Grating (FBG) technology has an all-fibre configuration, great flexibility and highly efficient filtering functions.

The Bragg wavelength of the FBG shifts about 0.01 nm/°C due to the temperature dependence of the refractive index of silica glass. This dependence can be compensated for by using a special package that applies stress to the fiber. Indeed this
control of Bragg wavelength has been used to give the device a degree of tunability [16].

Bragg gratings possess one of the sharpest roll-offs in filter function of all the competitive filter technologies. Devices containing FBGs can be fabricated with an extremely low loss of 0.1dB, low polarization dependent loss (PDL) and with low-cost packaging. These two features make them strong candidates for DWDM systems with channel spacings of 50GHz or less.

As it is an in-fibre element, it provides very low coupling and propagation loss. While the excellent filter shape is a key advantage for the FBG method, disadvantages are resulting complications as wavelength counts increase and the need for temperature stabilisation grows. Additionally as channel counts increase, fibre Bragg grating technology is not conducive to easy integration with active components such as switching matrices or wavelength conversion arrays as might be fulfilled by an integrated approach.

*Mach-Zehnder (MZ) based filters*

A MZ interferometer can be used as a filter. However the transfer function of the MZ filter is usually not narrow enough for WDM applications. Consequently cascaded MZ configurations are used to produce narrower filter functions. These filter architectures are called resonant couplers. A resonant coupler is a cascade of directional couplers and delay lines. The optical delay lines consist of two segments: a unit length which is the same for all stages and determines the free spectral range (FSR); and an incremental length segment that introduces a phase shift. The amplitude coupling coefficients and phase shifts determine the filter characteristic within one FSR. Although the basic MZ transfer function suffers from low finesse due to its inherent cosine shape much attention has also been focused on combining additional technologies within the MZ such as Bragg grating filters designed in various MZ configurations [17].
2.3.2. Two-Dimensional Integrated Optics (2DIO)

In a basic 2DIO transmission grating filter as shown in figure 2.5 the input signal containing a number of spectral channels, propagates through a single mode optical waveguide and emerges into a slab region in which confinement by the upper and lower cladding regions occurs only in the vertical direction. The transversely diverging output beam from the guide is collimated by the input reflector and then illuminates the transmission grating. The grating structure consists of a set of non-blocking triangular shaped reflecting elements such that they do not intercept the beams from adjacent elements. The diffracted output from the grating structure is then focused onto the output waveguides by an output focusing reflector. Each wavelength, by virtue of its individual diffraction angle, is focused to a separate output waveguide for detection or further processing.

Fabrication of the 2DIO component in a suitable material system has the potential to result in a device that is matched to single-mode fibre, is low loss and has a device footprint that is approximately 20 times smaller than an equivalent AWG component. The extreme compactness and uncomplicated structure of the component thus has the potential to result in high component yield upon mass production, and a far higher component count per wafer when compared to larger alternative structures such as AWGs [19].
2.3.3. Arrayed-Waveguide Grating (AWG)

AWG is a promising candidate for wavelength routing applications [20]. The AWG is constructed of 2 star coupler joined together using an array of waveguides of different lengths. The operational principle is very similar to MZ-based filters but it acts functionally like a diffraction grating. However it normally operates at higher diffraction orders which lead to a better resolution.

The main advantages of AWG are as follows: [21, 22, 23, 24, 25]

- Suitable and cheap for mass production as it uses PLC technology.
- Passive: no power consumption for the device itself if we don’t consider possible temperature controllers.
- Bi-directional: The same device can be used as multiplexer and demultiplexer by changing the input and output positions.
- Low insertion loss especially for higher channel count. The insertion loss of as low as 0.8 dB has been reported [24].
- The typical cross-talk level is as low as -30 dB although much lower crosstalk has been reported.
- Suitable for integration with photodetectors.
- Large channel number
- Narrow and accurate channel spacing
- It allows useful optical routing properties such as Latin routing. This provides the possibility of using only $N$ wavelength to construct a complete $N \times N$ routing.
- High wavelength selectivity
- Small size
- High stability

However, the main challenges in the design and manufacturing of AWGs are:

- Temperature sensitivity. To eliminate thermal drift, thermoelectric coolers have been used. Also, there are athermalization techniques by using materials with a negative thermal coefficient. Operation in the wide temperature range 0 to 85 degree centigrade has been reported.
- Flattening the spectral response of the AWG: because the flat response passband eases required wavelength control within a band.

AWGs will be discussed in detail in Chapters 3 and 4.
2.4. Wavelength Conversion and All-optical Regeneration Techniques

One of the main problems in any packet switching system is contention resolution. For realistic IP traffic which has a bursty pattern, the use of wavelength converters is recognized as essential for reducing the complexity of photonic WDM packet switches. Using theoretical modelling verified by simulations it has been shown that higher traffic loads as well as burstiness can be accepted when wavelength converters are used. Consequently, a larger throughput of the photonic packet switches can be obtained for the same space switch size [26].

It is also shown [27] that by using a wavelength converter it is possible to overcome the contention problem in a packet switched network with any possible configuration. This allows lower complexity of switch by using a substantially lower number of delay lines or buffers. When two packets with the same wavelength arrive at the same time in the buffer, two delay lines are needed to store them, but by using a wavelength converter it is possible to store them in the same fibre [28]. This has been shown schematically in figure 2.6.

![Figure 2.6. Effect of wavelength converter on buffering: (a) Two buffers needed without wavelength converter, (b) One buffer can store two different wavelengths.](image)

Scalability is another important issue to network providers being defined as the scale to which the network can easily grow in size, capacity, number of nodes, and hence in number of users. Without wavelength conversion, in order to establish a new optical connection along a path consisting of several links in a WDM network, a wavelength
Components for Dynamic Wavelength Routing

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must be free on each of the links of the path. Indeed without wavelength conversion at the network node it would be required that the free wavelength must be the same on each link. As a result, wavelength conversion can allow more transparency and interoperability of networks as it allows the wavelengths to be registered locally rather than globally.

It is also possible to use a wavelength converter as a label swapper in a packet-based system. If the label or optical header has such conditions in terms of electrical bandwidth or amplitude so that when the packet is converted to a new wavelength, the portion of label doesn’t convert, then a new label on the new wavelength can be added to the payload [29].

Also, in all networks there is a need of repeaters to overcome losses. Digital networks are known to be able to transmit information over many repeaters without severe degradation, because repeaters are of the 3R type. In this notation reamplifying is 1R, reamplifying and reshaping is 2R, and reamplifying, reshaping and retiming is 3R. It is ideal in all-optical networking to realize 3R regenerators without converting the signal from optical to electrical. Currently optical amplifiers being used as 1R type. Their main advantages are bit rate and modulation transparency plus multiwavelength operation.

Regenerative functionality is required in order to extend the transmission distances in the presence of signal degradation [30]. This can arise, for example, from chromatic dispersion, polarization mode dispersion, four-wave mixing, and optical amplifier noise [31]. To date all-optical regeneration and routing has not been implemented commercially because the cost-benefit trade-offs have been in favor of electronics at speeds up to 2.5Gb/s of existing commercial systems.

Wavelength converters should have several attributes. In order to perform at ever-increasing data rates, they must be able to operate at high speed. Also, as the networks are scalable, they have to be cascadable. Other requirements include low component count, low power consumption and low cost. In addition, for the purposes of dynamic wavelength routing, the output wavelength should be rapidly tuneable over a wide
wavelength range of ITU grid. Another important performance parameter is the conversion efficiency which is defined as "ratio of the output signal power with respect to the input" [32].

One aspect of a wavelength converter is the ability to have either variable or fixed input or output. As there is no reasonable application for a fixed-input-fixed-output, there are 3 other types of converters. The first is fixed-input variable-output. In this case the input is a fixed wavelength and the output can be tuned to any required wavelength. The second is variable-input fixed-output. This might be useful if a network node is only able to handle a set of specific wavelengths, then any incoming wavelength which may be different will be converted to one of the registered wavelengths. The third type is variable-input-variable-output. In this case both the input and output can be variable which gives a higher flexibility in network design.

To date, a range of wavelength conversion techniques have been developed. Conversion data rates of up to 100Gb/s [33] using several discrete or integrated components have been demonstrated. With the growing capability of wavelength converters, issues such as robustness, controllability, compactness and simplicity are becoming much more important, particularly because many applications for wavelength converters are likely to require substantial numbers of devices.

A straightforward method for achieving wavelength conversion is to use an optical to electronic converter consisting of a detector followed by an electrical regenerator and laser which retransmits the incoming signal on a new wavelength. This is commercially available and is variable-input fixed-output unless a tuneable or array of lasers used at the output. It is not in the scope of this thesis. Alternatively all-optical techniques are of interest where the input optical signal is directly converted to another wavelength. All-optical techniques are likely to be preferred in order to overcome the electronic bottleneck.

Different approaches have been used to implement wavelength conversion and regeneration, such as cross-phase and cross-gain modulation, and four-wave mixing in
semiconductor optical amplifiers (SOAs), and cross gain modulation in a distributed feedback (DFB) laser [34] and an integrated DFB laser followed by a SOA [35].

For ultra-fast communication applications there has been much interest in achieving wavelength conversion using non-linear media such as in optical fiber interferometric gates [36]. Wavelength conversion and signal regeneration by employing a nonlinear optical loop mirror [37,38] and electro-absorption modulator [39] has been realized. Although these are most successful and can allow levels of regeneration and pulse shaping, they normally require high peak optical powers to ensure sufficient nonlinear operation and hence have typically been limited to short pulse applications.

For systems operating at lower rates, there has been substantial interest in achieving wavelength conversion using diode lasers as the nonlinear elements. Laser-based converters have advantages in being single component and simple, but the maximum bit-rate determined by laser’s resonance frequency is normally not greater than 10Gb/s [40]. There are basically three optical effects in nonlinear elements which can be exploited to perform wavelength conversion and regeneration. These are four-wave mixing, cross phase and cross gain modulation.

2.4.1. Four Wave Mixing (FWM)

It is possible to use four-wave mixing in a nonlinear element such as optical fiber or a SOA to achieve wavelength conversion. Four wave mixing rises from a nonlinear optical response of a medium when more than one wave is present. As shown in figure 2.7, the outcome of four wave mixing is the generation of two new wavelengths, i.e., $2\lambda_1 - \lambda_2$ and $2\lambda_2 - \lambda_1$. Their intensity is proportional to the product of the interacting wave intensities. The phase and frequency of the generated conjugate wave is a linear combination of those of the interacting waves. Therefore, since the four wave-mixing process preserves both phase and amplitude information, this is the only category of wavelength conversion that is strictly transparent. Not only is the FWM wavelength conversion process non-inverting, it also preserves the signal format. In addition, this is the only method that allows simultaneous conversion of a set of multiple input wavelengths to multiple output wavelengths. Wavelength conversion at 100Gb/s has been achieved for conversion over a wavelength range of
3.2nm [41] and results have been demonstrated for conversion over larger spans. Examples include 2.5Gb/s over 80nm [42] and 40Gb/s over 24.6nm [43].

SOA-based components have a number of advantages as four-wave mixing components. Due to their intrinsic device gain, the FWM conversion efficiency is high compared with that in passive nonlinear elements. The operating range can be improved by increasing the SOA length and by adjusting the composition of the active layer.

The DFB/SOA has been demonstrated to perform wavelength conversion at 40Gb/s using the four wave mixing process. In addition, this four wave-mixing device can be placed at the mid-point of a transmission link to act as a dispersion compensation unit [44]. The effects of fibre dispersion at 40Gb/s in the first 50km span are removed after spectral inversion (phase conjugation) by the dispersion in the second 50km span. This approach to dispersion compensation has some advantages over other techniques in that it has the inherent potential to compensate for fibre non-linearities. There is also the need for only one compensation device at the mid-point of the link, regardless of the transmission distance. The disadvantage of this approach is that an active component is obviously required which will require control techniques for stability and reliability.
In conclusion, the main advantages of FWM for wavelength conversion application are its independance of modulation format, high speed and multi-wavelength operation. However it has a number of disadvantages including its low conversion efficiency, limited dynamic range and dependence of the output wavelength on both the input and pump wavelengths. Extinction ratio is nearly the same as the input [45].

2.4.2. Cross Phase Modulation (XPM)

The second technique is the cross-phase modulation (XPM). As shown in figure 2.8, a nonlinear element like SOA is used in one or two arms of a Mach-Zehnder interferometer. It uses refractive index changes in a nonlinear element caused by an optical data signal. Optical signals travelling through a nonlinear element undergo a relatively large phase modulation compared to the gain modulation.

![Cross-Phase Modulation (XPM)](image)

An input optical signal passes through one of the arms and modulates the phase of that arm. The interferometric nature of the device converts this phase modulation to an amplitude modulation of the probe signal at the new wavelength. The interferometer can operate in two different modes, a non-inverting mode where an increase in signal power causes an increase in probe power, and an inverting mode where an increase in signal power causes a decrease in probe power. To achieve high operation stability as well as compactness, the MZI should be integrated with the SOAs. Wavelength conversion at 100Gb/s has been achieved [46].
In conclusion, this technique can achieve lower noise, high extinction ratio and lower chirp. It is also possible to remove the output filter in a counter-propagation configuration [47].

However it is sensitive to input power, needs a complex control of bias points, has small input signal power and wavelength dynamic range. The conversion efficiency is higher than FWM but it is still low. Also, as a result of needing a stable bias point in the interferometric structure, the devices are required to be monolithically integrated.

2.4.3. Cross-gain Modulation (XGM)

Cross-gain modulation (XGM) employs interactions between two optical signals via the carrier population. Here the gain in a semiconductor optical amplifier saturates as the optical power level increases. Therefore it is possible to modulate the amplifier gain with an input signal and in turn encode this gain modulation on a new wavelength travelling through the amplifier, though with an inversion of the data. In

Cross-gain modulation, a continuous wave probe beam is injected into a nonlinear element like a SOA as shown in figure 2.9. A signal beam carrying information at $\lambda_1$ depletes the carriers thereby modulating the gain of the SOA. This depletion of carriers also causes a change in the refractive index. The probe beam at wavelength $\lambda_2$
encounters the modulated gain and refractive index and thus the probe amplitude and phase are changed by the input signal. One of the key shortcomings of this approach is deterioration in the signal-to-noise ratio due to the spontaneous emission background level. Typical noise figures are 7-8dB for semiconductor amplifiers, and the noise figure for the conversion process is usually higher than the intrinsic noise figure. Additionally the signal quality is further deteriorated by amplitude distortions and chirping caused by the carrier modulation. However very fast wavelength conversion with data rate of 100Gb/s has been demonstrated [48]. Despite some of the shortcomings this is one of the simplest all-optical wavelength conversion mechanisms that is available today. It has the highest conversion efficiency. However it needs optical filtering of the strong input wavelength at the output of the SOA. The extinction ratio is low and there is some distortion due to carrier density fluctuations [49].

Although wavelength conversion via cross-gain modulation in SOAs has been demonstrated, with separate lasing and amplifying components, it is advantageous, from a cost and complexity perspective, to develop integrated solutions. As a result, Bristol optics group has performed a large body of work using a single device that consists of a distributed feedback laser integrated with a semiconductor optical amplifier as shown in figure 2.10. This device was designed and fabricated by Nortel Networks at Harlow, UK. The DFB/SOA has been fabricated using the InP-InGaAsP material system and consists of a 800-µm long DFB section and a 500-µm long SOA section each of which can be independently biased. The mechanism for wavelength conversion using cross-gain modulation in this device is as follows. An external data signal at wavelength $\lambda_1$ is input into the laser side of the DFB/SOA. The DFB emits at a second wavelength $\lambda_2$. Cross-gain modulation within both the laser, which acts as an amplifier for wavelength $\lambda_1$, and amplifier transfers the input data signal onto the DFB wavelength, $\lambda_2$. For example, the presence of logic 1 depletes carriers and reduces the gain for the DFB laser imprinting logic 0 onto $\lambda_2$. In this case the data signal at the new wavelength $\lambda_2$ is the inverse of the input signal at $\lambda_1$. Finally, isolating the output signal at $\lambda_2$ using a bandpass filter completes the wavelength conversion process. Wavelength conversion can also be achieved at much lower input powers, by reversing the device and injecting the data signal into the SOA section [50].
way the low input power is amplified in the SOA section before causing gain saturation in the DFB section.

The highly non-linear response, with contrasts between the high and low levels of 50dB, also performs signal regeneration. For high input powers, the very high extinction ratio leads to reduced noise during the output zeros and for the low input powers the internal laser source will provide a low noise in the output ones.

Experimental investigation of this device has been carried out in the group before. A detailed investigation of the operation of this device and comparison with the single devices by modelling was in the scope of this thesis and the results will be demonstrated in chapter 5.

As mentioned before, cross-gain modulation is probably the simplest mechanism for wavelength conversion and it is very efficient. Also, it has large conversion range and shows good results up to 40Gb/s. However it suffers from degradation of extinction ratio which can be compensated in DFB/SOA structure. Another drawback is data inversion which can be eliminated by double conversion. It is very likely that in a real network application, two conversions will be used to restore the original wavelength. In this case data inversion is not a problem.

Figure 2.10. DFB/SOA structure[50].
2.5. Regenerative Dynamic Wavelength Routing

In a packet-based system a dynamic wavelength routing will be essential. As the consecutive packets may be destined for the different outputs, the router has to be capable of routing every packet to any output with a speed of ideally in nanoseconds scale. Also a wavelength routing approach is more compatible for WDM based systems because different wavelengths are already available and they can be used as a networking tool. For the purpose of our demonstration we have used AWG in conjunction with a tuneable wavelength conversion to perform dynamic wavelength routing. Regeneration in these networks is also very desirable, as different packets not only experience long distance propagation but also different route lengths and switch nodes each of which adds some additional noise to the signal. Fortunately, wavelength conversions are often capable of regeneration. The whole system which gives dynamic wavelength routing and also regeneration will be the ultimate goal of this thesis and the results of investigation on components and system demonstration will be given in the following chapters.

2.6. Summary

The main requirements of optical routers have been identified. There are two categories of optical routing. One is based on space switching, and the other is wavelength routing. Space switches can be constructed using MZ couplers based on electro-optics effect in LiNbO3 materials or thermo-optic effect on silica based devices. There are also space switches based on SOA gates. The high port count switches however are likely to be based on MEMS technology. Wavelength routing on the other hand uses wavelength as a network tool. The routing operation is carried out using wavelength conversion in conjunction with wavelength selective switches. Different technologies for wavelength selective switches have been introduced based on discrete filters and integrated devices, among them the AWG seems to be the technology of choice for large scale switches. Also, the concept of dynamic wavelength routing which is similar to conventional wavelength routing except the use of tuneable wavelength converter to give the dynamic operation has been discussed. Different approaches of wavelength conversion have been briefly discussed. Also a brief introduction to the concept of regenerative routing has been
given. This chapter gave a general view of the following chapters which will focus on AWG, a fixed wavelength converter based on DFB/SOA and a tuneable wavelength conversion to build a regenerative dynamic wavelength router.

2.7. References


CHAPTER 3

Arrayed-Waveguide Grating Characterization

In this chapter, after a review of the AWG and its applications, and also a short description of its structure and fabrication process, we will derive a simple theoretical analysis which will be the basis for the future investigations within the thesis. The analysis focuses on the spectral amplitude and phase response of the AWG to calculate some of its performance parameters. The result of measurements on the amplitude and phase response as well as link performance of a 16×16 AWG which is suitable for WDM applications are then demonstrated. For the case where AWG is used as an interleaved filter, it is also important to measure its short pulse response as this can indicate its dynamic performance. A novel nondestructive stable phase measurement technique is described in order to resolve the phase changes across each AWG channel.

3.1. Review

Wavelength multiplexers and demultiplexers are key components in WDM systems. To perform these functions there are different technologies including fiber Bragg gratings (FBG), thin film filters (TFF) and arrayed-waveguide gratings, sometime called phased-arrays or PHASAR and also waveguide grating routers (WGR). To highlight the advantage of an AWG, it should be noted that for a 40 channel multiplexer using TFF technology, at least 39 thin film filters are needed. A single AWG integrated device can replace these 39 discrete devices. Moreover the insertion loss of the AWG does not increase linearly with the channel count as it does for TFFs and FBGs [1]. The AWG basically operates like a diffraction grating, but at higher diffraction orders which leads to a better resolution. Also, it provides the possibility to have several inputs and outputs [2]. Its fabrication is based on planar lightwave circuits (PLC) technology.

PLCs are optical circuits laid on a wafer, and are made using tools and techniques developed to extremely high levels by the semiconductor industry. In this way
multiple components can be fabricated and interconnected at once, significantly reducing both the manufacturing and the packaging/assembly costs. PLC technology needs less labor because no manual assembly is required. This technology also gives a better component density as all functions are performed on a single chip result in a very small device.

However, there are some challenges for PLC technology. The main challenge is packaging, as the input/output light should be aligned very well to the optical fiber. One solution is using special grooves to align the fiber to the device. Another big challenge is thermal stability. At the moment there are two solutions for this. One is to use temperature controlled packages, and the other is using new materials in the waveguide to make athermal devices. The other important challenge in the design of a PLC device is the chip size. The ultimate limit is set by the size of uniform wafers available. As the bend radius of waveguide curve must be large to reduce loss, this gives a lower limit in the size of the circuit. Insertion loss is another problem which depends largely on the material. There are three main materials for AWG fabrication: silica, InP and polymers. InP-based devices cannot compete with silica-based devices with respect to fiber coupling loss or insertion loss. Also, Silica glass provides high reliability [3]. However, InP-based AWGs have good prospects for integration with active components such as detectors, modulators, switches, amplifiers. They provide smaller size and are also suitable for large-scale integration [4]. Polymeric 16×16 AWG routers with channel spacing of 0.8 nm (100 GHz) have also been fabricated [5].

Large scale multiplexers with narrow channel spacing are desirable for increasing the capacity of WDM systems. Increasing the channel number is limited by the phase error produced in either the phased array or the slab waveguide of an AWG. The AWG requires a large length difference between adjacent arrayed waveguides for narrower channel spacing. This leads to larger phase errors as a result of the fluctuations in the optical path lengths of the arrayed waveguides. Therefore this is a big challenge in the construction of high channel count AWGs. However, a 128 channel single chip AWG with 25GHz channel spacing [6], a 400 channel silica-based AWG with 25GHz channel spacing [7], and a 10-GHz spaced 512 channel AWG [8] have been reported.
To avoid high phase errors in high channel count single chip AWGs, one can increase the channel count by using a combination of AWGs. For example, a 25GHz spaced 1080 channel tandem AWG covering S, C, and L band by cascading a 2.5 THz spaced AWG and ten 25 GHz spaced 1×200 AWGs has been proposed [9]. Also, a large scale 10GHz spaced AWG using a 1×5 multiplexer and five 1×288 AWGs [10], a 320 channel multiplexer consisting of a 100 GHz spaced AWG and sixteen 10GHz spaced AWGs [11], a 10GHz spaced 1010 channel AWG using a cascade of a 1 THz spaced 1×10 and 10 band pass filters and ten 10GHz spaced 1×160 AWGs [12] and a 480 channel 10GHz spaced Mux/Demux using a three-stage parallel connection of a WDM splitter, two 100GHz spaced AWGs and 64 10GHz spaced AWGs were reported [13].

Since the introduction of AWG by Smit [14] in 1988, it has increasingly become one of the most common components in wavelength division multiplexed networks. Although the main application of the AWG is a WDM multi/demultiplexer and wavelength router, various other applications of this technology have been proposed. For example, a dispersion compensation scheme was proposed based on a reflection type AWG. Dispersion compensation is performed by decomposing the input waveform into its frequency components, modulating the phase of each component by a spatial filter, reflecting them from a mirror and reforming the waveform by combining the components. The device acts as a broadband compensator and can compensate negative as well as positive dispersion [15]. Spectral encoding and decoding of femtosecond pulses which is applicable to optical code division multiplexing (OCDM) application has been performed using AWG. This is similar to dispersion compensation application described before, but by encoding the phase of each component [16]. Also, a ten wavelength 200GHz channel spacing emitter for WDM applications has been demonstrated based on the monolithic integration on InP of ten DBR laser array with a square shaped transmission response AWG. This also performs the combining process of different wavelengths in a WDM system into a unique fibre [17]. Generation of femtosecond pulse train from AWG with the repetition rate determined by the delay spacing has been proposed [18]. An AWG-based optical packet switch [19] and digitally tunable optical filter [20] and laser [21] was developed. A bidirectional optical cross connect using a single AWG router and tuneable FBGs have been proposed for multiwavelength bidirectional WDM ring.
networks. By utilizing the periodic property of the AWG router and locating more tenable FBGs in the loops, it is possible to increase the number of wavelength channels without increasing the number of ports of the AWG router [22].

An add-drop multiplexer [23, 24, 25], a time to space conversion for signal processing applications [26, 27], and a frequency spectrum synthesizer using an AWG pair [28] have been reported. A 13-wavelength channel 10GHz pulse source using a dispersion-imbalanced fiber loop mirror and an AWG has been demonstrated with an output pulse-width of 5ps [29]. AWGs can be used as interleavers which can separate dense wavelength channels onto odd and even channels with the channel spacing of twice the original one easing the processing [30, 31]. An AWG can also be used as a router [32, 33] because an \( N \times N \) AWG multiplexer is capable of simultaneously processing \( N^2 \) optical channels at \( N \) different wavelengths. A 32×32 AWG router with uniform loss and cyclic frequency characteristic has been fabricated [34] and a 32×32 full mesh WDM metro scale network test-bed based on such an AWG has been established [35].

3.2. Structure and Fabrication Process

Figure 3.1 shows a structural view of an AWG. It consists of two star couplers connected by an array of waveguides with a constant length difference between adjacent waveguides. Also connected to the other sides of star couplers are input and output waveguides. The arrayed waveguides are arranged on a circle centred at the junction between the central input/output waveguide and star couplers. The radius of this circle is known as the focal length of star couplers (\( R \)). Every waveguide in the array is located along the circle with a constant separation which is called grating pitch (\( d \)) [36]. The input/output guides are also arranged on a circle centred at the junction between the central arrayed guide and star couplers with the same radius (\( R \)).

The arrayed waveguides are each made up of five sections. The first section is a straight guide exiting the first star coupler and this is followed by a curved waveguide section. The third section is a straight waveguide in the middle of the arrayed waveguide which connects to the fourth section which is another curved waveguide. The final section is a straight guide connecting to the second star coupler. This
geometry allows a constant length difference to be specified between adjacent waveguides across the array.

![Arrayed-Waveguide Grating Characterization](image)

**Figure 3.1. A structural view of an AWG.**

The star couplers are three layer slab waveguides which are sometimes called the free propagation regions (FPR). Figure 3.2 shows a cross section of the waveguides structure at the junction between star couplers and arrayed waveguides. The rectangular waveguides are arranged with a separation of $d$, each of which collimates a portion of incident field into the arrayed waveguides. Any light which is not collimated by the waveguides is lost between the arrayed waveguides and also increases the background noise. To reduce this energy loss, a number of solutions have been proposed. A common method which is used in the AWGs under study in this thesis is to make the waveguides at this point wider than that of the middle part of the arrayed waveguides.
The fabrication process is similar to that of many silica-based planar lightwave circuits. First, a lower cladding layer with a refractive index of \( n_1 \) is deposited, followed by a core layer with index of \( n_f \) typically <1% larger than of cladding layer. The core layer is then patterned using standard photolithographic techniques, and a channel waveguide pattern is transferred to the core layer using various etching techniques. A number of rib waveguides are produced by etching away the surrounding core using techniques such as reactive ion etching (RIE). The channel waveguides are then covered by a top cladding layer with the index of \( n_e \) usually of the same index as the lower cladding. The end result is a number of buried channel optical waveguides on the substrate wafer [37].

### 3.3. Analysis and Theory

The input signal \( S_{in} \) entering an input channel travels through the input waveguide of length \( l_i \) to the first star coupler. In the star coupler, the incoming field diffracts and enters arrayed waveguides. The field amplitude of each waveguide is proportional to \( a_k \) which depends on the field distribution, losses and the position of waveguide and its dimensions. The signal then travels through arrayed waveguide to the second star coupler. The second star coupler is acting as a wavelength dependant collimating device. The field of each arrayed waveguide is also diffracted in this star coupler and travels through the output waveguides of length \( l_o \) to the output channel. As a result,
the basic relation between input and output for a specified mode and wavelength can be written as follows:

\[ S_{\text{out}} = \sum_{k=1}^{n} a_k e^{-j(\beta_w l_1 + \beta_s l_{zik} + \beta_w l_{wk} + \beta_s l_{sk} + \beta_w l_o)} \]  

This results in the following transmission function:

\[ H_{\text{AWG}} = \sum_{k=1}^{n} a_k e^{-j(\beta_w l_1 + \beta_s l_{zik} + \beta_w l_{wk} + \beta_s l_{sk} + \beta_w l_o)} \]

Where \( S_{\text{out}} \) is the output signal from specified output of AWG, \( \beta_s \) is the propagation constant within star couplers (assumed the same for both), \( l_{zik} \) is the path length from junction between specified input waveguide and first star coupler to the junction between first star coupler and the \( k_{th} \) arrayed waveguide, \( l_{sk} \) is the path length from the junction between the \( k_{th} \) arrayed waveguide and second star coupler to the junction between second star coupler and specified output waveguide, \( \beta_w \) is the propagation constant of rectangular waveguides which can be calculated by effective index method and assumed to be the same for input and output waveguides and arrayed waveguides as all have the same structure and material, \( l_{wk} \) is the length of \( k_{th} \) arrayed waveguide, and \( H_{\text{AWG}} \) is the transmission function of the AWG. The loss of waveguides can be considered in the field distribution factor \( a_k \). We will use the above relations as the basis for the model in chapter 4. Any parameter used in the analysis is described in table 3.1 if has not been mentioned here. In the table two different AWGs have been described. We distinguish between them throughout this thesis by calling the first one as 64-array or 16x16 AWG and the second one as 9-array or interleaved AWG.

Here we try to simplify and calculate analytically the phase and amplitude of the AWG to allow a better physical understanding. As the length difference of adjacent arrayed waveguides in an AWG is constant, we have:

\[ l_{wk} = l_{w1} + (k-1)\Delta l, \quad k = 1, 2, \ldots, n \]

Where \( l_{w1} \) is the length of the shortest waveguide in the array. Also, we can use the following relations:
\[ \beta_w = \frac{2\pi f}{c} N_w \]  
(3-4)

\[ \beta_s = \frac{2\pi f}{c} N_s \]  
(3-5)

Where \( f \) is the optical frequency of the signal and \( c \) is the speed of light in vacuum which will be considered as \( 2.998 \times 10^8 \text{ m/s} \) in our calculations. Therefore we can rewrite the equation (3-2) as follows:

\[ H_{\text{AWG}}(f) = e^{-j\frac{2\pi f}{c} N_w (l_t + l_o + l_{w1} - \Delta L)} \sum_{k=1}^{n} a_k e^{-j\frac{2\pi f}{c} N_s (l_{stik} + l_{sok} + N_w k\Delta L)} \]  
(3-6)

To simplify this equation, we consider the central input and output waveguides, so that:

\[ l_{stik} = l_{sok} = R, \quad k = 1, 2, \ldots, n \]  
(3-7)

Therefore we can rewrite equation (3-6) as follows:

\[ H_{\text{AWG}}(f) = e^{-j\frac{2\pi f}{c} N_w (l_t + l_o + l_{w1} - \Delta L)} e^{-j\frac{2\pi f}{c} 2N_s R} \sum_{k=1}^{n} a_k e^{-j\frac{2\pi f}{c} N_w k\Delta L} \]  
(3-8)

By considering a symmetric spatial distribution of the field over the arrayed waveguides, which is a reasonable assumption for central input/output, we will have:

\[ a_k = a_{n-k+1}, \quad k = 1, 2, \ldots, n \]  
(3-9)

Using this symmetric property, with some substitution and changing the order, it is possible to show that:

\[ H_{\text{AWG}}(f) = e^{-\frac{2\pi f}{c} N_w (l_t + l_o + l_{w1} - \Delta L)} e^{-\frac{2\pi f}{c} 2N_s R} \sum_{k=1}^{n} a_k \cos \left[ \frac{2\pi f}{c} N_w \Delta L \left( k - \frac{n+1}{2} \right) \right] \]  
(3-10)

Therefore the amplitude and phase response of AWG can be derived as follows:

\[ \text{Amplitude} = \sum_{k=1}^{n} a_k \cos \left[ \frac{2\pi f}{c} N_w \Delta L \left( k - \frac{n+1}{2} \right) \right] \]  
(3-11)

\[ \text{Phase} = -\frac{2\pi f}{c} \left[ 2N_s R + N_w \left( l_t + l_o + l_{w1} + \frac{n-1}{2} \Delta L \right) \right] \]  
(3-12)

The above phase and amplitude response are based on two main assumptions: first, the constant length difference between arrayed waveguides which is very important as
our model shows the variation of more than 1 percent is not tolerable. The second is the symmetry of the field distribution, which is normally satisfied if the arrayed waveguides loss is negligible.

Table 3.1. Description of structural parameters of two AWGs under study.

<table>
<thead>
<tr>
<th>Description of Parameter</th>
<th>Notation</th>
<th>16x16 AWG</th>
<th>9-array AWG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of arrayed waveguides</td>
<td>n</td>
<td>64</td>
<td>9</td>
</tr>
<tr>
<td>Total number of input waveguides</td>
<td>n_i</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>Total number of output waveguides</td>
<td>n_o</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>Width of input waveguides at star coupler (μm)</td>
<td>w_i</td>
<td>19.2</td>
<td>18</td>
</tr>
<tr>
<td>Separation (pitch) of input/output waveguides at star couplers (μm)</td>
<td>D</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Width of output waveguides at star coupler (μm)</td>
<td>w_o</td>
<td>19.2</td>
<td>18</td>
</tr>
<tr>
<td>Separation of arrayed guides at star couplers (μm)</td>
<td>d</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Width of arrayed waveguides at star couplers (μm)</td>
<td>w_a</td>
<td>22.2</td>
<td>21.5</td>
</tr>
<tr>
<td>Width of arrayed waveguides away from star couplers (μm)</td>
<td>w</td>
<td>5.7</td>
<td>5.5</td>
</tr>
<tr>
<td>Focal length of star couplers (μm)</td>
<td>R</td>
<td>11893.61</td>
<td>11882.28</td>
</tr>
<tr>
<td>Length difference of adjacent arrayed waveguides (μm)</td>
<td>ΔL</td>
<td>50.82</td>
<td>1031.678</td>
</tr>
<tr>
<td>Material refractive index of core layer</td>
<td>n_f</td>
<td>1.4574</td>
<td>1.4574 @1523nm</td>
</tr>
<tr>
<td>Material refractive index of lower cladding layer</td>
<td>n_s</td>
<td>1.4464</td>
<td>1.4464 @1523nm</td>
</tr>
<tr>
<td>Material refractive index of top cladding layer</td>
<td>n_c</td>
<td>1.4464</td>
<td>1.4464 @1523nm</td>
</tr>
<tr>
<td>Thickness of core layer (μm)</td>
<td>h</td>
<td>6.7</td>
<td>7.0</td>
</tr>
<tr>
<td>Designed central wavelength (nm)</td>
<td>λ₀</td>
<td>1550</td>
<td>1550</td>
</tr>
<tr>
<td>Overall size of device (mm×mm)</td>
<td>-</td>
<td>40.42×13.32</td>
<td>17.51×20.87</td>
</tr>
<tr>
<td>Effective refractive index of slab section for TE zero order mode at central wavelength</td>
<td>N_s</td>
<td>1.455146</td>
<td>1.455146</td>
</tr>
<tr>
<td>Effective refractive index of waveguide section for TE Zero order mode at central wavelength</td>
<td>N_w</td>
<td>1.452564</td>
<td>1.452564</td>
</tr>
</tbody>
</table>
3.4. Performance Parameter Definitions

In order to assess the performance of an AWG device, several parameters have been defined as stated in the following sections.

3.4.1. Figure of Merit (FOM)

An ideal passband response of a filter is rectangular, i.e., the response for all transmitted light is lossless whilst otherwise complete rejection occurs. This is however not practical. Therefore we need a quantity to assess how near a filter response is to the ideal one. This quantity is called "figure of merit". It is a measure of the 'Squareness' of the wavelength response and quantifies how much the spectral response is flattened. It is particularly important when we consider in a system we may use a number of AWG mux/demux and filters and if their responses are not flat then the overall response will be sharper as more devices are cascaded and with a small change in the central frequency we will end up with a huge signal degradation [39]. A Flat response also will therefore relax the tolerance on the transmitted wavelengths. A common definition for FOM is the bandwidth at 0.5 dB below the peak divided by the bandwidth at 30 dB below the peak [40]. Ideally, this should approach 1, the ITU recommendation is 0.25 [41] and a Gaussian shape has a figure of merit of 0.13.

The passband shape of the AWG versus wavelength can be altered by the input/output waveguide design. The most popular shape is Gaussian. This shape exhibits the lowest loss at the peak but it is very “pointy” requiring very accurate sources. A cascade of several such filters results in a very narrow passband. Flat passbands are desirable but normally there is a compromise between insertion loss and figure of merit [42]. It has been confirmed that in order to obtain a flat spectral response, it is necessary to produce the rectangular electric field profile at the focal plane (the interface between the second slab and output waveguides). As the electric field profile in the focal plane is the Fourier transform of the field in the array output aperture (the interface between the array waveguide and second slab), such a rectangular field profile could be generated when the electric field at the array output aperture obeys a sinc distribution. Such sinc-shaped electric field amplitude distribution has been realized by introducing an additional loss to each array waveguide [43].
Several techniques have been reported to flatten the filter response such as using an interleaved filter before AWG [44]. In this method, the first interleaved filter designed to have a FSR equal to the channel spacing of the second one. A FOM of 0.3 has been achieved by this method [45]. As another example, a double phased array InP based-AWG has also been proposed to improve the FOM. It has two sets of arrayed-waveguides with different length increments. Each set is laid between the other set creating a second transmission peak which when superimposed on the original one leads to a flat response with a figure of merit of around 0.3 [46].

3.4.2. Crosstalk

The crosstalk of an AWG is defined as the difference between the maximum transmission in the pass-band and that of the rejection band. Although there is a small amount of crosstalk as a result of limited number of waveguides, the main practical cause of crosstalk is the phase error in each guide of arrayed waveguides. The phase error is mainly caused by the fluctuation in the length and the effective index of the waveguide, which is due to the fluctuations in the refractive index and core size [47]. Other sources of crosstalk include far-field tails overlapping at the outputs, the truncation of fields due to finite widths of apertures, and mode conversion at waveguide bends. The crosstalk is basically limited by the fabrication imperfections, not the design.

There are two types of crosstalk: adjacent and non-adjacent. Adjacent crosstalk is defined as the difference between the insertion loss at the central wavelength of a channel with that of the next channel. Non-adjacent crosstalk is the worst case difference between the insertion loss of a channel with the insertion loss of this channel at any other central wavelengths of the other channels.

The crosstalk limits the number of supported nodes in an AWG router and OADMs. In a WDM system there are two types of crosstalk: inter-channel and intra-channel. Inter-channel crosstalk can be removed by filtering as it is due to channels with different wavelengths. However, suppression of intra-channel crosstalk is very difficult as it is due to other channels but at the same wavelength and is not removable by filtering. Intra-channel crosstalk can be classified as either incoherent (generated by different sources) or coherent (generated by the same source in loop back connections) [48].
In an $N \times N$ network there are $N - 1$ sources with the same wavelength. If we neglect the different wavelength interference because it is smaller than same wavelength, then the crosstalk introduces a power penalty which is: [49]

$$\text{PowerPenalty (dB)} = -10 \log \left[ 1 - R_c (N - 1)Q^2 \right] \tag{3-13}$$

With this relation it is possible to calculate the maximum node number supported by an AWG with a specific crosstalk level ($R_c$) for a specific bit error rate or $Q$ factor and power penalty. From the above relation, it can be verified that the crosstalk value of higher count AWGs should be less than lower counts for the same bit error rate.

Various techniques have been used to reduce crosstalk in AWG. For example, the crosstalk of an AWG has been reduced by trimming a Si film deposited on the arrayed waveguides [50]. Also by using a phase compensating plate, crosstalk values of less than -37dB have been achieved [51]. The crosstalk has alternatively been reduced by phase error compensation after fabrication by using thin film heater. A crosstalk of less than -35 dB for the TE polarization mode in a 16x16, 10GHz-spacing arrayed-waveguide grating has been achieved. The crosstalk is very high in narrow channel spaced AWGs because in this case they require larger path length differences in arrayed guides, result in larger errors [52].

3.4.3. Insertion Loss

The insertion loss is defined as the relative amount of optical power going into the device ($P_{in}$) compared to the optical power coming out of the device ($P_{out}$) in dB:

$$\text{InsertionLoss} = -10 \log \left( \frac{P_{out}}{P_{in}} \right) \tag{3-14}$$

An acceptable insertion loss is often determined by that set by the overall system loss budget, which is a function of transmitter power, optical amplifier gain and receiver sensitivity amongst other factors. To differentiate between overall insertion loss and the loss incurred by the device, there are also additional definitions of on-chip loss and what is commonly termed total excess loss. The excess loss indicates both the on-chip loss and the coupling loss incurred at the input and output of the device. The on-chip loss as its name suggests does not include coupling losses but losses incurred just by the passage of the signal through the device.
The on-chip loss in AWG has three main origins: material intrinsic loss, waveguide bending loss and transition loss [53]. Of these the dominant loss is the transition loss at the interface between slab waveguide and arrayed waveguides owing to field mismatch as a result of the gaps between arrayed waveguides at this point. The gap size is limited by the finite resolution of the fabrication process. A method has been proposed to reduce this loss by using vertically tapered waveguides between arrayed waveguides [54]. Another method is by using a high refractive index region formed in the vicinity of arrayed waveguides with ultraviolet (UV) irradiation. Light from the slab is gradually assimilated in the high index regions as it propagates through them and then propagates smoothly into the array. The insertion loss of 2.1 dB including the fiber-to-chip loss of 0.8dB is reported [55].

The best way of reducing the fibre to waveguide coupling loss seems to be using lower index waveguides. However both the propagation loss and bending loss depend on relative refractive index ($\Delta n$) and there is a trade-off relationship between them. By increasing $\Delta n$, the bending loss decreases but the propagation loss increases [56]. Increasing the bending loss results in higher bending radius which in turn leads to a larger device size.

Another important performance requirement for WDM systems is the insertion loss uniformity across channels which is defined as the difference between the insertion loss of the best and the worst case channels [57]. For $N \times N$ AWG, the loss non-uniformity causes a crosstalk-to-signal ratio imbalance that results in additional signal degradation [58]. A complete $N \times N$ routing is only possible by a cyclic AWG which will be defined later with uniform loss across the wavelength range [59]. Loss imbalance in a cascade of AWGs can be reduced by employing cyclic AWGs and shifting the port connection between adjacent filters [60].

3.4.4. Channel Spacing

The channel spacing is defined as the center-to-center difference in frequency between neighboring channels in an AWG operating on the ITU grid, i.e. 200GHz, 100GHz and 50GHz. Its approximate relation to structural parameters of AWG is as follows: [61]
\[ \Delta \lambda = \frac{N_c d D \lambda_0}{N_w R \Delta L} \]  
\[ \Delta f = \frac{c}{\lambda_0^2} \Delta \lambda \]  

Where \( \Delta \lambda \) and \( \Delta f \) are wavelength and frequency channel spacing in nm and GHz respectively. By substituting values of table 3.1, we obtain values of 1.61nm or 200.9GHz for 64-array AWG and 0.79nm or 99.1GHz for 9-array AWG.

From the above equations it is clear that to increase the channel spacing we have to decrease either length difference of arrays or the focal length of slabs as the other parameters are normally fixed by manufacturing restrictions.

### 3.4.5. Free Spectral Range (FSR)

The response of an AWG is like any other grating type filter in being periodic in the frequency and wavelength domain. The period in frequency domain is called the free spectral range (FSR). It is possible to show from equation (3-11) that the peak frequencies of AWG are as follows:

\[ f_m = m \frac{c}{N_w \Delta L} , \ m = 0,1,2,..... \]  

As the equation (3-11) is for the central input/output, the above relation is valid only for this case. For the other channels, the difference in peak wavelengths which make a shift equal to channel spacing means the length difference for the other channels are different. This difference is coming from the small difference between the lengths of the input/output waveguides to the arrayed waveguides. As a result in any calculation it is very important to consider the accurate values of these lengths. The FSR in GHz which is the difference between two consecutive peak frequencies is [62]:

\[ FSR = \frac{c}{1000N_w \Delta L} \]  

From this relation, we can see that the free spectral range depends inversely on the length difference between arrayed waveguides. For the data of table 3.1, the FSR is 4061.17GHz or 32.55nm for the 64-array AWG and 200GHz or 1.6nm for the 9-array AWG.
It is well recognized that N×N interconnections can be achieved when the free spectral range (FSR) of an AWG is \( N \) times the channel spacing [63]. In this case the AWG is called cyclic. It is possible to show that a \( N \times N \) cyclic AWG is capable of supporting a complete routing of \( N \times N \) network using only \( N \) different wavelengths [64]. Considering equations (3-15), (3-16) and (3-18) an AWG can be cyclic if and only if the following relation is satisfied:

\[
N_{ch} = \frac{\lambda_0}{1000 \Delta \lambda dD}
\] (3-19)

Where \( N_{ch} \) is the number of channels. To make a cyclic AWG, we have to change the focal length of the star couplers to satisfy the above equation as the other parameters have restrictions.

### 3.5. Performance Characteristics of 2 Different Types of AWGs

The transmission characteristics of AWG is of interest in the design of network switches which exploit these characteristics. The most important parameters in the amplitude response are the bandwidth (BW), channel spacing, free spectral range (FSR), insertion loss and crosstalk as described in previous section. On the other hand, the most important requirement for the phase response is the linearity over a wide range of wavelengths. The first derivative of the spectral phase response is the total time delay through the device, and higher order derivatives of that is phase-induced distortion. As a result, if the phase response is linear, the time delay is constant for every wavelength and therefore there is no distortion due to phase. This is ideal for a linear system [65]. Theoretically, if there is no phase error in the fabrication process, the phase response of AWG must be quite linear as it can be concluded from the phase relation derived before.

In this section we describe the measured phase and amplitude responses of two AWGs introduced before. Also, the short pulse response of the 9-array AWG and link performance of the 64-array AWG has been measured. Our main objective however has been to find a method by which the small values of phase response can be measured as previously there had not been much work on phase measurement.
although it is very important for high data rate transmission applications. Highly accurate phase-error measurements have been made before [66], but these were only possible by integrating the device within a planar Mach-Zehnder interferometer which is a destructive method. Our measurement system can be built with standard laboratory equipment, in order to measure discrete devices easily and repeatedly.

3.5.1. Amplitude Response

Figure 3.3 shows the experimental set-up used to measure the spectrally resolved amplitude response of an AWG. A PC was used to drive the tunable laser. The light was transmitted through each input channel and measured at the output channel 3 and the transmitted power at each wavelength step was measured using an optical spectrum analyzer.

![Figure 3.3. Amplitude response measurement test set-up.](image)

The normalized transmission of a single channel is given in figure 3.4. Sidelobes had a maximum level of -30 dB below peak power. The insertion loss was 14dB including the insertion loss of AWG and misalignment and fiber lenses.

As we can observe from figure 3.4 and table 3.2, the FSR is 32.8nm which is equivalent to 4100GHz. The 3dB, 0.5dB, and 30dB bandwidths are 0.8nm or 100GHz, 0.34nm or 42.5GHz, and 2.4nm or 300GHz, respectively. The figure of merit is then calculated to be 0.142 for this AWG.
Figure 3.4. Amplitude response of 64-array AWG, input 14 to output 3.

Transmission for all input channels is given in figure 3.5. These responses are measured in the same manner and they are nearly identical to the shifted version of figure 3.4.

Figure 3.5. Amplitude response of 64-array AWG, from all inputs to output 3.

Table 3.2 contains a list of peak wavelengths for all AWG. As we can see from figure 3.5 and table 3.2 the channel spacing for this AWG is 1.6nm equals to 200GHz. The centre wavelength of each channel is normally designed to be from the ITU grid. However the designed optical length is different from the actual value due to the variation in refractive index, waveguide dimension and waveguide length caused during fabrication [67]. The centre wavelengths listed in the table are near to ITU grid...
wavelengths [68] by less than 0.1nm error which comes from both measurement and fabrication errors. The FSR, for this AWG, is not \( N \) times the channel spacing. Therefore it is not a cyclic AWG.

Table 3.2. List of peak Wavelengths which have the minimum insertion loss from every input to output number 3

<table>
<thead>
<tr>
<th>Input</th>
<th>First Wavelength(nm)</th>
<th>Second Wavelength(nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1539.4</td>
<td>1572.9</td>
</tr>
<tr>
<td>2</td>
<td>1537.8</td>
<td>1571.2</td>
</tr>
<tr>
<td>3</td>
<td>1536.2</td>
<td>1569.6</td>
</tr>
<tr>
<td>4</td>
<td>1534.6</td>
<td>1568.0</td>
</tr>
<tr>
<td>5</td>
<td>1533.0</td>
<td>1566.3</td>
</tr>
<tr>
<td>6</td>
<td>1531.5</td>
<td>1564.7</td>
</tr>
<tr>
<td>7</td>
<td>1530.0</td>
<td>1563.1</td>
</tr>
<tr>
<td>8</td>
<td>1528.3</td>
<td>1561.5</td>
</tr>
<tr>
<td>9</td>
<td>1526.8</td>
<td>1559.9</td>
</tr>
<tr>
<td>10</td>
<td>1525.2</td>
<td>1558.2</td>
</tr>
<tr>
<td>11</td>
<td>1523.7</td>
<td>1556.6</td>
</tr>
<tr>
<td>12</td>
<td>1522.2</td>
<td>1555.0</td>
</tr>
<tr>
<td>13</td>
<td>1520.6</td>
<td>1553.4</td>
</tr>
<tr>
<td>14</td>
<td>1519.0</td>
<td>1551.8</td>
</tr>
<tr>
<td>15</td>
<td>1517.4</td>
<td>1550.2</td>
</tr>
<tr>
<td>16</td>
<td>1515.8</td>
<td>1548.6</td>
</tr>
</tbody>
</table>

Figure 3.6 shows the amplitude response of 9-array AWG for all three channels. The responses for channels 1 and 3 are the same as a result of symmetric nature of the AWG. Crosstalk levels remain better than -25 dB over the measured range. The crosstalk for this AWG is worse than 64-array because it has larger length difference in the arrayed waveguides. The channel spacing for this AWG is 0.8nm equals to 100GHz. Also The FSR is 1.6nm equals to 200GHz. 3 dB, 0.5 dB, and 30 dB Bandwidths are measured to be 0.44nm or 55GHz, 0.2nm or 25GHz, and 1.12nm or 140GHz, respectively. The figure of merit for this AWG is calculated as 0.179. The performance parameters of two AWGs are summarized in table 3.3.
The possible application of this AWG in a WDM system is a wavelength interleaver as shown in figure 3.7. An interleaver can separate a single densely packed channel set onto two output fibers each with twice the channel spacing of the original input. Wider channel spacing filters will always be more readily available and less expensive. Cascading interleavers provides even further separation of the channels. An interleaver helps to increase scalability of systems [69].

As an example, if we have an AWGs similar to our 64-array AWG with 100GHz channel spacing and apply the output to this 9-array AWG, then at the output of this AWG, we will have two streams of 200GHz spaced spectrum which is easier for filtering and processing.
Table 3.3. Measured performance parameters of two AWGs

<table>
<thead>
<tr>
<th>Description of Parameter</th>
<th>16x16 AWG</th>
<th>9-Array AWG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel spacing (nm/GHz)</td>
<td>1.6/200</td>
<td>0.8/100</td>
</tr>
<tr>
<td>Free spectral range</td>
<td>32.8/4100</td>
<td>1.6/200</td>
</tr>
<tr>
<td>Crosstalk (dB)</td>
<td>-30</td>
<td>-25</td>
</tr>
<tr>
<td>3dB bandwidth (nm/GHz)</td>
<td>0.8/100</td>
<td>0.44/55</td>
</tr>
<tr>
<td>0.5dB bandwidth (nm/GHz)</td>
<td>0.34/42.5</td>
<td>0.2/25</td>
</tr>
<tr>
<td>30dB bandwidth (nm/GHz)</td>
<td>2.4/300</td>
<td>1.12/140</td>
</tr>
<tr>
<td>Figure of merit</td>
<td>0.142</td>
<td>0.179</td>
</tr>
</tbody>
</table>

3.5.2. Phase Response

In Dense WDM networks, the cascading of narrowband devices such as filters and multi/demultiplexers might result in phase induced degradation of the optical signal, specially at high bit rates, therefore a precise method for measuring the dispersion characteristics of individual optical components is necessary [70]. However less attention has been paid to phase response compared to the amplitude response of the AWG.

The AWG is basically a Mach-Zehnder based filter and because of the finite number of waveguides in the array, it is a finite impulse response (FIR) type filter. Unlike infinite impulse response (IIR) filters, there is not any relation between the phase and amplitude. In other words, the phase response cannot be derived from the amplitude response. Then, it has to be measured or calculated separately.

In AWG, as all wavelengths are diffracting and traveling in the same path, the resultant chromatic dispersion is very small. The most important point in phase response is linearity over a wide range of wavelengths. The first derivative of phase response in respect to angular frequency is the total delay of AWG:

\[ \tau_s = \left| \frac{d\theta(\omega)}{d\omega} \right| \]  

(3-20)

Where \( \theta(\omega) \) is the phase response of AWG and \( \omega \) is the angular frequency which is equal to \( 2\pi f \) and \( f \) is the optical frequency of the signal. The derivative of total delay in respect to wavelength is called dispersion, therefore:
Dispersion \( \frac{d\tau_s}{d\lambda} \) (3-21)

In an ideal system without any phase distortion, the total delay is independent of frequency and wavelength which results in zero dispersion. Non-zero dispersion causes pulse broadening which is considerable for shorter pulses or higher bit rates.

If we consider the phase relation of (3-12), then the total delay of AWG will be:

\[
\tau_s = \frac{2N_s R + N_w \left( l_s + l_o + l_{w1} + \frac{n-1}{2} \Delta L \right)}{c} (3-22)
\]

This delay seems to be constant, but as the effective refractive index in star couplers and waveguides are wavelength dependant, this causes very small variations in time delay therefore delay will be wavelength dependant, even when all the wavelengths have the same physical path.

One way of phase measurement is putting the device under test into one arm of a Mach-Zehnder (MZ) interferometer with a phase-shifter in other arm as shown in figure 3.8. The phase of phase-shifter is changing versus time as a saw-tooth function with the slope of \( b \). The input signal to the MZ interferometer will be divided equally into two arms. Each will have its own phase shift and will be added together at the output of interferometer.

\[
2\cos(\omega t) \quad \text{Output}
\]

According to the figure 3.8 the output which is summation of the signals from two arms, can be simplified as follows:

\[
Output = 2\cos\left[ (\omega + \frac{b}{2})t + \frac{\theta(\omega)}{2} \right] \cos\left[ \frac{b}{2} t - \frac{\theta(\omega)}{2} \right] (3-23)
\]
The first term is very high frequency which is not detectable by the scope. But the second term is low frequency and this term, which is actually the envelope, appears on the scope. The phase of this envelope is time-independent but related to the frequency and hence the wavelength of the input signal. If we consider one wavelength as the reference, then it is possible to measure the phase difference versus wavelength. Note that in this experiment it is very important to have linear phase shift, equal coupling into and equal loss between two arms. Any deviation causes instability and inaccuracy in the measurement. Therefore the resultant fringes are very unstable.

Figure 3.9. Experimental set-up used for phase measurement of an AWG.

To avoid these problems we have developed another setup which uses the same basics. Figure 3.9 shows the experimental set-up used in our phase measurement which is applicable to other devices with small phase responses. The main advantage of this method is that because both interfering waves are using the same path it is not sensitive to the coupler asymmetry and the length of the arms. The observation showed more stable fringes than the previous system. However, because what we are measuring is very small phase differences, even small instability may cause error. To reduce these problems, we used as little fiber as possible, fixed the fiber to avoid vibrations, protected the setup from air currents, and used a high degree of thermal insulation. The resultant fringes had good stability. To reduce the errors, each measurement has been made at least 3 times and these values have been averaged.
To construct the phase shifter, in the experiment, two meters of standard fiber were wound around a piezo-electric cylinder, 3.0 cm in diameter. A ramp voltage of up to 60V is applied across the cylinder at 330 Hz. This voltage causes a length stretch and hence a saw-tooth phase shift with the slope of $b$. The overall interference between clockwise and anticlockwise waves produces a fringe pattern. A typical fringe pattern is illustrated in figure 3.10. As the wavelength of the laser is tuned across a channel of the AWG, the fringes shift in phase. The phase response of AWG and the rest of the fiber in the loop all contribute to the measurement. To cancel the effect of the rest of the loop, we need to perform two sets of measurements: with and without AWG.

If the envelope of fringe without AWG is:

$$\cos(bt + 6) \quad (3-24)$$

Therefore the temporal position of the peaks is:

$$t_0 = \frac{mn - 6}{b} \quad (3-25)$$

Now when AWG is present, the phase of envelope is shifted by the phase of AWG as follows:

$$\cos(bt + 6 + \theta_A) \quad (3-26)$$

Therefore, the temporal position of the peaks is shifted to:

$$t_A = \frac{m\pi - \theta - \theta_A}{b} \quad (3-27)$$

Combining (3-25) and (3-27), results in:

$$\theta_A = b(t_0 - t_A) \quad (3-28)$$

In the experiment, we measured $t_0$ and $t_A$ for different wavelengths. $b$ is a parameter determined by the characteristics of the phase shifter and the applied voltage which was determined in our experiment to be 0.6981rad/ms. The phase of AWG has been calculated from the equation (3-28) and the result is shown in figure 3.11. It should be noted that this phase response is relative to the phase of the first wavelength (1561.6nm).
Arrayed-Waveguide Grating Characterization

Figure 3.10. Typical interference pattern (fringe) in phase measurement experiment.

Figure 3.11 shows the phase response across one wavelength channel of 64-array AWG. The route from input 8 to output 3 has been considered. The phase response is nearly linear in respect to the wavelength with a slope of 266 rad/nm.

![Graph showing phase data](image)

**Figure 3.11.** - Phase measured data for 64 arrays AWG.

Here we examine the results with approximate analysis. The phase response can be considered linear in respect of wavelength:

\[ \delta = A \lambda \]  \hspace{1cm} (3-29)

Where \( A \) is the slope of phase response in radians/nm. Using the general relations for delay and dispersion we have:

\[ \tau_s = \frac{A \lambda^2}{2 \pi c} \]  \hspace{1cm} (3-30)

\[ \text{dispersion} = \frac{A \lambda}{\pi c} \]  \hspace{1cm} (3-31)
From the equation (3-22) and using the values of table (3-1) and approximate value of 14mm for \( l_1, l_2 \) and \( l_3 \) we can calculate the total delay of 326.72ps for 64-array AWG. The phase slope can then be calculated approximately from equation (3-30) as 256.16 rad/nm and the dispersion will be from equation (3-31) as 0.422 ps/nm for this AWG. The approximate figure of phase response slope calculated here is near to the measured value.

3.5.3. Short-pulse Transmission Characteristics

A combination of wavelength division multiplexing (WDM) and optical time-division multiplexing is the most promising approach to Tb/s data transmission. As arrayed waveguide gratings (AWGs) represent the key component in WDM, their behavior in the OTDM environment, and also their short-pulse response, becomes an important issue. In this section, the short pulse transmission through an AWG is investigated. It was predicted by our model that if we apply pulses shorter than the delay difference between adjacent arrayed waveguides, the output will be a burst of pulses. This can be confirmed by an analytic approach and will be discussed in detail in chapter 4. Here an AWG can be considered as a number of parallel delay lines with a delay increment which can be calculated as follows:

\[
\Delta \tau = \frac{N \Delta L}{c}
\]  

(3-32)

This is exactly the inverse of FSR as can be seen from equation (3-18) considering appropriate units. On the other hand, the output of AWG is a summation of delayed version of input pulses. If the delay is very small compared to pulsewidth it is not possible to see a burst of pulses but for the pulswidths smaller than the delay increment, this burst is visible. The delay increment will be calculated as 244fs and 5ps for the 64-array and the 9-array AWG, respectively. As the 64-array AWG needs very short pulses in the order of femtoseconds which were not available at the time, we tried to verify this idea by using the 9-array AWG which needs picosecond pulses. In the experiment, short pulses with pulse-widths of 1ps, 3ps and 12.5ps have been applied to 9-array AWG and its output has been measured as shown in figure 3.12. 1ps pulse appeared at the output as a burst of pulses. Long input pulses transmitted through the AWG with little distortion and experienced only moderate broadening.
The envelope of the pulse train is determined mainly by the field distribution at the input to arrayed waveguide and transmission bandwidth of the AWG, being only slightly affected by the nature of the input signal. On the other hand, the pulse-width of the peaks inside the envelope is defined directly by the dispersion effects. In the experiment, the pulse-width of the peaks follows the theoretical curve with good accuracy. The width of the envelope increases for shorter input pulses as the component pulses are broadened by dispersion, and proportionately with longer input pulses.

![Figure 3.12. Output traces corresponding to input pulse-width of: (A) 1ps (B) 3ps and (C) 12.5ps](image)

### 3.5.4. Link Experiment

Although device characteristics are important, it is ultimately essential to use the AWG in a real system with data transmission. To observe the performance of AWG in presence of data modulated signal under different bit rates we set up the following experiment for the 16×16 AWG which was described before. A CW signal from a tunable laser source has been externally modulated at different speeds of 2.5, 5, and 10 Gb/s using a LiNbO3 MZ modulator. Then amplified and propagated down to 80 km of conventional single mode optical fiber. An EDFA has been used to compensate the fibre losses.
The signal applied to Input 8 of AWG with the wavelength of 1555.2nm, and routed to output 7. An EDFA was used to compensate for the insertion and alignment loss of AWG. Also a bandpass filter (BPF) suppresses the ASE noise of EDFAs.

Table 3.4. Summary of results of eye diagram measurements.

<table>
<thead>
<tr>
<th>Data Rate</th>
<th>Extinction Ratio/dB</th>
<th>Q factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5Gb/s</td>
<td>9.25</td>
<td>15.47</td>
</tr>
<tr>
<td>5Gb/s</td>
<td>7.94</td>
<td>12.42</td>
</tr>
<tr>
<td>10Gb/s</td>
<td>6.47</td>
<td>7.87</td>
</tr>
<tr>
<td>2.5Gb/s</td>
<td>7.53</td>
<td>9.03</td>
</tr>
<tr>
<td>5Gb/s</td>
<td>7.78</td>
<td>7.5</td>
</tr>
<tr>
<td>10Gb/s</td>
<td>5.98</td>
<td>6.78</td>
</tr>
<tr>
<td>2.5Gb/s</td>
<td>7.6</td>
<td>13</td>
</tr>
<tr>
<td>5Gb/s</td>
<td>6.99</td>
<td>8.57</td>
</tr>
<tr>
<td>10Gb/s</td>
<td>5.25</td>
<td>6.67</td>
</tr>
</tbody>
</table>

Figure 3.14 shows the measured eye diagrams at the output of modulator (point A), end of fiber (point B) and after AWG (point C) for data rates of 2.5Gb/s, 5Gb/s and 10Gb/s. The values of measured extinction ratio and Q factor of eye diagrams are summarized in table 3.4. We can conclude from the figures and the above table that AWG does not affect the quality of signals in the system for these bit rates.
Figure 3.14. Measured eye diagrams: (a) 2.5Gb/s, point A (b) 5Gb/s, point A (c) 10Gb/s, Point A (d) 2.5Gb/s, Point B (e) 5Gb/s, Point B (f) 10Gb/s, 20ps/div, 10mv/div, Point B (g) 2.5Gb/s, Point C (h) 5Gb/s, Point C (i) 10Gb/s, 20ps/div, 10mv/div, Point C.

3.6. Summary

In this chapter, we have reviewed the applications and the state of the art of AWGs. Then we have derived a closed relation for the amplitude and phase response based on our analytic approach. From this relation, it seems that the phase response of AWG is linear in respect to wavelength if the material loss is negligible and also there are not substantial errors in waveguide dimensions. Important performance parameters have been defined and their dependence on the other parameters of the AWG, especially its structure, has been discussed. The results of measurements on two different AWGs provided by Nortel Networks have been demonstrated. One of these was a 16×16 AWG router with an FSR of 4000GHz and channel spacing of 200GHz. The other one was an interleaver with FSR of 200GHz and channel spacing of 100GHz. The amplitude response of two devices and their performance characteristics have been measured. As there previously had not been much work on phase measurement of AWGs, we developed a phase measurement technique. This uses a Sagnac
interferometer and has the advantage over the conventional Mach-Zehnder method of being more stable and less sensitive to the coupler asymmetry. To reduce the errors further, each measurement has been made at least 3 times and the results were averaged. This novel method has been used to measure the phase response of a 64-array AWG which was linear in respect to wavelength with a slope of 266 rad/nm. The agreement between the measured phase slope with the approximate analytical calculated one gives enough confidence on the measurement technique. Also, to verify the prediction of the model concerning the short pulse response of the AWG, we measured the short pulse response of 9-array AWG. This measurement confirms that for the pulses shorter than the delay difference between arrayed waveguides which is 5 ps for this AWG, the output is a train of pulses. The envelope of the pulse train is determined by the field distribution among the waveguides. Finally, the performance of an optical communication link including an 16 x 16 AWG as a router for bit rates up to 10 Gb/s has been demonstrated. From these measurements, it seems that the AWG does not degrade the quality of routed signals.

3.7. References

Arrayed-Waveguide Grating Characterization


Chapter 3

Arrayed-Waveguide Grating Characterization


[40] E. A. Whiteaway, et al, "Novel AWG Interleaved Filters with a 50 GHz Channel Spacing Exhibiting High 'Figure of Merit' Pass-bands, and Low loss, Cross-talk, Dispersion, and Polarisation Sensitivity," OFC, Ecoc 2001?


CHAPTER 4

Limitations of Arrayed-Waveguide Grating

The purpose of this chapter is to investigate the performance limitations and the ultimate data rate limits of an AWG by simulation. To achieve this, a model has been developed in MATLAB. The model is based on calculating the field amplitude and phase after each stage (waveguides, star-couplers, etc). With this model, typical transmission characteristics including amplitude, phase and pulse response are calculated. Also the related performance parameters like crosstalk, bandwidth, free spectral range, channel spacing, and figure of merit have been investigated. The model results have then been verified by comparing the transmission characteristics of two AWGs by the model to those of measurements of chapter 3. The results of modeling show a good agreement with the experimentally measured data of previous chapter where available. By using this model, we have investigated the relations between performance characteristics of AWG and its structural parameters. This gives us an idea of the cause of its performance limitations and a better understanding of the device. The time domain response of AWG has also been investigated. This includes impulse response and short pulse response for both chirped and chirp-free pulses. From this model we have been able to predict, for the first time, the short pulse response of AWG which led us to the short pulse measurement of the AWG interleaver which was presented in chapter 3. Finally, the input-output pulse-width relation of AWG has been calculated to give the data rate limit of AWG. Moreover, the concept of athermalization of AWG and spectral slicing has been discussed.

4.1. Model Description

According to figure 4.1, the single-mode field at a specified input channel is considered as a signal with an amplitude and phase, and then propagated in a free propagation region (star coupler) to the point B. The output phase and amplitude of each waveguide is calculated at point C. Combined field patterns coming from all waveguides are calculated at point D, then propagated through the output waveguide.
to a specific output channel. The transmission function of AWG is considered as follows:

\[ H_{AWG} = \sum_{k=1}^{n} a_k r_k e^{-j(\beta_w l_1 + \beta_s l_{slk} + \beta_w l_{wk} + \beta_s l_{sk} + \beta_w l_o)} \]  

(4-1)

All the parameters in this equation are described in chapter 3. In the model we have taken the loss of waveguides into account which is represented by \( r_k \), although this does not affect the shape of transmission response of the AWG, as it is not wavelength dependent. Its only effect is increasing the insertion loss of whole spectrum, which will be removed in normalization. As the bending radius is more than 5 mm [1, 2], we have neglected the bending loss in our model. The propagation constant of each mode at given wavelength in the star couplers are calculated exactly using numeric solution to analytic relations of [3], but the propagation constant of arrayed rectangular waveguides calculated approximately using the effective index method [4, 5].

![Figure 4.1. Schematic diagram of an AWG.](image)

For an accurate solution we need to input all the geometric parameters. These parameters and their typical values are listed in chapter 3. In our model, we can consider an arbitrary distribution of field amplitude among arrayed waveguides which is represented by \( a_k \) whether it is Gaussian, uniform or any other distribution.
However as the star coupler is a free propagation region, the Gaussian distribution is a good approximation to the exact waveguide mode solution [6].

Knowing the focal length of the star coupler, pitch of the grating and input/output waveguides, we have calculated the exact distances between each input/output waveguide to every waveguide in the array, because the small error in these distances may cause a huge error in the result. Actually the difference between the responses of different channels is totally based on the difference in these lengths. We define:

\[ \theta_k = 2 \left[ \text{Fix} \left( \frac{n+1}{2} \right) - k \right] \sin^{-1} \left( \frac{d}{2R} \right) \]  \hfill (4-2) \\
\[ \theta_j = 2 \left[ \text{Fix} \left( \frac{N+1}{2} \right) - j \right] \sin^{-1} \left( \frac{D}{2R} \right) \]  \hfill (4-3)

Where \( \theta_k \) is the angle between the \( k_{th} \) and central arrayed waveguide from the centre of the circle and \( \theta_j \) is the angle between the \( j_{th} \) and central input/output waveguide from the centre of circle. The numbering of the arrays starts from the shortest waveguide and of the input/outputs from the nearest waveguides to the first arrayed waveguide. \( \text{Fix}(x) \) represents the integer value of \( x \) and using this ensures that one waveguide is always at the centre of the circles regardless of the number of waveguides being odd or even.

Therefore the exact length between \( k_{th} \) array waveguide and \( j_{th} \) input/output waveguide can be derived as follows:

\[ l_{ij} = R \sqrt{1 - 8 \sin \left( \frac{\theta_i}{2} \right) \sin \left( \frac{\theta_j}{2} \right) \cos \left( \frac{\theta_j + \theta_k}{2} \right)} \]  \hfill (4-4)

The total length of the \( k_{th} \) path between \( i_{th} \) input to \( j_{th} \) output is:

\[ l_{ik} = l_i + l_{ki} + l_{wk} + l_{kj} + l_j \]  \hfill (4-5)

Where \( l_i \) and \( l_j \) are the length of \( i_{th} \) input and \( j_{th} \) output waveguides. \( l_{wk} \) is also the length of \( k_{th} \) arrayed waveguide. \( l_{ki} \) and \( l_{kj} \) are the exact lengths between \( k_{th} \) arrayed waveguide and \( i_{th} \) input and \( j_{th} \) output, respectively.

We also know that the length difference in arrayed waveguides should be constant, therefore:

\[ l_{wk} = l_{w1} + (k-1)\Delta L \]  \hfill (4-6)
As a result, the difference between the $k_{ih}$ and $(k+1)_{ih}$ path from $i_{ih}$ input to $j_{ih}$ output is:

$$\Delta L_{ij} = l_{(k+1)j} - l_{(k+1)i} - l_{kl} + l_{(k+1)j} - l_{ij} + \Delta L$$  \hspace{1cm} (4-7)

Therefore the length difference depends on the input and output position. It can be concluded from the relation (4-3) that for the central input/output waveguides, $\theta_i = \theta_j = 0$ and hence $l_{kl} = l_{ij} = R$ and $\Delta L_{ij} = \Delta L$. This means that the length difference for the central input/output waveguides are exactly the same as the length difference in the array but for the other input/outputs it depends on the position of input/outputs and geometrical parameters of the star coupler and it may not be constant. However the constant path difference is a key requirement in an AWG as our model shows that the variation of more than one percent causes a huge amount of crosstalk which is not tolerable. Fortunately as we will show here, this variation is negligible and the length difference is approximately constant.

As the pitch of the grating and output/input waveguides are very small compared to focal length therefore the angles are very small, and then it is possible to approximate the relation (4-4) as follows:

$$l_{ij} = R(1 - \theta_j \theta_k)$$  \hspace{1cm} (4-8)

Therefore the length difference can be approximated as follows:

$$\Delta L_{ij} = \Delta L + \frac{dD}{R} \left[ 2F \left( \frac{N+1}{2} \right) - i - j \right]$$  \hspace{1cm} (4-9)

This implies that for any input/output other than the central ones, we have to consider an additional term for the length difference. This additional term which is due to the star coupler causes the peak wavelengths to be different and creates a space between channels or channel spacing. One disadvantage of using an AWG as a wavelength router is that the FSR for the different inputs/outputs are not the same as a result of this additional term. This is why it is very important to calculate the exact lengths in the slab. In the model we did not use the small angle approximation which was mentioned here. From the equation (4-9) it is possible to calculate the channel spacing as follows:

$$\Delta \lambda = \frac{N_r dD \lambda_{og}}{N_o R \Delta L}$$  \hspace{1cm} (4-10)
This is similar to the relation of chapter 3. The dispersion in the material refractive index with respect to wavelength is also considered in the model.

Based on the dimensions of the waveguides, four modes can in theory propagate. In the measurements, the fiber launch is optimized for zero order mode excitation. One might query why the waveguides are not set to be sufficiently thin to make them single mode to avoid this problem. In practice there are other effects such as the bend loss and the polarization sensitivity that must be taken into account. Another point is that even if a waveguide only guides the zero order TE and TM modes, one can find that the first order modes propagate over considerable distances unless they are far below cut-off [7]. The results of our model shown in the following sections are based on zero order TE mode unless stated otherwise. As the model shows and the results will be presented later, the device has good polarization independence.

Here we first compare the model results with the experimental data for the amplitude response of two AWGs. Then we investigate the performance limitations of AWG versus its geometrical data. After that the time domain response of AWG is discussed. From this the data rate limitation of AWG can be calculated.

4.2. Model Verification
To verify the model results, we compare the measured amplitude response and associated performance parameters of two AWGs with those from the model. A typical amplitude response for a 64-array AWG from model and experiment is shown in figure 4.2. Good agreement has been achieved not only in the shape of response but also in terms of the various performance parameters. Different parameters of this AWG are calculated by the model as follows: 0.5dB, 3dB, and 30dB bandwidths as 0.34nm, 0.82nm and 2.54nm respectively. The figure of merit is equal to 0.134. The peaks are matched well and crosstalk levels are nearly the same and are -30dB. The FSR is 31.8nm and channel spacing is 1.6nm from the model. These numbers are close to the measured values of chapter 3. However there are small differences. These errors are mainly due to measurement errors, restricted resolutions and some approximations in the model. It also should be noted that for the random error in length we used MATLAB random function in the model. These set of random errors are not necessarily
matched with a set of random error in the fabrication of this particular AWG chips. This is the main reason for that the response in the region out of pass-band is not following the measurement results. What is important in this region is the amount of crosstalk which is nearly the same in two cases.

Figure 4.2. Amplitude response of 64-array AWG (Input 1 to output 3) from model (Red/dashed), and measurement (Black).

Figure 4.3 shows the amplitude response of 9-array AWG. The parameters of this AWG measured from model as 0.2nm, 0.44nm and 1.04nm for 0.5dB, 3dB and 30dB bandwidths respectively. FSR is 1.6nm and channel spacing is 0.8nm. Also, figure of merit is calculated to be 0.177 and crosstalk is below -25dB. These numbers are close to experimental data of chapter 3 as well. In figure 4.3, the discrepancy in the experimental and modeling results for 9-array AWG is due to the fact that the exact structural data were not available for this device. The exact data for the 64-array AWG were available. The agreement between experimental and modeling data of 64-array AWG gives confidence on the model. The same model is used for the 9-array AWG, only the structural data are different.
4.3. Performance Limitations

Here we use the model to measure the performance dependence of AWG on its various geometrical parameters. These results show the main restrictions in improving the performance of AWG.

4.3.1. Crosstalk

Crosstalk as defined in chapter 3 is one of the main performance parameters of AWG which determines the maximum supportable number of nodes in a WDM system. The main source of crosstalk is the random error in the length of arrayed waveguides introduced during fabrication. Figure 4.4 shows the maximum level of crosstalk as a function of the maximum error in the length. As this figure shows any error more than 50nm which is about 0.1% of the length difference increases the crosstalk to more than -30dB which is not acceptable in a system applications.

Figure 4.3. Amplitude response of 9-array AWG from model (Red/dashed), and measurement (Black).
Figure 4.4. Crosstalk as a function of random error in the arrayed waveguide lengths.

Figure 4.5. shows the amplitude response for different values of random error in 64-array AWG. For an error of more than 1% of length difference, the peaks will disappear and the AWG does not function.

As shown in figure 4.5.(a), even when there is no random error, there is a small amount of crosstalk. This background crosstalk is related to number of arrayed waveguide. As shown in figure 4.6, the more waveguides results in the lower
crosstalk. In this figure, no random error in length difference has been considered to compare only the effect of number of arrayed waveguides. It should be noted that the more waveguides means the bigger chip size which is not desirable [8].

![Figure 4.6. Amplitude response of AWG for different numbers of arrayed waveguides: (a) 16 Waveguides (b) 64 Waveguides (c) 128 Waveguides.](image)

In the presence of random error in the length of waveguides, there is a limit in the improvement of the crosstalk as shown in figure 4.7 when the other parameters are fixed. The main reason for this is when we increase the number of waveguides, if the grating pitch (the separation of arrayed waveguides) is constant, then the amount of power entering the waveguides far from the central waveguide are so low that they can be ignored.

![Figure 4.7. Crosstalk versus number of arrayed waveguides.](image)

Therefore by decreasing the pitch of grating we expect to have lower amount of crosstalk which has been verified in figure 4.8.
4.3.2. Figure of Merit

Figure of merit is a parameter related to the shape of power distribution among the arrayed waveguides. As the star coupler is a free propagation region we used a Gaussian distribution of power as shown in figure 4.9. This is based on diffraction theory. Basically this determines the shape of amplitude response. The more uniform power distribution results in higher figure of merit. The shape of power distribution also affects the pulse response of AWG which will be discussed later in this chapter. This shape is dictated mainly by the free propagation nature of the star coupler. However focal length and number of arrayed waveguides can change the shape.
As a result, two parameters have more impact on the figure of merit. One is focal length of star coupler as shown in figure 4.10. The higher focal length results in higher figure of merit. When the focal length is higher the field will be diffracted more and the spot size will be higher therefore the amount of power into waveguides will be more uniform.

![Figure 4.10. Figure of Merit versus focal length of star couplers.](image)

The second parameter is the number of waveguides as shown in figure 4.11. The lower number of waveguides when the separation of waveguides are constant, results in less difference between the power for each waveguide compared to the central waveguide. This is because in this case all waveguides are near to the peak of power distribution function and therefore they see a uniform distribution, hence increasing the figure of merit. There is also a lower limit for the figure of merit because when the number of waveguides increases, some waveguides may not receive any power and they are not practically effective.
Figure 4.11. Figure of Merit versus number of waveguides.

4.3.3. Free Spectral Range (FSR)

Due to the periodic structure of the AWG, its amplitude frequency/wavelength response is periodic. The period is called the FSR that is an important parameter in AWG. The FSR depends inversely on length difference in array as shown in figure 4.12. Also shown in the figure is the dependence of the FSR on the position of input/output port. This has been explained before. The result of modeling for all possible combinations of input/outputs is reflected in table 4.1.

Figure 4.12. FSR versus length difference in array.
Limitations of Arrayed-Waveguide Grating

<table>
<thead>
<tr>
<th>Int 1</th>
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<th>Int 13</th>
<th>Int 14</th>
<th>Int 15</th>
<th>Int 16</th>
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</table>

The peak-to-peak variation of FSR between ports is from 31.19nm to 33.15nm. For the central input/outputs there is no other geometrical parameter which can affect the FSR. However the focal length, pitch of input/output waveguides and pitch of grating change the FSR for the other input/outputs. In fact, increasing the \( R \), increases the actual length difference and therefore decreases the FSR.

4.3.4 3dB Bandwidth

The bandwidth of AWG is affected mainly by the number of arrayed waveguides. The use of more guides results in lower bandwidth as shown in figure 4.13. As usual when the number of arrayed waveguides is involved, there is a limit. For this set of other parameters, any waveguides more than 64 do not have any impact. The reason behind the effect of waveguide number is that the more waveguide results in more terms in the summation which usually produces higher resolution and sharper peaks.
Also, if pitch of grating (separation of arrayed waveguides) increases, 3dB bandwidth increases as shown in figure 4.14.

The higher focal length decreases the bandwidth as shown in figure 4.15. Because this will result in more uniform distribution of power between arrayed waveguides which in turn results in sharper peaks. There is basically a trade-off between figure of merit and bandwidth.
The last parameters affecting bandwidth is the length difference in array as shown in figure 4.16. The more difference results in lower bandwidth. It was also been confirmed from the model that 3dB bandwidth varies from port to port from 0.78nm to 0.82nm for the AWG under study.

4.3.5. Channel Spacing

It can be concluded from the relation (4-10) that the channel spacing has a linear relation to the pitch of grating \( d \) and separation of input/output waveguides \( D \). It also depends inversely to the focal length and length difference in array. This has been confirmed by the model results shown in figure 4.17.
Channel spacing variation from port to port is also between 1.56nm to 1.64nm and gives an average value of 1.6nm.

### 4.3.6. Phase Response

The phase response of AWGs from model is linear with respect to wavelength in the passband region of AWG as shown in figure 4.18. The slope of phase for 64-array AWG is 264.2 radian/nm which is very close to the measured value of chapter 3.
According to a relation derived in chapter 3 for phase response of AWG, the phase response is related to effective refractive indices in slab and waveguide portion, length of input and output waveguides, focal length and length difference in array. The dependence of phase slope to various parameters are shown in figure 4.19.

\[ \theta = A\lambda \]  
(4-11)

Where \( A \) is the phase slope in radians/nm. The total delay is:
\[ \tau_s = \frac{d\theta}{d\omega} \]  
(4-12)

And the dispersion is:

\[ D = \frac{d\tau_s}{d\lambda} = \left( \frac{\omega^2}{2\pi c} \right) \frac{d^2\theta}{d\omega^2} = \frac{\lambda^2}{\pi c} \]  
(4-13)

Where \( c \) is the speed of light in vacuum and \( \omega \) is the angular frequency.

4.3.7. Wavelength Routing Table

Any router has a routing table which shows the address and protocol to route the signals from every input to any desired output. When AWG is being used as a wavelength router, we can consider the peak wavelengths of each input/output as the address which routes the signals from the input to the corresponding output. We consider a table containing all these wavelengths as the wavelength routing table of AWG. To measure this experimentally, we need to perform 256 measurements for an 16x16 AWG. The result of model for this AWG is reflected in table 4.2.

| In1 | Out1 | Out2 | Out3 | Out4 | Out5 | Out6 | Out7 | Out8 | Out9 | Out10 | Out11 | Out12 | Out13 | Out14 | Out15 | Out16 |
|-----|------|------|------|------|------|------|------|------|------|-------|-------|-------|-------|-------|-------|
| 1557.94 | 1556.14 | 1556.67 | 1555.01 | 1553.44 | 1552.34 | 1551.21 | 1547.94 | 1543.24 | 1538.74 | 1533.44 | 1528.74 | 1523.44 | 1518.74 | 1513.44 |
| 1556.14 | 1556.67 | 1555.01 | 1553.44 | 1552.34 | 1551.21 | 1547.94 | 1543.24 | 1538.74 | 1533.44 | 1528.74 | 1523.44 | 1518.74 | 1513.44 | 1518.74 |
| 1555.01 | 1553.44 | 1552.34 | 1551.21 | 1547.94 | 1543.24 | 1538.74 | 1533.44 | 1528.74 | 1523.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 |
| 1553.44 | 1552.34 | 1551.21 | 1547.94 | 1543.24 | 1538.74 | 1533.44 | 1528.74 | 1523.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 |
| 1552.34 | 1551.21 | 1547.94 | 1543.24 | 1538.74 | 1533.44 | 1528.74 | 1523.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 |
| 1551.21 | 1547.94 | 1543.24 | 1538.74 | 1533.44 | 1528.74 | 1523.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 |
| 1547.94 | 1543.24 | 1538.74 | 1533.44 | 1528.74 | 1523.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 |
| 1543.24 | 1538.74 | 1533.44 | 1528.74 | 1523.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 |
| 1538.74 | 1533.44 | 1528.74 | 1523.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 | 1513.44 | 1518.74 |

From this table it is possible to calculate the channel spacing of AWG. There is also a symmetry in wavelengths, but it is clear that this AWG is not cyclic.

4.3.8. Polarization Dependence

All the results presented so far were for TE polarization only. This section considers the polarization dependence of the device. As shown in figure 4.20, the amplitude responses of two polarizations are very similar with a small shift in wavelength. If we
compare the routing table of TM polarization which is shown in table 4.3 with that of TE mode which is shown in table 4.2, we can find that the peak wavelength shift due to polarization is between 0.03 to 0.04nm or less than 5% of the bandwidth. The FSR of different ports for TM mode is shown in table 4.4. By comparing to FSR table of TE mode, it can be found that the variation is less than 0.01nm. Bandwidth, channel spacing, crosstalk and figure of merit are not affected by polarization.

![Graph showing relative insertion loss vs wavelength](image)

Figure 4.20. Comparison between amplitude response of AWG for TE (Black) and TM (Red/dashed) modes (Input 1 to Output 3).

Table 4.3. Routing table of 16x16 AWG for TM mode calculated from the model

<table>
<thead>
<tr>
<th>Out1</th>
<th>Out2</th>
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Table 4.4. Free spectral range for all 256 combinations of input/outputs of AWG for TM mode.

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4.4. Time-Domain Response of AWG

So far, we investigated the spectral response features of AWG. To employ the device in systems with the application of OTDM and also to investigate its limits, we need to assess its time-domain response which is the subject of this section. For the time domain characteristics it is important to have the impulse and short pulse response.

4.4.1. Pulse Response

When a pulse is applied to one input of AWG, each arrayed receives a portion of the incident power. The amount of received power depends on the distribution function of the power and the position of the arrayed waveguide. At each output waveguide, there will be $n$ different pulses, separated with a delay related to the length difference in the array. As long as the pulse-width is lower than this delay, we will have $n$ different pulses, as illustrated in figures 4.21(b). But, when the pulse-width increases the pulses are going to overlap each other. When the delay become negligible compared to pulse-width, we will have a single pulse at the output. The shape of pulse or envelope of pulse train is similar to the field distribution. The time delay is roughly equal to time needed for light to travel length difference between guides which is equal to...
\[ \tau = \frac{N_e \Delta L}{c} \] where \( \Delta L \) is the length difference in array, \( c \) is speed of light in vacuum, and \( N_e \) is the effective refractive index in arrayed waveguide.

Using the values for two AWGs, we can calculate this time delay as 0.25ps for 64-array AWG and 5ps for 9-array AWG. The pulse response for two different input pulse-widths of below and above the value of inter-waveguide delay has been shown in figures 4.21 and 4.22 for 64-array and 9-array AWGs, respectively. The results for 9-array AWG show good agreement with the measurement pulse response presented in chapter 3.
It is also possible to explain this characteristic of AWG in terms of spectral response of AWG. The frequency response of AWG is periodic with the period of free spectral range (FSR). If we consider the shape of single pass-band as $H_1(f)$ and neglect the effect of phase which introduces delay, the overall response of AWG can be described as follows:

$$H(f) = \sum_{m=-\infty}^{\infty} H_1(f - mF) \quad (4-14)$$

Where $F$ is FSR and $f$ is the frequency. As we want to investigate the envelope in time domain, we need to calculate the impulse response of AWG which is inverse Fourier transform of its spectral response:

$$h(t) = \int_{-\infty}^{\infty} H(f) e^{i2\pi ft} df = \sum_{m=-\infty}^{\infty} \left[ \int_{-\infty}^{\infty} H_1(f - mF) e^{i2\pi ft} df \right] \quad (4-15)$$

By changing the variable and re-ordering the equations, we have:
According to the convolution theorem, the response of this system to an input signal of $x(t)$ is:

$$y(t) = \sum_{m=-\infty}^{\infty} h_i(t) x(t-m/F)$$  \hspace{1cm} (4-17)$$

In other word the output will be a train of shifted replica of the input with the period $1/F$ and a non-uniform amplitude determined by the inverse Fourier transform of single pass-band of the AWG. This equation can clarify some of the characteristics of AWG. To have uniform amplitude, the single pass-band should be an impulse which means the narrower the bandwidth of AWG results in more uniform train of pulses. To have impulse shape, the number of arrayed waveguides should be infinity which is neither practical nor desirable, as the number of copy of each pulse should not exceed the time gap between input pulses. Therefore we can have a case with a limited number of pulses at the output. In this case to have uniform amplitude, $h_i(t)$ should be a rectangular pulse shape. Which means the AWG single pass-band should be a sinc function. We can conclude that a sinc shape pass-band in AWG can result in more uniform amplitude for train of pulses.

In WDM applications, we have to avoid the input pulse-widths which result in a train of pulses at the output and this will set a limit to the data rates applicable to any AWG. However, this characteristic of AWG can have other applications such as repetition rate multiplication [9]. In WDM applications, normally the flat spectral response is desirable. In applications like router and multi-/demulti-plexer, the FSR should be higher than the wavelength range of WDM system to prevent interference. When the AWG is being used as interleaver lower FSR in order of channel spacing is desirable. However, in applications like repetition-rate multiplication which is a type of time interleaving, it is required that the FSR should be smaller than the input pulse bandwidth and a flat response is not desirable. As we have shown before, the best shape for the response in this case is a sinc type, and also lower bandwidth is needed. As a result, the AWG design for this application is slightly different, and in most
cases, the AWG which is optimized for WDM, might not be optimum for the repetition rate multiplication. For the latter application, two conditions should be satisfied. The first condition is to ensure a continuous train of pulses. As the output repetition rate is constant and equal to inverse of inter-waveguide delay ($\tau$), therefore:

$$n\tau R_i = 1$$  \hspace{1cm} (4-18)

And:

$$R_o = nR_i$$ \hspace{1cm} (4-19)

Where $R_i$ and $R_o$ are input and output repetition rates. The above equation implies a constant input and output repetition rate which is totally related to the number of waveguides and free spectral range. The FSR is the inverse of inter-waveguide delay. The other condition which is important in a short pulse generation is its constant amplitude. Unfortunately as it can be seen from the figures the output pulses from our AWG do not have constant amplitude. Therefore this AWG chip is not suitable for this kind of application as it was optimized for WDM applications such as interleaver.

### 4.4.2. Chirped Pulse Response

As in practical optical communications applications, pulses may have chirp, it is important to investigate the chirped pulse response of AWG. An input chirped Gaussian pulse can be considered as follows:

$$x(t) = e^{-a_0^2} e^{-jCa_0^2t^2}$$  \hspace{1cm} (4-20)

Where $C$ is the chirp value. The Fourier transform of this pulse is:

$$X(f) = \frac{1}{a} \sqrt{\frac{\pi(1-jC)}{1+C^2}} e^{-\frac{\pi^2f^2}{1+C^2}}$$  \hspace{1cm} (4-21)

Now if the filter has a Gaussian amplitude response and we consider the Taylor expansion of its phase response to the second order, it will be:

$$H(f) = Be^{-k^2f^4} e^{-\left(\theta_0 + \theta_0'f + \frac{\theta_0''}{2}f^2\right)}$$  \hspace{1cm} (4-22)

Where $\theta_0$, $\theta_0'$ and $\theta_0''$ are the values of phase, its first and second derivative, respectively, calculated at the centre frequency of the signal. Then, the output pulse in time domain is:

$$y(t) = F^{-1}[X(f) \times H(f)]$$  \hspace{1cm} (4-23)
\( F^{-1} \) denotes for inverse Fourier transform. Constant phases and amplitudes can be neglected. Also the first order derivative of phase introduces only a delay and do not have impact on the shape, therefore:

\[
y(t) = F^{-1} \left( e^{\frac{\pi^2 f^2 t^2 + jC}{1+C^2}} e^{\frac{-j\theta_0 f^2}{2}} e^{-j\frac{\theta_0 f^2}{2}} \right) = e^{-\Delta t^2} e^{-j\rho x^2}
\]  

(4-24)

As a result, the output pulse is very similar in shape to the input pulse with different parameters as follows:

\[
P = \frac{2\pi^2 C - \theta_0 a^2 (1 + C^2)}{2(\pi^2 + k^2 a^2 + k^2 a^2 C^2)}
\]  

(4-25)

\[
A^2 = \frac{\pi^2 a^2 (1 + C^2)}{(1 + P^2) \pi^2 + k^2 a^2 + k^2 a^2 C^2}
\]  

(4-26)

\( P \) is the value of chirp for output pulse. For a specific set of input chirp, pulse-width and phase, the chirp can be set to zero. \( A \) relates to the output pulse-width. It is also possible to find the conditions where the output pulse is narrower than the input pulse.

From equation (4-26), it can be concluded that the chirp may broaden the spectrum of pulse and this spectrum then may cover more than one FSR of AWG, results in train of pulses. From this, it is possible to define allowable chirp. It can be defined as the value of chirp which broadens the spectrum the input pulse to the value of FSR. This depends on the input pulse-width as well as the FSR of AWG. Apart from spectrum broadening, chirp may have another interesting effect. As the leading and trailing edges of the pulse have different frequencies, they may travel with different speed. If the leading edge travels faster, then the chirp will cause broadening of pulse in time domain. If the leading edge travels slower, then this may result in pulse compression [10]. In this case actually the dispersion of the medium and the chirp are canceling each other.

Figure 4.23 shows the chirped pulse response of 9-array AWG. As long as the input pulse-width is less than inter-waveguide delay of AWG, we have a train of chirped pulses (figures a and b). In figure b, the chirp is higher and it seems the conditions for pulse compression for each individual pulse has been satisfied, therefore the individual pulses are narrower. When the input pulse-width exceeds the inter-waveguide delay, we will have a single pulse when there is no
chirp. The chirp distorts the pulse. When the chirp increases, a train of pulses appears at the output. This is when the chirp broadened the input pulse so that its spectrum is more than one FSR. The frequency and level of these pulses depends on the value of chirp. For high value of chirp (figure f), the output pulse is completely distorted.

Figure 4.23. Chirped pulse response of 9-array AWG: (a) input pulse-width=1ps, C=5 (b) input pulse-width=1ps, C=50 (c) input pulse-width=10ps, C=1 (d) input pulse-width=10ps, C=10 (e) input pulse-width=10ps, C=-10 (f) input pulse-width=10ps, C=100.
4.4.3. Data Rate Limit of AWG

In using AWG for high performance WDM applications it is important to assess the likely maximum channel bit rates that can be achieved for given filter bandwidths. The minimum possible output pulse-width of each device determines the maximum data rate which can be processed with that device without distortion. Due to the limited bandwidth and dispersion the output pulse-width is usually different from the input.

To allow a very simple analysis of the properties of a typical AWG and also to assess those aspects of its filter performance which are important in high speed limits, an analytical form has been found which can represent the propagation of a Gaussian pulse in a dielectric waveguide [11]. This uses a Fourier transform method and Taylor expansion of amplitude response and propagation constant $\beta(\omega)$ around the central frequency of the source. The simulation is an extension of past studies of pulse propagation in single-mode fibre which, in numerical form, have been used to assess the propagation of an arbitrary input pulses [12]. However a closed form is used to determine the propagation of a Gaussian pulse from a single frequency source or that of limited bandwidth [13, 14]. However, apart from [15], these references assume a flat amplitude response for the optical fibre, including the fourth term of the expansion to investigate the effect of phase response. We use a Fourier analysis and Taylor expansion to the fourth order, and generalize that relation for any filtering device, this in turn allowing us to apply the relation to the special case of an AWG.

To introduce the approach taken in this work, a device with an overall transfer characteristic of $H(\omega) = A(\omega)e^{-j\theta(\omega)}$ can be considered as two cascaded systems consisting of a pure amplitude response, $H_1(\omega) = A(\omega)$ followed by a pure phase response $H_2(\omega) = e^{-j\theta(\omega)}$. In order to determine the pulse response, let us assume that the $1/e$ half-width of intensity for the input to the overall system is $\sigma_i$, for the output of first system is $\sigma_1$, and that of overall system is $\sigma_o$. To derive the relation between the input and output pulse-width of first system, let:

$$A(\omega) = e^{-\sigma(\omega)}$$  \hspace{1cm} (4-27)

Using a fourth order Taylor expansion we find:
\[ \alpha(\omega) = \alpha_0 + \alpha_1 \omega + \frac{1}{2} \alpha_2 \omega^2 + \frac{1}{6} \alpha_3 \omega^3 \]  

(4-28)

Where \( \alpha_0 = \alpha(0) \) and \( \alpha_1, \alpha_2, \) and \( \alpha_3 \) are respectively the first, second, and third order derivatives of \( \alpha(\omega) \) calculated at the central angular frequency of the source.

In a practical filter system, normally \( \alpha(\omega) \) is approximately a symmetric function around the central filter frequency, so that \( \alpha(-\omega) = \alpha(\omega) \) and \( \alpha_1 = \alpha_3 = 0 \). It can therefore be shown that:

\[ \sigma_1^2 = \sigma_i^2 + \alpha_2 \]  

(4-29)

Solutions can then be derived for the response to a Gaussian input pulse. For this case, \( \alpha(\omega) \):

\[ \alpha(\omega) = \frac{\ln 2}{\pi^2 B^2} \omega^2 \]  

(4-30)

\( B \) is the Full Width Half Maximum (FWHM) frequency bandwidth, then:

\[ \alpha_2 = \frac{2 \ln 2}{\pi^2 B^2} \]  

(4-31)

And:

\[ \sigma_1^2 = \sigma_i^2 + \frac{2 \ln 2}{\pi^2 B^2} \]  

(4-32)

This broadening term is due to the limited bandwidth. If \( B \to \infty \) in (4-32), \( \sigma_1 = \sigma_i \), and it is the same as when we assume a flat amplitude response. As in the single mode fiber the bandwidth assumed to be unlimited, this term has been neglected.

For the response to a non-Gaussian pulse, we can define an equivalent Gaussian bandwidth, according to equations (4-29) and (4-32), as:

\[ B_{\text{equivalent}} = \frac{1}{\pi} \sqrt{\frac{2 \ln 2}{\alpha_2}} \]  

(4-33)

For the second system with a flat amplitude response, we can use the approach of reference [16], which has primarily been applied to analyse the performance of single mode fibre. By adopting this approach for a single frequency input,

\[ \sigma_o^2 = \sigma_1^2 + \frac{(\theta_2)^2}{4 \sigma_1^2} + \frac{(\theta_3)^2}{32 \sigma_1^4} \]  

(4-34)
Where $\theta_2$ and $\theta_3$ are the second and third order derivatives of phase response calculated at central angular frequency of source.

Equations (4-29) and (4-34) can then be used to calculate the output pulse-width versus input pulse-width of an AWG. An example of the simulation of a Gaussian filter response at a series of bandwidths is shown in figure 4.24. As anticipated, for large bandwidths the output pulse-width is very high for ultra-short pulses, and it decreases to a minimum point as the input pulse width increases. Beyond that point the output pulse-width increases monotonically. The minimum transmitted pulse duration also decreases with increasing bandwidth.

As the minimum pulse-width allows an estimation of the allowed transmission bandwidth it is helpful to determine its value. This is readily achieved by combining equations (4-29) and (4-34), and setting the derivative to zero. This shows that,

$$ (\sigma_{i\min}^2 + \alpha_2)^3 = \frac{\theta_2^2}{4} (\sigma_{i\min}^2 + \alpha_2) + \frac{\theta_3^2}{16} $$

To allow a rough estimate and a closed form, we let $\theta_3 = 0$ so that,

$$ \sigma_{i\min}^2 = \frac{\theta_2^2}{2} - \alpha_2 $$

Consequently, for high bandwidths when $\alpha_2$ is small, the right term of (4-36) is positive, and a minimum can be found. Alternatively, for low bandwidths, $\alpha_2$ becomes large and the right term of (4-36) is positive, and so there is no minimum point. Thus for high bandwidths, relation (4-34) is dominant so that approximately $\theta_{e\min}^2 = \theta_2$, and for small bandwidths, relation (4-29) is dominant. Actually (4-29) represents the broadening due to limited bandwidth and (4-34) represents the broadening due to phase response.

As a result, the minimum output pulse-width for the linear phase response versus wavelength which has been used for figure (4-24) in the case of broad band system is approximately 2.3ps. As the bandwidths decrease, the output pulse-width will increases up to a value of 6ps at 147GHz which is the equivalent bandwidth of AWG.
In an AWG, the temporal profile of the output signal varies depending on the input pulse duration as mentioned before. When the input pulses are considerably shorter than the inter-waveguide delay, regular bursts of pulses are observed at the output. As the input pulses become longer, the separate peaks in the output became less distinctive, appearing as a residual substructure in the output envelope. The condition where there is a burst of pulses is not suitable for WDM applications, though it may have other applications such as repetition rate multiplication.

![Figure 4.24. Input-Output pulse-width relation for a system with linear phase response in wavelength domain and Gaussian amplitude response with frequency bandwidths: 147, 200, 500, 1000, 2000, and 4000GHz.](image)

Applying equations (4-27) and (4-28) to the experimental data of chapter 3 for 64-array AWG, $\alpha_2$ is calculated to be $6.48 \text{ ps}^2$, resulting in Gaussian equivalent bandwidth of 147GHz, according to equation (4-33). A linear phase response in the wavelength domain with the slope of -261.5 radians/nm has been calculated for this device. The output pulse-width versus input pulse-width of this AWG is shown in the figure 4.25 using analytical approach. From, that figure, the minimum output pulse-width of this AWG is calculated as 6ps. As a result, the maximum data rate which can be processed with this AWG is approximately 166Gb/s. For comparison, we have plotted the input–output pulse-width calculated directly from the AWG model by
applying Gaussian pulses with different pulse-widths. The relative difference between two curves is less than 0.7 percent.

![Graph](image)

**Figure 4.25.** Input-Output pulse-width of the AWG with FWHM bandwidth of 100GHz (Gaussian equivalent bandwidth of 147GHz) calculated by the analytical method and using the direct simulation of the AWG.

### 4.4.4. Spectral Slicing and Coding using AWG

One of the applications of AWG can be spectral slicing. If we apply a broadband pulse at one input of AWG, at each of its outputs we will have a part of its spectrum or a slice of the input spectrum. This is a sort of multi-wavelength source. Also it is possible to use this method as a pulse shaping device which will be shown in this section. Any dispersive device such as a pair of diffraction grating can be used for this application. However diffraction grating systems do not have sufficient spectral resolution for high signal spectrum efficiency. For the purpose of pulse shaping, we have to combine a number of slices to achieve a desired shape. If the number of outputs or slices is enough it is also possible to use the same method for spectral coding. In our mathematical description, we will consider a Gaussian pulse as input, AWG ports as filters with Gaussian amplitude frequency response and linear phase response, and the output frequency response will be a product of input and filter frequency response. The time domain equivalent of each signal will be derived using inverse Fourier transform. The input Gaussian pulse can be considered as follows:
\[ x(t) = A e^{-a t^2} \] (4-37)

Its Fourier transform, will be:

\[ X(f) = A \sqrt{\frac{\pi}{a}} e^{-\frac{\pi^2 f^2}{a}} \] (4-38)

Now we can approximate the response of \( k_{th} \) output of AWG as Gaussian amplitude with linear phase:

\[ H(f) = B e^{-b(f-f_k)^2} e^{iM(f-f_k)} \] (4-39)

Now the corresponding output which is the product of input and filter response in frequency domain, will be as follows:

\[ Y_k(f) = AB \sqrt{\frac{\pi}{a}} e^{-\frac{\pi^2 f^2}{a}} e^{-b(f-f_k)^2} e^{iM(f-f_k)} \] (4-40)

As a result the amplitude and phase in time domain will be:

\[ |y_k(t)| = \frac{AB \pi}{\sqrt{(ab+\pi^2)}} e^{\frac{b\pi^2 f_k^2}{ab+\pi^2}} e^{-\frac{a\pi^2}{ab+\pi^2} \left(\frac{iM}{2\pi}\right)^2} \] (4-41)

\[ \theta_k(t) = \frac{2ab\pi f_k t - M\pi^2 f_k}{(ab+\pi^2)} \] (4-42)

From this the output pulse-width can be calculated as follows:

\[ PW_k = \frac{2}{\pi} \sqrt{\frac{(ab+\pi^2)}{a} \ln(2)} \] (4-43)

Also, the relation between input and output pulse-width is:

\[ PW_k = \frac{1}{\pi} \sqrt{(ab+\pi^2)PW} \] (4-44)

From the above relations, it can be seen that amplitude is an even and phase is an odd function in terms of \( f_k \). If we combine two outputs in which they have opposite \( f_k \), we will have the same amplitude but opposite phase. Then:

\[ y_k(t) + y_{k+1}(t) = |y_k(t)| \left( e^{j\theta_k(t)} + e^{-j\theta_k(t)} \right) = |y_k(t)| \left[ 2 \cos(\theta_k(t)) \right] \] (4-45)

Hence, this is a method of pulse shaping (or coding). Any combination of outputs can be considered.
4.5. Athermalization of AWG

The precise control of center wavelength is important because AWGs multiplex and/or demultiplex densely packed optical signals with a channel spacing of about 1 nm or less [17]. Conventional AWGs have a temperature dependence of about 0.013 nm/°C, which is caused by thermally induced refractive index change in silica glass waveguides. In practical use, thermo-optic coolers or heaters are used to compensate for the temperature dependence. This introduces additional components, therefore athermal AWGs are desirable [18].

Athermal AWG requires no thermal control for practical use. The idea is using another material for a portion of arrayed waveguides with opposite thermal slope to the main material for example polymer to compensate silica [19]. The length of second material should normally be increasing like the arrayed waveguides which shapes a groove. The groove may cause an excess loss up to 2dB [20].

Here we investigate the theoretical basis of this method and apply that to our AWG using a polymeric material. Let $l_{i}$, $l_{o}$, $l_{mk}$ be the lengths of input guide, output guide, and the main portion of $k_{n}$ array waveguide, respectively. These are assumed to be the same material (e.g., SiO₂) with the same effective refractive index ($N_w$). Total number of paths is equal to the number of arrayed waveguides. $l_{w2k}$ And $N_{w2}$ are the length and effective refractive index of second material (e.g., polymer) which has been added in the middle of $k_{n_{th}}$ array waveguide for the athermalization purpose, the length should be determined. $N_x$ is the effective refractive index of star couplers in the AWG. Also $l_{si(k)}$ and $l_{so(k)}$ are the length of $k_{th}$ path in the input and output star couplers, respectively.

The optical path lengths can be derived as follows:

$$K_{th}Path = [N_w(l_i + l_o + l_{wk}) + N_{w2}l_{w2k} + N_x(l_{si(k)} + l_{so(k)})] \frac{2\pi}{\lambda} \quad (4-46)$$

$$\text{Path at} \ (k - 1)_{th} = [N_w(l_i + l_o + l_{w(k-1)}) + N_{w2}l_{w2(k-1)} + N_x(l_{si(k-1)} + l_{so(k-1)})] \frac{2\pi}{\lambda} \quad (4-47)$$

Difference between 2 paths:

$$\text{Difference} = [N_w(l_{wk} - l_{w(k-1)}) + N_{w2}(l_{w2k} - l_{w2(k-1)}) + N_x(l_{si(k)} - l_{si(k-1)}) + N_x(l_{so(k)} - l_{so(k-1)})] \frac{2\pi}{\lambda} \quad (4-48)$$
For the peak wavelengths the above difference should be a multiple integer of $2\pi$, then:

$$m\lambda = [N_w(l_wk - l_{w(k-1)}) + N_w^2(l_{w2k} - l_{w2(k-1)}) + N_s(l_{sik} - l_{s(k-1)}) + N_s^2(l_{sok} - l_{s(k-1)})]$$

(4-49)

If we want the peak wavelengths be constant over temperature variation, then the derivative of above equation respect to temperature should be zero. It is assumed that only refractive indices are temperature dependant. The result will be:

$$l_{w2k} - l_{w2(k-1)} = -\frac{1}{N'_w} [N'_w(l_{wk} - l_{w(k-1)}) + N'_s(l_{sik} - l_{s(k-1)}) + N'_s(l_{sok} - l_{s(k-1)})]$$

(4-50)

By applying the constant length difference relation of arrayed waveguides as follows:

$$(l_{w2k} - l_{w2(k-1)}) + (l_{wk} - l_{w(k-1)}) = \Delta L$$

(4-51)

We will have:

$$(l_{w2k} - l_{w2(k-1)}) = \frac{1}{(N'_w - N'_w^2)} [N'_w\Delta L + N'_s(l_{sik} - l_{s(k-1)}) + N'_s(l_{sok} - l_{s(k-1)})]$$

(4-52)

For the central input/outputs where the lengths in star couplers are constant regardless of number of arrayed waveguides, the above relation will be simplified as follows:

$$l_{w2k} = l_{w2l} + (k-1)\frac{N_w}{(N'_w - N'_w^2)}\Delta L$$

(4-53)

This results in a groove shape for the second material lengths. Also by combining this relation with (4-51), we will have:

$$l_{wk} = l_{wl} - (k-1)\frac{N_w^2}{(N'_w - N'_w^2)}\Delta L$$

(4-54)

The first and second materials have normally a positive and negative slope for their refractive index relation, respectively. Equations (4-53) and (4-54) give the optimum lengths for two material. Based on these equations and table (4-5), we have calculated the peak wavelengths of the normal silica based AWG and athermalized one and the results are shown in figure (4-26).
Figure 4.26. Temperature dependence for (a) Peak Wavelength for silica and athermalized AWGs (b) Effective refractive index of polymer and silica waveguide.

From this figure we can see the variation is 0.0159/deg for silica AWG and the peak to peak variation in athermalized AWG is 0.15 nm.

Table (4-5). Effective refractive index of star coupler, silica and polymer waveguide and peak wavelengths of silica AWG and athermalized AWG.

<table>
<thead>
<tr>
<th>Temperature Degree Centigrade</th>
<th>$N_s$</th>
<th>$N_w$</th>
<th>Peak Wavelength/nm (Silica AWG)</th>
<th>$N_{w2}$</th>
<th>Peak Wavelength/nm (Athermal AWG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.453580</td>
<td>1.451640</td>
<td>1536.920</td>
<td>1.455590</td>
<td>1537.460</td>
</tr>
<tr>
<td>4</td>
<td>1.453661</td>
<td>1.451711</td>
<td>1537.000</td>
<td>1.455421</td>
<td>1537.500</td>
</tr>
<tr>
<td>8</td>
<td>1.453716</td>
<td>1.451776</td>
<td>1537.070</td>
<td>1.455216</td>
<td>1537.530</td>
</tr>
<tr>
<td>12</td>
<td>1.453781</td>
<td>1.451831</td>
<td>1537.130</td>
<td>1.454971</td>
<td>1537.550</td>
</tr>
<tr>
<td>16</td>
<td>1.453836</td>
<td>1.451886</td>
<td>1537.180</td>
<td>1.454697</td>
<td>1537.560</td>
</tr>
<tr>
<td>20</td>
<td>1.453892</td>
<td>1.451952</td>
<td>1537.260</td>
<td>1.454402</td>
<td>1537.580</td>
</tr>
<tr>
<td>24</td>
<td>1.453957</td>
<td>1.452007</td>
<td>1537.310</td>
<td>1.454077</td>
<td>1537.590</td>
</tr>
<tr>
<td>28</td>
<td>1.454012</td>
<td>1.452072</td>
<td>1537.380</td>
<td>1.453722</td>
<td>1537.600</td>
</tr>
<tr>
<td>32</td>
<td>1.454078</td>
<td>1.452127</td>
<td>1537.440</td>
<td>1.453348</td>
<td>1537.610</td>
</tr>
<tr>
<td>36</td>
<td>1.454133</td>
<td>1.452183</td>
<td>1537.500</td>
<td>1.452933</td>
<td>1537.600</td>
</tr>
<tr>
<td>40</td>
<td>1.454188</td>
<td>1.452248</td>
<td>1537.570</td>
<td>1.452508</td>
<td>1537.600</td>
</tr>
<tr>
<td>44</td>
<td>1.454254</td>
<td>1.452303</td>
<td>1537.620</td>
<td>1.452044</td>
<td>1537.590</td>
</tr>
<tr>
<td>48</td>
<td>1.454309</td>
<td>1.452369</td>
<td>1537.690</td>
<td>1.451569</td>
<td>1537.590</td>
</tr>
<tr>
<td>52</td>
<td>1.454374</td>
<td>1.452424</td>
<td>1537.760</td>
<td>1.451064</td>
<td>1537.570</td>
</tr>
<tr>
<td>56</td>
<td>1.454429</td>
<td>1.452479</td>
<td>1537.810</td>
<td>1.450539</td>
<td>1537.550</td>
</tr>
<tr>
<td>60</td>
<td>1.454495</td>
<td>1.452544</td>
<td>1537.880</td>
<td>1.450005</td>
<td>1537.540</td>
</tr>
<tr>
<td>64</td>
<td>1.454550</td>
<td>1.452600</td>
<td>1537.940</td>
<td>1.449460</td>
<td>1537.520</td>
</tr>
<tr>
<td>68</td>
<td>1.454605</td>
<td>1.452665</td>
<td>1538.010</td>
<td>1.448905</td>
<td>1537.500</td>
</tr>
<tr>
<td>72</td>
<td>1.454671</td>
<td>1.452720</td>
<td>1538.070</td>
<td>1.448360</td>
<td>1537.480</td>
</tr>
<tr>
<td>76</td>
<td>1.454726</td>
<td>1.452776</td>
<td>1538.130</td>
<td>1.447836</td>
<td>1537.460</td>
</tr>
<tr>
<td>80</td>
<td>1.454791</td>
<td>1.452841</td>
<td>1538.190</td>
<td>1.447361</td>
<td>1537.460</td>
</tr>
</tbody>
</table>
4.6. Summary

We have developed a model based on the calculation of amplitude and phase response of field traveling from any input port to any output port of AWG. The model has then been verified by comparing some performance characteristics with the measurements of chapter 3. The performance limitation of AWG versus different geometrical parameters and manufacturing restrictions has been investigated. The main parameters limiting the crosstalk are the random error in length difference of arrayed waveguide and the number of waveguides in the array. Figure of merit which is an important parameter about the shape of amplitude response is influenced by the power distribution among the arrayed waveguide which in turn is influenced by the focal length of star coupler and number of arrayed waveguides. Free spectral range is mainly determined by the length difference and also the dimensions of waveguides or effective refractive index. As the length difference in star coupler depends on the position of input/output waveguides, the FSR also varies from port to port. Also, this difference which is very important parameter in AWG router determines the channel spacing. This was calculated exactly in the model. Channel spacing depends on the focal length, length difference in array and pitch of input/output as well as pitch of grating. The 3dB bandwidth is another important performance parameter, which relates to the pitch of grating, number of arrayed waveguides, focal length and length difference in array. We found that the phase response in the passband is linear with respect to wavelength and the slope is mainly determined by the average length from the input to output waveguide. The results of model for TE and TM mode shows the device is not highly polarization sensitive. In addition to the spectral response, the time domain response of AWG was also investigated. This includes impulse and short pulse response for both chirp-free and chirped pulses. For the input pulses narrower than the inter-waveguide delay, the output of AWG is a train of pulses. This region is not desirable in WDM application, although it can be exploited for applications such as repetition rate multiplication subject to having uniform amplitude. Combining this with the limitation due to finite bandwidth, gives the data rate limit of AWG as about 166Gb/s. We analyzed the concept of spectral slicing with an AWG theoretically and concluded that this is not only a method of constructing multi-wavelength source, but also a method for pulse shaping. Finally, the limitation of AWG due to temperature and its athermalization method has been investigated. It has been shown that by
employing a polymer material with opposite temperature slope of refractive index, it is possible to compensate the temperature dependence. The length of these waveguides is so that a groove is made in the middle of arrayed waveguides.

4.7. References


CHAPTER 5

Wavelength Conversion and All-Optical Regeneration Using DFB/SOA

To date, integrated components have been shown to provide excellent wavelength conversion and regeneration functionality, but detailed comparative studies have not been carried out to determine the precise merits of the different devices. In this chapter therefore simulation using the VPI TransmissionMaker software of Virtual Photonics Incorporation is used to investigate in detail a wavelength converter and all-optical regenerator based on cross-gain modulation in an integrated distributed feedback (DFB) laser and semiconductor optical amplifier (SOA). The software is then used to highlight the advantages of the integrated component over single devices. It is shown that for otherwise similar components, the Q factor of the converted signals are much higher in the case of the integrated device at bit rates of up to 10Gb/s, than those found in the single DFB laser and SOA. Also, it is shown that the integrated device improves not only conversion range and sensitivity, but also gives very good regeneration with a dynamic range of 8 dB in a 40km fibre span. Moreover in some cases it can increase the extinction ratio. Also, using a second SOA before DFB/SOA improves the sensitivity and gives better performance in very low input powers. This can increase the extinction ratio as well.

5.1. Theory of Wavelength Conversion in Semiconductor Lasers

In a laser wavelength converter, an input light with a different wavelength is being injected into the active region. These injected photons influence the number of generated photons of the lasing wavelength through carrier depletion. Therefore the amount of output power of the laser depends on the input power. The dependence of the converted signal power on the input power and bias current to the laser active region can be explained on the basis of rate equations. However the normal rate equations have to be modified to include the effect of external injected optical signal, as follows [1]:
\[
\frac{dS_{\text{out}}}{dt} = -\frac{S_{\text{out}}}{\tau_p} + V_g A_g \left( 1 - \varepsilon S_{\text{out}} - 2\varepsilon S_{\text{in}} \right) (N - N_0) S_{\text{out}} + \beta_{sp} BN^2
\]  
(5-1)

\[
\frac{dN}{dt} = \frac{\eta I}{qV} - \frac{N}{\tau_s} - V_g A_g \left( 1 - \varepsilon S_{\text{out}} - 2\varepsilon S_{\text{in}} \right) (N - N_0) S_{\text{out}} - V_g A_g \left( 1 - \varepsilon S_{\text{in}} - 2\varepsilon S_{\text{out}} \right) (N - N_0) S_{\text{in}}
\]  
(5-2)

Where \( V = dwL \) is the cavity volume and \( v_g = \frac{c}{n_g} \) is the group velocity. All the parameters and their typical values for an InGaAsP laser are listed in table 5.1. The carrier lifetime has also the following relation with carrier density [2]:

\[
\frac{N}{\tau_s} = AN + BN^2 + CN^3
\]  
(5-3)

Photon lifetime can be calculated from internal and mirror losses as follows:

\[
\tau_p = \frac{1}{v_g \left( \alpha_m + \alpha_{\text{int}} \right)}
\]  
(5-4)

In the steady state, where the time derivatives are zero, the carrier density rate equation (5-2), will be changed as follows (by considering \( \varepsilon = 0 \)):

\[
\frac{\eta I}{qV} = \frac{N}{\tau_s} + V_g A_g \left( N - N_0 \right) S_{\text{out}} + V_g A_g \left( N - N_0 \right) S_{\text{in}}
\]  
(5-5)

Near threshold, when the laser has not yet started lasing, the second term is negligible, then:

\[
\frac{\eta I_{\text{th}}}{qV} = \frac{N_{\text{th}}}{\tau_s} + V_g A_g \left( N_{\text{th}} - N_0 \right) S_{\text{in}}
\]  
(5-6)

As a result:

\[
I_{\text{th}} = \frac{qVN_{\text{th}}}{\eta \tau_s} + \frac{qVg_{\text{in}} \nu_p}{\eta I} S_{\text{in}}
\]  
(5-7)

Where:

\[
g_{\text{th}} = A_g \left( N_{\text{th}} - N_0 \right)
\]  
(5-8)

By using the following relation to convert photon density to optical power [3]:

\[
P = \frac{1}{2} \frac{hc \alpha_m V}{\lambda} S
\]  
(5-9)

We will have:

\[
I_{\text{th}} = \frac{qVN_{\text{th}}}{\eta \tau_s} + \frac{2g_{\text{th}} \nu_{\text{in}} p_{\text{in}}}{\eta h \alpha_m c}
\]  
(5-10)
In the absence of injected signal, where only the first term of the above equation exists, the laser needs a minimum current to start lasing which is called threshold current. This current is needed to increase the gain to the threshold value to overcome the cavity losses. The above equation shows that the threshold current linearly depends on the injected power. Also using carrier rate equation we can find that:

$$P_{out} = \frac{\eta_{in} h \alpha_m}{2 q_8 \lambda_{out}} - \frac{\eta_{in} h \alpha_m}{2 \tau_s \lambda_{out} g_{th}} \frac{\lambda_{th}}{\lambda_{out}} P_{in}$$  \hspace{1cm} (5-11)

The above equation shows the basic operation of the gain saturation process. When the input power increases, it reduces the output power and can turn the laser off. Another explanation for the process is that as the input power increases, the threshold current increases, as a result, for a given bias current, when we increase the input power we reach to the point where that current becomes below threshold and there is no lasing.

Figure 5.1. Characteristics of a laser based on rate equations: (a) Number of carriers in cavity versus bias current (b) Number of Photons in cavity vs bias current (c) Light-Current of the laser (d) Static transfer function of the laser.
Table 5.1. Parameter definitions and the values used in laser model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{out}$</td>
<td>Converted light photon density, proportional to the output power of converted wavelength.</td>
<td>$m^{-3}$</td>
<td>$3 \times 10^{21}$</td>
</tr>
<tr>
<td>$S_{in}$</td>
<td>Injected light photon density in active region which is proportional to the input signal power.</td>
<td>$m^{-3}$</td>
<td>$10^{21}$</td>
</tr>
<tr>
<td>$N$</td>
<td>Carrier density</td>
<td>$m^{-3}$</td>
<td>$1.06 \times 10^{24}$</td>
</tr>
<tr>
<td>$N_0$</td>
<td>Transparent carrier density</td>
<td>$m^{-3}$</td>
<td>$1 \times 10^{24}$</td>
</tr>
<tr>
<td>$\tau_p$</td>
<td>Photon lifetime</td>
<td>$s$</td>
<td>$3.6042 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\tau_s$</td>
<td>Carrier lifetime</td>
<td>$s$</td>
<td>$1 \times 10^{-9}$</td>
</tr>
<tr>
<td>$c$</td>
<td>Speed of light in vacuum</td>
<td>$m/s$</td>
<td>$2.99793 \times 10^{8}$</td>
</tr>
<tr>
<td>$n_g$</td>
<td>Group refractive index</td>
<td>-</td>
<td>3.7</td>
</tr>
<tr>
<td>$v_g$</td>
<td>Group velocity</td>
<td>$m/s$</td>
<td>$8.1025 \times 10^7$</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>Optical confinement of light in the active layer</td>
<td>-</td>
<td>0.56</td>
</tr>
<tr>
<td>$A_g$</td>
<td>Differential gain coefficient</td>
<td>$m^2$</td>
<td>$10 \times 10^{-20}$</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Gain saturation coefficient</td>
<td>$m^3$</td>
<td>$9.4 \times 10^{-23}$</td>
</tr>
<tr>
<td>$\eta_i$</td>
<td>Current Injection Efficiency</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>$I$</td>
<td>Bias current</td>
<td>$A$</td>
<td>0.16</td>
</tr>
<tr>
<td>$q$</td>
<td>Electron charge</td>
<td>$C$</td>
<td>$1.60218 \times 10^{-19}$</td>
</tr>
<tr>
<td>$V$</td>
<td>Active layer volume</td>
<td>$m^3$</td>
<td>$588 \times 10^{-18}$</td>
</tr>
<tr>
<td>$d$</td>
<td>Active layer thickness</td>
<td>$m$</td>
<td>$0.21 \times 10^{-6}$</td>
</tr>
<tr>
<td>$w$</td>
<td>Active layer width</td>
<td>$m$</td>
<td>$3.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>$L$</td>
<td>Active layer length</td>
<td>$m$</td>
<td>$800 \times 10^{-6}$</td>
</tr>
<tr>
<td>$A$</td>
<td>Linear Recombination Coefficient</td>
<td>$s^{-1}$</td>
<td>$10^8$</td>
</tr>
<tr>
<td>$B$</td>
<td>Bimolecular Recombination Coefficient</td>
<td>$m^3 s^{-1}$</td>
<td>$10^{-16}$</td>
</tr>
<tr>
<td>$C$</td>
<td>Auger Recombination Coefficient</td>
<td>$m^6 s^{-1}$</td>
<td>$1.3 \times 10^{-41}$</td>
</tr>
<tr>
<td>$\beta_{sp}$</td>
<td>Spontaneous emission coefficient</td>
<td>-</td>
<td>0.001</td>
</tr>
<tr>
<td>$h$</td>
<td>Plank constant</td>
<td>$j s$</td>
<td>$6.626 \times 10^{-24}$</td>
</tr>
<tr>
<td>$\alpha_m$</td>
<td>Mirror Loss</td>
<td>$m^{-1}$</td>
<td>1424.3</td>
</tr>
<tr>
<td>$\alpha_{int}$</td>
<td>Internal Loss</td>
<td>$m^{-1}$</td>
<td>2000</td>
</tr>
<tr>
<td>$I_{th}$</td>
<td>Threshold bias current</td>
<td>$A$</td>
<td>0.022</td>
</tr>
<tr>
<td>$N_{th}$</td>
<td>Threshold carrier density</td>
<td>$m^{-3}$</td>
<td>$1.06 \times 10^{24}$</td>
</tr>
<tr>
<td>$g_{th}$</td>
<td>Threshold gain</td>
<td>$m^{-1}$</td>
<td>6000</td>
</tr>
<tr>
<td>$\lambda_{in}$</td>
<td>Wavelength of injected signal</td>
<td>$nm$</td>
<td>1552.52</td>
</tr>
<tr>
<td>$\lambda_{out}$</td>
<td>Wavelength of converted signal or lasing wavelength</td>
<td>$nm$</td>
<td>1550.12</td>
</tr>
</tbody>
</table>
We solved the rate equations for the steady state numerically, to achieve the light-current, number of carrier and photons for a bulk Fabry-Perot laser with similar parameters as the quantum well laser which has been used in this chapter. The results of our modeling are shown in figure 5.1. As the aim of this chapter was to compare the performance of different structures for wavelength conversion in a system with all the components, we used the VPITransmissionMaker software for the rest of this chapter.

5.2. Device Structure and Operation Principles

The integrated DFB laser and SOA has already been investigated experimentally in the group as a wavelength converter and all-optical regeneration. The aim of this chapter is to have a detail investigation of the operation of the device to compare it with the single devices. The device consists of an 800-micron-length DFB laser monolithically integrated with a 500-micron-length SOA with independent current biasing as shown in figure 5.2. When a digitally modulated optical input signal is injected into the DFB section of the device, the input signal “1” level suppresses the DFB laser output power via gain saturation, producing a converted “0”. The output power can then recover for a “0” level input, resulting in a complementary signal at the lasing wavelength. The SOA section can cause further cross-gain mixing between the input wavelength and the output of the DFB, increasing the extinction ratio of the DFB output.

The wavelength converter is a variable input fixed output device as the input wavelength can vary across much of the range of gain spectrum, but the output wavelength is constant and equal to the lasing wavelength of the DFB section. Device is basically single wavelength. However, it can act as a tuneable wavelength converter by incorporating a tuneable laser section [4].
The switching characteristics of this device under static conditions, which is shown in figure 5.3 displays a nonlinear transfer function. This figure has a similar shape as figure 5.1 (d). The transfer characteristic of the device can allow noise removal during wavelength conversion by presenting a threshold to switching [6]. Any small noise fluctuations in the flat regions of the response are removed due to the flatness of the transfer function in these regions. For example if the average power of the input bit "0" is $P_0$ as shown in the figure, any noise in the range of about 5dB does not change the output power. The same is happening in the other flat region for the input bit "1". To have a clean output, the average powers for "0" and "1" should be in the flat regions. This means the operation of device highly depends on the power levels and extinction ratio of the input data stream. Another point which should be noted is that the level of removable noise for bits "1" and "0" is not the same and relates to their individual power level.
Wavelength Conversion and All-Optical Regeneration using DFB/SOA

This process can also allow extinction ratio improvement in addition to noise removal. Thus the device has the ability to both reshape and reamplify the input optical signal which is called 2R regeneration. A full regeneration should also perform retiming which makes it 3R regeneration. The process of extinction ratio improvement is due to a sharp decreasing edge of the curve as shown in figure 5.3. The highest extinction ratio is achievable if the average powers for bits “1” and “0” are in the flat regions as near as possible to the edges of the curve. The decreasing edge is due to DFB laser’s turning off at high input powers, which can cause some distortion as a result of turn-on delay and dynamic response of the laser particularly at high bit rates. When there is a bit “1” after a bit “0” the laser goes off and there is no problem. The problem occurs when a bit “0” occurs after a “1”. In this case the laser which is already off has to turn on. If the following bit is the same or the bit rate is low, the laser has enough time to settle down, otherwise one bit is removed or it has very low extinction ratio. This fact is demonstrated in figure 5.4. As shown in figure 5.4 (a), where the average input power is high, the laser turns off for the input bits “1” and as indicated one bit is missing in the data stream. The figure also shows that the high input power can give a better extinction ratio for the converted wavelength at the expense of higher bit error rates. One way of avoiding this problem is to reduce the input power as shown in figure 5.4(b). This prevents the laser from turning off. However as the bit “1” is no
longer in the flat region, the noises for this bit is not fully removed and the extinction ratio is very small. This figure also shows the inversion of the converted signal compared with the input signal.

![Waveform](a)

**Figure 5.4.** Converted signals compared to the input signals of a DFB/SOA for two different input average power levels, the stronger signal is the converted one: (a) Input power is 10dBm (b) Input power is 5dBm.

Apart from the dynamic response, another parameter which degrades the converted signal is the chirp. Chirp is the deviation of lasing wavelength of laser as a result of injected power. The injected signal changes the carrier density and this in turn may change the index of the medium causing variation in the lasing wavelength. To study this effect, an input sequence with a wavelength of 1552.52nm is injected into DFB/SOA as shown in figure 5.5 (a). The converted signal at a wavelength of 1550.12nm is filtered out and is shown in figure 5.5 (b). The frequency of signal at the output of the device before filtering is shown in figure 5.5 (c). This figure shows that at any given time only one wavelength is present, because the input and output wavelengths are in opposite phase, when the input is “1”, the converted wavelength is suppressed. This figure shows a variation of output frequency. This variation is less than ±10 GHz when the input signal is zero and about ±15 GHz when the input signal is “1”. The more input power produces more chirp as expected. Figure 5.5 (d) shows the frequency chirp for the converted signal.

![Waveform](b)

In conclusion, apart from the spontaneous emission, there is 2 main source of signal degradation in wavelength conversion process. One is the dynamic effect and the other is the chirp as explained in this section.
5.3. Performance Criteria

The overall performance of a digital transmission system is assessed by bit error rate. Bit error rate is determined by the RMS (Root Mean Square) average of noise or its standard deviation and the distance between signal levels. This in turn is reflected in a value called optical signal to noise ratio (OSNR) at the input to optical receiver which is defined as the peak-to-peak signal current divided by RMS noise current [7]. This form of signal to noise ratio is known as Q factor [8] which can be written mathematically as:

\[
Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0}
\]  

(5-12)

Where \( I_1 \) and \( I_0 \) are the average electrical currents in receiver and \( \sigma_1 \) and \( \sigma_0 \) are the RMS noise values for the bits “1” and “0”, respectively. If \( \rho \) is the responsivity of the receiver, then:

\[
Q = \frac{\rho(P_1 - P_0)}{\sigma_1 + \sigma_0}
\]  

(5-13)

Figure 5.5. Chirp in DFB/SOA: (a) An input sequence (b) The converted signal (c) The instant output frequency (d) Frequency chirp of converted signal.
Where $P_1$ and $P_0$ are the average optical power for the bits "1" and "0", respectively. Some papers consider $Q^2$ as the performance figure of merit criteria to emphasize the electrical power instead of optical power and some consider a dB value. We however consider the above definition in all our results in this chapter. The relation between bit error rate and $Q$ factor for a system with Gaussian noise is [9]:

$$\text{BER} = \frac{1}{2} \text{erfc} \left( \frac{Q}{\sqrt{2}} \right)$$  \hspace{1cm} (5-14)

Where:

$$\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} \, dt$$  \hspace{1cm} (5-15)

Some typical numbers are shown in table 5.2. Although the relation between BER and $Q$ factor is less accurate for non-Gaussian impairments the $Q$ factor itself is a valid criterion for the assessment of signal quality particularly when we compare two systems. For our future discussions, we use a $Q$ factor of more than 6 as acceptable values which corresponds to bit error rates lower than $10^{-9}$.

<table>
<thead>
<tr>
<th>Q factor</th>
<th>Bit Error Rate (BER)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$2.28 \times 10^{-2}$</td>
</tr>
<tr>
<td>3</td>
<td>$1.35 \times 10^{-3}$</td>
</tr>
<tr>
<td>4</td>
<td>$3.17 \times 10^{-3}$</td>
</tr>
<tr>
<td>5</td>
<td>$2.87 \times 10^{-7}$</td>
</tr>
<tr>
<td>6</td>
<td>$9.9 \times 10^{-10}$</td>
</tr>
<tr>
<td>7</td>
<td>$1.28 \times 10^{-12}$</td>
</tr>
</tbody>
</table>

The other parameter which is used in some results is extinction ratio which is defined as:

$$\rho = \frac{I_1}{I_0} = \frac{P_1}{P_0}$$  \hspace{1cm} (5-16)

This parameter is related to power penalty in a transmission system. For a system with an equal probability for "1"s and "0"s, the average power will be:

$$P_{av} = \frac{P_1 + P_0}{2}$$  \hspace{1cm} (5-17)

From (5-13)-(5-17), we can easily derive:
As we can see from the above equation, in a transmission system, for a constant $Q$, a lower extinction ratio results in higher average transmitted power. This additional power is called "power penalty". In an ideal system where the transmitted power for bit "0" is zero, there is no power penalty. However in a practical system this power is not zero, as the lasers need a bias current.

In the case of wavelength conversion in which the input power to the system is already set to a specific range, then low extinction ratio, as long as we have a good value of $Q$ should not be a problem. In this case, optical modulation amplitude (OMA) which is defined as the difference between average optical power of bits "0" and "1" can be considered instead of extinction ratio as the detectors are sensitive to the difference [10].

5.4. Characterization of DFB and SOA

VPI TransmissionMaker is used here to characterize the devices. The software enables a convenient simulation of complex optical systems. The emphasis of the software is the design of links and networks with many components like fibers and amplifiers. It uses the concept of multiple signal representation technique and has a very powerful graphical user interface (GUI). It has an extensive library of optical and electronic modules covering all the range of required components and uses a transmission line laser model (TLLM) [11]. User can specify a significant number of parameters to simulate any laser structure. We have defined the parameters so that the resultant laser and SOA can be as near to the experimentally employed device as possible. However as some of the parameters of that device were not available, we used the default values of the software which are typical values. Although this can produce results which are not similar to those of the real device, the comparison which is the main aim of this chapter is valid because we used same parameters for single devices as the integrated one. The parameters used in our modeling for both DFB and SOA sections are summarized in table 5.3. Those parameters, which have not been mentioned in this table, are the default values for the standard multi-quantum well DFB laser and SOA in the VPI software. To allow direct comparison, the single
DFB and SOA converters are assumed to have the same structure as that in the integrated device. They also have the same parameters as the table and the data rate is 10Gb/s unless otherwise stated. Also, where we use a SOA before DFB, all the parameters are the same as this SOA except the length and bias current which are 250micron and 100mA, respectively. It also should be noted that some parameters are not applicable to SOAs, which are shown as N/A in the table.

Table 5.3. Parameters used for DFB and SOA in VPI model.

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>DFB</th>
<th>SOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>LaserChipLength /micron</td>
<td>800</td>
<td>500</td>
</tr>
<tr>
<td>ActiveRegionWidth /micron</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>ActiveRegionThickness /nm</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>OneSide_SCH_RegionThickness /nm</td>
<td>210</td>
<td>210</td>
</tr>
<tr>
<td>MQWsConfinementFactor</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>SCH_ConfinementFactor</td>
<td>0.56</td>
<td>0.56</td>
</tr>
<tr>
<td>GroupEffectiveIndex</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>IndexGratingCouplingCoefficient 1/m</td>
<td>2500</td>
<td>N/A</td>
</tr>
<tr>
<td>QuarterWaveShift</td>
<td>ON</td>
<td>N/A</td>
</tr>
<tr>
<td>FixedInternalLoss 1/m</td>
<td>2000</td>
<td>2000</td>
</tr>
<tr>
<td>MQW_Materiallinewidth...</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>CurrentInjectionEfficiency</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>LinearRecombinationCoefficient 1/s</td>
<td>1e-8</td>
<td>1e-8</td>
</tr>
<tr>
<td>BimolecularRecombinationCoefficient m^3/s</td>
<td>1.0e-16</td>
<td>1.0e-16</td>
</tr>
<tr>
<td>AugerRecombinationCoefficient m^6/s</td>
<td>1.3e-41</td>
<td>1.3e-41</td>
</tr>
<tr>
<td>LinearMaterialGainCoefficient m^2</td>
<td>10e-20</td>
<td>10e-20</td>
</tr>
<tr>
<td>TransparencyCarrierDensity m^-3</td>
<td>1.5e+24</td>
<td>1.5e+24</td>
</tr>
<tr>
<td>PopulationInversionParameter</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>InitialCarrierDensity m^-3</td>
<td>1e+24</td>
<td>1e+24</td>
</tr>
<tr>
<td>Bias Current /mA</td>
<td>160</td>
<td>200</td>
</tr>
</tbody>
</table>

For the DFB section, the light-current (LI) curve and spectrum are important. The LI curve is shown in figure 5.6. According to this figure, the threshold current for this laser is 25mA. Also, the spectrum of the laser section is shown in figure 5.7 which shows a lasing wavelength of 1550.12nm.
Figure 5.6. Light current of Laser section.

Figure 5.7. Spectrum of laser section.

For the SOA section, as the gain saturation property is exploited in the conversion process, we have considered two wavelengths of 1552.52nm and 1550.12nm incident on the SOA and plotted the gain of second wavelength versus the input power of the
first wavelength in figure 5.8. The input power of second wavelength is the variable parameter. This is important to our application as it determines the conditions for extinction ratio improvement as we discuss shortly. It should be noted that in all our explanation in this chapter the second wavelength (λ₂) which is 1552.52nm contains the input data and the first wavelength (λ₁) of 1550.12nm is the converted wavelength of the devices. Also, all the powers are in dBm and gains and extinction ratios are in dB.

\[ \text{Input power of wavelength } \lambda_1 \text{ is } P_1 + P, \text{ and of wavelength } \lambda_2 \text{ is } P_1 + R. \]

According to figure 5.8, the gain of SOA section is inversely related to the power of each wavelength. Let two signals with wavelengths λ₁ and λ₂ be applied to a SOA. We assume that the input data is on wavelength λ₂ and the powers for bits “0” and “1” are \( P_0 \) and \( P_0 + R \), where \( R \) is the input extinction ratio in dB. If the input power of wavelength λ₁ is \( P_1 \) and \( P_1 + R \), then for the gain of wavelength λ₂, 4 different states are possible:

1. Input power of wavelength λ₂ is \( P_0 \) and of wavelength λ₁ is \( P_1 \) therefore the gain of wavelength λ₂ is assumed to be \( G \).

Figure 5.8. Gain of SOA for second wavelength versus the input power of first wavelength at different powers of the second wavelength.
2-Input power of wavelength $\lambda_2$ is $P_o$ and of wavelength $\lambda_1$ is $P_1 + R_1$ therefore the gain of wavelength $\lambda_2$ is $G - M_1$ where $M_1$ increases as $R_1$ increases. In respect to state 1, we are moving in the same curve to the right.

3-Input power of wavelength $\lambda_2$ is $P_o + R_1$ and of wavelength $\lambda_1$ is $P_1$ therefore the gain of wavelength $\lambda_2$ is $G - L$ where $L$ increases as $R_1$ increases. In respect to state 1, we are moving down to another curve.

4-Input power of wavelength $\lambda_2$ is $P_o + R_1$ and of wavelength $\lambda_1$ is $P_1 + R_1$ therefore the gain of wavelength $\lambda_2$ is $G - L - M_2$ where $M_2$ increases as $R_1$ increases. In respect to state 3, we are moving on the same curve to the right.

Here we derive the output extinction ratio ($R_o$) for two different situations. First situation is when the data on both wavelengths are in-phase. In this case we will have state 1 for bit "0" and state 4 for bit "1", therefore:

$$R_o = |R_i - L - M_2| \quad (5-19)$$

In this case if $R_i \leq L + M_2$ then the output will be inverted. The extinction ratio will be decreasing unless $L + M_2 \geq 2R_i$.

The second situation occurs when the data on two wavelengths are in opposite phase. In this case we will have state 2 for bit "0" and state 3 for bit "1", therefore:

$$R_o = |R_i + M_1 - L| \quad (5-20)$$

In this case if $M_1$ is greater than $L$ then the output is not inverted and the extinction ratio will be improved. Greater $M_1$ will occur for greater $R_1$. The other condition where the extinction ratio will improve is when $L - M_1 \geq 2R_i$ which means very low input extinction ratio. The above results are valid when the first wavelength is a CW in which case $M_1$ and $M_2$ will approach zero.

**5.5. Performance of DFB/SOA**

In order to investigate the performance of the device, a setup which is shown in figure 5.9 was entered into the software. A CW signal with a wavelength of 1552.52nm has been modulated with an NRZ data at a data rate of 10Gb/s (or 2.5Gb/s in some cases) using a Mach-Zehnder type modulator and propagated down a span of conventional single mode optical fiber followed by appropriate length of dispersion compensation...
fiber. The signal has then been amplified with an Erbium-Doped Fiber Amplifier (EDFA) to compensate the fiber loss, so that the average input power to the device is equal to transmitter output. This signal is the input to the DFB/SOA. At the output of the device, a new wavelength of 1550.12 nm is present which is modulated with the input data stream in addition to the original wavelength. The input wavelength is then filtered out using an optical filter. The data on the converted wavelength is then detected and monitored for the Q factor calculation and comparison with the input data where necessary. It should be noted that in some cases for the comparison purpose we excluded the optical fiber from this system. Instead, to see the effect of noise on the performance we distorted the signal with an additive white Gaussian noise (AWGN).

To assess the overall performance of the device we plotted the Q factor versus input power. This plot can give main parameters which are important in wavelength conversion and regeneration applications. If we define Q factor of more than 6 as acceptable value, then the range of input powers where the Q factor of converted wavelength is acceptable is called input power dynamic range (IPDR) of conversion. The lowest input power needed for conversion is called sensitivity. In case we need to assess the regeneration operation, we need to compare the Q factors before and after the device. In any point where the output Q factor is higher than the input, we have regeneration. According to this criteria, we can define IPDR and sensitivity of regeneration.

Figure 5.10 shows the performance of DFB/SOA in terms of Q factor and extinction ratio for two bit rates of 2.5 Gb/s and 10 Gb/s. An additive white Gaussian noise with an RMS level of 5 dBm is added to the modulated data. For the case of 2.5 Gb/s, the regeneration range is between 5 to 10.5 dBm showing an IPDR of 5.5 dB. There is a clear extinction ratio improvement in this range as well. This is just because for the
low bit rates, the dynamic response of the laser allows it to be turned off, as the bit duration is enough for the laser to settle down. As a result, in this case we can have both extinction ratio and very good Q factors.

![Graphs showing Q factor and extinction ratio for different bit rates.](image)

*Figure 5.10. Effect of bit-rate: (a) Q factor for 2.5 GB/s (b) Extinction ratio for 2.5 GB/s (c) Q factor for 10 GB/s (d) Extinction ratio for 10 GB/s.*

The regeneration range, in the case of 10 GB/s is shifted to (-1dBm to 6dBm), although the Q factors are lower than 5 and they are not acceptable. Only for a part of this range we can have extinction ratio improvement (3dBm to 6dBm). We decreased the noise level to 0dBm, -3dBm, and -10dBm. The results are shown in figure 5.11. As the noise decreases, both the input and output Q factor increase. The lower noise gives higher IPDR and better sensitivity. However as the conversion range is in the low input power region, then these power levels do not turn the laser off. As a result the extinction ratio is very low as reflected in the figures. It also should be noted when the level of noise is very low, the input Q factor is very high and consequently the improvement is very small. Therefore the device has more improvement when the input signal is noisier.
Here we investigate the effect of bias current to both devices on the performance of DFB/SOA to justify the bias current we have chosen as the default value. Figure 5.12 show the effect of DFB bias current on the performance of the device. As the bias current increases, the Q factor increases and so does the IPDR. However, there is a saturation point. From this point, any increase in the current does not improve the performance but degrades it. As a result, there should be an optimum point which has been found from the figure 5.13 as 160mA which is chosen as the default value for our simulations.
The same has been carried out for the SOA section, which is shown in figure 5.14. There is also a saturation and optimum point, which is 200mA. This current has then been chosen as a default value for our simulations.
Finally, to observe the operation of the device in a real system, we included the fiber and measured the Q factor of transmitted wavelength before and after regenerator and the results are shown in figure 5.15. We will have regeneration in the range of 0.5dBm to 8.5dBm. This gives an IPDR of 8dB for the regeneration operation. For the conversion only when the Q factor improvement is not important, the IPDR is about 12dB. It should be noted that these values are valid for 40km of fiber, and is not applicable to other length of fibers. The optimum points and IPDR and whole performance depends on the level of distortion.
5.6. Comparison with Single Devices

Figure 5.16 shows the static transfer function of DFB/SOA compared to single SOA and DFB. As can be concluded from this figure, the SOA after DFB has two effects: one is a simple amplification of about 5dB and the other effect is the extinction ratio improvement as two inputs to this SOA are in opposite phase as investigated in section 5.3. From this figure we can also conclude that a single SOA needs very high input powers and can give very small values of extinction ratio.

![Figure 5.16. Static transfer function of DFB/SOA compared with single devices.](image)

These devices have been entered into the software with a setup shown in figure 5.17 for a direct comparison. A distorted signal have been applied to all three devices to observe wavelength conversion and regeneration properties. As the input power is varied, the simulation is used to calculate the Q factor of the input and all converted signals.
A comparison of the operation of integrated and single devices is shown in figure 5.18. We have chosen a noise level of -10dBm to have conversion for all devices. For the DFB laser, we have conversion in the range of -1dBm to 5.5dBm, which gives an IPDR of 6.5dB and sensitivity of -1dBm. For single SOA, the sensitivity 2dB higher and the conversion range is from 1dBm to 17dBm, which gives an IPDR of 16dB. The Q factor of DFB/SOA output is as high as twice the best value available from the single devices. It has also better sensitivity. The conversion range is from -4.5 to 6.5 which is 11dB wide. The dynamic range is however smaller than SOA. Also, it is worth pointing out that there is an optimum point for each device in a specific circumstances. It is ideal to employ the wavelength converter for this optimum input power. This of course introduces a restriction in the system design. The optimum point for these data is 3.5dBm, 5dBm and 9dBm for DFB/SOA, DFB and SOA, respectively.

Figure 5.17. The setup used to compare DFB/SOA with single devices using VPI software.
A sample eye pattern of input data and converted data from three devices has been shown in figure 5.19. The input average power is 2dBm, and AWGN with a power of -10dBm is used. The Q factor is 13.13 for the input eye. For the converted signal, the Q factor from DFB/SOA, single DFB, and single SOA are 14.92, 6.84 and 6, respectively.

5.7. Effect of SOA before the Integrated Device

In the previous section we have shown that a DFB/SOA can give a better performance as a wavelength convertor and regenerator compared to single devices. However it requires a significant level of input power and for the low powers the extinction ratio decreases dramatically. This power requirement could be readily overcome by placing an integrated SOA at the input. As seen from figure 5.20, the transfer function of SOA/DFB/SOA is identical to DFB/SOA with 5dB shift to left. This 5dB shift means not only an improvement in the sensitivity of the same amount, but also the shift of
performance to the lower powers. We indicated before that the extinction ratio for high data rates is decreasing in the range of acceptable conversion. It can however be improved for higher input powers. Using an SOA before the device actually gives this higher power to the device.

![Graph showing input power to the device versus output power of converted wavelength in dBm.](image)

*Figure 5.20. Static transfer function of SOA/DFB/SOA compared with DFB/SOA.*

To compare the overall performance of the devices, we used a setup shown in figure 5.21. An input signal with a wavelength of 1552.52nm is distorted by a Gaussian noise and applied to both devices.

![Diagram of the setup used to compare DFB/SOA with SOA/DFB/SOA using VPI software.](image)

*Figure 5.21. The setup used to compare DFB/SOA with SOA/DFB/SOA using VPI software.*
The Q factor comparison in the presence of a -10dBm AWGN is shown in figure 5.22. The sensitivity of the device improved by 1dB. However, the maximum achievable Q factors and IPDR decreased significantly. This SOA needs to be optimised in terms of length and bias current to push the DFB/SOA to work in the optimum range of its condition, i.e., the gain and conditions of first SOA should give the output range which is in the conversion range of DFB/SOA. As the performance of the devices depend on the input power range and noise levels, the optimization process depends on the system in which they are used.

To see the regeneration operation of the device (SOA/DFB/SOA), we plotted Q factor comparison with the input data as shown in figure 5.23. This device gives Q factor improvement in the low input power range of below -1.5dBm in presence of -10dBm AWGN. It is very sensitive to the level of noise, which means it can not remove higher level of noise.

5.8 Summary
In this chapter, the operation of a wavelength converter was theoretically using a new monolithic amplifier. It was functioned at an optimum structure and operational parameters. To demonstrate all-optical regeneration, we used this converter. Further experiments were conducted.
A sample eye diagram comparison is shown in figure 5.24. The average input power to devices is -2dBm. The input eye pattern has a Q factor of 8.14 and extinction ratio of 11.95dB. The converted signal from DFB/SOA has a Q factor of 9.23 which is better than the input but the extinction ratio for this eye is as low as 1.5dB. The SOA before the device increases the Q factor to 9.97 and extinction ratio to 4.4dB. For these conditions, the SOA before device improves both Q factor and extinction ratio.

5.8. Summary

In this chapter, the operation of a laser wavelength converter has been investigated theoretically using a rate equation model. Then, after a description of the device structure and operational principles of DFB/SOA as a wavelength converter and optical regeneration, we used the VPI TransmissionMaker software to investigate the
performance of the device. This software was used because it models all the system components including fiber, amplifier and optical filters. Although some parameters of the real device were not available and we instead used the default values of the software, this should not affect the main results which are the comparison of the single devices and the integrated one.

The main causes of the performance degradation in the wavelength conversion operation have been identified. Apart from the spontaneous emission, they are dynamic effect of the laser and frequency chirp. Effects of dynamic response depend on the level of the input power, bit rate and bit pattern. The frequency chirp increases with input power. Therefore the overall performance of the converted signal depends not only depends on the input signal and noise power, but also on the bit rate of the input signal. We investigated the conditions under which the SOA can improve the extinction ratio and shown that even if the power levels condition are suitable for extinction ratio improvement, the dynamic response does not allow this to happen for high data rates. We have then compared the performance of integrated DFB/SOA with the single devices. The integrated device has very high Q factors of as high as twice the single devices. It also has better sensitivity and higher IPDR. Compared to a single SOA, the integrated device needs much lower input powers to function and does not need an additional CW source. We have also shown that it is possible to improve the sensitivity of the DFB/SOA up to 5dB by integrating a SOA before the device. This however increases its sensitivity to noise level causing performance degradation, and also decreases the dynamic range. This SOA can in some cases increase the extinction ratio.

5.9. References


CHAPTER 6

Regenerative Routing

This chapter which is in fact the main aim of this thesis, demonstrates a novel prototype of a regenerative dynamic wavelength router incorporating a 16×16 AWG and a tunable wavelength converter using a Sampled-Grating Distributed Bragg Reflector (SG-DBR) laser. After characterization of the laser, its operation as a tunable wavelength converter is investigated. A main drawback of this converter which is its input wavelength sensitivity is also discussed. Finally, the switch is assessed for 16×16 routing and shows an improvement of $Q^2$ value up to 9.5dB even for very low input signal $Q$ factors. $Q$ factor measurements as a function of received power show that for low received powers where the S/N ratio is poor, a good improvement in the signal quality is achieved because of regeneration. An input power dynamic range (IPDR) of about 10dB for regeneration is demonstrated for this router.

6.1. Tunable Wavelength Conversion

There is currently considerable interest in the development of optical routers, particularly for use in packet switched environments. A combination of wavelength-agile wavelength converter with a passive wavelength router such as AWG can provide a large space switch without any other technology [1]. In this switch, the choice of the wavelength on wavelength conversion sets the output path from the passive wavelength router and hence ensures that the packet reaches its required destination. In addition, it has been recognized that tunable wavelength conversion is essential for reducing the complexity of photonic WDM packet switches under bursty traffic by reducing the number of required delay lines as buffers [2]. It is also an essential subsystem in order to avoid wavelength blocking by dynamically converting the wavelength when it is necessary. Moreover, it can ease the network management by assigning the wavelengths globally rather than locally. Basically, the wavelength converters needed in packet switched networks have to be agile and the output wavelength has to be tuneable with switching times in the order of nanoseconds.
Tuneable wavelength conversion has been demonstrated using four-wave mixing in a fibre [3], SOA [4] and semiconductor-fibre ring cavity [5]. These configurations generally require one or two pump signals. Cross-gain modulation in a laser is much simpler and does not need a CW laser. However the degradation of extinction ratio is a problem. Tuneable wavelength conversion for data rates up to 10Gb/s has been demonstrated by using a grating assisted coupler sampled reflector (GCSR) [6] and a super structure grating DBR (SSG-DBR) laser [7]. In this chapter we used a sampled SG-DBR laser to demonstrate tuneable wavelength converter.

In addition to wavelength conversion, it has become apparent that the widespread use of routers will be enhanced if regeneration is provided. This is important as in many networks, path lengths vary and there is a need for regeneration to ensure that packets can be routed through arbitrary link lengths to required destinations. It is desirable to accomplish both wavelength conversion and regeneration using a single device. The work in this chapter demonstrates a tuneable wavelength conversion with regeneration property using a single chip SG-DBR laser. First we introduce the characteristics of the device under test and its operational principles as a tuneable wavelength converter and regenerator. Then we use the device in a real system together with an AWG to prototype a regenerative wavelength router. This scheme not only provides the wavelength routing functionality needed in a packet-based system, but also the data regeneration which is very important in such networks.

6.2. SG-DBR Laser Characterization

Tunable lasers covering a wide range of wavelengths are an essential part of WDM systems. They can increase the functionality and flexibility of these systems. This is firstly because they can reduce the number of spare laser sources in the inventory of network providers which is particularly important when the channel spacing reduces. With the progress of the technology, the number of WDM channels may increase to around 200-300. This will result in a higher number of sources with different wavelengths. Therefore a network provider will need to have a huge number of spare lasers in its inventory for the case of any problem. With tunable lasers it is possible to reduce the number of spares covering all the range of wavelengths used in the system. For this application however, re-settable wavelength lasers are enough and there is no
need for dynamic tuning. The second and more important reason to use a tunable laser is its application to dynamic wavelength routing which is of interest to this thesis. A tunable laser needs to fulfill a number of requirements to be suitable for such applications. The main requirements for a tunable laser can be classified in four groups: The first requirement group is to have longitudinal single-mode operation, namely with high side mode suppression ratio (SMSR) of more than 30dB, high coupled output power to the fiber, high intensity modulation bandwidth compatible for data rates more than 2.5Gb/s and switching times in nanosecond range. The second group which is its tunable operation criteria includes having a tuning range of at least 30nm, stability of wavelength channels, a higher number of accessible ITU grid channels, and quasi-continuous tuning by steps defined by the channel spacing. The third group considers the transmission system criteria which include lower output power variation across the tuning range of less than 3dB, high reliability of the device in terms of power, threshold current and accessible wavelengths and low variation of dynamic effects such as chirp and extinction ratio over the tuning range. The fourth group relates to its simplicity in manufacturing, mass-production, and characterization such as the number and complexity of control currents [8].

A simple way of having a tunable laser is to use an array of DFB lasers in which different wavelengths can be selected as they are needed. In this approach a huge number of laser chips are needed in order to cover a wide range. Another way is using three-section DBR lasers with a tuning range of in the order of 8-10nm. These tunable lasers are single devices but do not cover the entire range needed. As a result, the ideal solution is the widely tunable laser technology.

There are two main viable approaches to this technology: The first approach is sampled grating DBR or Super Structure Grating DBR (SSGDBR) lasers which employ multi-element mirrors. The SSGDBR is very similar to SGDBR with phase modulation of the gratings rather than the amplitude modulation used in the SGDBR. However, the formation of these phase gratings is more complex. As a result, the SG-DBR lasers are easier to manufacture. The second approach is to use the Grating Coupled Sampled Reflector (GCSR). The GCSR structure is relatively complex with two vertical waveguides, three different band-gap regions, three changes in lateral structure, and two different gratings. It is significantly more difficult to fabricate than
the SG-DBR laser. Both approaches can provide up to a 100nm tuning range, have very high side mode suppression ratio (SMSR) and have a 4 control electrodes. However, the SG-DBR which is the first monolithic device with tuning range of over 30nm, is the simplest to produce, provides higher output power and can easily be integrated with modulators, amplifiers, etc [9].

A widely tunable DWDM laser presents an inherently difficult problem because conceptually, it must be made more sensitive than is required to cover a narrower tuning range; at the same time, very precise wavelength selection and high stability is required. The SG-DBR overcomes this conflict by using a tuning mechanism with two degrees of freedom. Instead of using one “knob” with the really fine control required to select the channel, two “knobs” with courser control are used in tandem. This is very similar to a row and column address in a matrix. In this way the tuning sensitivity required to achieve one-hundred 50GHz spaced channels (equivalent to 40nm) in a SG-DBR is actually less than that of a conventional DBR that can obtain only twenty 50GHz channels (equivalent to 8nm).

In the experiment demonstrated in this chapter we used a SG-DBR laser provided by Marconi-Caswell (Now a part of Bookham Technology, UK). Figure 6.1 shows a typical schematic of the SG-DBR laser. It is made up of a front grating, rear grating, gain and phase sections. The gratings are what give the laser its name, “sampled grating”. A conventional DBR mirror is formed by a continuous grating having a narrow reflectivity spectrum that is used to select the desired ITU channel. This mirror can be tuned electrically over a maximum range of about 8-12nm.

![Structural view of a sampled-grating DBR laser.](image)
A sampled grating is a modification of the continuous grating such that grating teeth are periodically removed along the length of the grating, i.e. the grating has been “sampled” as shown in figure 6.2. By sampling the grating, multiple reflection peaks are formed. These peaks are spaced apart in wavelength at a period inversely proportional to the period of the sampling.

The front and rear gratings of the laser are sampled at different periods such that only one of their multiple reflection peaks can coincide at a time as shown in figure 6.3. This is known as the Vernier effect. In this way the desired ITU channel can be selected by tuning the two gratings. The laser operates at a wavelength where a reflection peak from each mirror coincides. With the injection of current in one grating, this peak will move allowing the laser to select another cavity mode. This gives the coarse tuneability.
The power reflection of a sampled grating is [10]:

\[ R_s = - \sum_{p=-\frac{n+1}{2}}^{\frac{n+1}{2}} \frac{j\kappa_p^* \tanh[\sigma_p L_g]}{\sigma_p + j\delta_p \tanh[\sigma_p L_g]} \]  

(6-1)

Where \( n \) is number of samples, \( L_g \) is the total length of sampled grating. \( \delta_p \) and \( \sigma_p \) are defined as follows:

\[ \delta_p = \frac{2n\alpha_{\text{eff}}}{\lambda} - j\frac{\alpha}{2} \frac{\pi}{\Lambda} - \frac{\pi p}{Z_0} \]  

(6-2)

\[ \sigma_p = \sqrt{|\kappa_p|^2 - \delta_p^2} \]  

(6-3)

Where \( \lambda \) is the wavelength, \( n_{\text{eff}} \) is the effective refractive index, \( \alpha \) is the net propagation power loss, \( \Lambda \) is the period of un-sampled grating and \( Z_0 \) is the interval between sub-gratings. \( \kappa_p \) is the coupling constant of a sub-grating which is:

\[ \kappa_p = \kappa_s \frac{Z_1}{Z_0} \frac{\sin(\pi p Z_1 / Z_0)}{(\pi p Z_1 / Z_0)} e^{-j p Z_1 / Z_0} \]  

(6-4)

Where \( \kappa_s \) is the coupling constant of the continuous, un-sampled grating, \( Z_1 \) is the length of a sub-grating, and \( Z_1 / Z_0 \) is called the duty cycle of sampled grating. A typical spectrum of our SG-DBR is shown in figure 6.4.

![Figure 6.4. A typical spectrum of SG-DBR](image)

Experimentally, to see the tuning operation of the output wavelength, we measured the wavelength versus different bias currents applied to the front and rear grating and the results are shown in figure 6.5. The bias current to gain section is 70mA and no
current applied to phase section and the other grating for each figure. These results also indicate the quasi-continuous tuning of this laser. The wavelength changes versus bias currents of rear and front gratings as a step function and not continuously. The phase section bias current covers the range between the discrete wavelengths which is not more than 8nm.

Figure 6.5. Measured peak wavelength versus: (a) Front grating bias current (b) Rear grating bias current.

As in any laser, the light-current curve is important and for the laser under test is shown in figure 6.6 which shows a threshold current of 25mA when the bias current to the other sections are zero.
6.3. Wavelength Conversion by SG-DBR Laser

Tunable wavelength conversion and regeneration of high bit rate signals can be achieved using wavelength tunable semiconductor lasers. Here, a SG-DBR laser which is characterized in the previous section is used. The wavelength conversion principle is conceptually simple. The theory of conversion in SG-DBR laser is similar to that of any normal laser as discussed in chapter 5. The main difference is its mirrors which are sampled gratings. The mirrors however do not affect the conversion operation. Their main impact is the wavelength selectivity which not only determines the output wavelength of the laser but also can affect the amount of coupled power of the input wavelength into the laser cavity. For the conversion operation, the laser is biased above threshold and emits at a specific wavelength. When light is injected into the laser cavity, it forces the laser to switch off as a result of saturation. Thus if a bit “1” is injected, the output at original wavelength of laser will be suppressed and if bit “0” is injected the laser will emit at its lasing wavelength.

To investigate the wavelength conversion operation in steady state, the static transfer function of laser is useful. It is the output power of lasing wavelength versus the input power. For the SG-DBR laser under investigation in this chapter, the static transfer function for three different input wavelengths, is shown in figure 6.7. According to this figure, in addition to wavelength conversion, it is also possible to have noise
removal and possibly extinction ratio improvement or 2R regeneration. The input
power sensitivity varies by changing the input wavelength. Output wavelength in this
experiment was set to 1556.8nm which means the current setting has not been
changed while the input wavelengths were different.

Figure 6.7. Static transfer function for different input wavelengths while the output
wavelength was 1556.8nm.

Figure 6.8 shows some sample eye diagrams of conversion for different input and
output wavelengths, where the data rate was 2.5Gb/s. This figure shows that the
performance for up-conversion (where output wavelength is larger than the input one)
and down-conversion (where output wavelength is smaller than the input one) is
slightly different. This can be explained from the theory of wavelength conversion.
According to equation (5.9), the relation between input and output powers is as
follows:

\[
P_{out} = \frac{\eta_i h c \alpha_m}{2q g_{th} \lambda_{out}} - \frac{V N_{\text{th}} h c \alpha_m}{2 \tau \lambda_{out} g_{th}} - \frac{\lambda_{in}}{\lambda_{out}} P_{in}
\]

(6-5)

This equation shows that the linear slope of static transfer function depends on the
ratio of input and output wavelengths. This ratio is more than one for down-
conversion and less than one for up-conversion. This can result in different
performance for up- and down- conversion.
The SG-DBR laser has a broad tuning range of 40nm, the output wavelength being tuned by the selection of bias current to four different sections. It should therefore be possible to achieve wavelength conversion from any input wavelength to any output wavelength. Consequently, this approach is expected to give a variable-input variable-output wavelength converter which is ideal. However, the experiment shows that the conversion property depends on the input wavelength. One way of avoiding this problem has been suggested by using a DFB wavelength converter at the input to give a constant wavelength into SG-DBR laser at which the SG-DBR can have conversion.

The sensitivity of conversion to the input wavelength is investigated experimentally. For a specific set of currents where the output wavelength is 1555.2nm, a CW signal was injected into the laser. At the output of the laser, the lasing wavelength was filtered out and its power was measured. The input wavelength was swept in a 50nm range while all other parameters were constant. The result is shown in figure 6.9. The more suppression of the lasing wavelength means the better conversion with higher extinction ratio. As it can be concluded from this figure, the conversion for this laser
can only happen in 3 wavelengths with different levels of extinction ratios. The best result was in wavelength 1548.25 which was used in the experiments of this chapter.

![Image](image.png)

*Figure 6.9. Input wavelength sensitivity of wavelength conversion in SG-DBR laser.*

To explain this phenomenon, consider the spectrum of SG-DBR laser which shows a strong peak at oscillating wavelength of $\lambda_0$. It has also some sub-peaks at wavelengths $\lambda_1, \lambda_2, \ldots$, which are at the reflection peaks of rear grating. As it was explained in the operation of the laser, the main peak is at a wavelength where the peaks of both gratings coincide, which is a unique wavelength. The sub-peaks are where the rear grating has peak but the front grating does not. These wavelengths actually see a half mirror in laser producing a weaker output. These wavelengths need lower power to saturate the laser as they have more confinement in the cavity.

It is also important to look closer to this wavelength to find the sensitivity to the input wavelength drift which is shown in figure 6.10. We believe that the shape of this figure is determined by the shape of reflection peak of rear grating. Any drift from the central wavelength reduces the extinction ratio dramatically. When a CW signal is modulated by data, its spectrum expands. As a result the higher the data rate, the higher the drift and the lower the extinction ratio. This can be the main limiting factor for the wavelength conversion data rate of this device. The experiment shows that for data rates more than 5Gb/s, the converted signal is not acceptable for this laser. This input wavelength sensitivity is the main disadvantage of using this laser as wavelength
converter compared to DFB laser. The DFB laser is a wide-band converter limited only by the gain bandwidth of the active region as explained in chapter 5.

-10
-15
-20
-25
-30
-35

1548.2 1548.22 1548.24 1548.26 1548.28 1548.3
Wavelength of Input Signal/nm

Figure 6.10. Sensitivity to input wavelength drift.

6.4. Regenerative Routing using SG-DBR and AWG

It is possible to construct all-optical wavelength routed regenerative space-switches, which demonstrate the flexibility and functionality required for future networks. This can be achieved by combining compact wavelength-tuneable regenerators with passive optical routing components such as arrayed waveguide gratings. Here tuneable wavelength conversion of an incoming data stream is used with the output wavelength being set according to incoming header information. The choice of the wavelength on wavelength conversion then sets the output path from a passive wavelength router such as an arrayed waveguide grating (AWG) and hence ensures that the packet reaches its required destination in a regenerated form.

By placing the wavelength tunable regenerative component discussed in previous section at the input to the passive routing element, a data signal on any of the input channels can be routed to any of the output channels by converting to the appropriate wavelength and then passing through the passive router. Figure 6.11 shows the experimental setup used for this demonstration. A tunable laser source set at a wavelength of 1548.25nm is externally modulated using a LiNbO3 Mach-Zehnder intensity modulator with non-return-to-zero PRBS data at 2.5Gb/s or 5Gb/s. The data
rate was limited by the available operating speed of the laser which in turn may be limited by the input wavelength sensitivity as discussed before. This signal is amplified and filtered in order to suppress spontaneous noise, then propagated along 80km of single mode fiber (SMF) so that the performance of the switch on impaired signals can be assessed. At the end of the link, the received data is first amplified using an EDFA to compensate for coupling loss and then this data, with a degraded Q factor, is coupled into the SG-DBR laser. At the output of the laser, a converted signal with modified Q factor is generated at a wavelength of 1555.2 nm, determined by a particular setting of bias currents of four sections of the laser. The output signal which contains two wavelengths, is then applied to input 7 of a 16×16 AWG, the converted wavelength causing the signal to be routed to output number 8. The other wavelength is filtered out by AWG without the need for another filter. The response of the AWG for these particular input/output pair is shown in figure 6.12. Varying the tunable laser wavelength allows routing to different outputs of the AWG. The regenerative functionality makes this approach a highly attractive solution to the demand for all-optical routing sub-systems. The static transfer function of the wavelength converter for the input wavelength of 1548.25 nm and output wavelength of 1555.2 nm is shown in figure 6.13.

![Experimental setup](image)

*Figure 6.11. Experimental setup used (BPF: Band-Pass Filter)*
To assess the operation of the conversion and routing system, we have measured eye-patterns and the corresponding Q factors at the output of optical fiber and router. Typical eye-patterns are shown in the figure 6.14. The Q factor improves from 5.62 to 9.33 for 2.5Gb/s and from 5.47 to 7.44 for 5Gb/s. The corresponding $Q^2$ values improves from 15dB to 19.4dB for 2.5Gb/s and from 14.76dB to 17.43dB for 5Gb/s. This gives an improvement of 4.4dB and 2.67dB for 2.5Gb/s and 5Gb/s, respectively.
In order to assess further the regenerative qualities and dynamic range of the router, the Q factor of the signals before and after the switch have been plotted as a function of received optical power and shown in figure 6.15. A considerable improvement of the signal quality is achieved, particularly at lower received powers, indicating the potential of the approach. At both data rates the router has an input power dynamic range (IPDR) of about 10 dB. The $Q^2$ value improves up to 9.5 dB and 8 dB for data rates of 2.5 Gb/s and 5 Gb/s, respectively. As indicated in the figures the improvement is much higher for lower input powers where the S/N ratio is much lower and in fact regeneration is much needed. Also as data rate increases the output Q factor decreases and the observations show that for this particular laser chip, the Q factors for 10 Gb/s are less than 6 which is not acceptable.
6.5. Summary

In this chapter, a widely tunable SG-DBR laser which is one of the best available types of tunable lasers is characterized. Its main tuning property is demonstrated. The output wavelength is determined by setting the bias currents to 4 different sections, i.e., front and rear gratings, phase section and active region. The lasing wavelength varies in a step-wise function in respect to the gratings bias currents. The phase section tunes the wavelength across each step which is about 8nm.

The device has then been used as a tunable wavelength converter. Despite expectations, it can not operate as a perfect variable-input-variable-output wavelength converter. This is due to its input wavelength sensitivity which has been investigated experimentally. The device operates as a wavelength converter only at peak wavelengths of the rear grating. It is also sensitive to the input wavelength drift which
may determine its ultimate data rate limit. The cross-gain modulation normally introduces chirp which was not investigated separately, but the impairments due to chirp are contributing in the overall quality of signal. Using this wavelength converter and an AWG router, a dynamic wavelength routing has been demonstrated for data rates up to 5Gb/s limited by the speed of laser which in turn may be determined by the input wavelength sensitivity. The scheme is potentially extendable to high port count switch architectures with scope for cascaded operation. In addition to dynamic routing which is essential for a packet-based system, this approach provides regeneration. The Q factor measurements show a considerable improvement in the quality of converted signal compared to that of input signal, particularly in the case of low input S/N ratio where the regeneration is much needed. The $Q^2$ value improves up to 9.5dB and 8dB for data rates of 2.5Gb/s and 5Gb/s, respectively.

6.6. References

The main points of the experimental and modeling work presented in chapters 3, 4, 5 and 6 are concluded in this chapter. Also the possible future approaches to continue this work are suggested.

7.1. Conclusions

Future optical networks require high performance and low-cost components for performing a variety of all-optical functions such as wavelength conversion, routing, and signal regeneration. The requirements are for simple optical processing at bit rates beyond the bandwidth of presently available electronics. As concluded in chapter 1, there is a distinct role for a dynamic wavelength routing subsystem allowing the future realization of highly functional packet-based WDM networks. The main components of such subsystem are wavelength selective switches and wavelength converters. In this thesis, different technologies for wavelength selective switches have been discussed. They can be based on discrete filters and integrated devices. Among them the AWG seems to be the technology of choice particularly for large-scale switches. As a result a part of this thesis focused on detail investigation of the AWG. Also, we have investigated the main techniques for wavelength conversion and concentrated on a single chip component that consists of a distributed feedback laser integrated with a semiconductor optical amplifier. This device shows excellent performance for use as a signal regenerator and wavelength converter. Finally, a regenerative wavelength-switching node has been demonstrated which makes use of tunable wavelength conversion and passive wavelength routing. This shows promise for uses in future photonic packet switching architectures.

In chapter 3, we have reviewed the applications and the state of the art of AWGs. Then we have derived a closed relation for the amplitude and phase response based on our
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analytical approach. From this relation, it seems that the phase response of AWG is linear if the material loss is negligible and also there are not substantial errors in waveguide dimensions. The main important performance parameters of an AWG have been defined and their dependence on the other parameters of the AWG, especially its structural parameters has been discussed. The results of measurements on two different AWGs provided by Nortel Networks have been demonstrated. One of these was a 16×16 AWG router with FSR of 4000GHz and 200GHz channel spacing. The other one was an interleaver with FSR of 200GHz and channel spacing of 100GHz. The amplitude response of two devices and their performance characteristics have been measured. As there previously had not been much work on phase measurement of AWGs, which is important in high-speed applications, we have developed a phase measurement technique. The setup based on a Sagnac interferometer. The output fringes shift in time according to the phase of AWG. By measuring the time shift while varying the wavelength, it is possible to calculate the phase response of the device. As the calculations are based on the difference between two sets of measurements, it has less error than the conventional methods. This novel method has been used to measure the phase response of the 16×16 AWG. The agreement between the measured phase slope with the approximate analytical calculated results give enough confidence on the measurement technique. Also, to verify the prediction of our model concerning the short pulse response of the AWG, we have measured the short pulse response of AWG interleaver. This measurement confirms that for the pulses shorter than the delay difference between arrayed waveguides, the output is a train of pulses with an envelope which is determined by the field distribution among the waveguides. Finally, the performance of an optical communication link including an 16×16 AWG as a router at bit rates up to 10Gb/s has been demonstrated. From these measurements, it seems that the AWG does not degrade the quality of routed signals.

Chapter 4 presents a model which was developed based on the calculation of the amplitude and phase response of field traveling from any input port to any output port of AWG. The model has then been verified by comparing some performance characteristics with the measurements of chapter 3. The performance limitation of AWG versus different geometrical parameters and manufacturing restrictions has been investigated. The main
parameters limiting the crosstalk are the random error in length difference of arrayed waveguide and the number of waveguides in the array. Figure of merit which is an important parameter about the shape of amplitude response is influenced by the power distribution among the arrayed waveguide which in turn is influenced by the focal length of star coupler and number of arrayed waveguides. The free spectral range is mainly determined by the length difference and also the dimensions of waveguides or effective refractive index. As the length difference in star coupler depends on the position of input/output waveguides, the FSR varies from port to port. Also, this length difference which is very important parameter in the AWG router determines the channel spacing. This was calculated exactly in the model. The channel spacing depends on the focal length, length difference in the array and the pitch of the input/output as well as the pitch of the grating. The 3dB bandwidth is another important performance parameter, which relates to the pitch of the grating, the number of arrayed waveguides, the focal length and the length difference between arrayed waveguides. We found that the phase response in the passband is linear with respect to wavelength and the slope is mainly determined by the average length from the input to output waveguide. The pulse response of AWG which is important in time domain applications has been investigated for both chirp-free and chirped pulses. For input pulses narrower than the inter-waveguide delay, the output of AWG is a train of pulses. This range of input pulses is not desirable in WDM applications. As a result this gives a lower limit on the input pulse. The other limiting factor for the supported speed of an AWG is its finite channel bandwidth. The minimum bit rate among these two limits gives the data rate limit of the AWG. We have calculated this data rate limit. We analyzed the concept of spectrum slicing with AWG theoretically and concluded that this is not only a method of constructing multi-wavelength source, but also a method of pulse shaping. Finally, the limitation of the AWG due to temperature, which can be overcome by athermalization method, was investigated. By applying the analytical result of this method to an AWG under study we have calculated the length of a polymer as a negative refractive index versus temperature slope material to compensate for the temperature dependence of AWG peak wavelength. Athermalization can result in removing a power consuming bulk circuit of temperature controller.
In chapter 5, the operation of wavelength conversion in a laser has been theoretically investigated and the static transfer function of the laser has been derived. Then the device structure and operational principles of DFB/SOA as a wavelength converter and optical regeneration has been described. The device consists of an 800-micron long DFB laser followed by a 500-micron long SOA. We used the VPI TransmissionMaker software to investigate in detail the performance of the device. The results of the modeling show that the performance not only depends on the input signal and noise power, but also on the bit rate of the input signal. This is found to be due to dynamic response of the laser. We investigated the conditions under which the SOA can improve the extinction ratio and shown that even if the power level conditions are suitable for extinction ratio improvement, the dynamic response does not allow this to happen for high data rates. We have then compared the performance of integrated DFB/SOA with the single devices. The integrated device has very high Q factor as high as twice that of single devices. It also has better sensitivity and higher input power dynamic range (IPDR). Compared to a single SOA, the integrated device needs much lower input powers to function and does not need an additional CW source. We have also shown that it is possible to improve the sensitivity of the DFB/SOA up to 5dB by integrating a SOA before the device. This however increases its sensitivity to noise level causing performance degradation, and also decreases the dynamic range. This SOA can in some cases increase the extinction ratio.

In chapter 6, a widely tunable SG-DBR laser which is one of the best types of available tunable lasers is characterized. Its main tuning property is demonstrated. The wavelength dependency to gratings bias current which is a step-wise function has been measured. The device was then used as a tunable wavelength converter operating based on cross-gain modulation. One of the main disadvantages of this device which is input wavelength sensitivity has been investigated experimentally. Using this wavelength converter and an AWG router, a dynamic wavelength routing has been demonstrated for data rates up to 5 GB/s limited by the speed of laser. The scheme is potentially extendable to high port count switch architectures with scope for cascaded operation. In addition to dynamic routing which is essential for a packet-based system, this approach provides regeneration. The Q factor measurements show a considerable improvement in the quality of converted
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Signal compared to that of input signal, particularly in the case of low input S/N ratio where the regeneration is much needed.

7.2. Future Work

A number of suggestions for the future work can be made on three main subject of the work presented in this thesis.

7.2.1. AWG

As we mentioned before, if the input pulse applied to an AWG is considerably shorter than its inter-waveguide delay, the output will be a train of pulses with a pulsewidth nearly the same as the input pulses separated by the inter-waveguide delay. Each single pulse produces \( n \) pulses where \( n \) is the number of arrayed waveguides. By selecting an appropriate inter-waveguide delay, number of arrayed waveguides and input repetition rate, it is possible to multiply the repetition rate by \( n \). However the main problem is that these pulses do not have uniform amplitude. This is found to be due to non-uniform distribution of optical power between arrayed waveguides. Finding solutions and realizing AWGs for this special purpose can be a possible extension of this work.

7.2.2. Wavelength Conversion using DFB/SOA

Our main aim in this subject, which was reflected in chapter 5, was comparing the integrated device with single devices. The comparison based on similar devices. Each of the devices is not necessarily optimized particularly in terms of the dimensions. This can be a suggestion for future work. This optimization is a complex process as the performance of the device is related to various parameters of the system like the noise and input power. The optimization also depends on the application and the range of input powers needed.

7.2.3. Regenerative Routing

To continue this work, three specific directions are suggested. The first suggestion is to use more than one wavelength carrying data at the same time to have a more complete
picture of the behavior of system. This is extremely difficult to do in AWG chip and needs a packaged AWG. Also the components of impairments of the output signal are needed to be recognized. These impairments are mainly due to dynamic response and chirp characteristics of the laser. Secondly, the exact theory of conversion operation of SG-DBR laser seems to be more complicated than a conventional laser and it was beyond the scope of this thesis. It is therefore useful to find a comprehensive theory to explain its behavior particularly its input wavelength sensitivity. This investigation may result in a design which can reduce this sensitivity. Thirdly, it is desirable to use an electronic control circuit to control the output wavelength of SG-DBR laser. This circuit has to be controlled by the header data of a packet.