Wavelength-Agile Photonic Integrated Circuits For

All-Optical Wavelength Conversion

A Dissertation submitted in partial satisfaction of

the requirements for the degree

Doctor of Philosophy in Electrical and Computer Engineering

by

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Abstract

Wavelength-Agile Photonic Integrated Circuits For All-Optical Wavelength Conversion

by

Milan L. Mašanović

The purpose of this thesis was to explore the possibilities for monolithic integration of widely-tunable all-optical wavelength converters using an offset quantum well integration platform in Indium Phosphide.

Tunable wavelength converters represent one of the enabling technologies for future Wavelength Division Multiplexed (WDM) optical networks, where the switching and routing functions are expected to be pushed into the optical layer. In particular, all-optical wavelength conversion techniques, that allow for transcription of data from one wavelength to another without passing through electronics, represent an attractive solution due to their better scalability with bit rate, simple design, low power consumption and potential for monolithic integration, when compared to the classical optical-electronic-optical approaches. TAOWC photonic integrated circuits (PIC) that were designed, fabricated and characterized as part of this project employed widely-tunable Sampled-Grating Distributed Bragg Reflector (SGDBR) lasers monolithically integrated with all-optical, Mach-Zehnder interferometer (MZI) semiconductor optical amplifier (SOA) based wavelength converters.

Important aspect of the monolithic integration are covered in this thesis:
the benefits and challenges of monolithic integration, properties of the integration platform used and the tradeoffs in the different component designs. Analysis and guidelines for TAOWC device design are presented. This covers the main functional building blocks (laser, optical amplifier, wavelength converter) of the PIC, as well as the photonic interconnections (passive waveguides, light couplers), with a critical role to optically link all of the building blocks together into a single PIC. Special attention is given to the analysis of possible sources of coherent back reflections into the on-chip laser and reflections mitigation through device/component design, since reflection can be fatal for the device performance.

Finally, results of the experimental characterization of the device operation are presented, together with a demonstration of the optical routing function. In this work, we have demonstrated regenerative, error-free wavelength conversion with low power penalties for bit rates up to 10 GB/s, with high input sensitivities (-5 dBm for 10 Gbps, -10 dBm for 2.5 Gbps), significant output powers of 0 dBm for the converted signal, up to 10 dB of signal gain, over 45 nm input and 35 nm output wavelength range.
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Chapter 1

Introduction

The ability and the desire for constant communication between human beings is the distinguishing characteristic of mankind.

Communication between humans can be divided in two different categories by analyzing the evolution and the consequences of communication through history.

We define the first category as the *utilitarian communication*. Utilitarian communication has enabled the rise of the human civilization as a whole through the exchange of concepts, ideas, and knowledge over time. On the other hand, this category has also been used successfully throughout history as an important tool in achieving and maintaining the supremacy and advantages of certain civilizations relative to others. That is why the communication technologies have always been of strategic importance.

The second category of communication is the *leisurely communication*. Leisurely communication fulfills the need for humans to be heard and understood, to start and maintain the relationships with other humans and also to entertain themselves. This stems from the essence of the human nature.

While the impact of communication needs of modern multinational corpo-
rations, governments and institutions on rapid development of infrastructure is undisputed, we are at a point where the individuals and their needs are also an important factor in driving the modern communication applications, such as Internet related (e-mail, web), wireless (cell phones) and television.

Modern era communications rely heavily on the ability to transfer the ever increasing amounts of information across the globe. Switching from co-axial copper cables to the optical medium of data transmission by deployment of optical fibers in the early 1980s upped the transmission channel capacity by a factor of 1 million.

Optical fibers are capable of supporting terabits of data, which is equivalent to 17 million simultaneous digital phone conversations in a single fiber at any time [1]. Their low propagation losses in the 1500–1600 nm wavelength range (less than 0.3 dB/km), together with the development of inexpensive semiconductor lasers, amplifiers (Erbium doped fiber amplifiers) and photodetectors in this wavelength range have enabled the deployment of the first generation optical networks.

1.1 Optical Networks

The first generation optical networks were essentially point-to-point links where the fiber optic link was used only as a replacement for the copper cables [2]. The optical signal propagating through the optical fiber was detected electronically, regenerated using a semiconductor transponder, and transmitted optically over fiber to the next opto-electronic repeater. The routing and switching functions were done electronically at the network nodes. In addition, each node had to handle not only the traffic destined for it but also all other traffic that was being routed through that node.
With the increase of the transmission rates to 10 Gbps and higher, the fiber medium impairments like dispersion and nonlinearities [3] start to emerge. On the other hand, the electronic processing of every packet at a node becomes more challenging in terms of requirements for electronics, buffering and power consumption and processing power. Therefore, the second generation optical networks have been created to incorporate some of the switching and routing functions in the optical layer of the network [2].

The main approach in realizing the second generation optical networks is frequency division multiplexing in the optical domain. This concept is utilized in electrical communications to increase the communication channel capacity. Optical frequency division multiplexing involves combining data transmitted on different optical wavelengths within the same fiber, thus it is most commonly referred to as wavelength division multiplexing (WDM). WDM offers a potential for very effective use of fiber bandwidth directly in the time domain [4] while allowing for using the wavelength to perform functions like routing and switching. WDM networks have been deployed in local metropolitan area networks (MAN) and local area networks (LAN) over the past few years. Currently, WDM networks are using hundreds of wavelengths operating at a bit-rate of 10 Gbps each. All the routing and switching is still done electronically and the cost of converting signals from the optical to the electrical domain and back again is expected to increase as the bit rate per channel increases. Physical size increase, thermal dissipation and power consumption increase with increasing bandwidth are other major limiting factors of electronic switching and routing [5]. In addition, it is understood that as transmission rates continue to grow, the speed of the electronic circuitry will not be able to compete with the speed of the optical transmission.
In the next generation optical networks [1], it is expected that all-optical switches will be used to perform switching and routing functions in the optical domain. The major advantage to this approach is the tremendous bandwidth potential. By avoiding electronic switching telecommunication networks can be more easily scaled to high bit-rates [5].

The all-optical approach may lead to potential lowering of cost per bandwidth, but it will most certainly help with reduction of the footprint of the gear and its power consumption and dissipation issues. This is contingent on development of photonic integrated circuits, which are small in size, consume low energy and capable of switching large bandwidths of data very fast.

1.2 The Role of Optical Wavelength Conversion

Wavelength conversion of optical signals provides solutions to problems originating from the connectivity restrictions imposed by certain architectures, allowing for local reconfiguration in the network and thus enabling contention resolution [2].

In digital transmission, there is also a need to regenerate the signal in order to extend the reach of the network. Regeneration, as the name suggests, produces a new copy of the signal correcting for timing and amplitude errors and also reshapes the digital data pulses. When amplitude noise and extinction ratio reduction are the sources of signal impairments, amplification and reshaping processes are sufficient to regenerate the signal and to prevent from noise and distortion accumulation [2]. A device that accomplishes amplification and signal waveform reshaping is said to have 2R (Reshaping Repeater) regeneration capabilities. In many cases, the process of wavelength conver-
Finally, wavelength conversion can be used in the process of wavelength routing, where the wavelength of an optical data stream in a network node is used by a wavelength router element [7] to spatially route the signal to different outputs of the node.

To summarize, the capability for wavelength conversion in the future networks is desired due to its versatility of application to both contention resolution, signal routing and signal integrity restoration.

To illustrate the applications of wavelength conversion to network functions, we provide more details about the wavelength routing application and contention resolution applications.

Wavelength converters, used in conjunction with wavelength demultiplex-
ers, optical routing elements and multiplexers are vital in some architectures proposed for an optical cross connect, the optical network element that performs the routing of WDM channels in an optical networking scenario [2]. A schematic of an optical cross-connect is given in the top part of Figure 1.1. At the input of the switch, the incoming data streams at different wavelengths are demultiplexed, resulting in a single data stream (wavelength) per fiber. The output wavelength router performs a function of spatial routing of the signals at its inputs, based on their wavelength wavelength. In the core of the switch, each wavelength is led into a wavelength converter block, where the original data is transcribed onto a different wavelength determined by the required final destination at the output of the wavelength router.

A schematic of an optical wavelength interchanger is shown in the bottom of Figure 1.1. Input signals to the node are demultiplexed down to a single data stream per fiber, then they are transferred to appropriate wavelengths based on the availability at the output of the node, and finally multiplexed back together at the output of the interchanger. Therefore, the role of this network element is to redistribute the data in a network node according to the wavelength availability at the output of the node, in order to minimize contention and prevent signal blocking.

### 1.3 Wavelength Conversion Approaches

Broadly speaking, two fundamentally different wavelength conversion approaches have been adopted: optical-electronic-optical (O-E-O) and all-optical approach, Figure 1.2. In this section, through analyzing the principles, advantages and limitations of the O-E-O approach, the need for all-optical approaches and their potential benefits are discussed.
1.3.1 Optical-Electrical-Optical Wavelength Conversion

O-E-O approach represents the most straight-forward solution to wavelength conversion. An incoming optical signal at wavelength $\lambda_1$ is electronically detected using a photodetector, the electrical signal is regenerated, amplified and then re-modulated onto an optical carrier at an output wavelength $\lambda_2$.

The O-E-O converters have low input optical power requirements (-14 dBm for $10^{-9}$ BER at 10 Gbps) and potentially a large (15 dB) input power dynamic range. They generate high-quality output signals, since they are based on well-optimized and reliable components. The research work on these components is focusing on the reduction of the cost, size and power consumption, as well as the achievement of operation at high bit rates (greater than
10 Gbps). One of the main advantages of this approach is that it can be combined naturally with electronic repeaters, since the O-E-O wavelength converter is an electronic repeater. Thus, this approach to wavelength conversion is somewhat a legacy approach and it does not require a shift in paradigm of classical network design, since it assumes that the switching and routing functions in the network are performed electronically. One the its key drawbacks originates from this approach - all of the WDM signals have to be optically terminated in every network node, regardless of their final destination.

While O-E-O wavelength converters provide for natural reshaping and re-amplification regeneration (2R) of the signals (electronic retiming can be incorporated in the process as well), they suffer from the limited transparency with respect to the data formats and data-rate. That means that a particular component will only work for certain predetermined bit rate and a given data format. This limits the upgradeability and the usefulness of the network.

Some of the key drawbacks to this approach are related to its cost and scalability with increasing data rates. The wavelength conversion process consumes significant electrical power (driving, cooling and controlling a detector, amplifier, laser and modulator), and the power consumption and component complexity increases with bit rate.

Experiences from modern electronic demonstrate that integration is one of the main means to increase the performance and stability while reducing the component cost. Currently, there is no integration platform that would allow monolithic integration of the O-E-O wavelength converters on the same chip.

In conclusion, alternative approaches to O-E-O wavelength converters are of great interest, and all-optical wavelength converters are particularly good
candidates, due to their potential for low cost, power efficient high bit rate operation.

1.3.2 All-Optical Wavelength Conversion

Unlike O-E-O wavelength converters, all-optical wavelength converters are able to shift an optical data channel to a different wavelength, irrespective to the bit-rate of the incoming signal (up to a certain maximum bit rate), and without conversion to electrical format. The electrical power consumption remains constant with the data bit rate, and due to the number of electrical components associated with all-optical wavelength converters, it is generally lower by a factor of 2 for bit rates of 10 Gbps [10]. This difference is expected to increase for higher bit-rates.

The all-optical schemes require a nonlinear optical gate, controlled optically by the input signal, and a CW local source, which generates the new wavelength. All-optical wavelength conversion techniques used today are mainly based on either Kerr nonlinearity in optical fibers or on the optical power dependence of the refractive index in semiconductor devices.

The nonlinear nature of the processes involved can be exploited in certain implementations to provide for optical pulse reshaping. Signal regeneration using cross-phase modulation in semiconductor optical amplifier interferometer based wavelength converters [11] for bit rates up to 40 Gbps. Fiber nonlinearity based approaches to wavelength conversion offer the advantages in terms of the capability for ultrafast regenerative speeds of operation (80 Gbps) [12]. These fiber ”devices” are scalable to even higher bit rates, however, they are not very efficient, work only for RZ data format (due to the underlying physics of the processes involved) and are difficult to scale down in terms of their dimensions using today’s technology.
Another all-optical based approach, wave mixing, offers great advantages in terms of high bandwidth and potential format independence [13]. This particular approach, however, still has very low efficiencies, and further improvements are needed to make it more practical.

All-optical approaches based on cross-absorption modulation in electroabsorption modulators are being investigated, and have been demonstrated to have very large bandwidth [18]. However, the mechanism of cross-absorption modulation requires large optical input powers to generate a large number of carriers required. Unfortunately, the sweep-out time increases with the number of carriers, and EAM-based wavelength converters using the saturation mechanism have an inherent tradeoff between speed and extinction ratio [19].

Recently, a new mechanism of cross-absorption modulation was proposed and experimentally demonstrated to assist wavelength conversion using a single traveling-wave electroabsorption modulator [20]. It utilizes the propagation of the photocurrent generated by the incoming signal to modulate the data onto the existing continuous wave signal in the traveling-wave EAM. This method does not depend on the absorption saturation effect, and the optical pumping levels can be reduced. In order to fully exploit the benefits of this approach, structures in which a separate traveling-wave detector is electrically interconnected to a separate traveling-wave modulator would be of interest. Recent successful demonstrations of monolithically integrated tunable opto-electronic integrated circuit wavelength converters [8, 9], consisting of an integrated photodetector and a widely-tunable laser/modulator, show a promising development in this direction. In principle, by optimizing the detector and the laser/modulator part independently, a number of advantages of the O-E-O approach can be brought into this design. Still, significant
challenges in component and integration platform and process development remain to achieve the full potential benefits of this approach. In addition, the conversion process in these devices still relies on carrier transport through electrodes, thereby increasing the device complexity and posing limitations that will be encountered with increasing bit rates (10 Gbps and higher).

In conclusion, the all-optical wavelength conversion represent an attractive alternative to the O-E-O based approaches at lower bit rates (10 Gbps or less), and potentially the only viable alternative for ultra high speed data rates (80 Gbps or higher) that are envisioned for the core of the future optical high capacity networks.

The focus of this thesis is on the integrated all-optical wavelength conversion using cross-phase modulation (XPM) in semiconductor optical amplifiers (SOAs). Other all-optical techniques and implementations of wavelength conversion, such as fiber-based wavelength converters, cross absorption modulation, fiber interconnected electroabsorption modulator based wavelength converters, converters using wave mixing effects, are beyond the scope of this thesis, and the reader is referred to the references [14], [22], [23], [13], [15], [16], [17], [18] and [21] for a more detailed description.

1.4 Tunable Wavelength Converter

The wavelength conversion function is to transcribe the incoming data stream at an input wavelength $\lambda_1$ to an output wavelength $\lambda_2$.

Historically, in all-optical implementations of the wavelength converter, both the original data and the new wavelength continuous wave (CW) signal were supplied externally, as illustrated in the top of the Figure 1.3.

A tunable wavelength converter (TWC) can be defined as a wavelength
Using this definition, all of the O-E-O wavelength converters with adjustable output wavelength would fall into the tunable wavelength converter category. For an all-optical wavelength converter to be classified as tunable, it would have to be co-packaged or integrated with the CW source.

Now, a list of the desirable properties for an ideal tunable wavelength converter will be given, and those properties discussed and described.

For the input signals, a widely tunable wavelength converter should operate for a wide range of input signal power levels, including very low input signal power levels (-10 dBm or less). The input power range determines the TWC’s dynamic range, and the input power level required for proper operation determines the sensitivity. A large input dynamic range is desirable,
because the power of the input signal may depend on the path the signal takes through the network.

A wide input signal wavelength range, covering at least one full optical band of 40 nm [24], would be advantageous from the exploitation and cost point of view. The performance of the wavelength converter should be completely insensitive to the polarization of the incoming light.

On the output, the wavelength converter should provide sufficiently high output power (but not to high as to excite nonlinear effects in the fiber), high quality signal over a wide output wavelength range.

The quality of the converted signal is assessed by the signal extinction ratio, signal-to-noise ratio, optical pulse shape and the signal chirp. Frequency chirping of the edges of the pulse can have serious effects on signal propagation at high bit rates and high distances [3], so controllable chirp is need for some TWC applications.

Regenerative properties to improve the signal quality and increase the signal power relative to the input would be another advantage.

Wavelength conversion should be possible between any combination of wavelengths at the input and output while maintaining the same properties of the signal with regard to quality, sensitivity, power and other metrics listed. The process of wavelength conversion should be bit-rate and data format transparent.

Total rejection of the input signal at the output is desirable, as illustrated in Figure 1.3. Otherwise, optical filters would need to be used at the wavelength converter output.

For real wavelength converters, the requirements are application specific and may be relaxed based on the function and position that a wavelength converter has in the network. As an example, in a long haul networks,
the output power and signal chirp of more importance than in the local, or metropolitan area networks that are of smaller geographical scale.

## 1.5 Preview of This Thesis

The purpose of this thesis was to explore the possibilities for monolithic integration of widely-tunable all-optical wavelength converters using an offset quantum well integration platform in Indium Phosphide. The tunable integrated wavelength converters that were designed, fabricated and tested
as part of this work employed Sampled-Grating Distributed Bragg Reflector (SGDBR) lasers as widely tunable light sources, which were monolithically integrated with different Mach-Zehnder interferometer (MZI) semiconductor optical amplifier (SOA) based wavelength converters.

This thesis is organized as follows:

Chapter 2 deals with the photonic integration issues, advantages and challenges. In this chapter, an overview of different integration platforms in indium phosphide is given, with special emphasis on the offset quantum well integration platform.

In Chapter 3, the state of the art and the background on the integrated semiconductor optical amplifier (SOA) based wavelength converters is given.

Chapter 4 discusses the main (active) integration building blocks. Properties and design issues of the semiconductor optical amplifiers, Mach-Zehnder interferometer SOA wavelength converter and the Sampled Grating Distributed Bragg Reflector laser are covered in this chapter.

Photonic interconnection elements are discussed in Chapter 5. The elements covered include straight and curved waveguides and light splitters and combiners. Main properties and design rules for these components are given in this chapter.

Chapter 6 deals with the widely-tunable wavelength converter device design and fabrication. Three different designs that were successfully fabricated as part of this work are discussed, and critical issues related to their design and performance, including the reflection properties and the speed of operation, are analyzed in this chapter.

Chapter 7 contains the bulk of the experimental characterization results for all three generations of the tunable wavelength converters. These results cover the static and dynamic performance of the devices, regenerative
properties and performance in several optical system experiments.

Finally, Chapter 8 concludes the thesis, with a summary, conclusions and directions for future work.
References


Chapter 2

Photonic Integration Issues and Platforms

This chapter deals with the monolithic integration of photonic integrated circuits in Indium Phosphide.

First, we analyze the drawbacks of realization of complex optical functions like wavelength conversion using discrete, fiber interconnected components. This analysis is done from the perspective of a Mach-Zehnder Interferometer semiconductor optical amplifier based (MZI-SOA) wavelength converter, but its validity is mostly general, applicable to any high-level optical network application.

Next, the benefits that monolithic integration can bring to a tunable wavelength converter are discussed. These benefits come with a number of challenges, which are covered in the following section.

Last, a short overview of some state-of-the-art photonic integration platforms in Indium Phosphide is given, with a special emphasis on the integration platform used in this work, Offset Quantum Wells (OQW).
2.1 Drawbacks of Non-integrated Approaches

With ever increasing requirements for high performance, high reliability, low cost optical network modules that perform complex optical network functions, it is becoming increasingly difficult to fulfill all the demands without reverting to photonic integration. One of such functions is optical wavelength conversion, as already discussed in the previous chapter. If a tunable MZI-SOA wavelength converter module were to be implemented using a set of fully-optimized discrete components interconnected with fiber, major issues and limitations would be imposed by this approach. These issues relate both to the performance and to the cost of TWC module.

The performance related issues are as follows:

1. Light coupling losses - every time a signal is coupled from an optical fiber to a device, at least 40% of the power is lost due to coupling. This
puts increased demands on the separate component design, since they need to be over engineered to compensate for these losses

2. Noise figure - coupling losses are added directly to the noise figure of the component

3. Speed of operation - high photon density helps improve the efficiency and speed of operation, therefore, the coupling between individual components directly affects the signal extinction ration and maximum bit rate

4. Polarization - every component has a certain degree of polarization dependence, therefore, random fluctuations in the interconnecting fiber will cause polarization fluctuation which will affect the performance

5. Stability - temperature fluctuations of the interconnecting fibers will lead to random phase changes that may affect the wavelength converter performance. Also, different devices will experience different temperature fluctuations

To control the cost and make a component practical for deployment and exploitation, these issues need to be addressed:

1. Packaging - 70% of the cost of a single component is in the packaging

2. Power Dissipation - independent thermoelectric cooler needed for each individual component

3. Control - it is more complicated to control the distributed system, especially for fast operating point changes/wavelength switching
4. Complexity - modern, high performance wavelength converters have up to a dozen of optically active components. As an example, a high performance tunable all-optical wavelength converter would require fully packaged components from the following list: one tunable laser, 4 semiconductor optical amplifiers and four light splitters.

5. Space - physical space/volume limits the rack space, especially for arrays of wavelength converters. As an example, in a $128 \times 128$ optical switch, 128 tunable wavelength converters would be required.

Recent advances in photonic integrated circuit integration platforms and processing techniques have allowed monolithic integration in Indium Phosphide as an approach that can resolve most of these issues, while satisfying most of the requirements for an ideal tunable wavelength converter.

The monolithic integration approach was therefore taken in this thesis in order to realize a robust, high performance, monolithically integrated, widely–tunable all–optical wavelength converter. An illustration comparing the discrete and the integrated approaches is given in Figure 2.1.

### 2.2 The Case For High-Level Functional Integration

The primary objectives of optoelectronic and photonic integration are similar to those of electronic integration: enhancing the performance, reliability, robustness and increasing the functionality while lowering the manufacturing cost. Over a period of thirty years, the electronics industry has moved from discrete transistors to very large-scale integrated circuits (VLSI), with which up to 100 million transistors can now be integrated on a single chip. The
performance, cost and reliability improvements achieved through these developments have been largely responsible for enabling all the advancements in electronic information transmission and processing.

The new optical networks will employ complex schemes for data transmission and routing, and will involve a great variety of optically cascaded emitters, modulators, filters, amplifiers, detectors, switches, multiplexers, wavelength converters... A large portion of the cost of such architectures is due to the difficulty of achieving single-mode optical connections between the guided-wave components. These devices utilize tightly confining waveguides for optimized performance, resulting in difficult submicrometer alignment tolerances when such structures are coupled to single-mode optical fibers. By replacing individually aligned connections with lithographically produced waveguides, PICs offer the promise of cost reduction, dramatically reduced size, and increased packaging robustness.

Looking at integrated all-optical wavelength converters and their advance over time, integration has provided for much greater stability and reliability in the device operation as well as improved performance.

The early work on all-optical wavelength converters employed individual semiconductor optical amplifier modules, both as stand alone components in cross-gain modulation configurations [1], or interconnected using optical fiber to demonstrate more advanced wavelength conversion techniques like cross-phase modulation [2]. Improved performance enabled by device integration was apparent from the first integrated Mach-Zehnder interferometer semiconductor optical amplifier based wavelength converter that consisted of several passive waveguides and 2 SOAs [16]. Today, the level of functional integration is such that it enables photonic integrated circuits of high sophistication, with on-chip integrated probe sources, signal pre-amplification and
power and signal monitoring capabilities [28], [5].

Further integration of the MZI-SOA wavelength converters with on-chip tunable probe sources offers additional important advantages: low-loss coupling between the converter and the probe laser which helps to speed up carrier dynamics in the wavelength converter, stable and constant probe signal polarization and power due to elimination of fiber interconnects between the laser and the MZI, improved conversion efficiency and noise figure due to high photon preservation between different components on chip, size reduction, simplified external coupling and packaging (single fiber in - single fiber out), reduced component cost when compared to stand alone tunable laser + wavelength converter due to possibility for mass production and automated device testing and verification.

It is to be expected in the future that the level of functionality of a single photonic chip will continue to grow. Single chip wavelength routers are already a clear possibility today, and it is hard to predict all the applications that will emerge in the years to come. However, in order to exploit all of these benefits, significant integration challenges need to be overcome. These challenges of integration are discussed in the next section.

2.3 Challenges of Integration

Like electronic integrated circuits, which involve the replication of huge numbers of components of various functionalities (transistors, diodes, resistors, capacitors, etc.), photonic integration requires the integration of fundamentally different types of devices. Generally, photonic devices have been largely based on similar materials, typically III-V semiconductor materials, and are processed using many of the analogues approaches that form the basis for
Figure 2.2: Advantages and challenges of high level functional integration

Silicon integrated circuit fabrication.

Optical components rely on both the optical and electronic properties of their constituent materials and they critically depend on heteroepitaxially grown material with accurately controlled composition and dimensions to achieve optimum performance. As a result, PICs are typically more complex in structure than silicon ICs. These materials are enabled by advances in epitaxial growth techniques like metal-organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE), with large area uniformity and reproducibility of growth that they offer.

While the feature sizes of most photonic integrated circuits are still on a scale of a micrometer which is a factor of 10 above the limits of standard fabrication processes used in electronic integration, the main challenge in photonic integration comes from the fact that in their most versatile form, PICs
are built up from components that are very different in functionality: light emitters, waveguides, modulators and detectors. Each of these different components in principle requires a differently optimized material structures to achieve desired performance. Therefore, the heteroepitaxial material growth becomes even more complex by this fact, and often, several growths on the same wafer are required as various points of the device fabrication process in order to satisfy this need for PICs functional versatility.

This analysis leads to the conclusion that an integration platform that will provide simple and robust capabilities to separately optimize all of the PIC components is essential for successful photonic integration.

A basic photonic integration platform needs to allow for design and fabrication of at least three different waveguide types: optically active waveguides, passive interconnect waveguides and grating containing waveguides. In a more complex platform, several different active sections may be required (for example, for separate optimization of the laser and the optical amplifiers), as well as different passive sections that could be used for photonic interconnection components (low loss) or optical modulators (high controllable absorption/index change). The main requirements for active and passive waveguides in an integration platform are summarized in Table 2.1.

Looking at active waveguides, properties (1,2) would allow for low threshold current lasers, (1,3) for highly nonlinear or (1,4) for high saturation power SOAs, and (2) low power dissipation and high efficiency.

For passive waveguides, (1) and (4) are compatible and can be used for low-loss interconnections, (2) would be needed for a tunable laser’s mirrors or a modulator, and (3) for compact photonic interconnects. However, both (2) and (3) directly conflict with (1), due to InP material properties.

In any case, some kind of tradeoff is necessary - either in sacrificing some
Table 2.1: Main requirements for optically active and passive waveguides in an InP photonic integration platform

aspect of the device performance, or in creating a fabrication process that is highly complex and resource consuming.

Other requirements and restrictions become more apparent with the analysis of specifics about the components whose integration will be attempted.

Integrating a (tunable) laser on the same chip poses a significant challenge on its own. First, the laser design has to be such to allow for integration with other components. That eliminates all the traditional distributed feedback (DFB) lasers and distributed Bragg reflector (DBR) lasers, because of their need for a facet to provide reflection required for the lasing action. In recent years, new, widely tunable lasers with lithographically defined mirrors and full 40 nm tuning range have been designed and improved. Details about some of the most important of these structures can be found in [6], [7], [8], [9].

Another challenge to consider when integrating lasers as part of a PIC is the suppression of coherent reflections into the laser. The origin of these reflections can be any of the integrated components or interfaces that are downstream from the laser mirrors and have a direct waveguide connection with the laser. Coherent reflections into the laser cavity would be detrimental
for its performance, by either fully destabilizing the single mode operation, or by increasing the laser linewidth which would result in degraded transmission performance. These issues will be analyzed in more detail in Chapter 6. Therefore, the choice of both active and especially passive components (like light splitters/combiners) integrated to a laser has to be such to minimize back reflection. Active and passive waveguide interfaces have to be designed in order to minimize the amount of back reflection into the laser mode. Facet reflections need to be effectively suppressed. Finally, amplified reflections further increase the already high demands on the chip optimization.

Thermal issues become important when the density of optically active components on chip increases to more than 2 per 70 $\mu m$. Care needs to be taken to avoid thermal crosstalk between different components on chip, as well as to allow for proper heat dissipation.

In the end, minimizing the chip area is important from the aspect of cost reduction and increased yield per wafer. With tens of integrated components on the same chip, electrical interconnecting and the wirebonding pad size becomes an issue and often a limiting factor in the chip area reduction. Therefore, in the future, some of the interconnecting techniques developed for electronic integrated circuits will have to be implemented and used for photonic circuit integration.

### 2.4 Integration Platforms in InP

Photonic integrated circuits in InP materials system of various complexities and performance have been reported. The goal of this section is to provide a quick overview and comment about the important aspects for the most common InP photonic integration platforms in use.
Optical guiding in an InP integration platform is provided by a InGaAsP waveguide layer clad by either InP or air in the transverse direction. The lateral waveguide structure determines the level of guiding in the structure, and we distinguish between weakly and strongly guiding structures, as will be explained in great detail in Chapter 5.

An active region, either a bulk waveguide layer or a set of quantum wells with a bandgap value close to 1.55 $\mu$m, is incorporated into the transverse waveguiding structure of the active region.

As already explained and indicated in Table 2.1, generally, a large optical overlap of the active waveguide mode with the active region is desired for the most efficient performance. Therefore, it is beneficial that the active region be as close to the transverse mode maximum as possible. That goal will be fulfilled the best by an active region centered in the middle of the waveguide, as shown in Figure 2.3 (a) and (b). This approach usually requires a more complex fabrication process to define the active sections of the PIC.

In terms of the ease of fabrication, and the minimization of epitaxial growth steps, an offset quantum well (OQW) integration platform where quantum wells are grown on top of the waveguide layer and can be effectively removed while preserving the passive waveguide underneath can be of interest.

In the remainder of this chapter, alternatives to the offset quantum well (OQW) based processes are described. Then, an analysis of advantages and tradeoffs resulting from the use of OQW is given.

### 2.4.1 Selective Area Growth

Selective area regrowth (SAG) [10, 11, 12] uses precursor diffusion dynamics in MOCVD to grow epitaxial layers with different bandgaps in a single wafer
growth run. By appropriately placing a dielectric mask on the surface of the wafer, its size and shape around the growth area will influence the transport properties of the metalorganic compounds, thus determining the growth rate and the composition of the material grown. Compared to a completely un-
masked substrate, the growth which occurs inside the masked layer will be thicker and richer in In, thus changing both the quantum size of the wells and the composition is such a way to shift the bandgap to the lower energy in the gap compared to regions away from the mask [13]. This is illustrated in Figure 2.3 (a). The layers grown can be both quantum wells, or different bandgap waveguides and the active region can be centered or offset.

This fabrication platform is attractive because it requires a single epitaxial growth. However, since a diffusion process is used to grow material on a patterned surface, the uniformity of the quantum wells can suffer. Also, tight calibration of the growth parameters needs to be maintained, and the dielectric mask placement may constrain the device design. In addition, the dielectric mask design and placement affect the number of devices per wafer produced and the overall yield.

### 2.4.2 Butt Joint Growth

Starting with the centered quantum well base structure, the most straightforward way to render sections of a wafer passive would be to etch away the active regions completely, and replace them with passive waveguide instead. This is illustrated in Figure 2.3 (b).

The integration platform that uses this approach is the butt joint growth (BJG)[14, 15, 16]. After the initial growth of a fully active base structure, the active sections from parts of the wafer are removed, and a set of new passive (or active) layers is then regrown in areas that were etched away. The old active regions are protected during this growth by a dielectric mask. Finally, the entire wafer is regrown with the cladding material, usually in two separate steps - one for the active and one for the passive sections, in order to optimize the doping levels and reduce the propagation losses. This scheme
offers the ability to achieve very low mode mismatch between the butt joint sections (about 0.5% or less) and large overlap of the optical mode with the active region. Using BJG, it is possible to grow multiple waveguide regions on the wafer when more than two different bandgaps are required (e.g. lasers plus an EAM), requiring multiple regrowths as well. This allows for full integration platform tailorability, including the polarization independence, and makes the BJG process really attractive. This technology is the most commonly employed technology in the PIC industry.

The transitions between the sections grown in different growth runs are locations where defects in the material can occur and lead to degraded device performance (leakage, optical scattering) and reflections. Tight control of the composition of the butt joint material grown need to be maintained to realize low loss, low back reflection transitions [16].

The main drawback to the BJG techniques is the number of epitaxial growth and processing steps required, which can significantly impact the yield, the cost and the reproducibility, particularly for complex, large PICs. Also, tight control of the but joint growths is required to achieve low-loss, low reflection interfaces between different bandgap sections.

### 2.4.3 Quantum Well Intermixing

Quantum well intermixing (QWI) has emerged as a powerful new fabrication process for post growth band edge control in photonic circuit integration [17]. Applicable to quantum well based active regions, this process achieves intermixing of the quantum wells with the barriers to increase the bandgap of the quantum well region and make it non-absorbing. The mechanism of intermixing is based on the fact that quantum wells represent an inherently metastable system due to a large concentration gradient of atomic species at
the quantum well/barrier interface. To increase the intermixing process efficiency, the surface of a semiconductor is implanted with impurities or phosphorus (to create vacancies)[18], and those are thermally propagated through the quantum well active region of the wafer. The impurities/vacancies cause the redistribution of atoms from the quantum wells and barriers effectively raising the band edge, and rendering the material transparent. This is illustrated in Figure 2.3 (c). By controlling the time of propagation of the vacancies, it is possible to create multiple bandgaps on the wafer [19]. Integration platforms based on QWI allow for large flexibility in terms of the band edge control for the individual components in a PIC while requiring a minimal number of epitaxial growths [19]. Initial concerns existed about the device reliability due to the impurity and defect introduction, however, studies have shown that no significant differences in device lifetimes exist, and this technology has been commercialized [20].

At the moment, QWI integration platforms in InP seem to offer one of the best tradeoffs in terms of the device design flexibility and process complexity.

2.4.4 Asymmetric Twin Waveguide Platform

Another approach that has been investigated and commercialized [21] for integrating multiple bandgaps on the same device is using multiple waveguide layers on the same epitaxial stack and moving the light vertically between the layers as and when needed. This technique, known as the Asymmetric twin waveguide technology (ATW) [22, 23, 24], permits the integration of multiple bandgaps on the same wafer, after a single epitaxial growth. The different layers are selectively etched to create active, passive or filter waveguides in materials with desired bandgaps. The waveguides on these layers can then be coupled using laterally tapered adiabatic vertical couplers, without
additional losses or reflections. A single taper section is typically a few 100\,\textmu m in length, and integrating multiple devices can require a lot of space for integrating these couplers. A cross section of an active-passive transition in ATW technology is illustrated in Figure 2.3 (d).

This integration platform requires thick epi stacks for integrating multiple devices, so control of strain during epitaxial growth is of great importance. Additionally, transition lengths (100 to 400\,\mu m each) to couple between active and passive regions are required at every interface, which lead to a reduced device yield per wafer. Waveguide tapers in the active regions leave quantum wells exposed, which may lead to large surface recombination losses, thereby potentially reducing the optical pumping efficiency. The main benefit of the technology is the simple, regrowth-free fabrication process.

### 2.4.5 Offset Quantum Well Platform

Offset quantum well based platform represents an attractive integration platform due to its simplicity, maturity and robustness. Though not as versatile and advances as QWI or BJG based platforms, its characteristics make it an attractive choice for prototyping of the novel functional photonic integration concepts, such is the work in this thesis.

A cross-section of an active-passive interface in this technology is shown in Figure 2.4. The active region consists of multiple quantum wells and barriers in InGaAsP material system that are located on top of the InGaAsP waveguide layer. Simple chemical etching allows for selective removal of the quantum wells from the top of the waveguide, thereby rendering such areas of the chip optically passive in the first step of the fabrication process. By optimizing the thicknesses of the active region and the waveguide epitaxial layers, it is possible to achieve very low reflections and loss at the active-
Finally, using this platform, a single epitaxial overgrowth of p-InP is required to fabricate highly complex PICs, which makes the fabrication process simple, cost effective, high yield, reproducible, and robust.

The key abilities to realize active and passive waveguides with efficient, low loss and low reflection transitions, were demonstrated by a variety of complex PICs, [25, 26, 27, 28, 9], and made this technology attractive commercially [29, 30].

More details about the optimization of our OWQ integration platform will be provided in Chapter 6.
2.5 Chapter Summary

In this chapter, monolithic integration of photonic integrated circuits in Indium Phosphide was discussed.

Realization of complex optical functions like wavelength conversion using discrete, fiber interconnected components has drawbacks in terms of stability, complexity, practicability and basic performance. Therefore, photonic integration can offer practical solutions with enhanced performance, reliability, robustness and increase in the functionality while lowering the manufacturing cost. Various challenges need to be overcome when integrating highly complex functions onto the same chip, some of which are separate component optimization and coherent reflection suppression. Different integration platforms in Indium Phosphide have been demonstrated in the past. This work is based on the Offset Quantum Wells (OQW) integration platform, which enables simple, robust prototyping of state-of-the-art photonic integrated circuits.
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lithic integration of widely tunable lasers and electroabsorption modula-


Chapter 3

Integrated SOA-based
Wavelength Converters -
Background and
Prior State of Art

In the past years, research on integrated wavelength converters has been one of the major driving forces in increasing the complexity and the functionality of the photonic integrated circuits. In fact, some of the first simple photonic integrated circuits (PICs) to be designed and fabricated were all-optical wavelength converters [1].

With the latest developments in the PIC technologies, the feasibility, functionality and characteristics of the SOA-based integrated wavelength converters in particular have recently been dramatically improved, and some of these components have been turned into commercially available products.

SOA-based all-optical wavelength converters, with their simple operation, high quality converted signals and the ability for signal regeneration, repre-
sent today the most practical approach in realizing the wavelength conversion function in the dominant, intensity modulated optical systems (non-return to zero (NRZ) and return-to-zero (RZ) modulation formats used in modern WDM networks)[2].

In this chapter, background and previous work in the field of the SOA-based wavelength converters is given. The chapter consists of two parts.

The first part gives an overview of the principles of the cross-gain and cross-phase modulation in semiconductor optical amplifiers. Various techniques used to achieve wavelength conversion using these effects are covered as well, quoting the best to date performance for each of these approaches.

The second part of the chapter provides a survey of the work that has been done in the field of monolithically-integrated tunable wavelength converters in InP.

3.1 Cross-Gain and Cross-Phase Modulation - An Overview

Optically controlled modulation of an optical signal is achieved in an optical medium where the optical intensity contained in the medium can control the optical gain, loss and refractive index of the medium. The varying intensity of the "control" optical signal in the medium, the pump, causes an intensity change of a constant optical signal entering the same medium, the probe. Simultaneously, the phase change of the both signals occurs, due to the intensity dependent refractive index of the medium.

The effect of change in intensity of the pump signal that generates the intensity change in the probe signal, is called cross-amplitude modulation. In SOAs, the dominant cross-amplitude effect is due to a change in optical
Figure 3.1: Schematic of a SOA gain curve dependence on the SOA input power

gain of the medium, while in the electroabsorption modulators (EAMs), this effect is observed through the change of absorption of the medium.

Similarly, the effect of change in intensity of the pump signal that causes the phase change of the probe signal is called cross-phase modulation.

Cross-amplitude and cross-phase modulation effects are coupled and always occur together because any change in the signal gain or absorption will cause a change in the refractive index, as shown by Krammers-Kroning relations (see Chapter 4).

3.1.1 Wavelength Converters Using Cross-Gain Modulation

Cross gain modulation (XGM) wavelength conversion is based on the SOA gain nonlinearity. The gain of a SOA, defined as the ratio between the output
and the input signal power, is constant as a function of the input power, until a certain level of the input power is reached, when the gain starts to saturate due to a finite amount of carriers (holes and electrons) that are being supplied to the gain medium. This level of power defines the SOA saturation power. For XGM to occur, initially, only the probe signal is present in the SOA. When an intensity modulated, high power, pump signal enters the SOA, the gain of the amplifier is brought into saturation by the pump signal and is modulated due to the gain saturation. The probe signal at the output carries the same (inverted) information as the input pump signal. This is illustrated in Figure 7.14. More details about the SOA design, gain and characteristics will be given in the next chapter.

XGM based wavelength conversion is very simple to implement, as it requires only a single SOA device. The process of wavelength conversion can be polarization independent, depending on the design of the SOA gain medium [3],[4]. The extinction ration can be controlled by controlling the power levels of the pump and probe signals, and can be as much as 16 db for conversion from longer to shorter wavelength [5].

Both quantum well and bulk active region SOAs can be used for XGM wavelength conversion. Generally, bulk active region SOAs are preferred since they provide higher optical overlap between the mode and the gain region, thereby reducing the gain recovery time, increasing the speed of operation and the saturation effects.

The XGM-SOA wavelength converter can be operated such that the pump and the probe signals co-propagate or counter propagate. While the counter propagating mode is attractive since it does not require optical filtering at the output, the maximum speed of operation will be limited (less than 20 Gbps) by the time it takes the signal to propagate through the SOA, called
Figure 3.2: Schematic illustrating the cross-gain modulation based wavelength conversion process in semiconductor optical amplifiers

the transit time. The maximum transit time is determined by the length of the signal pulse - problems occur when the pulse width becomes shorter than the propagation time through the SOA.

The main drawback of XGM is that the extinction ratio cannot be maintained for conversion from shorter to longer wavelength [5]. This is due to the differential gain decrease as a function of wavelength, as discussed in the next chapter. In addition, the signal-to-noise ratio is deteriorated due to a large spontaneous emission bandwidth. Finally, large chirp is introduced in the process of wavelength conversion. Still, cascadability studies have shown that up to 25 hops through the recirculating loop are possible [7]. The extinction ratio degradation that occurred for down conversion was recovered in the up conversion, resulting in no degradation in performance for 25 loop hops.

In co-propagating mode of operation, the bandwidth can be enhanced by extending the length of the SOA which leads to the effect of the saturation filtering. Large photon densities in the end part of the SOA enable the transfer of the higher frequency components to the probe signal, effectively reducing the gain recovery time and consequently increasing the bandwidth of operation [2]. A conversion speed of 40 Gbps, with the extinction of 9 dB was reported in [8]. The record speed of conversion was achieved in [9] -
error free conversion at 100 Gbps in a 2 mm long SOA with a grating at the output to suppress the chirp.

3.1.2 Integrated Wavelength Converters Using Cross-Phase Modulation in SOAs

Even though cross-gain and cross-phase modulation in SOAs occur at the same time, it is possible to exploit and enhance the effect of cross-phase modulation and use it for different types of wavelength converter structures.

For wavelength conversion, the phase change in the SOA needs to be converted to an amplitude change. This is achieved using optical filtering, using an SOA interferometric structure [14], or using a bandpass filter after the SOA [25].

Cross-phase modulation based wavelength converters are characterized by large converted signal extinction ratios, low wavelength dependence, higher optical power efficiency and low chirp of the converted signals. This technique has been shown to provide 2R signal regeneration, for both NRZ and RZ data formats. These properties make cross-phase modulation one of the most attractive integrated all-optical conversion techniques [2].

Similar to XGM wavelength converters, in most XPM configuration, the wavelength conversion can be performed in both co and counter-propagating modes of operation. For SOA length between 500 and 1000 µm, the maximum bit rate for counter propagating mode of operation is between 16 and 8 Gbps [6], so for high speeds of operation, co-propagating schemes are the method of choice.
Figure 3.3: Schematic of wavelength conversion process using cross-phase modulation in Mach-Zehnder interferometers (top) co-propagating mode (bottom) counter-propagating mode

3.1.2.1 Mach-Zehnder Interferometer WC

In a Mach-Zehnder interferometer, the CW signal is split between the two branches of the interferometer. The bias of the SOAs in the branches determines the gain of the signal, as well as relative phase of the signal at the output of the two branches. For non-inverting mode of operation, the output of the interferometer is turned off by adjusting the bias of the SOA in one branch of the interferometer in order to achieve $\pi$ relative phase shift between the two branches. The output of the MZI can be modulated by the data signal, which compresses the gain of the SOA in the common branch and swings the phase difference ideally between 0 and $\pi$.

MZI-SOA wavelength converters have been fabricated using both mul-
tiple quantum well active regions [10], [11], and bulk active regions [1]. As noted for the XGM-SOAs, the bulk active region provide high optical overlap between the mode and the gain region, which reduces the gain recovery time and increases the nonlinear effects (like index change) and speed of operation. Wavelength converters on all-active platform have also been reported [12], [19]. These devices benefited from the lowest recorded gain recovery times enabling 40 Gbps operation. However, realization of the passive interconnections using an active platform led to complex control and potential stability issues.

Counter-propagating XPM wavelength conversion requires no optical filtering at the output, but its speed is limited by the transit effects to around 10 Gbps [14].

On the other hand, wavelength conversion at data rates of up to 40 Gbps was reported in the co-propagating regime of operation [13].

Further increase in bit rates can be achieved by operating the MZI-SOA WCs in the differential phase modulation scheme. In this mode of operation, short RZ pulses are injected in both arms of the MZI with a time delay of 8-12 ps. When the pulse enters one of the arms, the phase in this arm is shifted practically instantaneously. The phase recovers slowly after the pulse has passed. The same happens in the other arm, but 8-12 ps later. Since the output of the MZI is controlled by the phase difference between the two arms, the phase shift in the first arm opens the MZI and that of the other arm closes it. Penalty free wavelength conversion at 40 Gbps over 30 nm was demonstrated using this method [18].

Maximum output wavelength range reported for wavelength conversion in MZI-SOA WCs was 30 nm [15]. For the input wavelength range, full C-band and L-band coverage at 10 Gbps was demonstrated in [17].
One of the particularly attractive characteristics of MZI-SOA wavelength converters is their ability to perform 2R signal regeneration, for signals both in RZ and NRZ data formats. This property is based on the highly non-linear optical-optical transfer curve of these devices. Signal regeneration was demonstrated in various experiments with a variety of devices, for bit rates up to 40 Gbps [10], [11], [1].

A scheme that retains the advantages of faster device response and lack of need for signal filtering at the output is the dual-order mode MZI [19]. In this device, the SOAs that are placed in the arms of the interferometer can support two lateral modes. Special multimode interference (MMI) couplers [20] are used to couple and decouple the data and the CW light within the MZI-SOA. This results in the input signal rejection of 28 dB. This device is all active, including the MMI regions, which poses significant challenges for device control and stable operation.

3.1.2.2 Michelson Interferometer WC

The Michelson interferometer is a very compact and simple scheme, which involves reflection of the CW probe light from the rear facet of the device (refer to Figure 3.4). The concept of operation is similar to that of the MZI-
SOA. The CW signal passes twice through the two SOAs, interacting with the light in co- and counter-propagation thereby accumulating the required phase change. Therefore, for the same amount of the phase change as an MZI-SOA WC, half of the SOA length is required, relative to a MZI-SOA WC. This makes the MI-SOA WC device a particularly compact one. Also, no extra input waveguides are needed for the input data signal, as this signal is coupled through the back facet, Figure 3.4. The device requires only two fibers to be aligned. Besides the transit time limitation drawback due to partial counter-propagation of the input signal, the converted signal exits the device through the input waveguide, so a circulator must be used at the device input/output. Error-free operation at 10 Gbps has been demonstrated with a MI-SOA WC in [21].

3.1.2.3 Sagnac Interferometer WC

Sagnac interferometers allow for another implementation of wavelength conversion using cross-phase modulation. SI-WCs generally do not require pump signal filtering at the output, due to the built in mechanism that separates the input signal from the converted data. As with high speed MZI-SOA WCs, the effect used to perform wavelength conversion is the differential phase modulation. The mechanism of operation is similar to terahertz optical asymmetric demultiplexers (TOAD) [22].

A schematic of one implementation of a SI-WC [23] is shown in Figure 3.5. A continuous wave signal is coupled into the Port 1 and is equally split by a 2x2 MMI coupler into the left and right branch of the waveguide loop. The SOA is placed asymmetrically into the loop. The two components of the CW signal propagate in the clockwise and counterclockwise directions, interfering at the input MMI and dropping out of Port 1. Introduction of a time varying
control signal at the Port 3 introduces a time dependent phase change in the SOA. When CW components in the loop experience different index changes relative to each other, the total phase difference is such that the signal is dropped out of Port 2 for duration of the index change caused by the control signal.

These devices have been implemented using both MQW and bulk-active integration platforms. Full C-band operation using has been reported [23], at bit rates of 10 Gbps [23], [24]. One of the main limitations of this technique is that it works only for RZ data formats.

3.1.2.4 Delayed Interference WC

Wavelength conversion using delayed interference also exploits the effect of differential phase modulation. However, this techniques is attractive because it only requires a single SOA (or EAM) to induce the phase shift. A schematic of a DI-WC is shown in Figure 3.6. A single SOA is located before the Mach-Zehnder interferometer. The interferometer branches have different lengths such that the long branch provides a time delay of $\delta t$ with respect to the
Figure 3.6: *Schematic of wavelength conversion process using cross-phase modulation in delayed interference configuration*

short branch. The phase electrode in the short branch can be used to tune the output into inverting or non-inverting mode of operation. The RZ pump and CW probe signals are injected into the SOA simultaneously, and the pump signal performs the phase modulation of the probe. The power of the signals is adjusted to achieve a full $\pi$ phase shift. The response of the SOA is instantaneous, whereas the fall time is dictated by gain recovery times and is relatively slow. The phase-shifted probe signal reaches the output of the MZI through the short branch, and opens the gate. After the delay $\delta t$, the $\pi$ shifted CW signal appears from the long branch, the phase difference between the two branches is reduced to 0 and the gate is closed. The width of the pulses generated is therefore determined by the time delay $\delta t$. Error-free wavelength conversion with 7 dB penalty, in an integrated SOA-DI-WC was demonstrated at 100 Gbps, in the inverting mode of operation [25]. The main issues with this device design are balancing the losses and phase in the interferometer, high input power requirements (8 dBm) and degraded device performance in the non-inverting regime of operation.
3.1.3 Survey of the Monolithically-Integrated Tunable Wavelength Converters

This section covers the previous work on monolithically-integrated lasers and all-optical wavelength converters in InP. All of the devices reported to date used either XGM or XPM in SOAs for the wavelength converter realization. The tuning range of the devices reported spanned from 5 nm for DFB based devices, to 10 nm for the digitally-tunable wavelength converter. All of the devices presented somewhat depended on the temperature tuning for full wavelength range coverage. That made them unsuitable for applications where fast wavelength switching is required, such as protection switching or optical packet switching.

3.1.3.1 An Integrated DFB-SOA Wavelength Converter

This device consisted of a 800 \( \mu \text{m} \) long DFB laser integrated with the 500 \( \mu \text{m} \) long SOA section, Figure 3.7. It was fabricated in a multiple quantum well (MQW) technology. For wavelength conversion, the input signal was injected directly into the DFB section of the device, suppressing the DFB output power due to gain saturation. Additional cross-gain modulation took place in the SOA section which helped increase the extinction ratio of the output further. The non-linear transfer function of the device allowed for bit
reshaping and signal regeneration at 10 Gbps. The wavelength conversion was error free.

As with any DFB laser, limited tunability (5 nm) was possible using temperature tuning. The speed of operation was limited by the optical power in the device/SOA combination as well as the maximum tolerable level of coherent reflections back into the laser.

3.1.3.2 An Integrated DFB-MZI-SOA Wavelength Converter

Schematic of the distributed-feedback laser integrated with a MZI-SOA wavelength converter is shown in Figure 3.8. The laser was a $\lambda/4$ shifted DFB connected to the MZI using a Y branch 1x2 splitter. The input signal was coupled into the preamplifier SOA, which provided for 5.5 dB input dynamic range. The device was capable of error-free wavelength conversion at 2.5 Gbps over 20 nm of input wavelength range. As in the previous case, the speed of operation and the output power were limited by the level of back reflections into the laser that could be sustained. The device was fabricated in an offset quantum well integration platform, using an optimized
compressive-tensile-strained MQW stack for polarization independent gain. The chip dimensions were 3.6x0.5 mm². As with any DFB laser, limited tunability (5 nm) was possible using temperature tuning.

3.1.3.3 An Integrated Digitally-Tunable Laser and MZI-SOA Wavelength Converter

The digitally-tunable laser (DTL) integrated with the MZI-SOA wavelength converter schematic [28] is shown in Figure 3.9. The digitally tunable laser is positioned in the left side of the chip, and it consists of a 4-channel arrayed-waveguide grating (AWG) based demultiplexer, 4 active regions and a 1x2 MMI splitter for coupling the power out of the cavity, similar to [29]. The laser cavity extends through the MMI splitter and loops to the back facet which is high-reflection coated. The cavity modes are therefore determined by the two back facet reflections, whereas the AWG acts as a filter to insure single-mode operation of the laser. By switching on different SOAs in the cavity, different super modes can be chosen. The wavelengths between these
modes could be covered using, per example, temperature tuning.

The Mach-Zehnder wavelength converter is in the right side of the chip. It employed even splitting between the two branches of the MZI. The bulk-active region SOAs were 500 µm long. Input signal was preamplifier, and split through a 28%–72% MMI splitter before entering the MZI. The 28% portion of the signal was fed into a photodetector. This provided for continuous power monitoring capability, and could be used to adjust the preamplifier bias in order to improve the input dynamic range.

The chip was fabricated using a 3 step MOCVD process for butt joint integration of passive and active waveguides. The WC chip dimensions were 3.5x7.5 mm².

The WC showed better that 14 dB static optical extinction, and the laser side-mode suppressio ratio of 25 dB over 10 nm laser tuning range. However, due to facet reflection problems [28], the on-chip laser was unstable in dynamic operation above 1 Gbps.

### 3.2 Chapter Summary

In this chapter, background and previous work in the field of the SOA-based wavelength converters were covered.

In the first part of the chapter, the principles of the cross-gain and the cross-phase modulation in semiconductor optical amplifiers were discussed. Various techniques used to achieve wavelength conversion using these effects were also covered, including the best to date performance for each of these approaches. In the second part of the chapter, a survey of the work that has been done in the field of monolithically-integrated tunable wavelength converters in InP was provided.
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Chapter 4

Integration Building Blocks

The performance of a photonic integrated circuit will critically depend on the performance and design of its individual active building blocks. Additionally, in order to be able to choose the right design tradeoffs for the individual building blocks, that will have minimal effect on the overall degradation of PIC performance, it is necessary to have a good understanding of the behavior, properties and design of the individual functional blocks.

In this chapter, the main active building blocks for the widely tunable wavelength converter are discussed and analyzed: the semiconductor optical amplifier, the Mach-Zehnder interferometer SOA wavelength converter and the SGDBR laser. The analysis of the block performance is done based on the integration platform used in this work, and the design rules and guidelines are set for the optimum PIC design.

4.1 Semiconductor Optical Amplifiers

A semiconductor optical amplifier is a photonic active component that under suitable operating conditions can provide light amplification. The process of
amplification is based on stimulated emission of photons, generated by the
electron-hole recombination in the active region of the amplifier. As with
any stimulated emission, an inversion of carriers is needed to sustain it - in
SOAs, this inversion is achieved by electrical pumping of the amplifier.

A cross-section of an SOA is shown in Figure 4.1. The light is confined
by a high index waveguide, which can be buried, rib-loaded or ridge type.
The active region of the amplifier can be either bulk or quantum well based.
The material is considered to be bulk if the de Broglie wavelength of carriers
is much smaller than the smallest dimension of the active region. If this
dimension is on the order of $\lambda_B$ then the active region is termed as quantum
well.

In some implementations, the waveguide is the active region at the same
time. The active region can be located in the middle of the waveguide, or on
the top. This will in part determine the SOA optical properties, mainly the

Figure 4.1: Schematic cross-section of a bulk SOA
gain and the maximum output power.

The amplification process is accompanied by additive amplified spontaneous emission noise, and this noise cannot be avoided. The amplifier ends are always reflective to some degree, and those reflections cause ripple in the amplifier gain.

SOAs can be classified into two basic types: Fabry-Perot SOAs and travelling-wave SOAs. In Fabry-Perot SOAs, the reflections from the amplifier facets are significant whereas in the travelling-wave designs, these reflections are negligible. In this work, we dealt with multiple quantum well based travelling wave SOAs, so the emphasis of the analysis will be on these structures. At the end of this section, a comparison will be given between our SOAs and bulk active material SOAs, in order to access the differences and advantages of both approaches.

4.1.1 Gain in Direct Bandgap Semiconductors

From elementary solid state physics, it is known that there are three types of radiative transitions in a semiconductor: stimulated absorption ($R_{12}$), stimulated emission ($R_{21}$) and spontaneous emission ($R_{sp}$). The first two types of transition are the dominant carrier recombination mechanisms when the light is present. Stimulated emission will generate photons that are identical in energy and phase as the photons causing the emission, so these photons will be generated into the same optical mode.

The total net stimulated rate of emission, and therefore the optical gain, depends on the number of photons already present and the number of state pairs in the two bands that are available. The number of state pairs has two main components to it: the density of total state pairs, which is purely material dependent, and the fraction of available state pairs, which is dependent
4.1.1.1 Definition of Optical Gain

The definition of optical gain through a small segment of optically active media is illustrated in Figure 4.2. The simplest way of defining optical gain is as follows: an incoming number of photons $N_p$, passing through a small length of the active region $\Delta z$, will grow by $\Delta N_p$. This growth can be described in terms of gain per unit length as

$$ N_p + \Delta N_p = N_p e^{g \Delta z} \quad (4.1) $$

If $\Delta z$ is small, then the exponential can be approximated, $exp(g\Delta z) \approx (1 + g\Delta z)$. Also, using the fact that $\Delta z = v_g \Delta t$, where $v_g$ is the group velocity, we get $\Delta N_p = N_p v_g \Delta t$. Finally, the expression for material gain is

$$ g = \frac{1}{N_p} \frac{dN_p}{dz} = \frac{1}{v_g N_p} \frac{dN_p}{dt} = \frac{1}{v_g N_p} (R_{21} - R_{12}) \quad (4.2) $$

where $R_{21}$ and $R_{12}$ are stimulated emission and stimulated absorption rates respectively.
The net stimulated recombination rate is given by

\[(R_{21} - R_{12}) = R_r (f_2 (1 - f_1)) - R_r (f_1 (1 - f_2)) = R_r (f_2 - f_1) \quad (4.3)\]

where \(R_r\) is the radiative transition rate that would exist if all state pairs were available to participate in the transition. \(f_1\) and \(f_2\) are occupational probabilities, and they can be described using Fermi statistics even under non-equilibrium conditions by using separate Fermi levels for conduction \((E_{Fc})\) and valence \((E_{Fv})\) bands

\[f_1 = \frac{1}{e^\frac{E_1 - E_{Fv}}{kT} + 1} \quad (4.4)\]
\[f_2 = \frac{1}{e^\frac{E_2 - E_{Fc}}{kT} + 1}. \quad (4.5)\]

These levels are called quasi Fermi levels, and their separation equals the bias applied to the P-N junction.

4.1.1.2 Photon Generation and Loss

The active region of the SOA is usually the lowest bandgap region in the double heterostructure, which ensures high efficiency of the carrier injection.
into this region. A band diagram of an arbitrary semiconductor active region is shown in Figure 4.3. The injected current provides a light generation source, whereas various radiative and non-radiative processes and leakage are the cause for recombination.

The fraction of the terminal current $I$ that generates carriers in the active region is denoted by the internal quantum efficiency $\eta_i$. Therefore, the number of electrons that are injected into the active region per second is given by $\frac{\eta_i I}{q}$, where $q$ is the charge of an electron. The rate equation for the carriers in the SOA active region is then

$$\frac{dN}{dt} = \frac{\eta_i I}{qV} - R$$

(4.6)

where $V$ is the volume of the active region, and $R$ is the rate of recombining electrons per unit volume of the active region.

The recombination processes consist of the spontaneous recombination $R_{sp}$, non-radiative recombination $R_{nr}$, leakage $R_l$ and stimulated recombination $R_{st}$. Only the stimulated recombination process requires the presence of photons, therefore, the other mechanisms combined are defined as natural decay processes, and are described by a carrier lifetime $\tau$ [8],

$$R = \frac{N}{\tau} + R_{st}.$$  

(4.7)

The carrier lifetime is not independent of the carrier concentration $N$, and that fact plays a role in the dynamic processes in the SOAs, explained further in this chapter. Finally, the rate equation for the carriers is

$$\frac{dN}{dt} = \frac{\eta_i I}{qV} - \frac{N}{\tau} - v_g g N_p$$

(4.8)

where we have used the equation (4.2) for $R_{st}$.

When it comes to photons, their main sources of generation are spontaneous and stimulated emission. The losses happen due to intrinsic material
absorption, free-carrier absorption and scattering, and they can be characterized similarly to electron losses by the photon lifetime $\tau_p$.

Since the photons are usually more spread out within the volume of the amplifier (due to the mode not being completely and strictly confined to the active region), we need to take into account the fact that only photons that are inside the active region will actually contribute to the photon generation due to stimulated and spontaneous emission. This fact is mathematically described by a confinement factor $\Gamma$, which can be thought of as the ratio between the volume of the active region and the volume of the mode [8],

$$\Gamma = \frac{V}{V_{\text{mode}}}.$$  \hspace{1cm} (4.9)

The rate equation for photons a single mode of the waveguide is then

$$\frac{dN_p}{dt} = \Gamma R_{st} + \Gamma \beta_{sp} - \frac{N_p}{\tau_p}.$$  \hspace{1cm} (4.10)

The coefficient $\beta_{sp}$ enables us to account for the spontaneous emission generated into this one particular mode of the waveguide. The spontaneous emission, in general, is distributed between all possible modes supported by the waveguide.

Using these rate equations enables us to predict and optimize a lot of the properties of the SOAs, as well as to perform accurate numerical modelling of their performance. However, for an accurate model, we need to have good knowledge and understanding of the active region and optical gain it provides. That is explained in the next section.

### 4.1.2 MQW Active Region

Quantum well active regions represent an attractive solution for SOAs and offer significant advantages, some of which are high optical bandwidth, high
saturation output power, high differential gain and low transparency currents [1],[2].

To optimize the performance of any semiconductor optical amplifier, it is crucial to have good understanding of the relationships linking the injected current and the optical gain.

4.1.2.1 Expression for Quantum Well Gain

The stimulated radiative transitions between electrons and holes occur because the field of the photons alters the phase of the electron wave function in such a way that it becomes similar to the phase of the hole wavefunction in a different band. This phase matching results in strong coupling between the two states. Since there is a number of states that are actually coupled to one electron (described by the density of states), the electron transforms to one of these states with very low probability of going back to its initial states. This results in a generation of a photon identical to the one whose field caused the transition.

The laws of transition of electrons between different bands in presence of an optical perturbation are described using Fermi’s Golden Rule [4].

According to the Fermi’s Golden Rule, it is possible to express $R_r$ in function of the spatial overlap between the initial and final wave functions of the electron transition with the existing electrical field at a particular energy, as well as the available reduced density of states,

$$R_r = \frac{2\pi}{\hbar} |H'_{21}|^2 \rho_f(E_{21}).$$  \hspace{1cm} (4.11)

Therefore, the gain of a quantum well for a particular photon energy $E_{21}$ is given by

$$g_{21} = \frac{2\pi}{\hbar} \frac{|H'_{21}|^2}{v_g N_p} \rho_f(E_{21}) \cdot (f_2 - f_1).$$  \hspace{1cm} (4.12)
Since the electromagnetic perturbation $|H'_{21}|$ is proportional to the field strength, it is possible to further reduce this expression for gain by linking the perturbation strength to the photon density $N_p$. The final expression for the two-state gain in a quantum well is given by

$$g_{21} = \frac{\hbar \pi q^2}{n\varepsilon_0 n_0^2} \frac{1}{\hbar \nu_{21}} |M_T(E_{21})|^2 \rho_f(E_{21}) (f_2 - f_1).$$  

(4.13)

$M_T$ is called the transition matrix element and it describes the band-to-band interaction strength. Its magnitude is for the most part evaluated experimentally and this element is responsible for the optical gain sensitivity to the polarization of the incoming light. More details about the transition matrix element and how to calculate it can be found in [6], [8].

Finally, to account for the total gain, one needs to sum the two-state gain over all possible transition pairs in the quantum well (Figure 4.4 (a)),

$$g_{total_{21}} = \sum_{n_c} \sum_{n_v} g_{21}(n_c, n_v).$$  

(4.14)
Due to the complex band structure of the valence band, there will be a multitude of quantized energy bands in the valence zone, resulting from the quantization of both the heavy hole and the light hole bands. By calculating the matrix element $M_T$ for these different bands, it turns out that the transitions to the light hole band will produce mainly photons of the TM polarized light, whereas the transitions to the heavy hole band will generate photons that are TE polarized. Depending on the relative position of these bands with respect to the bandgap, the gain of the quantum wells will provide more gain for one polarization of light. By engineering these positions, it is possible to achieve polarization independent gain in MQW active material. This is discussed further in the section talking about strained quantum wells.

In order to predict the gain accurately, additional energy broadening must be taken into account. This broadening takes into account the energy level uncertainty and causes the removal of very sharp features and transitions that are predicted for gain spectra of structures with reduced dimensions (like quantum wells). To obtain the new expression for total gain at energy $h\nu_0$, (4.14) must be integrated over all transitions with an appropriate lineshape function,

\[ g(h\nu_0) = \int g_{21} \Delta(h\nu_0 - E_{21}) dE_{21}. \]

(4.15)

The lineshape function that has a simple mathematical form and a good degree of accuracy was proposed by Chinn, [12]. This lineshape function was used to calculate the gain for the quantum wells used in this work.

### 4.1.2.2 Total (Reduced) Density of States $\rho_f(E_{21})$

When looking at transitions in a semiconductor, it can be observed that both initial and final states of transition are not cingular, but rather there is a plentitude of available transition pairs within the energy range $\delta E_{21}$ for
any given transition energy \( E_{21} \). Therefore, \( \rho_f(E_{21}) \) should be interpreted as the density of transition pairs per unit energy. This density is usually referred to as the reduced density of states. Assuming that the conservation of momentum rule applies, where the transition is possible for only those states that preserve the value of \( k \), we have

\[
\rho_r(E_{21}) \delta E_{21} = \rho(k) \delta k
\]

\[
\frac{1}{\rho_r(E_{21})} = \frac{1}{\rho(k)} \left[ \frac{dE_2(k)}{dk} - \frac{dE_1(k)}{dk} \right],
\]

(4.16)

where \( \rho(k) \) is the density of states, and \( E_1(k) \) and \( E_2(k) \) are the expressions for energy bands as a function of wave vector \( k \). The density of states for bulk and quantum well structures are given by

\[
\rho_{\text{bulk}} = \frac{\sqrt{E}}{2\pi^2} \left[ \frac{2m^*}{\hbar^2} \right]^{3/2}
\]

\[
\rho_{\text{qw}} = \frac{m^*}{\pi \hbar^2 w}
\]

(4.17)

where \( m^* \) is the electron (or hole) effective mass, and \( w \) is the width of the well. These functions are illustrated in Figure 4.4 (b).

The definition of the reduced density of states (4.16) enables us to calculate the reduced density of states based on the known band structure \( E_k \).

To accurately determine the band structure of the quantum well in both the conduction and the valence band, methods for both non-degenerate and degenerate band effective mass calculations have been proposed by Luttinger and Kohn [5]. These methods use a so-called \( k \cdot p \) formalism to set up and solve a Schrodinger-like equation for the envelope function of the electron state. Although this method has been employed to calculate the band structure of the active region of the SOAs used in this work, the method itself has been well documented and explained in [8], [8] and therefore won’t be discussed further in this thesis.
4.1.2.3 Relationship Between Carrier Density and Gain

Finally, to obtain the relation between the carrier concentration and the optical gain, we need to exploit the quasi Fermi levels and their influence on both of these parameters. Under the forward bias condition, the quasi Fermi levels in the conduction and valence band are linked to the electron and hole densities \( n, p \) by

\[
\begin{align*}
    n &= \frac{m_e k T}{\pi \hbar^2 L_z} \sum_{n_e} \ln \left( 1 + e^{\frac{E_{F_e} - E_{c1}}{k T}} \right) \\
    p &= \frac{k T}{\pi \hbar^2 L_z} \sum_{n_{hh}} m_{hh} \ln \left( 1 + e^{\frac{E_{F_v} - E_{hhi}}{k T}} \right) + \frac{k T}{\pi \hbar^2 L_z} \sum_{n_{lh}} m_{lh} \ln \left( 1 + e^{\frac{E_{F_v} - E_{lhi}}{k T}} \right)
\end{align*}
\]

(4.18)

It can be shown that in order to achieve optical gain, the quasi Fermi level separation needs to be higher than the bandgap of the semiconductor. As first observed by Bernard-Duraffourgh [3], only within the region of photon energy where

\[
(E_{F_e} - E_{F_v}) > E_{21} \geq E_g
\]

(4.19)

the photons will experience the optical gain.

Now, it is possible to calculate the gain as a function of sheet carrier density for any multiple quantum well material.

Before we analyze the properties of the MQW gain, we need to address the issue of strain in quantum wells.

4.1.2.4 Strain in Quantum Wells

Polarization sensitivity of the gain of MQW active regions can be influenced greatly by the introduction of strain in the quantum wells [9], [10]. Stain
Figure 4.5: Band edge profile for quantum wells with (a) no strain (b) compressive strain (c) tensile strain

in quantum wells is introduced by growing the quantum well regions out of material whose native lattice constant is larger or smaller than that of the barrier material.

Since the energy gap of a semiconductor is related to the lattice spacing, we would expect the distortions in the lattice to lead to the changes in the bandgap of the quantum well material.

In a lattice-matched quantum well, the heavy and the light hole valence bands are degenerate. The effect of strain is to reduce this degeneracy by separating these bands. The strain also changes the effective masses of the holes, making the valence band more parabolic, and therefore reducing the optical transparency condition.

The shift in energy bandgap can be computed knowing the deformation potentials of the material of interest [8], [8]. The band edge shifts are given by

\[
\begin{align*}
\delta E_c &= -a_v(2\epsilon_{xx} + \epsilon_{zz}) \\
\delta E_{hh} &= a_v(2\epsilon_{xx} + \epsilon_{zz}) + b(\epsilon_{xx} - \epsilon_{zz}) \\
\delta E_{lh} &= a_v(2\epsilon_{xx} + \epsilon_{zz}) - b(\epsilon_{xx} - \epsilon_{zz})
\end{align*}
\] (4.20)
Figure 4.6: Calculated material gain curves as function of carrier density in the quantum well (7 nm wide InGaAsP QW with 8 nm wide InGaAsP barriers

with

\[ \epsilon_{xx} = \frac{a_0 - a}{a} \]
\[ \epsilon_{zz} = -2C_{12}C_{11}^{-1}\epsilon_{xx} \]  

(4.21)  

\[ a_c, a_v \text{ and } b \] are the conduction band, valence band and shear deformation potentials respectively. \( a \) and \( a_0 \) are the well and barrier lattice constants respectively, and \( C_{11} \) and \( C_{12} \) are shear elastic coefficients respectively. The values of all of these parameters depend on the well and barrier composition.

In a compressively strained quantum well, the bandgap will increase. The degeneracy in the light hole and heavy hole band edge will be removed, and the heavy hole band edge will be shifted less than the light hole band edge. Therefore, the TE gain will increase at the expense of the TM gain. On
the other hand, tensile strain will lead to decrease of the bandgap. If enough tensile strain is introduced in the well, the light hole band edge will be shifted more than the heavy hole band edge, leading to the increase in the TM gain. TM gain can become equal or exceed the TE gain provided by the well [11]. The effects of strain on the bandedge are illustrated in Figure 4.5.

4.1.2.5 Gain Calculation

Using the formalism presented, it is possible to calculate the material gain for the InGaAsP quantum well active region. The calculated TE material gain for the quantum wells used in this work as a function of the carrier density in the quantum wells is shown in Figure 4.6. This gain model is further used to assess properties of the SOAs.

4.1.2.6 MQW Refractive Index Change

One of the genuine features of the semiconductor active materials is that the gain change $\Delta g$ induced by varying the injected carrier density causes the refractive index changes at the peak gain energy. The primary reason for this effect is due to strongly asymmetric spectral shape of the gain curves. Since the gain changes correspond to the variation of the imaginary part of the refractive index, the Kramers-Kronig relation can be used to calculate the change of the real part of the refractive index,

$$\Delta n(\omega) = \frac{c}{\pi} P \int_0^\infty \frac{\Delta g(\omega')}{\omega'^2 - \omega^2} d\omega'$$

(4.22)

where $P$ denotes the principal value of the integral, and the integration is performed over the entire range of frequencies $\omega$.

Using 4.22, we can compute the change of the refractive index of the quantum well material caused by the change in gain of the quantum wells.
4.1.3 Fundamental Characteristics of MQW SOAs

The required characteristics of an SOA depend on the desired application. As a gain element, as SOA should have high gain and large gain bandwidth, negligible facet reflectivities, low polarization sensitivity, high output saturation power, low noise figure and no nonlinearities. These requirements usually result in devices whose length in less that 600µm [13].

As a non-linear element, it is desired that an SOA have low input saturation power, large area of overlap between the active region and the mode, large carrier densities and lengths greater than 600µm in order to benefit from high frequency filtering [13], [14].

In this section, fundamental characteristics of the SOAs based of an offset quantum well active region, used in this work, are introduced, investigated and explained through the simulations. All of the results are obtained using a transmission-matrix method based SOA model [15], [16]. More details about the SOA structure are given in Chapter 6.

4.1.3.1 Gain Bandwidth

A typical large-signal gain spectrum of a MQW SOA, for different bias currents is shown in Figure 4.7. The gain bandwidth is defined as the wavelength range over which the signal gain is more than half of its maximum value. It can be observed that the gain bandwidth is about 40 nm, with gains as high as 19 dB.

The gain bandwidth of MQW SOAs is generally greater than that of the bulk SOAs. In bulk, Figure 4.4, the density of states is a continuous function of energy, leading to stronger dependence on photon energy. In a quantum well, the staircase type energy dependence (illustrated in Figure 4.6) leads to flatter gain spectrum and therefore wider bandwidth.
Figure 4.7: Simulated MQW SOA gain as function of wavelength for 3 different bias currents. SOA length is 500 µm, and the input light power is -10 dBm.

4.1.3.2 Gain Saturation

The gain of an SOA is influenced by both the intensity of the current and the input power of the signal. As the optical power of the input signal increases, the carriers in the active region will become depleted, leading to the reduction in gain.

The gain at a position $z$ in an SOA can be modelled [17, 18] as

$$g(z) = \frac{g_0}{1 + \frac{I(z)}{I_{sat}}}$$  \hspace{1cm} (4.23)

where $g_0$ is the unsaturated gain coefficient, and $I_{sat}$ is the output saturation
Figure 4.8: Simulated MQW SOA gain as function of the input power, for different bias currents. SOA length is 500 µm, and the input light wavelength is 1570 nm.

Intensity. Further,

\[ I_{\text{sat}} = \frac{h \nu}{a \tau} \]

\[ P_{\text{sat}} = \frac{AI_{\text{sat}}}{\Gamma} = \frac{Ah \nu}{\Gamma a \tau}, \]  

(4.24)

where \( a \) is the differential gain, \( \tau \) is the carrier lifetime as defined in equation (4.7) and \( A \) is the area of the active region.

Analyzing the equation (4.24), we can conclude that for large optical saturation powers, we need a large optical area of the amplifier, small differential gain and carrier lifetime. This is more obviously achieved in bulk SOAs whose active area cross section is large, and the differential gain is lower than the one in the quantum wells. Calculated differential gain for the MQW SOAs used in this work is shown in Figure 4.9. These values about
an order of magnitude higher that the values typically obtained for the bulk active material at same carrier concentrations. Differential gain also plays a role in the dynamic behavior of the SOAs, as will be explained later.

Large output saturation power is important for the applications like power amplification. For wavelength conversion applications, the desired regime of operation for the SOAs is non-linear, so ideally the SOAs will have a small input saturation power. The input saturation power is defined as

\[ P_{\text{isat}} = \frac{P_{\text{sat}}}{G} \]  

(4.25)

where \( G \) the single-pass gain that the signal receives at that given pump level. Results of simulations of gain as a function of the input power for our SOA structures are shown in Figure 4.8. The offset multiple quantum well based SOAs have low input saturation power which can be contributed to their low optical area \( A \) and small confinement factor \( \Gamma \).
4.1.3.3 Mechanisms for SOA Refractive Index Change

As already explained, the gain and the refractive index in a SOA are interrelated through the Kramers-Kronig relations. In addition, the refractive index in a SOA will also change in function of the bias current, through the carrier plasma effect. Therefore, an optical power fluctuation in a SOA will induce the refractive index change and chirp. This effect is especially pronounced in the SOAs used for cross-gain modulation wavelength conversion, where large gain/index changes are needed to obtain efficient wavelength conversion.

This effect of power dependent index change leads to the phase change of the signals propagating through the SOAs and is key for performing wavelength conversion using cross-phase modulation.

One way to quantify the amount of index change in an SOA is through the linewidth enhancement factor $\alpha$, which can be defined as

$$\alpha = \frac{4\pi \frac{dn}{dN}}{\lambda \frac{dg}{dN}}.$$  \hspace{1cm} (4.26)

The name for this parameter comes from its influence on the linewidth of semiconductor lasers. The value of this parameter is important, because it will determine the maximum possible amount of phase change in an SOA.

In Figure 4.10, we are showing the calculated values for $\alpha$ in our MQW active regions. These values match well previous experimental data for similar type structures [20]. As expected, the values are a little lower than those for typical bulk active regions [19]. Also, the value of the parameter increases when approaching the bandgap wavelengths due to the rapid decrease of the differential gain.
4.1.3.4 Dynamic Effects

In all schemes of wavelength conversion employing the nonlinearity of the SOAs, a time varying pump signal affects the number of carriers in the SOA, which in turn affects the gain and the refractive index that both pump and probe experience as they propagate through the SOA.

One of the most important parameters in the dynamic operation of the SOAs is the gain recovery time, $\tau_g$. This time expresses the speed with which the SOA carrier number achieves its steady-state value after insertion or removal of the switching light. Consequently, the gain recovery time limits the switching speed or data rate for wavelength conversion in the device.

The analytic expression for the gain recovery time in a small section of
an SOA can be obtained as follows.

The rate equation for the carrier concentration in the active region of an SOA was introduced in (4.8) and is repeated here for completeness,

$$\frac{dN}{dt} = \frac{\eta_i I}{qV} - \frac{N}{\tau} - v_g g(N)N_p. \quad (4.27)$$

The material gain $g(N)$ is a non-linear function of the carrier concentration $N$, therefore this equation can only be solved numerically. However, in most of the practical cases of interest for wavelength conversion using cross-phase modulation, when the power of the signal going into any section of the SOA is changed, the carrier concentration changes by very little. This is the consequence of the fact that the SOA is usually saturated by the probe beam that is continuously passing through it. Therefore, the equation (4.27) can be linearized by employing the first order Taylor expansion around the steady-state value of the carrier density, denoted as $N_{pump}$. Using

$$g(N) = g(N_{pump}) + \frac{dg}{dN}(N - N_{pump}), \quad (4.28)$$

we obtain the following rate equation

$$\frac{dN}{dt} = \frac{\eta_i I}{qV} - \frac{N}{\tau} - v_g g(N_{pump})N_p - v_g \frac{dg}{dN}(N - N_{pump})N_p. \quad (4.29)$$

This equation can be reduced to the form

$$\frac{dN}{dt} = C - N \left( \frac{1}{\tau} + v_g N_p \frac{dg}{dN} \right), \quad (4.30)$$

where $C$ is a constant.

The standard solution for this type of equation is of the form

$$N = C\tau \left(1 - e^{-\frac{t}{\tau_t}}\right), \quad (4.31)$$

where the total gain recovery time $\tau_t$ is given by the expression

$$\tau_t = \left( \frac{1}{\tau} + v_g N_p \frac{dg}{dN} \right)^{-1}. \quad (4.32)$$
Figure 4.11: Simulated MQW SOA gain recovery times (a) due to non-radiative, leakage and spontaneous recombination, in function of carrier density (b) due to stimulated recombination, in function of optical power and carrier density.
The first component of total gain recovery time, $\tau$, was defined as the carrier lifetime. Now we define the second component of the total gain recovery time as stimulated recovery time. The number of the photons can further be expressed as a function of the optical power,

$$P = \frac{E}{\Delta t} = \frac{\Gamma N_p \hbar \nu A \Delta z}{\Delta t} = \Gamma N_p \hbar \nu Av_g,$$

where $A$ is the cross-sectional area of the active region and $\Delta z$ is the length of the segment.

Finally, the closed form expression for the gain recovery time is

$$\tau = (A + BN + CN^2)^{-1}$$

$$\tau_{st} = \left( \frac{dg}{dN} P \Gamma \frac{PT}{Ah\nu} \right)^{-1}$$

$$\tau_t = \left( \frac{1}{\tau} + \frac{1}{\tau_{st}} \right)^{-1}.$$

Figure 4.12: Simulated MQW SOA total gain recovery time in function of optical power and carrier density
The calculated values for carrier lifetime, stimulated recovery time and the total gain recovery time are shown in Figure 4.11 and Figure 4.12 respectively. These values were calculated for varying carrier concentrations and optical powers in the SOA segment. It can be observed that the stimulated recovery time dominates the total gain recovery time for low concentrations and high optical powers. This is consistent with the operating conditions of a highly saturated SOA. Thereby, the presence of the high power probe beam can significantly speed up the gain recovery time of the SOA and enable the high-speed operation [21, 22, 23]. Another effect that was mentioned in the previous chapter is the effect of high-frequency filtering in long SOAs. Basically, as the signal gets amplified while propagating through the SOA, the pulse will get distorted, and this distortion will help bring the SOA into deeper saturation, reducing the carrier lifetime in the SOA and making it susceptible to interaction with the higher frequency content in the signal [24].
4.2 Mach Zehnder Wavelength Converter

Design and Operation

A Mach-Zehnder interferometer SOA-based wavelength converter exploits the effect of cross phase modulation in semiconductor optical amplifiers. As already mentioned in the Chapter 3, cross-phase modulation (XPM) is the effect observed due to the intensity dependent refractive index in a semiconductor optical amplifiers.

A schematic of a typical MZI-SOA WC is shown in Figure 4.13. The MZI-SOA generally consists of an input waveguide followed by a light splitter which splits the incoming probe light between the two branches (uniformly or non-uniformly). The branches are defined by a set of curved waveguides whose role is to laterally separate the two semiconductor optical amplifiers in the branches. The required spacing is determined mostly by desire to prevent the heat crosstalk between the two branches. The two branches are reunited with another set of curved waveguides and a light combiner. One (or both) branches also include another light combiner which enables coupling of the external (pump) data to one or both branches of the MZI.

4.2.1 MZI Principles of Operation

For the wavelength conversion, the continuous (CW) probe signal is split between the two branches of the interferometer. Variation in the amount of current supplied to the SOAs in the two branches changes the output probe signal powers and phases in both branches. By introducing the pump (data) signal, Figure 4.14, in one of the branches of the interferometer (further referred to as common SOA), the pump light interacts with the gain of the SOA, initially increasing the amount of stimulated emission and thereby
reducing the carrier density in the SOA active region to a new steady-state level. This change in carrier concentration and SOA gain leads to the change in the refractive index, as explained in section 4.1.3.3. Therefore, the phase and the amplitude of the probe signal in common SOA get modulated by the intensity variation of the pump signal. The interferometer configuration serves to transfer this phase modulation into the intensity modulation - the probe signals from both branches are recombined at the output, and the
Figure 4.15: *Typical electrical transfer curve of a MZI-SOA WC - one SOA current is fixed, and the other is varied*

variation of their relative phase leads to their interference and therefore the total signal intensity variation.

MZI-SOA wavelength converters can operate in two modes of operation: non-inverting and inverting mode.

In the non-inverting mode of operation, the output of the interferometer is shut down with no pump signal present (the phase difference between the two branches is set to $\pi$ rad by adjusting the SOA currents), and the pump signal turns the interferometer on, thereby replicating the pulse stream at the new wavelength.

In the inverting mode of operation, the output of the interferometer is turned on with no pump signal present (the phase difference between the two branches is set to some initial value by adjusting the SOA currents), and the
pump signal turns the interferometer off by changing the phase difference to π rad, thereby inverting the pulse stream at the new wavelength.

Typical electrical transfer characteristics for a MZI-SOA is shown in Figure 4.15, indicating the optimum setpoints for both modes of operation. Typical optical transfer curves for inverting and non-inverting modes of operation are shown in Figure 4.16.

4.2.2 MZI-SOA WC Operation Analysis

The electric field vectors of the probe signal mode at the output of the MZI-SOA can be represented as

\[
\begin{align*}
\vec{E}_1 &= \vec{E}_0 \cdot C_1 \sqrt{G_1} \cdot e^{j\phi} \\
\vec{E}_2 &= \vec{E}_0 \cdot C_2 \sqrt{G_2},
\end{align*}
\]

\hspace{1cm} (4.35)
Figure 4.17: Schematic of the MZI-SOA WC performance

where $C_1$ and $C_2$ are the power splitting constants for the light splitter and combiner, $G_1(I_1, P_1)$ and $G_2(I_2, P_2)$ are the total (power) gains for the SOAs in the branches 1 and 2 for the given operating conditions (bias currents $I_1, I_2$ and input powers $P_1, P_2$), and $\phi$ is the phase change between the signals in two branches, dependant on the operating point of the interferometer $(I_1, I_2, P_1, P_2)$. This is illustrated in Figure 4.17.

The input (pump) signal introduces a change in the total gain $G_1$ of the common branch, denoted by $\Delta G$, and thereby a change in the total output phase of the probe signal in the same branch, denoted by $\Delta \phi$.

Having in mind that the power of the optical signal is proportional to the square of the optical field, in the non-inverting mode of operation,

\[
P_{\text{min}} = K|\vec{E}_0|^2 \left( C_1 \sqrt{G_1} \cdot e^{j\phi} - C_2 \sqrt{G_2} \right)^2 + ASE
\]
\[
P_{\text{max}} = K|\vec{E}_0|^2 \left( C_1 \sqrt{G_1 - \Delta G} \cdot e^{j(\phi + \Delta \phi)} + C_2 \sqrt{G_2} \right)^2 + ASE,
\]

where $K$ is the proportionality constant between the electric field and the power, and $ASE$ is the power of the broadband non-coherent amplified spontaneous emission from the MZI-SOAs. For inverting mode of operation,
Figure 4.18: (a) Necessary power ratio for the two branches of the MZI-SOA WC to obtain given extinction (assuming $\pi$ rad phase shift) (b) Necessary phase difference between the two branches of the MZI-SOA WC to obtain given extinction (assuming equal power in the branches)

\[
P_{\text{max}} = K|\vec{E}_0|^2 (C_1\sqrt{G_1} \cdot e^{j\phi} + C_2\sqrt{G_2})^2 + ASE
\]

\[
P_{\text{min}} = K|\vec{E}_0|^2 (C_1\sqrt{G_1} - \Delta G \cdot e^{j(\phi + \Delta \phi)} - C_2\sqrt{G_2})^2 + ASE
\]

The extinction ratio of the wavelength converter is defined by

\[
ER = \frac{P_{\text{max}}}{P_{\text{min}}}
\]

and it represents of the most important measured of quality of digital signals. In order to maximize the $ER$, it is very important that the minimum power $P_{\text{min}}$ be as close to zero as possible. However, the minimum power level will always be non-zero, due to the $ASE$ noise present.

A vast majority of the implementations of a MZI-SOA WC reported to date use the SOA currents to control both the signal gains and the phase. The common SOA is always biased at a higher current level because this regime of operation provides higher saturation and lower gain recovery times, as already explained.
Due to some difference in power between the two branches of the SOA, the output extinction will always be limited. This is illustrated in Figure 4.18 (a). The plot shows the required ratio between the power of the two branches of the MZI in order to achieve a desired level of extinction, assuming that the phase difference between the two branches is $\pi$ rad. We can conclude that even with 25% difference in power, we can get extinctions better than 15 dB.

On the other plot, Figure 4.18 (b), required phase difference between the branches of the SOA is plotted in function of the desired extinction ratio. This plot shows that for extinction ratios better than 15 dB, a phase difference required is 130 degrees or more (assuming equal power in both branches).

To achieve good extinction ratio, both of power and phase have to be set properly. Based on the analysis provided, it becomes clear that both conditions can be satisfied with configurations that use SOAs for both power and phase control.

Analyzing the equation (4.36) for the non-inverting mode of operation, we can conclude in order to minimize the minimum power $P_{\text{min}}$ in the non-inverting case, we need to have asymmetrical splitting of the probe signal, that is, $C_2 > C_1$. That way, the higher gain of the SOA1 (Figure 4.17) may yield a smaller total output power, enabling the equalization of powers coming out of both branches and minimizing the minimum power (provided that a full $\pi$ rad phase shift is achieved). However, in this regime of operation, the common SOA (SOA1) is pumped with lower optical power, which degrades the maximum speed of the wavelength converter due to higher gain recovery times.

On the other hand, in the inverting mode of operation, described by
equations (4.37), the gain compression due to the pump signal in the common SOA happens when the fields from the two branches are subtracted (one level produces a zero in the inverting mode of operation). Therefore, in this configuration, it may be possible to optimize for both high extinction ratio and higher speed operation at the same time.

4.2.3 MZI Performance Enhancement

In the previous section, we have demonstrated that in order to optimize the operating conditions of the MZI-SOA WC, conditions for high common SOA current bias, power balance between the branches, and phase difference have to be met. The best way to achieve this is by introducing the capability in the interferometer for independent power splitter ratio and branch difference phase control. This can be realized easily in the highly integrated devices based on active-passive integration platforms. More details about this design and its realization will be given in Chapter 6.
4.3 SGDBR Laser

Sampled grating Distributed Bragg Reflector laser belongs to the class of widely tunable integrated diode lasers that can achieve tuning ranges 5x to 10x higher than standard DBR lasers.

Besides its impressive performance as a tunable laser source (high output power (>10 mW in fiber) over the entire tuning range (40 nm) with low linewidth (2 MHz) and high side-mode suppression ration (>40 dB)), important inherent properties of this laser make it an ideal source for use in advanced photonic integrated circuits.

The laser mirrors are fully lithographically defined and no facet reflection is needed for the laser operation. That property enables the integration of additional components downstream from the laser, provided that they do not cause any significant coherent reflections.

The laser consists of sections of both active and passive waveguides, therefore, standard, relatively simple fabrication processes of the SGDBR laser can be easily extended to more complex components without significant increase in the process complexity.

Successful integration of SOAs and modulators with the SGDBR lasers has been accomplished over the past years. In addition, the performance of the lasers has been improved significantly using more optimized laser designs and a new, more versatile integration platform and process, based on quantum-well intermixing [25].

The goal of this chapter is to briefly analyze the performance and show the design guidelines for a good SGDBR laser. For a more detailed version of this analysis, the reader is referred to [26].
4.3.1 Principles of Operation

A typical Sampled-grating DBR laser, shown in Figure 6.2, is a four section device and it consists of the front mirror, gain section, phase section, and the rear mirror. Optionally, a back facet absorber (an active section used in reverse bias as an absorber) may be added behind the back mirror, to help reduce the back side reflections.

The gain section contains a multiple quantum well active region. This active region can be located in the middle of the waveguide (for device realizations in the burrier ridge stripe architecture), or on top of a quaternary waveguide, if using an offset quantum well based platform.

Both the front and the back mirrors of the laser consist of periodically sampled DBR gratings. This produces a comb-like reflectance spectrum, as shown in Figure 4.20. The mirror design relies on the Vernier effect and the sampling periods of the two mirrors are designed to be slightly different, yielding mirrors that have different peak reflectance spacing. The design insures that only one set of mirror reflectivity peaks be aligned at any time.

The tuning of the mirrors is accomplished by using the carrier plasma effect. Electrical current pumped through the mirrors causes an increase in the free carrier absorption which produced a negative index change, as
Differential tuning of the front mirror relative to the back and vice versa allows for the adjacent reflectivity peaks to be aligned, and for the laser to switch its wavelength of operation to this new wavelength. The spectral area between the mirror peaks can be covered by tuning both mirrors simultaneously.

Back facet detector section is operated in reverse bias, and can be used for power monitoring, but it also has a function of terminating the output of the laser from the back mirror thereby relaxing the requirements for the antireflective coating.

Typical overlapped spectra of the modes lasing at the back-mirror supermode positions for a SGDBR laser are shown in Figure 4.21.
Figure 4.21: Typical overlapped spectra for a SGDBR laser (in this case, from the monolithically integrated wavelength converter chip)

4.3.2 SGDBR Operation Analysis

The properties of an SGDBR laser critically depend its design. To achieve good desired performance over the desired tuning range, the laser integration platform needs to be optimized for maximum gain in the active regions and sufficient index tuning in the mirrors. Finally, a good sampled grating mirror design is critical for the overall laser performance.

4.3.2.1 Sampled Mirror Analysis

There are four main parameters in the sampled mirror, and those are illustrated in Figure 4.22: the depth of the grating, \( D \), the length of the mirror burst, \( Z_1 \), the sampling period, \( Z_0 \) and the number of bursts, \( N \).
The sampling period \( Z_0 \) only depends on the chosen mirror peak spacing, \( \Delta \lambda \), and is therefore easily determined.

The important spectral properties of a sampled mirror are its 3dB spectral envelope bandwidth, \( \lambda_{envelope} \), the reflectances of the peaks in the center and at the edge of the operating range, \( R_c, R_e \), and the full-width at half maximum (FWHM) of the single peak, \( FWHM_P \).

The reflectances \( R_c, R_e \) are determined by the number of bursts and by the grating depth. In order to increase the efficiency of the mirror, the grating depth should be as large as possible, given the technological constraints (the ability to bury the grating during regrowth). As far as the dependence on the number of bursts goes, it has been shown that the reflectance will saturate after about 7 bursts [6].

The \( FWHM \) parameter will crucially influence the side-mode suppression ratio of the laser, and can be reduced by keeping the burst length short, and the number of bursts high. The same trend is noticed for the influence of these parameters on the spectral envelope bandwidth, \( \lambda_{envelope} \).

Taking all of these considerations into account, it is possible to chart a finite design space for the mirrors which can then be numerically analyzed in order to choose the optimum designs.
4.3.2.2 Active Region

The available gain for the active region of the laser will depend on the efficient pumping of the quantum wells and on the optical mode overlap between the active region and the lasing mode. High modal gains are advantageous because they enable lasing at low carrier densities. That, in turn, makes the laser more efficient because it limits the non-radiative recombination as well as the carrier leakage from the quantum wells. Finally, such lasers would yield low threshold currents and higher output powers.
4.4 Chapter Summary

In this chapter, we have discussed the basic properties and analyzed the design parameters critical for performance of semiconductor optical amplifiers, Mach-Zehnder SOA wavelength converter and SGDBR laser.

The analysis of the building block performance was done based on the integration platform used in this work, and the design rules and guidelines were given for the optimum PIC design.

The properties of the semiconductor optical amplifiers critically depend on the active region design. Offset quantum well active regions provide for high differential gain, large gain bandwidth, and large output saturation power. The gain recovery time will be influenced in part by the photon density in the active region.

Mach-Zehnder interferometer wavelength converter allows for regenerative operation in both inverting and non-inverting modes of operation. The output extinction ratio is critically determined by the ability to cancel the fields of the two interferometer branches in the OFF state. Better results can be achieved using independent phase control of the interferometer.

The properties of the SGDBR laser are greatly influenced by the proper sampled mirror design. Strict design ruled need to be followed in order to achieve high output power, side-mode suppression ratio and wide tuning range.


References


Chapter 5

Photonic Interconnection

Elements

Interconnects in photonic integrated circuits encompass all the passive optical components that are used to optically connect different functional blocks. They consist of straight optical waveguides, curved optical waveguides, light splitters and combiners and total internal reflection (TIR) optical mirrors. This section will discuss in detail properties of all of these components except TIR mirrors, as they have not been used in this work. Interested readers are referred to [1, 2] to learn more about this topic.

Important desirable properties for the interconnects are low propagation loss, low polarization dependence, low back reflections, compactness (size for light splitters and length–per–angle for bends) and ease of fabrication.

These properties will be determined by the techniques used to guide the light on the chip. The optimum type and design of the interconnects will be determined by the intended application.

This chapter classifies the photonic interconnects and analyzes the important properties and photonic integration requirements. Then, bend wave-
Photonic interconnects can be classified into strongly and weakly guiding, based on the transverse effective index difference between the core and the cladding [8] of a waveguide component.

Four main types of waveguides employed for photonic interconnects are shown in Figure 5.1, and will be discussed from the perspective of their realization in the InP/InGaAsP material system.

Figure 5.1 a) shows a surface ridge waveguide, which consists of an InP ridge on top of the continuous InGaAsP waveguide layer. The wings of the

Figure 5.1: Schematic of the three main passive waveguide types (a) deep ridge (b) buried ridge (c) surface ridge

uides as well as multimode interference based light splitters and combiners are treated in great detail.

5.1 Photonic Interconnects Classification

Photonic interconnects can be classified into strongly and weakly guiding, based on the transverse effective index difference between the core and the cladding [8] of a waveguide component.

Figure 5.1 a) shows a surface ridge waveguide, which consists of an InP ridge on top of the continuous InGaAsP waveguide layer. The wings of the
InP ridge (also InP) determine the index contrast of this waveguide. The highest contrast will be achieved when the InP wings are completely removed. The main advantages of this type of waveguides are that they can be fabricated using crystallographic wet etching techniques [4], resulting in low sidewall roughness and reduced scattering losses [7]. The low optical confinement of the mode, due to the small index contrast, additionally reduces the scattering losses. This platform can be used to realize low loss straight waveguides and light splitters and combiners. Bends can also be realized in this platform, however, they cannot be very compact, due to the small index contrast. Therefore, band radii on the order of 500 $\mu$m are generally used. Crystallographic wet etching can be used to etch the bend waveguides as well, however, the amount of undercut will change as the function of angle relative to the crystal $[0 1 1]$ direction, and the bends will be etched through at the critical angle of $45^\circ$, due to a high preferential etch rate at this crystal orientation [4].

Figure 5.1 b) shows a loaded ridge waveguide, which consists of an InGaAsP ridge on top of the continuous InGaAsP waveguide layer. The whole structure is then clad by InP. The dimensions and the composition of the ridge waveguide will determine the index contrast for this structure. The applicability, advantages and disadvantages of this structure are similar to those of the ridge waveguide, with an additional regrowth complication explained in more detail for the buried ridge waveguide.

Figure 5.1 c) shows a deep ridge waveguide, which consists of an InGaAsP waveguide layer clad by InP transversely and by air laterally. This combination provides the largest index contrast possible, and allows for very compact components (splitters, bends) to be designed. Components in this technology are fabricated using reactive ion etching, which will cause significant sidewall
roughness [5] and consequently increased propagation losses.

Figure 5.1 d) shows a buried ridge waveguide, which consists of an InGaAsP ridge waveguide clad by InP in all directions. This combination provides large index contrast, with similar benefits and disadvantages to the deeply etched ridge concept. One specific point to be made about these waveguides is that the process of regrowth over the InGaAsP ridge requires extreme precision in control of the growth parameters (temperature and pressure) in order to prevent regrowth anomalies (also known as rabbit ears)[6].

5.2 Photonic Interconnects Properties

The propagation loss of the interconnect will be determined by the optical materials used for their fabrication, the waveguide structure and the fabrication process. The loss mechanisms in optical interconnections are absorption, scattering and leakage. Absorption arises from imperfect waveguide transparency, scattering is caused mainly by imperfect refractive index distribution while leakage involves the transfer of optical energy from guided modes into radiation [7].

Residual band edge absorption from the waveguide can be avoided by choosing a significantly higher waveguide bandgap (usually, 0.2 eV or more). Free-carrier absorption, particularly in the p–doped material is a major mechanism of loss in optical waveguides [8]. Therefore, it would be beneficial not to dope the passive waveguides at all. The doping schemes employed depend on the fabrication process design, and this condition os often impossible to meet. However, techniques like proton implantation exist that can help reduce the losses due to doping of the waveguides.

Another major mechanism for waveguide loss is the optical field scatter-
ing. Scattering depends of both the effective index difference amplitude $\Delta n^2$ and its spatial periodicity. [8]. Hence, the strongly guiding waveguides will yield higher scattering losses [7].

Finally, leakage in InP material system only occurs in the bends, and will be analyzed more in the next section.

The polarization dependence of the waveguide will be determined by the waveguide structure and the material parameters of the waveguide. The refractive index will generally have some degree of polarization dependence, due to the different interaction (absorption) of the material with TE and TM light. In principle, it is simple to achieve polarization independence in strongly guiding structures as they can be designed to be symmetric by proper choice of waveguide thicknesses and compositions [9].

The size and compactness of photonic interconnects will be mostly determined by the index contrast of the waveguiding structure used. More about this topic will be covered in the section about the multimode interference.

Finally, it is desirable that the passive waveguides maintain the single mode properties of the components on chip. Multimode waveguides can lead to higher losses due to coupling of the light into higher order modes which are generally mode prone to scattering and radiation losses. The number of modes that a waveguide supports is determined by its index and geometrical properties [8].

### 5.3 Photonic Integration Requirements

When designing an ideal photonic integrated circuit, it would be beneficial to use different types of interconnecting waveguides to perform different function on chip. Weakly guided waveguides would be preferred for straight in-
terconnects, whereas strongly guiding waveguides would be useful to achieve the maximum possible compactness of the chip by realizing sharp bends and light splitters.

Several integration platforms have been reported [10, 11] where hybrid surface/deep ridge interconnect waveguide combinations were used to fabricate PICs in InP. These hybrid integration platforms resulted in complex fabrication process, but were necessary in order to realize the desired PICs.

Also, while strongly guided structures result in light splitters and combiners that are more compact, serious issues with back reflections exist for these components. Hence, these structures will not satisfy the strict requirements in reflection minimization posed by the on-chip tunable laser.

In our work, the dimensions and the device architecture are such that use of a optical interconnections based on weakly guided surface-ridge waveguides is justified. Some of the main reasons for this are:

- small spatial separation (70 µm) of the components that needs to be achieved (mainly determined by the desired separation of the SOAs in the MZI branches)
- compatibility with the active waveguides which employ the same waveguide structure
- low reflection, loss, and length interfaces between active and passive waveguides (compared to some other technologies)
- compatibility with other interconnection components (light splitters and combiners)
- compatibility with the rest of the fabrication process (active and passive waveguides defined in a single fabrication step)
While additional chip size reduction of 10% could be achieved using one of the hybrid technologies, the performance of the chip would be marginally improved while raising a host of issues and potential problems with reflections and the more complicated fabrication process.

5.4 Bends using Surface Ridge Waveguides

Even though weakly guiding surface ridge configuration is not the most optimum for design of compact bends in InP, relatively compact bends can be designed using this approach if large angles and spatial separation are not required, which is the case in our wavelength converter design.

In addition to the regular loss mechanisms in optical interconnection elements (absorption and scattering), loss due to mode radiation can occur if the bends are not designed properly.

The radiation loss will exponentially depend on the bend radius \( R \) and the effective index contrast. For a given bend radius, a certain minimum effective index contrast is required to prevent catastrophic leakage of the light. The index contrast, as already discussed, will be determined by the height of the InP wings on the side of the waveguide.

Figure 5.2 shows a simulation of the transmission through a semi–circular loop as function of the InP wing thickness as indicated in the figure. The radius of curvature for the waveguide is kept constant at \( R = 400 \, \mu m \). For a ridge height of 1.8 \( \mu m \), the wing height of only 0.2 \( \mu m \) will cause all the light to leak out of the waveguide.

In order to get the highest index contrast possible while preserving all the good properties of the surface ridge waveguide, it is important to remove all of the InP wings from the sides of the ridge. This is a difficult task in a
standard process using reactive ion etching, since the uniformity of the etch rate will vary sufficiently over the sample to either overetch or underetch in some areas. Hence, using a selective wet chemical etch is beneficial because the etch depth will be precisely defined by the waveguide quarternary layer. On the other hand, due to a crystalographic nature of the selective wet etches [4], the slope and the waveguide width in the bend will vary with the bend angle relative to the [0 1 1] direction. Lower waveguide width increases the radiation of the waveguide, so steps need to be taken to include this width change into the mask design and compensate for it.

Another issue with the bends arises at the interfaces between bends and straight waveguide, or when connection 2 bends of opposite curvature. The
Figure 5.3: *Fundamental mode profiles for a 2-D waveguides – Waveguide width is 3 µm, and modes for straight, right bend R = 400 µm, left bend R = 400 µm are shown.*

fundamental mode of a curved waveguide of the same geometrical properties will be different than that of the identical straight waveguide, and its position will be towards the outer edge of the bend. This is illustrated in Figure 5.3, which shows the fundamental modes for a straight waveguide and two bends with opposite curvature. The mode shift can be understood by using conformal mapping techniques which enable the analysis of the radial propagation using the same techniques as those for the straight waveguides [12]. The refractive index of the bend waveguide increases with the increasing distance from the origin of the bend, and the mode tends to escape towards the outer edge of the waveguide.

In order to minimize the losses and maximize the coupling between the
light in a straight and that in a bend waveguide, the two waveguides are offset by a fraction of the waveguide width. The amount of offset can be computed by maximizing the overlap integral of the two fundamental modes.

5.5 Light Splitters and Combiners

The most commonly used photonic interconnection components for light splitting and combining are based on the phenomenon of multimode interference (MMI). The main properties that make MMI components so attractive are their simple structure, ease of fabrication, low inherent loss, large optical bandwidth and low polarization dependence [13].

Functions that are frequently needed in connecting different block in a photonic integrated circuit are those of light splitting (from one input into two outputs) and of light mixing (light from two input is mixed and sent to both outputs).

Traditionally, the way to realize these functions was using approaches like Y–branches and directional couplers. However, both of these approaches are inferior when compared to the MMI components due to either their high scattering loss and back reflections (Y–branch), or their length and complex fabrication requirements (directional couplers) low fabrication tolerances.

In this section, we will examine the multimode interference based components, as they have been extensively used in the design of our widely tunable wavelength converters. After briefly covering the theory of operation and important design relationships, we will discuss the important properties of the MMI components.
5.5.1 Multimode Interference Couplers

Functions that MMI components are used to perform are power splitting or mixing of M input waveguide to N output waveguide, shortly called $M \times N$ power splitting and combining [14, 15]. Figure 5.4. MMI couplers are based on the principle of self imaging. This is a property of the multimode waveguides by which an input field profile is periodically reproduced as a single or multiple images while propagating through the multimode waveguide. Therefore, in order to create a MMI effect, it is crucial to have a waveguide that supports a large number of modes. As will be explained later, the larger the number of supported modes, the better the imaging properties of the MMI coupler.

Multimode interference couplers can be modelled using various approaches, including numerical beam propagation methods, guided mode propagation analysis [16] or ray optics. Numerical BPM models provide the most accurate predictions and results when designing and optimizing the MMI components. However, the mode propagation analysis represents the best theoretical tool to analyze the MMI components, and to formally derive their imaging properties that are of interest.

Most of the MMI coupler implementations (including this work) are de-
fined with a lateral step index waveguide. They are single mode in the
transverse direction, and their lateral dimensions are usually much larger
than the waveguide thickness, which allows for analysis using the effective
index approximation[8].

5.5.2 Analysis of Multimode Interference Effect

A typical step-index multimode waveguide is shown in Figure 5.5. This
waveguide width is $W_m$ and it supports $m$ lateral modes with numbers $i = 0, 1, \ldots (m-1)$ at a free-space wavelength $\lambda_0$. Defining the waveguide effective
index as $n_r$, and cladding effective index as $n_c$, the lateral wave number $k_{yi}$
and the propagation constant $\beta_i$ are related to the waveguide effective index
by the dispersion relation

$$k_{yi}^2 + \beta_i^2 = k_0^2 n_r^2 \quad (5.1)$$

where

$$k_0 = \frac{2\pi}{\lambda_0} \quad (5.2)$$

$$k_{yi} = \frac{(i + 1)\pi}{W_{ei}} \quad (5.3)$$

The effective mode width $W_{ei}$ takes into account the polarization de-
dependent lateral penetration depth of each mode field due to Goos-Hanchen
effect [8]. In general, this effective width can be approximated by the effective
width corresponding to the fundamental mode [13],

$$W_{ei} = W_m + \left( \frac{\lambda_0}{\pi} \right) \left( \frac{n_c}{n_r} \right)^{2\sigma} (n_r^2 - n_c^2)^{-\frac{1}{2}} \quad (5.4)$$

where $\sigma = 0$ for TE and $\sigma = 1$ for TM.

Using the binomial expansion and taking into account the fact that $k_{yi}^2 << k_0^2 n_r^2$, the propagation constant $\beta_i$ can be deduced from (5.1)-(5.3)

$$\beta_i = k_0 n_r - \frac{(i + 1)^2 \pi \lambda_0}{4 n_r W_{ei}^2} \quad (5.5)$$

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We observe that the propagation constants in a step-index multimode waveguide show a nearly quadratic dependence with respect to the mode number $i$. At this point, we can also define the beat length of the two lowest-order modes $L_\pi$

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4n_r W^2}{3\lambda_0}$$

(5.6)

This quantity will be useful for describing the lengths of the key MMI components used in this work.

### 5.5.3 Guided-Mode Propagation Analysis

Using the principles of the guided-mode propagation analysis, an input field profile $E(y, 0)$ at a distance $z = 0$ and contained within a finite width $W$ can be decomposed by a complete set of functions represented by all modes of the waveguide (guided and unguided)

$$E(y, 0) = \sum_i c_i \psi_i(y).$$

(5.7)

The field excitation coefficients $c_i$ can be estimated using overlap integrals

$$c_i = \frac{\int E(y, 0) \psi_i(y) dy}{\sqrt{\int \psi_i^2(y) dy}}.$$  

(5.8)

When the spatial distribution of the input field is narrow enough not to excite any unguided modes, the input field may be decomposed into the guided modes alone

$$E(y, 0) = \sum_{i=0}^{m-1} c_i \psi_i(y).$$  

(5.9)

Using this approach, the field profile at a propagation distance $z$ can be
written as superposition of the individual modes of the MMI waveguide,

\[ E(y, z) = \sum_{i=0}^{m-1} c_i \psi_i(y) \cdot e^{j(\omega t - \beta_i z)}. \]  

(5.10)

Taking the phase of the fundamental mode as a common factor out of the sum and implicitly assuming the time dependence \( e^{j\omega t} \), the equation for the field profile gets transformed into

\[ E(y, z) = e^{j\omega t} \cdot \sum_{i=0}^{m-1} c_i \psi_i(y) \cdot e^{j(\beta_0 - \beta_i)z}. \]  

(5.11)

In order to further analyze the periodicity of the mode beating, we can substitute the expression (5.6) into the equation (5.11) to get

\[ E(y, z) = e^{j\omega t} \cdot \sum_{i=0}^{m-1} c_i \psi_i(y) \cdot e^{j(i+1)\pi z / 3L\pi}. \]  

(5.12)

Therefore, the types of the images formed will be determined by the modal excitation factors \( c_i \) and by the properties of the mode phase factor

\[ e^{j(i+1)\pi / 3L\pi} \cdot z. \]  

(5.13)

5.5.3.1 General Interference

General interference effects in multimode waveguides occur when input excitation (waveguide position and field) are such that all of the modes of the multimode waveguides get excited.

The interference can yield both single and multiple images of the input field profile, based on the multimode waveguide length.

Inspecting the equation (5.12), we notice that \( E(y, z) \) will be identical to \( E(y, 0) \) if

\[ e^{j(i+1)\pi / 3L\pi} = 1 \text{ or } (-1)^i. \]  

(5.14)
The first condition means that the phase changes of all the modes along \( z \) must differ by exactly \( 2\pi \). In this case, all modes will interfere with the same relative phases as for \( z = 0 \), thereby giving an image that is a direct replica of the input image, as seen in Figure 5.5.

The second condition means that the phase changes must be alternatively even and odd multiples of \( \pi \). In this case, the even modes will be in phase whereas the odd modes will be in antiphase. Given the odd symmetry of the odd modes of the multimode waveguide, the interference image produced will be a mirrored image with respect to the plane \( y = 0 \).

Both of these conditions will be fulfilled at distances

\[
z = p(3L_\pi) \quad \text{where} \quad p = 0, 1, 2, \ldots \quad (5.15)
\]

Another application of general interference-based MMIs that is of interest for our work is generation of multiple images of the input filed, which can be used to generate waveguide components like 3dB couplers.

If we consider images that are obtained half way between the direct and mirrored image positions,

\[
z = \frac{p}{2}(3L_\pi) \quad \text{where} \quad p = 1, 3, 5, \ldots \quad (5.16)
\]

the total field at these lengths can be written as

\[
E(y, \frac{p}{2}3L_\pi) = e^{j\omega t} \cdot \sum_{i=0}^{m-1} c_i \psi_i(y) \cdot e^{ji(i + 2)p(\frac{\pi}{2})},
\]

where \( p \) is an odd integer. Analyzing this expression and separating it for \( i \) even and \( i \) odd we have

\[
E(y, \frac{p}{2}3L_\pi) = e^{j\omega t} \cdot \sum_{i \text{ even}} c_i \psi_i(y) + \sum_{i \text{ odd}} c_i \psi_i(y) \quad (5.18)
\]
Figure 5.5: General interference based MMI component - imaging properties as a function of the multimode waveguide length

\[
\frac{1 + (-j)^p}{2} E(y, 0) + \frac{1 - (-j)^p}{2} E(-y, 0)
\]  (5.19)

Equation (5.18) represents a pair of images identical in intensity distribution to the input image, with amplitudes \(\frac{1}{\sqrt{2}}\) of the original amplitude. Hence, having two symmetric input waveguide in an MMI component could be used to produce an efficient 3dB coupler.

5.5.3.2 Symmetric Interference

Opposite to general interference, restricted interference effects in multimode waveguides occur when input excitation (waveguide position and field) are such that some of the modes of the multimode waveguides do not get excited. A special case of restricted interference that is of particular interest in this work is symmetric interference. Symmetric interference can be used to produce \(1 \times N\) light splitters in a very length efficient way. In symmetric interference components, only even modes of the multimode waveguide are
excited. Noting that

\[ \text{mod}_4[i(i + 2)] = 0 \text{ for } i \text{ even} \quad (5.20) \]

The length periodicity of the mode phase of (5.13) will be reduced 4 times. Therefore, it is beneficial to use symmetric interference components whenever possible in order to minimize the component size, which helps with the propagation losses and chip area utilization.

5.5.4 MMI Physical Properties

5.5.4.1 Imaging Quality

The quadratic dependence of the propagation constants with the mode number is an approximation - therefore, the guided modes will accumulate small deviations in phase at the imaging distances, which will result in blurring of the reconstructed image. Some alleviation of this problem is achieved by using numerical modelling (such as BPM) to optimize the component lengths. Another effect that affects the MMI imaging properties is the scattering of the light at the edges of the MMI waveguide. The amount of this scattering will be mode dependent, thereby further degrading the imaging properties of the component. Consequently, it is of interest to use the shortest MMI components possible.

The imaging resolution of a MMI component is in principle determined by the highest supported multimode waveguide mode, and can be estimated as equal to the cosine-like lobe width of that highest supported lobe

\[ \rho = \frac{W_e}{m} \quad (5.21) \]

A more accurate analysis, involving the use of line-spread function [13],
Figure 5.6: Output power \( P_{out} \) of a 1x2 MMI splitter normalized to the input power \( P_{in} \) as a function of the splitter length predicts that this resolution will range from 0.89\( W/m \) (for a flat mode spectrum) to 1.50\( W/m \) (for a Gaussian mode spectrum). Show simulations of:

5.5.4.2 Inherent Loss and Optical Bandwidth

The inherent loss of a MMI component depends on the quality of the imaging of the input of the MMI onto the output. Basically, the inherent loss mechanisms will be the diffraction of the input field in the multimode waveguide section and the coupling losses between the imaged field and the output access waveguide. This loss is generally low due to good imaging properties and resolution of the MMIs.

Additional losses present in all optical interconnects due to absorption and scattering will be present as well, and it is important to keep the length of the components as short as possible.
Finally, the imaging length of the MMI needs to be matched for the material/waveguide structure chosen. Any departure from the optimum MMI component length will lead to the increase in the MMI inherent loss. This is illustrated in Figure 5.6, where the output power per waveguide in function of the MMI coupler length is plotted for a $1 \times 2$ light splitter.

Optical bandwidth of the MMI components is limited by the changing mode propagation constants and refractive index values as a function of wavelength. The optimum imaging length and the filed patterns slowly change with wavelength, degrading the image at the output, and reducing the power coupled into the output access waveguides.

The optical bandwidth of an MMI component will be inversely proportional to the width squared of the MMI waveguide. Since the length of the component has a square dependence on the MMI width, shorter MMI components are also expected to have higher optical bandwidth. Both $1 \times 2$ and $2 \times 2$ MMI couplers exhibit 3 dB bandwidths far in excess of 100 nm [17]. Therefore, the bandwidth does not pose any practical limitations to the MMI component design and choice. A measured optical bandwidth for a cascaded MMI-based light splitter is shown in Figure 5.10.

### 5.5.4.3 Polarization Dependence

Polarization dependence of the MMI components stems from the polarization dependence of the material system and the waveguide structure used for their fabrication. The level of polarization dependence is low, just as that of the passive waveguides. It is possible to make polarization insensitive MMI components by properly choosing the material and geometrical properties of the waveguide [18].
5.5.4.4 Reflection Properties

MMI-based interconnecting components can be a source of major reflections. This is especially true for MMI $1 \times 2$ and $2 \times 2$ light splitters and combiners that are fabricated using strongly guided structures [20]. We distinguish between reflection back into the input waveguides and internal resonance modes due to the occurrence of simultaneous self-images [19]. Because of self-imaging, reflection can be extremely efficient, even in the case of MMI devices with optimized transmission. Various techniques can be employed in order to suppress back reflections in the MMIs. This makes them more attractive for integration with lasers than other components like Y-branches.

More on this topic will be discussed in the next chapter when talking about the design of the tunable all-optical wavelength converter devices.

5.5.5 Cascaded MMI Splitter

In this section, the design for a novel 2-stage 1x2 MMI light splitter is presented and experimental measurements described. The new splitter design demonstrates a large output waveguide separation (12 $\mu m$) with much shorter device lengths (500 $\mu m$) than comparable conventional designs (typical 1 mm) and exhibits even splitting ratios over 100 nm optical bandwidth. Another key advantage of this design is in its compatibility with processes using wet crystallographic etches that yield low loss waveguides. Other class of light splitters that utilize S-bends and/or Y branches is fabricated using reactive ion etching, typically yielding higher scattering and/or radiation waveguide losses. While this other class of splitters can be compact (< 500 $\mu m$), the total propagation losses (splitter + other waveguides) in a complex PIC will potentially be higher compared to wet etched waveguides.
As we have explained in section 5.5.2, the beat length in a multimode waveguide is proportional to the square of the width of the multimode waveguide. In a standard $1 \times 2$ MMI light splitter, the width of the multimode region is equal to twice the desired output waveguide spacing. Therefore, in order to achieve same output waveguide spacing $T$ (Figure 5.7 a)), we have designed a splitter that consists of two-stages, and whose overall length is shorter than that of a standard MMI splitter. The new splitter layout is shown in Figure 5.7. The function of the first stage is to evenly split the incoming light. It is based on a standard 1x2 MMI splitter (MMI-1), using symmetric multimode interference as the light splitting effect. The second stage is then used to increase the output waveguide spacing by offsetting the light from one edge at the input to the other edge at the output. This second stage consists of two identical 1x1 mirrored-image replicators (MMI-2) based on general multimode interference, as already explained. The separa-
tion of the output waveguides \( T \), defined in Figure 5.7 a), can be expressed as a function of the widths of MMI-1, MMI-2 and the input/output (access) waveguides \( X \) as:

\[
T = \frac{W_1}{2} + 2(W_2 - X)
\]  
(5.22)

where \( W_1 \) and \( W_2 \) are effective widths of the MMI waveguides. Effective widths take into account the lateral penetration depth of each mode [13] and in our case they are close to actual physical dimensions of the MMIs. The total length of the splitter is equal to the sum of the components’ lengths for MMI-1 and MMI-2 respectively,

\[
L_{\text{total}} = \frac{3}{8} \rho W_1^2 + 3\rho W_2^2
\]  
(5.23)

where \( \rho \) is constant for a given transverse waveguide geometry and wavelength. Combining 5.22 and 5.23, for known output waveguide spacing \( T \) and access waveguide width \( X \) (Figure 5.7 a)) results in a simple quadratic equation for total length, \( L_{\text{total}} \), as a function of \( W_1 \) or \( W_2 \).

Finding the minimum of this function gives following expressions for \( W_1 \) and \( W_2 \)

\[
W_1 = \frac{2}{3} T + \frac{4}{3} X
\]  
(5.24)

\[
W_2 = \frac{T}{3} + \frac{2}{3} X
\]  
(5.25)

To illustrate the advantages of the proposed design, we performed calculations for InP based devices with 1.4Q quaternary waveguide. Comparison of lengths of the standard and new \( 1 \times 2 \) splitters as a function of the output waveguide spacing \( T \) is shown in Figure 5.8 a). For \( T = 12 \, \mu m \) and \( X = 2 \, \mu m \), the new splitter is 50% shorter. Figure 5.8 b) shows the relative difference in length between the standard and the new splitter as a function of output waveguide spacing, for various access waveguide widths \( X \). The part
Figure 5.8: (a) Length vs. output waveguide spacing - single and cascaded splitters (b) Relative difference in length for cascaded and new splitter
of design space of interest is for $\Delta < 0$, where the new splitter is shorter. For most applications in the InP material system, the width of access waveguides will be $3 \mu m$ or less. For output waveguide separations large enough to achieve low optical, electrical and thermal crosstalk, as well as to allow for reasonable processing tolerances ($T > 10 \mu m$), the new splitter design offers as much as 50% length reduction. To verify the design of the new splitter, we have performed extensive simulations using the beam propagation method (Figure 5.7 b)). Device parameters for the simulations were adjusted and optimized according to our intended fabrication platform. Optical loss inherent to this device was found to be $0.29 \, dB$.

5.5.5.1 Fabrication and Experimental Results

We fabricated the new splitter using our standard offset quantum well InP PIC platform (Fig. 3(a)). Standard $1 \times 2$ splitters with identical output waveguide separation were fabricated on the same sample. For repeatable testing, both types of splitters were integrated with TE polarized on-chip light emitting diodes (LEDs). An SEM image of the new splitter is shown in Figure 5.9 a). The length of the new splitter is 526 $\mu m$, whereas the length of the corresponding standard MMI splitter is 780 $\mu m$. Near-field output images obtained for the standard $1 \times 2$ splitter and the new $1 \times 2$ splitter, in two separate measurements, are shown in Figure 5.9 b) and c). Both chip facets (LED and splitter side) were anti-reflection coated. Images were obtained using integrated LEDs biased at the same level as a light source and imaging the device output facet onto an IR camera using a high numerical aperture lens. The differences in the output spot sizes and shapes are attributed to the effect of spatial filtering of the output waveguides in the case of the new splitter. The light coming out of the new splitter propagates
through additional 300 $\mu$m of quasi single mode waveguides before it reaches the facet - due to difference in length of the two splitters. To fully characterize the new splitter, we have measured the excess loss and the power imbalance of the splitter as functions of wavelength. Again, we have used the LED on chip as a broad-band light source, and monitored the spectrum of the light coming out of both ends of the device (directly from the LED and from the splitter). The spectra were recorded using high resolution, high sensitivity optical spectrum analyzer. We define excess loss as loss due to coupling, absorption and index change with wavelength, given by

$$\alpha = -10 \log \left( \frac{P_{O1} + P_{O2}}{P_{O1_{opt}} + P_{O2_{opt}}} \right) + \alpha_{inh}$$ (5.26)

where $P_{O1}$ and $P_{O2}$ are output powers from outputs 1 and 2 respectively, $P_{O1_{opt}}$ and $P_{O2_{opt}}$ are output powers for the optimum wavelength, and $\alpha_{inh}$ is the inherent splitter loss. The result of our measurement is shown in Figure 5.10 a). The excess loss is less than 1.5 dB over 80 nm. Figure 5.10 a) also shows the comparison with simulated excess loss for our particular structure. The agreement between the two is good. Although our model for
refractive index takes into account dispersion, we did not include changes of index due to change in absorption. That is the reason for walk-off of the two curves at lower wavelengths.

The power imbalance represents the ratio between measured output powers from the two splitter outputs as a function of wavelength, and is given
by

\[ IB = 10 \log \left( \frac{P_{O_1}}{P_{O_2}} \right) \]  

(5.27)

where \( P_{O_1} \) and \( P_{O_2} \) have already been defined. The imbalance is measured to be less than 0.25 dB over 100 nm, Figure 5.10 b). We believe that the main cause for power imbalance is due to the imperfect, single layer AR coating.

**5.6 Chapter Summary**

Photonic interconnects can be classified based on the type of guiding used in their design. Weakly guiding components have better reflection and propagation losses properties, whereas the strongly guiding structures provide for the more compact designs.

The dimensions of the bend-waveguides will be determined by the maximum amount of the radiation losses tolerable, and they critically depend on the refractive index contrast between the core and the cladding of the waveguide.

Multimode interference components represent an attractive solution for passive light splitters and combiners, due to their low loss, low polarization dependence and compact size. Different types of multimode interference phenomena can be used for different splitter/combiner realizations. The most compact components are based on the symmetric mode interference.
References


Chapter 6

Device Design and Fabrication

This chapter covers the design of three different versions of the widely-tunable all-optical wavelength converter chips.

First, integration platform optimization is examined. Then, SGDBR, input amplifier and Mach-Zehnder interferometer wavelength converter designs are covered. Detailed consideration is given to the coherent reflection suppression and various PIC components are optimized to fulfill these strict design requirements. In the second part of the chapter, the fabrication process is described and critical process control steps are outlined.

6.1 Integration Platform Optimization

In order to maximize the gain of the active regions, which will in turn minimize the SGDBR laser threshold current and provide for the best efficiency of the SOAs, a maximum possible number of quantum wells should be used in the active regions. The number of wells used will be limited by the ability to efficiently pump them electrically, and by the maximum thickness of the active region that can be grown under the given strain [1, 2].
Table 6.1: Comparison between different epitaxial structures used

<table>
<thead>
<tr>
<th></th>
<th>Generation I/II Base Structure</th>
<th>Generation III Base Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Composition</td>
<td>Thickness</td>
</tr>
<tr>
<td>Quantum Wells</td>
<td>$x = 73.5%$</td>
<td>7 nm</td>
</tr>
<tr>
<td></td>
<td>$y = 51.3%$</td>
<td></td>
</tr>
<tr>
<td>Barriers</td>
<td>$x = 73.5%$</td>
<td>8 nm</td>
</tr>
<tr>
<td></td>
<td>$y = 84.5%$</td>
<td></td>
</tr>
<tr>
<td>Waveguide</td>
<td>1.435Q</td>
<td>350 nm</td>
</tr>
</tbody>
</table>

For the reasons of gain maximization and SOA dynamics, the overlap of the optical field with the multiple quantum well active region has to be maximized. This can be achieved by adjusting the thickness and the composition of the InGaAsP waveguide layer and well as the number of quantum wells and barriers. Care has to be taken when doing this to minimize the losses and refractive index discontinuity at the interface.

Another important parameter of choice in the base structure is the waveguide composition. Choosing the waveguide with low bandgap and high Q number (expressed in wavelength of the bandgap given in micrometers) will help with the tuning efficiency of the SGDBR laser’s mirrors [3]. However, high Q waveguides will have higher absorption losses [26, 1], therefore greatly influencing the SGDBR output power and the total properties of the integrated wavelength converter - its minimum nominal input power, gain of the SOAs and total chip output power.

Taking all of this into consideration, the integration platform was designed. Two different base structures were used in this work, and their
characteristics are listed in the Table 6.1. The active region consisted of 7 quantum wells and 8 barriers and was the same in both platforms.

The first and the second generation of the devices employed a lower bandgap waveguide optimized for the highest possible tuning of the laser, while in the second generation the goal was to improve chip sensitivity and output power at the expense of the total tuning range.

One final tradeoff that is important to cover is the issue of doping during regrowth. In order to produce good quality P-I-N junctions necessary for the operation of the diodes (both active and passive), all of the top InP is p-doped with Zn, $P = 10^{18} \text{cm}^{-3}$. That means that a relatively large free-carrier absorption will be introduced [4] in the photonic interconnect components as well, which is undesirable. Since the overlap of the optical mode with the highly doped waveguides in the passive section is only 13.2%, (Figure 6.1), the free-carrier absorption loss will be limited to about $< 20 \text{dB/cm}$. Additional
absorption due to band-tails in the waveguide layer will occur for waveguide compositions with higher Q number, [5]. This absorption will be more of a problem for the 1.435Q waveguide in the first type of the heterostructure used.

The free carrier absorption loss due to P doping can be reduced by a factor of 5, by implanting the passive waveguides with protons, as has been suggested by [6].

6.2 First and Second Generation Tunable Wavelength Converter Designs

The first two generations of operating tunable wavelength converters utilized common SGDBR and SOA designs, while the differences were in the design of the interferometers.

The first generation devices, Tunable All-Optical MMI-MZI wavelength converter (TAOMI-WC) employed Mach-Zehnder interferometer consisting only of the MMI components and straight waveguides.

The second generation devices, Tunable All-Optical Wavelength Converter (TAO-WC), utilized a Mach-Zehnder interferometer consisting of the MMI components, curved S-bends and SOAs.

In this section, the design of the common components (SOAs, SGDBR lasers and outputs) will be presented. Then, the specifics of each tunable wavelength converter will be discussed.
6.2.1 SGDBR Laser Design

The design goal for the SGDBR laser was to achieve tuning over 40 nm with
SMSR better than 40 dB, and the output power greater than 10 mW over
the entire range.

For the case of square gratings used in this work, the relation between
the grating etch depth and the coupling coefficient is given by the expression

$$\kappa = \frac{8 \Delta \pi}{\pi \lambda}$$ (6.1)

where $\Delta \pi$ is the effective index difference and $\lambda$ is the Bragg wavelength.

The tuning range is determined by the repeat mode spacing, $\lambda_{RMS}$, which
is defined as the spacing between periodically aligned front and back mirror
reflectivity peaks, and is determined by the front and back mirror peak re-
reflectivity spacings, $\lambda_f, \lambda_b$,

$$\lambda_{RMS} = \left| \frac{\Delta \lambda_f \cdot \Delta \lambda_b}{\Delta \lambda_f - \Delta \lambda_b} \right|$$ (6.2)

This equation tends to overestimate the actual tuning range because of the
fact that the mirror reflectivity peaks are not equally spaced, and because
the tuning using carrier injection causes the peaks to shift toward higher
wavelength. On the other hand, large $\lambda_{rms}$ will cause the decrease in the
side-mode suppression ratio, so that needs to be taken into account as well.
The values for the front and back mirror peak spacing are limited in their
maximum value by the available index tuning in the waveguide.

The sampling period, $Z_0$, is chosen based on the chosen mirror peak
spacing, and is described by

$$Z_0 = \frac{\lambda^2}{2 \cdot \bar{n}_g \cdot \Delta \lambda}.$$ (6.3)

Finally, the number of mirror bursts and their lengths are optimized in
order to maximize the SMSR and the laser output power. Following these
design guidelines, the optimized values were chosen for the SGDBR laser implementation, and are listed in Table 6.2.

The ridge width of the laser was 3\( \mu m \). This width provides for the optimum active region electrical pumping without the excess lateral carrier leakage [7]. Due to the mask layout error, the mirror design was flawed, resulting in the tuning range of only 22 nm. While the whole 22nm tuning range coverage was possible, the tuning itself was erratic. The reason for such behavior was in the fact that the sampling periods \( Z_0 \) of the two mirrors were incompatible, resulting in the reduced repeat mode spacing \( \lambda_{RMS} \). The sampling period of the front mirror was \( Z_0 = 61.5 \mu m \), and that of the back mirror \( Z_0 = 46 \mu m \). The corresponding mirror peak spacings can be calculated from equation 6.2, and they are \( \Delta \lambda_f = 4.88 \mu m \) and \( \Delta \lambda_b = 6.53 \mu m \). Finally, this results in the repeat mode spacing \( \lambda_{RMS} = \left| \frac{\Delta \lambda_f \cdot \Delta \lambda_b}{\Delta \lambda_f - \Delta \lambda_b} \right| = 19.3 nm \).

This mistake was corrected in the third generation design. The reflectance of the mirrors used is shown in Figure 6.2.

<table>
<thead>
<tr>
<th>SGDBR laser parameters</th>
<th>Length (( \mu m ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>540</td>
</tr>
<tr>
<td>Phase</td>
<td>80</td>
</tr>
<tr>
<td><strong>Periods</strong></td>
<td><strong>( Z_1 (\mu m) )</strong></td>
</tr>
<tr>
<td>Front Mirror</td>
<td>5</td>
</tr>
<tr>
<td>Back Mirror</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 6.2: SGDBR laser parameters
Figure 6.2: Reflectivity spectra of the front and the rear sampled mirror design used

6.2.2 Input SOA Design

The width of the input SOA ridge was set by the same requirements for efficient electrical pumping, as for the SGDBR laser. The only free parameter to choose was the SOA length, which determines the amount of available gain and the amount of optical power available for the MZI input. Longer SOA lengths result in the higher input signal distortion, by introducing large gain for the rising edge of the signal - however, this effect actually helps the speed of cross-phase modulation in the MZI-SOA, because it insures that the phase change happens fast, the speed dictated by the large number of photons in the leading edge. Simulated gain versus SOA length curves for different input power levels are shown in Figure 6.3. As can be concluded from these results,
increasing the length of the SOA beyond a certain value does not result in large additional gain, but increases the device power consumption and the amount of ASE noise generated. Based on our simulations and this analysis, the optimum length for the input SOA was chosen to be 600 \( \mu m \).

### 6.2.3 MMI Optimization

Due to the quadratic dependence between the MMI imaging length and the width of the multimode waveguide, equation 5.6, it is important to optimize the MMI design and the calibrate the fabrication process. BPM simulation of the optimum MMI coupler length as a function of the MMI width change due to processing tolerances is plotted in Figure 6.4. A width change in 0.2 \( \mu m \) can lead to an additional loss of 7%.

The imaging properties will depend on both the waveguide layer thickness
Figure 6.4: Dependence of the MMI splitter optimum length on the waveguide width variation due to processing effects

and its composition. A variation of these parameters is to be expected in any epitaxial growth. These two parameters will determine the refractive index and transverse effective index of the MMI waveguide. A calculated excess loss as a function of the waveguide composition (Q number) and thickness is shown in Figure 6.5. The maximum extra loss to be expected in the plot for the case where both the thickness and the composition are off at their limits is 0.6 dB. Hence, these components won’t have a detrimental effect on the device performance.

In order to optimize the MMI coupler lengths, a number of devices were fabricated with values varying around the calculated and simulated optimum values. Then, these devices were individually tested by observing the images recreated on the device facet. The imaging was performed using a near-field
Figure 6.5: Excess loss of an MMI 1x2 splitter as a function of the waveguide layer composition (InGaAsP) and thickness (0.3-0.35\,\mu m)

Figure 6.6: The layout of an active/passive optimization test mask for 1x2 MMI splitters. Output near-field images for different splitter length shown.
technique, employing a high numerical aperture lens and an infrared camera. The light into the splitters was coupled by integrating LEDs on the same chip. Figure 6.6 shows the layout of the MMI test mask and the results of imaging from different device outputs, emphasizing the MMI with the optimum length.

These optimized components can then be used as parts in our photonic integrated circuits.

6.2.4 MZI-SOA Design

The role of the MZI-SOAs is to behave as nonlinear elements and to provide the phase change necessary for the wavelength converter operation. Two main parameters of interest are the amount of phase change and the gain recovery lifetime, which will limit the maximum speed of operation. Simulated total phase change in a SOA as a function of the SOA length is shown in Figure 6.7. The amount of the phase change will depend on the amount of index change, which in turn depends on the amount of the gain and carrier concentration change. One disadvantage in using the offset quantum well platform is in the fact that the optical mode overlap with the active region is only 7%. Since most of the change in index happens in the active region (assuming large release times from the quantum wells), it is clear that the index change is reduced by a factor of 13. As a result, really large pump power variations would be needed to achieve a full $\pi$ rad phase shift. This effect is also illustrated in Figure 6.7. Fortunately, for good operation of a MZI-SOA wavelength converter, the full $\pi$ phase swing is not required, in either inverting or non-inverting mode of operation. With known maximum attainable phase shift, the point of operation of the device can be chosen such that the device is led into the maximum extinction state with the available phase
change (inverting) or out of the maximum extinction phase (non-inverting mode of operation). The amount of maximum phase shift will influence the maximum output power attainable, so it is desirable to have as large phase change as possible.

As already discussed in Chapter 3 and 4, the gain recovery time will limit the maximum wavelength conversion speed. The total gain recovery time will depend on the carrier lifetime, determined by material properties and the carrier concentration, and the stimulated recovery time, which is determined by the number of photons present and the differential gain (which is again determined by the carrier concentration in the active region).

Graphs showing the carrier concentration, signal power and the lifetimes as function of the position within the SOA are shown in Figure 6.8 and

Figure 6.7: Simulated phase change in a SOA as a function of the SOA length. The probe signal is kept constant at 4 mW and the power of the pump signal is varied.
Figure 6.8: Simulated carrier concentration and optical power in a 1000 \( \mu m \) long SOA as a function of position within the SOA. The input signal power is 6 mW and the bias current is 200 mA.

Figure 6.9 respectively. The total gain recovery time will be dominated by the slow tail in the front end of the SOA. This tail can be minimized by pumping the SOA with large input powers (probe and pump). However, large pump power will decrease the gain of the amplifier (by reducing the carrier density), so the same SOA will provide even less phase change for the same input (pump) power levels. As the signal gets amplified within the SOA, the gain recovery gets reduced to values below 50 ps for large SOA input powers, Figure 6.9. The effect of self-filtering, discussed in Chapter 4, will further improve the wavelength converter response. This effect will be more prominent for longer lengths of the SOA. Taking into account the analysis presented, as well as the practical constraints (overall device length, pump currents, heat dissipation), the MZI-SOA length(s) in the first and second device generations were chosen to be 1000 \( \mu m \).
Figure 6.9: Simulated gain recovery (recombination) times in a 1000 µm long SOA as a function of position within the SOA. The input signal power is 6 mW and the bias current is 200 mA.

6.2.5 Reflection Suppression

The variations in carrier density within the laser cavity result in variation in the output wavelength of the laser, which creates a finite spectral linewidth for the lasing mode. Linewidth is a key parameter that determines the performance of lasers in data transmission systems, since the phase fluctuation due to finite linewidth causes additional intensity modulation after fiber transmission due to fiber chromatic dispersion and nonlinearities [16].

Coherent reflections back into the laser can have dramatic effect on laser’s linewidth and noise properties. These effects have been extensively analyzed in [8, 19, 18, 20, 21]. According to [21], the expression for linewidth with external feedback is given by

$$\Delta \nu = \frac{\Delta \nu_0}{[1 + C \cdot \cos(2\beta L_p + \arctan \alpha)]^2},$$  \hspace{1cm} (6.4)
where $\Delta \nu_0$ is the unperturbed linewidth, $C$ is the feedback coefficient, $L_p$ is the length of the external cavity, $\beta$ is the mode propagation constant and $\alpha$ is the linewidth enhancement factor. For $C < 0.05$, the linewidth change will be less than 10% regardless on the phase of the reflection, and the laser can be considered sufficiently isolated for many applications.

The feedback coefficient can be expressed in terms of the reflectivity and transmittivity of the front mirror, $r_2$, $t_2$, power feedback coefficient, $f_{ext}$, and round trip times of both internal $\tau_c$ and external $\tau_e$ cavities,

$$\tau_e = \frac{2L_p}{v_g}$$
$$\tau_c = \frac{2L_{eff}}{v_g}$$

$$C = t_2^2 \cdot \frac{\sqrt{f_{ext}}}{r_2} \cdot \frac{\tau_e}{\tau_c} \cdot \sqrt{1 + \alpha^2}.$$  \hspace{1cm} (6.5)

Using this formalism, calculated maximum tolerable reflections as a function of distance from the laser are shown in Figure 6.10. We notice that the requirements for low reflections increase drastically with the distance from the laser cavity, due to the linear dependence between the coupling coefficient $C$ and the external cavity length $L_p$. Two design rules can be derived from this analysis:

1. the length of the front end of the device should be as short as possible

2. the facet reflection will have the largest impact on the device performance, both due to its high amplitude and due to its largest distance from the laser

It is important to emphasize that Figure 6.10 does not include the reflection amplification, so the real conditions and requirements are actually a little more stringent. Fortunately, the SOAs in the MZI always operate in
Figure 6.10: *Calculated maximum tolerable back reflection amplitude (relative to the original signal) as a function of the length of the external cavity.* The cutoff condition is original linewidth change of 10%

deep saturation, meaning that they only provide up to 6 dB of gain for the reflected signal. Any additional propagation loss of the passive waveguides also helps in reducing the reflected signal power.

In the rest of this section, we will analyze in detail the techniques employed in the tunable wavelength converter design to reduce the back reflections.

### 6.2.5.1 Active-Passive Interfaces

In our offset quantum well integration platform, the waveguide and the ridge layers are continuous through both active and passive areas of the chip. The only index discontinuity happens due to the active region that has been re-
Figure 6.11: *Illustration of the imaging properties and the main source of reflection in a 2x1 MMI light coupler. The phase difference between two (coherent) input signals is $\pi$*

moved in the passive section. The effective index difference at the interface at the active passive interface is about 1.3% In order to minimize the reflections back into the fundamental mode at the active/passive interfaces, as well as to prevent any unwanted resonances on chip, it is sufficient to angle interface region by a sufficient amount ($7^\circ$ or more). The effect that an angled interface has on the reflection is analyzed further in this section. More details can also be found in [1].

### 6.2.5.2 MMI components

MMI-based interconnecting components can be a source of major reflections. This is especially true for MMI 1x2 and 2x2 light splitters and combiners that are fabricated using deep etched ridge designs [9, 10], because of the large index difference at the interface semiconductor/waveguide. In our integration platform, this issue is helped by a relatively small index discontinuity mainly due to the continuous waveguide layer that exists in all areas of the chip.
Figure 6.12: Simulated back reflection into the fundamental mode of a 3µm input waveguide for a 2x1 MMI light coupler, as a function of the output taper angle. Two input light signals were used, their relative phase difference equal to $\pi$ rad

For the 2x2 light couplers, most of the back reflections are caused by non-optimized MMI imaging lengths, causing the light to hit the edge/facet of the multimode waveguide and image back into the input waveguide [9, 10].

For the 2x1 light couplers, if the two signals at the input are coherent and out of phase, they will image perfectly onto the edge of the MMI waveguide, and thereby, due to the reciprocity of the component, image back into the input waveguide. This is illustrated in Figure 6.11.

By properly optimizing the component design, these reflections can be reduced to a tolerable level. One way to remove the reflected light is to introduce the evacuation waveguides, as has been done in [10]. Our approach
in this work was to introduce tapers along the waveguide interface. That way, the imaging properties of the MMI are destroyed due to the perturbed phase of the imaged fields, and the light is scattered both back and forward without being coupled back into the fundamental mode. To give an example, Figure 6.12 shows a result of calculated back reflection into the fundamental mode using a bi-directional beam-propagation simulation,\[8\]. The parameter varied here was the length of the tapered region. It can be observed that for taper angles higher that 10°, the back reflections will be significantly reduced. The imaging properties of the component for the input light signals in phase will remain unaffected as long as the taper region length is less that 25% of the length of the whole MMI waveguide.

Another approach used was to utilize a 2x2 MMI coupler at the output in order to constantly remove the light from the MMI. The phase change of the input signal is only moving the output image between the two output waveguides. More on this design will be shown in the TAOPC-WC section.

6.2.5.3 Facet Reflections

The biggest and the most influential source of reflections on any InP chip would be the device output facet. In particular, in our tunable wavelength converter chip, any reflections from the facet will be additionally amplified by the MZI SOAs, as well as the SGDBR booster SOAs. Since both of the SOAs of the Mach-Zehnder operate in saturation, their carrier concentration will be clamped, so the amount of gain will depend on the level of saturation but will not exceed 6 dB.

In the past, several different approaches to facet reflection minimization have been investigated and reported. Those include buried facets \[12\] and angled output waveguide, both in combination with the antireflection coat-
Figure 6.13: Calculated reflectance as a function of angle and ridge width for our integration platform.

In an effective index, 2D approximation of a waveguide, the full TE mode power width \( w_{\text{full}} \) can be analytically expressed as a function of the waveguide width, wavelength and the effective 2D refractive indices. Assuming that the mode has a Gaussian distribution, the effective reflectivity of the angled facet will approximately be given by

\[
R_{\Theta}(\Theta) = R_f(\Theta) \cdot e^{-\left(\frac{2\pi \cdot n_{\text{clad}} \cdot w_{\text{full}} \cdot \Theta}{\lambda_0}\right)^2},
\]

(6.6)

where \( \Theta \) is the angle measured relative to the direction perpendicular to the facet and \( R_f \) is the Fresnel reflectivity of a TE plane wave,

\[
R_f(\Theta) = \frac{n_{\text{wgd}} \cdot \cos \Theta - \sqrt{1 - n_{\text{wgd}}^2 \cdot \sin^2 \Theta}}{n_{\text{wgd}} \cdot \cos \Theta + \sqrt{1 - n_{\text{wgd}}^2 \cdot \sin^2 \Theta}}
\]

(6.7)

Analyzing the equation (6.6), we conclude that the reflectivity can be
Figure 6.14: *Calculated reflectance as a function of wavelength for applied AR coating. Ridge width 4.5\(\mu\)m, angle 7\(^{\circ}\)*

reduced both by increasing the angle and by increasing the effective mode width. This is illustrated in Figure 6.13. In our work, the reduction has been achieved by adiabatically broadening the waveguide width at the very output of the device (in order not to introduce additional transverse modes within the device). On the other hand, the coupling efficiency to and from the chip will degrade at large fiber angles and output waveguide widths, and that limits the extent to which these benefits can be exploited.

In order to suppress the reflections from the facets additionally, an anti-reflection coating needs to be applied. The anti-reflection coating can be viewed as a wave reactive impedance matching. To achieve good anti-reflective properties over a wide range of wavelengths, a multi-layer coating needs to be applied. This requires precise control of the layer thicknesses and refractive indices. Multi-layer coatings can be analyzed and design using techniques of mode decomposition into plane waves [14, 15]. A calculation based on this technique for the AR coating used in our work is shown in
Figure 6.14. Theoretically, very low reflectances can be achieved. In reality, the uncertainty in the refractive index values and the layer thicknesses will limit the values to numbers that are higher than those calculated.

as a function of the output waveguide angle for two different output waveguide widths - 3 \( \mu m \) and 5 \( \mu m \). The values of the parameters in the calculation are based on the InP/InGaAsP material system used in this work. Clearly, for the output angle of 6.5 ° or higher, the envelope of the modal reflectance will be lower than 10\(^{-4}\). Therefore, applying a multilayered AR coating on this type of output facet can provide for the broadband reflectance that meets the design requirements.

6.2.6 TAOMI Architecture

The first generation devices, Tunable All-Optical MMI-MZI wavelength converter (TAOMI-WC) employs a Mach-Zehnder interferometer consisting only of the MMI components and straight waveguides.

The idea behind this design was to create a MZI that would consist only of straight waveguides, thereby eliminating potentially leaky curved waveguides, as already explained in the previous chapter. That enables for fabrication of the device using selective, wet crystalographic etching, producing smooth waveguide sidewalls and reducing the scattering loss.

The overall device layout schematic is shown in the center of the Figure 6.15, while the other parts of the figure zoom in onto the details of the device input section, mid section and output section. The schematic is not to scale, while the chip dimensions are indicated.

In this device, the interferometer is defined by a combination of two 16 \( \mu m \) wide and 760 \( \mu m \) long multimode interference (MMI) based 1x2 light splitters [15] in combination with 2 MMI based 2x2 couplers that are 12 \( \mu m \) wide.
Figure 6.15: *Schematic of the TAOMI-WC device and relevant details (1)*

Device output (2) SGDBR output - MZI input (3) Device input

[15], straight waveguides and 1mm long SOAs (Figure 6.15). The total waveguide separation in the interferometer is 17 $\mu$m and is set primarily by the fabrication tolerance for the minimum separation of the two MZI-SOA electrodes. The input signal is coupled onto the chip through a tapered, angled input waveguide, and then amplified by a 800 $\mu$m long input semiconductor optical amplifier. The 2x2 MMI coupler is used to mix the input signal with
the continuous wave signal generated by the SGDBR laser in one of the interferometer’s SOAs. Unused output branch of the 2x2 MMI coupler extends into the unpumped active region and is adiabatically tapered into a point in order for all of the stray light to be absorbed. This prevents any back reflections that could destabilize the laser. The output waveguide is tapered and angled to reduce the AR coating requirements. The total device length is 5.6 mm. The electron micrograph of a TAOMI chip is shown in Figure 6.16.

### 6.2.7 TAO-WC Architecture

The second generation devices, Tunable All-Optical Wavelength Converter (TAO-WC), utilized a Mach-Zehnder interferometer consisting of the MMI components, curved S-bends and SOAs. The curved waveguides employ very
Figure 6.17: Schematic of the TAOWC device and relevant details (1) Device output (2) SGDBR output - MZI input (3) Device input

large radius of curvature $R = 2000\mu m$, which prevents the radiation losses. The S–bends are designed with offsets between different sections to maximize coupling, and due to the large radius of curvature, the offsets required are very small, ($<0.05\mu m$).

These devices are fabricated using a combination of reactive ion etching and selective wet etching. Since the angles of curvature involved are fairly
low (10°), and the change of direction gradual due to the large radius employed, no faceting on the sidewalls occurs using the wet etching, which again produces very smooth side walls and enables full ridge definition and removal of any InP "wings" in the side of the ridge which would be detrimental due to drastic lowering of the refractive index difference causing leakage, as already pointed out in the previous chapter. The wet etching does undercut the waveguides, thereby effectively reducing their width, and this undercut has almost linear angle dependence, so it can be compensated for in the mask design.

The separation between the SOAs is another design parameter to take into consideration. Larger separation results in the larger device size, and larger length of the passive interconnecting waveguides. As noticed from the first generation design, 2 SOAs in close proximity will have an effect of raising the active region temperature, which will in turn lower the gain and the differential gain and adversely affect the device performance. Therefore, simple simulations of heating and heat transfer were performed using a finite-difference software tool [11] to optimize the spacing between the two SOAs. For SOA spacing equal to or larger than 70μm, the thermal crosstalk between the two amplifiers becomes negligible. Thus, SOA separation of 70μm was chosen for this generation device design and all subsequent designs.

The overall device layout schematic is shown in the center of the Figure 6.17, while the other parts of the figure zoom in onto the details of the device input section, mid section and output section. The schematic is not to scale, while the chip dimensions are indicated.

In TAO-WC, the interferometer is defined by a combination of four 1x2 MMI light splitters and combiners (180 μm long and 13 μm wide), by S-bends with curvature radius of 2mm and two 1mm long SOAs (Figure 6.17). The
laser and the interferometer are connected via a 1x2 multimode interference splitter and the total waveguide separation in the interferometer is 70 µm. The input signal is coupled onto the chip through a tapered input waveguide, and then amplified by a 800 µm long input semiconductor optical amplifier. The same MMI splitter/combiner design is used to connect the input waveguide and the SGDBR signal with one of the interferometer’s SOAs, as well as to combine the light from the two branches at the interferometer output. The output waveguide is tapered and angled to reduce the AR coating requirements. The total device length is 4.87 mm. The electron micrograph of a TAO-WC chip is shown in Figure 6.18.

Figure 6.18: Electron micrograph of the TAO-WC chip
6.3 Third Generation Design

**TAO-PC-WC Architecture**

The third generation wavelength converter design also utilized a Mach-Zehnder interferometer consisting of the MMI components, curved S-bends and SOAs. However, significant design changes, aimed at improving the performance, were implemented in this device version. The summary of design changes is: optimized sampled-grating DBR mirror design, two functional (longer) in-
put SOA (for increased yield and redundancy), two booster-amplifier SOAs located in the branches of the MZI, passive waveguide phase sections in the Mach-Zehnder branches, and finally a dual-output multimode interference 2x2 coupler at the wavelength converter output.

The tunable SGDBR laser is 1.7 mm long and it has been designed according to parameters is table 6.2. The interferometer branches are defined by four S-bends and two 1.5 mm long SOAs. The output light of the SGDBR laser is equally split using a 1x2 multimode interference (MMI) based light splitter, and then amplified by 2 post-amplifier SOAs that are located after the splitter, in the interferometer S bends. This amplified light is then coupled with the light from the input waveguides using 2x1 MMI combiners into the SOAs in the branches of the MZI. The input signal is coupled onto the chip through a tapered, angled input waveguide, and then amplified by the input SOA running alongside the laser. In order to completely eliminate the thermal crosstalk, the input SOAs, on the sides of the SGDBR laser, are about 200 µm away laterally from the SGDBR active region.

Several device versions, with varying input SOA lengths (1-1.5 mm) have been implemented in order to improve the device sensitivity.

Two 250 µm long SOAs are used to amplify the continuous-wave light from the SGDBR laser. These amplifiers provide about 5 dB of gain resulting in more than 12 mW of optical power entering each MZI-SOAs. This high-power optical pumping sets the MZI-SOAs in the high-photon density operation regime, thereby reducing the gain recovery time to less than 60 ps and enabling 10 GB/s operation. This effect has already been discussed in Chapter 3.

For optimum MZI-SOA wavelength converter performance, in Chapter 3, we have concluded that it would be extremely useful to have the ability
to control the phase of the interferometer and the gain of the two branches independently. Therefore, two phase control sections consisting of 100 µm long passive waveguides were incorporated into this design. The effect used to achieve the index change is the same as for the mirror tuning, the carrier plasma effect. This separation of phase control provides for easier optimization of the operating bias point of the wavelength converter as well as better extinction for both inverting and non-inverting modes of operation, in part because the gain of the MZI-SOA can be adjusted to compensate for high ASE light power of the input amplifier in the OFF state of the wavelength converter.
The branches of the MZI are joined by a MMI-based 2x2 coupler at the output. Depending on the relative phase of the CW light in the MZI branches, the total light power will be distributed between the two output waveguides with two extreme cases: for the phase difference of $-90^\circ$, all of the light will be coming out of one waveguide whereas for the phase difference of $+90^\circ$, all of the light will be coming out of the other waveguide. This output scheme is useful because it allows for the CW light to be continuously removed from the chip, which helps with light evacuation from the chip. Both of the output waveguides are curved and tapered before they reach the facet in order to minimize the back reflections, as already discussed.

The total device length is 5.53 mm. The electron micrograph of a TAOPC-WC chip is shown in Figure 6.20.
6.4 Offset Quantum Well Fabrication Process

In this section, we discuss the fabrication process for tunable all-optical wavelength converters. First, material growth is briefly described. Then, the offset quantum well fabrication process is described in detail. Finally, critical steps of the process are analyzed and several process verification methods described.

6.4.1 Material Growth

Material used in this work was grown using Metal Organic Chemical Vapor Deposition process. The growth was initially performed at UCSB, and subsequently at Agility Communications Inc. [29].

MOCVD uses metal organic precursors for source materials. The precursors, which can be in the liquid or solid phase, are transported by a carrier gas (usually Hydrogen) to the heated InP substrate, where they decompose and adsorb to the surface. The growth for temperatures between 575° and 650° is mass transport limited, which insures that there is a direct relation between the concentration of the source material in the carrier gas and the concentration of that material in the growing film. This enables the controllable and reproducible growth of InP/InGaAsP material with different composition.

The control of the source material concentration is crucial for tight growth conditions control, and requires precise environmental condition control of the sources. The standard source material for group–III constituents are trimethylindium (TMI) and trimethylgalium (TMGa). Previously, gases arsine and phosphine were used as standard sources for group–V elements. Recently, these sources have been successfully replaced by liquid metal–organic
precursors tertiarybutylphosphine (TBP) and tertiarybutylarsine (TBA), which offer significant risk reduction over gaseous sources, while providing the same purity level and growth quality.

The growth start with a n–doped InP substrate, and first, a lightly–n–doped buffer layer is grown in order to reduce the optical loss from the highly doped substrate layer. Subsequently, the waveguide layer is grown, followed by the 10 nm thick InP stop-etch layer. Then, the stack of barriers and quantum wells is grown with compositions as indicated in table 6.1. Finally, a quarternary separate confinement heterostructure [8] layer followed by a p–InP cap are grown on top of the active region. The detailed cross-section of the base structure is shown in Figure 2.4.

6.4.2 Fabrication

The first step of the process is to etch-off the quantum wells in the areas that are to become passive sections of the device. The surface of the wafer is covered with 100 nm of SiN, and the sample is patterned using photore sist/dry etching of the nitride. A combination of selective wet chemical etches is used to perform this step. InP is removed using $H_3PO_4 : HCl$ (3 : 1) whereas quaternary layers (SCH, QWs and barriers) are removed using $H_2SO_4 : H_2O_2 : H_2O$ (1 : 1 : 10). Subsequently, the SiN mask is removed and replaced with a new layer of SiN 30nm thick. Mirror burst are opened in this mask, for the formation of the sampled gratings. Gratings are lithographically defined using holography as described in [1] and then etched directly into the top of the waveguide layer using methane/hydrogen/argon reactive ion etching (RIE). The hard mask is then removed from the surface of the wafer and the surface is thoroughly cleaned before regrowth. Then, the sample is regrown with a 1.8 µm thick p-doped InP upper cladding layer.
Figure 6.21: Offset Quantum Well Fabrication Process
and a 100nm p+-InGaAs contact layer (Fig. X). It is important to emphasize that this is the only regrowth step required in the entire process. All growth is performed using MOCVD crystal growth technology. After the regrowth, SiN hard mask with combination of photoresist/RIE etching is used to define ridges in InP. The ridges are formed using a combination of methane/hydrogen/argon RIE/\(\text{H}_3\text{PO}_4 : \text{HCl} \) (3 : 1) wet chemical etching. Upon defining the ridges, the surface of the sample is isolated with a SiN dielectric film. The tops of the ridges are exposed and the top metal contacts (Ti/Pt/Au) are evaporated using E-beam evaporation. Then, the surface of the sample is protected by a thick mask and proton implanted in order to provide electrical isolation between different electrodes on the mask. Same technique can be used to reduce the absorption loss caused by p-doping, as already discussed in the previous chapter. In this case, all of the passive waveguide sections would be implanted.

After the sample has been implanted, it is thinned down, the back side (Ti/Pt/Au) contacts are evaporated and the sample is annealed again.

Electron micrographs of different device sections are shown in Figure 6.22. Figure 6.22 a) represents a transition between the passive and the active waveguide, going into the booster SOAs (TAOPC-WC device). The line of separation between device section with quantum wells (top) and without (bottom) is clearly visible. Figure 6.22 b) shows the output of the SGDBR laser going into the tapered 1x2 MMI splitter. Finally, Figure 6.22 c) shows the output waveguide and the facet. The actual 350nm thick InGaAsP waveguide layer can be noticed at the bottom of the ridge.
Figure 6.22: Electron micrograph images (a) interface area between active and passive section (b) output of the front mirror of the SGDBR laser going into the 1x2 MMI light splitter (c) output facet of the device
6.4.3 Process Analysis and Verification

In this process, there are several critical processing steps that will ultimately limit the yield of the wafer. Standard verification procedures have been developed to track the yield in the course of the process. This section discusses these critical step points and process verification procedures in greater detail.

6.4.3.1 Active-Passive Etch

With the active-passive etch, the key parameter that needs to be controlled is the etch depth. Underetching would prove detrimental to the device performance because of the large absorption loss of the unpumped quantum wells in the passive regions. Overetching, on the other hand, would reduce the waveguide thickness and affect the mode loss and losses of the index-dependent passive components, like MMI coupler.

To insure the exact etch depth, an InP stop etch layer is grown between the active region and the waveguide. Due to the selectivity of the etch used in this step, the etch rate will drop dramatically when InP is reached.

In order to confirm full removal of all of the quantum wells, after the etch completion, the sample is checked using a micro-photoluminescence setup. Line scans, as one shown in Figure 6.23 are performed across the wafer, to verify the completion of this step.

6.4.3.2 Grating Formation

Formation of the gratings is the crucial step in defining the laser’s mirrors. Several issues need to be addressed here: first, the pitch of the grating needs to be adjusted so that the Bragg wavelength is matched to the laser’s quantum well photoluminescence spectrum peak. Second, the depth of the grating will determine the the coupling coefficient $\kappa$ of the laser mirrors and
Figure 6.23: Photoluminescence line scan after the active-passive removal etch. The scan is performed along the white line, blue areas represent the active region on the sample. The stars correspond to the wavelength scanned.

Figure 6.24: Grating scan in the atomic force microscope. Top - grating area scan (scan area 6x2 nm²). Bottom - cross-sectional scan showing flat bottoms of the grating and the grating depth.

ultimately limit the performance of the laser and the photonic integrated circuit as a whole. Therefore, it is of utmost importance to control all the parameters determining the grating.
The pitch of the gratings can be adjusted by exposing a number of test samples prior to the real sample exposure, and measuring the diffraction angle using a He-Cd laser, [1]. When the pitch is adjusted, it is important to verify that the photoresist used in holography has been developed completely. This step is performed using an atomic force microscope (AFM). Finally, after the gratings have been etched into the semiconductor, it is important to verify the grating depth, again using the AFM. A sample image of a grating scanned by an AFM is shown in Figure 6.24.

### 6.4.3.3 Via Step

The purpose of this processing step is to remove the dielectric cap from the tops of the active and passive ridges to be contacted by metal. Due to the sample topology, this is done using a semi self-aligned process, where the surface of the sample is first planarized using a thick photoresist. Then the areas about 5+ times wider than the ridge are defined in this layer and the resist is partially exposed in order to reach the top of the ridges within 100-200 nm. After that, the remaining resist is etched back in oxygen plasma in a controllable manner until the ridge tops are exposed. The etch steps and visual inspection are performed cyclically. Before the tops of the ridges are exposed, an interference pattern can be observed under the optical microscope, created by thin film interference caused by the thin photoresist layer. In this step, it is crucial not to create any pinholes elsewhere in the field of the sample, as that would create a shunt path for current and prevent proper device operation.

Figure 6.25 shows a sample whose tops of the ridges have (a) almost been exposed and (b) have fully been exposed. The interference pattern is noticeable in Figure 6.25 a).
6.5 Chapter Summary

The purpose of this chapter was to cover the design of three different versions of the widely-tunable all-optical wavelength converter chips.

Integration platform optimization was performed in such way to maximize the amount of gain from the active sections of the chip. Coherent reflections were suppressed through the choice of the integration platform, the design of the active and passive components and interfaces. Reflection suppression became more critical further away from the cavity of the laser, therefore, tapered bent waveguides were used at the chip outputs in combination with a multilayer antireflection coating.

The devices were fabricated using an offset quantum well integration process with a single regrowth step. This process proved to be very robust and repeatable, and several mechanisms for the control of the critical steps in the device fabrication were developed and described.
References


Chapter 7

Widely-Tunable Wavelength Converter

Experimental Investigation

In this chapter, results of experimental characterization of the tunable wavelength converter devices are presented. After covering the experimental procedure, static and dynamic device performance is described and analyzed. The dynamic performance includes bit-error rate results, regenerative properties, chirp as well as analog device properties. Finally, results from several optical system experiments are described at the end of the chapter.

7.1 Experimental Procedure

The performance of the tunable wavelength converters greatly depends on its internal and external operating conditions that are set during the experiment. While the optimization of the internal operating parameters will depend on the input signal parameters (power and wavelength), two the critical
Figure 7.1: Photograph of the chip on carrier and the coupling/probing mechanism

External parameters of operation must be controlled at all times to allow for optimized and repeatable device testing - device temperature and optical coupling. The total power dissipation of the device is in the range 1.14–2 W, therefore, good thermal contact between the device and the thermoelectric cooler is of utmost importance. For all the experiments, the devices were initially soldered down as bars onto copper studs, using the AuSn solder. Later on, individual devices were separated from the bars, soldered and wirebonded onto aluminum nitride submounts. Mounted devices were clamped to a gold-plated copper stud either mechanically or using vacuum and the stage was cooled to 17°C using a thermo-electric cooler.

The light was coupled into and out of the devices using conical-tipped lensed-fibers mounted on piezo-controlled translational stages, Figure 7.1.
Figure 7.2: Schematic of the test setup used for experiments

The spot size of the lensed fibers was 5 μm. The tapered waveguides at device inputs and outputs improve the coupling efficiency to the device, because they expand the mode laterally to match the spot size of the lensed fiber. The alignment to the chip changed as a function of the device bias currents. This was due mainly to the expansion of the copper stud used for chip mounting.

The average coupling losses were measured to be in the range of 4–4.8 dB. This was performed using an integrating sphere setup for estimating the total power coming out of the chip.

Electrical connections to the devices were realized either with probe needles, or with a probe card, shown in Figure 7.1. For static measurements, the input signal was generated by a widely tunable external cavity laser, and then amplifier by an erbium doped fiber amplifier (EDFA), filtered using a thin film tunable filter, and coupled to the device using a polarization controller.

For dynamic measurements, the input signal to the converter was generated using an external cavity widely-tunable laser source and a lithium-niobate electro-optic modulator. Polarization controllers were used at both
the input to the modulator and the device under test (DUT). The input signal was also amplified by an EDFA and filtered using a thin-film filter.

For wavelength conversion, the data was generated using a bit error rate tester’s (BERT) pattern generator with non-return to zero (NRZ) \(2^{31} - 1\) pseudo-random bit sequence (PRBS) data at 2.5 and 10 Gbps. The wavelength of the converted data at the output of the DUT was filtered using a 0.8-1.2 nm thin-film tunable filters and detected with a receiver consisting of a P-I-N diode with an electrical amplifier. The test setup schematic is shown in Figure 7.2.

### 7.2 Static Characteristics of the Tunable All-Optical Wavelength Converters

#### 7.2.1 Passive Waveguide Loss and SOA Gain Measurements

Passive waveguide loss is an important parameter to know, as it is used in device optimization, preamplifier design, splitter characterization etc., as discussed in Chapter 6.

Most of the traditional passive loss measurement techniques, like those based on waveguide cutback [1] or Fabri-Perot resonances [2], employ a form of end-fire coupling, where the light is coupled using lenses or lensed fibers into a passive waveguide. These techniques are not particularly suitable for most of the waveguides in InP material system, since the substrates are optically transparent for infrared light, which gives rise to light coupling into a number of guided and substrate modes if the spot size is not perfectly matched to the waveguide mode size and shape. These modes then interfere
and make the data extraction ambiguous.

One of the benefits of having an integration platform is the fact that the passive test structures can be integrated with on board light sources for device loss characterization. Some active passive methods still rely on the cutback technique [3], and the main problem with those is in the non-reproducible output light coupling between different data points.

The method used in this work that gave the most reproducible results did not require any light coupling from the chip. An SGDBR laser, or an SOA longer than 800 $\mu$m (to generate a large ASE power) was integrated with passive output waveguides, which were contacted at certain regular distances. By reverse biasing the electrodes at different distances from the light source, using Franz-Keldysh effect, it is possible to accurately measure the photocurrent generated which corresponds uniquely to the power detected, and then to extract the total propagation losses. It is preferable to use an on-chip light sources that can generate in excess of 1 mW of power, since the photocurrent reading will be more accurate due to its value being 2 orders of magnitude higher than various leakage currents that exist on chip. An SGDBR laser is therefore an excellent candidate for a PIC diagnostics tool as well. Using this technique, our passive losses were estimated to be 4.3 dB/mm for a 1.435Q waveguide structure and 2.5 dB/mm for the 1.4Q waveguide structure.

A similar method can be used to measure the gain of the semiconductor optical amplifiers that are part of the PIC. First, the SOA needs to be reverse biased in order to measure the optical power going into it. Then, a second active detector is needed at the output of the SOA that will be used as a photodiode to record the photocurrent generated by the SOA output as a function of the SOA bias current and input power.
Figure 7.3: Reflection of the ASE light from the back mirror - spectra recorded through the back facet of a SGDBR laser, for different current densities in the mirror section

7.2.2 Tunability

As already explained in Chapters 3 and 6, the tuning range of a SDGBR laser depends on the laser mirror design, and the maximum index change in the optical waveguide that can be achieved by electrical pumping, which is determined by the waveguide composition. The amount of tuning in SGDBR mirrors can be measured using the back side absorber as a LED by forward biasing it, and then observing the position of the reflection peaks from the back mirror through the back facet, while changing the current density provided to the back mirror. Results of such measurement are shown in Figure 7.3. More
that 7 nm of mirror tuning range was measured, which is consistent with our
design expectations, and provides for continuous tuning of our SGDBRs over
the entire range covered by the sampled mirrors.

In the first two device generations, the integrated tunable lasers had a
tuning range of 22 nm. The tuning results, shown as overlapped spectra,
for both the first (TAOMI) and the second (TAO-WC) generation device de-
signs are shown in Figure 7.4 and Figure 7.5 respectively. These spectra
were recorded through the output facet of the device, with laser gain sec-
tions biased at 85 mA and MZI-SOAs biased at 200 mA each. For the third
generation device design, TAO-PC-WC, the mirror design was further opti-
mized as discussed, and the tuning range was extended to 35 nm, as seen in
Figure 7.6.
Figure 7.5: Overlapped spectra for TAO-WC devices

Figure 7.6: Overlapped spectra for the TAO-PC-WC device
7.2.3 MZI Phase Change Measurements

The amount of phase change achieved in a MZI-SOA wavelength converter will influence the output power and the efficiency of the device.

The phase change by caused by the external pump signal was measured using the TAO-PC-WC device, since the number of different control electrodes on this device allow for a good and simple way of doing this measurement. The schematic of the device with important sections used in this measurement is shown in Figure 7.7.

Similarly to the SOA gain measurements, the light was coupled into the input preamplifier after being amplified by an EDFA and passed through the filter and the attenuator. The SGDBR laser’s gain electrode was biased at 100 mA, the booster-SOAs were biased at 45 mA, and the bias level to the MZI SOAs was varied.

First, the intensity of the CW light generated by the laser was measured in the MZI-SOAs by applying the reverse bias of 3 V and measuring the photocurrent generated. Then, the laser was turned off, and the intensity of the external signal in the MZI SOA was measured using the same method,
for a set of different input powers.

The laser was turned back on, and the output power from the interferometer was minimized using the phase electrode and monitoring the device output power. Then, different pump signal levels were sent into the devices (same values for which the intensities in the MZI-SOA were measured). Each of these signal levels would change the phase of the MZI, and move the device from its local minimum. Then, the MZI phase electrode was adjusted in order to bring the MZI back into the minimum, and the new phase current was recorded.

The results of these measurements of input power versus phase current were translated into the curves of input power versus phase change using the

\[
Y = A + B_1X + B_2X^2 + B_3X^3
\]

Figure 7.8: *Measured phase change as a function of the phase electrode current in the MZI*
Figure 7.9: Measured phase change as a function of pump signal light in the MZI-SOA

information from the phase sweep of the MZI. For the SGDBR gain section, booster SOAs and MZI-SOAs turned on, the output power of the device was maximized by adjusting the bias to one of the phase electrodes. Then, the current to the other phase electrode was continuously changed, which changed the output power from a maximum through a minimum to another maximum, corresponding to a phase change of $2\pi$. This curve, Figure 7.8 was the fitter with a polynomial and the fit was used to calculate the phase shifts caused by external pumping of the MZI SOA.

The results of these measurements are shown in Figure 7.9. The phase change was measured for two MZI-SOA bias currents, 200 and 250 mA. The SGDBR power in the MZI-SOA was 11.9 mW. The maximum phase shift measured was around 65°. The model predicted the value of 55° which represents a good match to the value measured, and proved the validity of the index change model in the SOA.
Consequently, the maximum output power in the dynamic regime of operation is expected to be lower by around 5.5 dB from the maximum output power coupled from the device. This is consistent with 0 dBm average wavelength converted output power measured, and 5 dBm maximum static output power with the interferometer fully on.

7.2.4 Static Wavelength Conversion

The principles of operation of SOA-based MZI wavelength converters were described in Chapter 4. The initial designs implemented, TAOMI-WC and TAO-WC, employ even splitting ratio between the two interferometer branches. Accordingly, the output power of the interferometer can be controlled by adjusting the biases of the SOAs in the branches of the interferometer in order to achieve $\pi$ relative phase shift between the two branches. Figure 7.10 shows
a static extinction map, where extinction at the output was measured as a function of the currents applied to the SOAs in the interferometer arms. In the region of low bias currents (\(\mu\)120 mA), for one SOA current set, there exists a combination of currents where the extinction ratio is greater than or equal to 20 dB. However, with the increase in the SOA bias currents, the extinction ratio is reduced to as low as 10 dB at 250 mA on either of the SOAs. This phenomenon can be explained by noting that the large difference in power levels emitted from the two branches of the interferometer when added, even with totally opposite phase, still yields significant power coming out of the interferometer. The effects of this power imbalance are analyzed later in this chapter.

The requirements for high-speed operation (Chapter 4) are such that the common SOA should be operated under high current density in order to reduce the gain recovery times.

Therefore, we have conflicting demands on the device set point in terms of the high speed of operation and the desired high extinction ratio for these devices.

Figure 7.11 shows the static electrical transfer functions of the interferometer as a function of integrated laser wavelength. For these measurements, the bias current to the common SOA was kept constant at 200 mA. The extinction peaks around the material gain peak wavelength (1555 nm). The total phase change in the other SOA due to the bias current change from 0 to 200 mA is around 5\(\pi\). This number can be extracted by counting the minima in the electrical transfer curve.

Typical optical transfer curves for TAO-WC, for both inverting and non-inverting modes of operation, as function of the input signal wavelengths, are shown in Figure 7.12. In these measurements, the bias of the input pream-
Figure 7.11: *Static electrical transfer function as a function of wavelength (TAO-WC)*

Figure 7.12: *Optical transfer functions for inverting and non-inverting modes of operation (TAO-WC)*
plifier was kept constant at 80mA. The interferometer set points were chosen based on static electrical transfer functions Figure 7.11 taken for no input pump signal present (for non-inverting operating point), and with maximum input pump signal present (for inverting operating point). Extinction ratios were measured to be better than 8 dB in the non-inverting and better than 16 dB in the inverting mode of operation. The high nonlinearity of the optical transfer curves allows for input signal regeneration, as long as the extinction ration of the input signal is lower that the maximum attainable extinction ration of the wavelength converter.

In Chapter 6, we have explained the operating principles of the TAO-PC-WC device. This device type employs two phase control sections in the MZI, consisting of 100 µm long passive waveguides. Phase electrodes provide for the ability to independently adjust the SOA gains in the MZI and the relative phase between the two branches, using carrier plasma effect. This method of phase control is very efficient and has low wavelength sensitivity, as shown in Figure 7.13. We observe better than 25 dB of extinction over 30 nm range,
with less than 4 mA required to turn the interferometer off completely. The measurements were taken without an output filter, therefore, the degradation in extinction observed for wavelengths more than 20 nm away from the SOA gain peak are due to reduced ASE suppression at those wavelengths.

### 7.2.5 Extinction Ratio Analysis

The optimum operating point of the MZI is determined by maximum achievable extinction ratio of the output signal. As explained in Chapter 4, to get the infinitely high (ideal) extinction ratio, the light power at the output of both MZI branches has to be equal, with the relative phase equal to $\pi$. Since in the TAOMI and TAO-WC device designs both the output power and the phase depend on the SOA bias currents, there is a tradeoff between the field intensity and the phase change in the MZI that needs to be made. This ultimately limited the extinction ratio of the converted signal and thus the performance of these two device types.

The difference in extinction ratios observed in TAOMI and TAO-WC, for inverting and non-inverting modes of operation, can be explained by analyzing the device principle of operation.

Due to the cross-gain effects in the common SOA of the MZI, the device operation will always yield a higher output extinction ratio in the inverting mode of operation, as illustrated in Figure 7.15.

In the inverting mode of operation, the output of the MZI is on the high level with no probe signal present Figure 7.15. In order to achieve the carrier lifetime that is as low as possible, the bias current of the common SOA should be the higher than that of the other MZI SOA. Once the probe signal is present in the common SOA, the gain compression will reduce the power of the pump signal in this branch of the MZI. This causes two effects - phase
Figure 7.14: Gain compression effects on the SOA gain
change in the interferometer and the power level equalization between the two branches of the MZI. These effects allow for better extinction, due to better cancellation of the fields of similar power coming from the two branches of the SOA. In conclusion, in the inverting mode of operation, the two signals are added together when they both carry more power and subtracted when they have similar power levels therefore yielding high extinction ratio.

For the non-inverting mode of operation, the output of the MZI is on the low level with no probe signal present. To achieve this level, the two SOAs in the MZI have to be biased differently, to yield $\pi$ relative phase shift. However, these different bias levels will limit the output extinction at the low level, due to significantly different field intensities in the two interferometer branches. Once the probe signal is present in the common SOA, it will cause the gain compression effect, Figure 7.14 which will reduce the power of the pump signal in the common SOA, causing the phase change. Consequently, signals from two MZI branches will be added together when power of one of them is reduced by the gross gain effects of the probe signal.
Accordingly, in the non-inverting mode of operation, the two signals are being added when they both carry lower optical power, and subtracted when their power levels are different, due to the necessary difference in SOA bias currents to achieve the OFF state. This effect reduces the maximum obtainable extinction in the non-inverting case.

We can conclude this analysis of the static performance of the TAOMI-WC and TAO-WC wavelength converters by noting that the extinction of the MZI can be improved with the capability of adjusting the phase and the power in the MZI branches independently. This new control scheme was realized in the TAO-PC-WC device.

The independent phase control in the MZI provides for easier optimization of the operating bias point of the wavelength converter, as well as better extinction for both inverting and non-inverting modes of operation. This is illustrated in Figure 7.16. Gains of the SOAs in the branches of the MZI can be adjusted to compensate for high ASE light power of the input amplifier in the OFF state of the wavelength converter. The same techniques can be used for compensation of the non-uniform splitting of the light at the entrance to the MZI, which may occur due to processing induced imperfections. That way, the electric field intensities at the output of the two branches of the MZI can be matched closely, contributing, to an increased extinction ratio at the output. The extinction ratio will be limited by the ASE level from the MZI-SOAs. Small difference in ER is still noticeable for the inverting and non-inverting modes of operation, due to the same effects as already discussed. However, using the independent phase control, and adjusting the zero level of the MZI precisely, the extinction will be as close to ideal as possible. In this case, the level of phase change in the MZI is not crucial for the device performance - suppressing the power of the CW light in the common branch.
of the MZI will still yield to a large output signal. However, the amount of phase change will determine the maximum output power attainable, as well as the intensity dependent jitter of the converted output signal.

7.3 Dynamic Performance for Digital NRZ Wavelength Conversion

Some of the important properties that were evaluated for integrated tunable wavelength converters are their input signal dynamic range, wavelength sensitivity of the wavelength conversion process, bias sensitivity of the wavelength conversion process, dynamic extinction ratio and regenerative properties.
7.3.1 Operating Condition Optimization

For TAOMI and TAO-WC, optimum injection currents for the wavelength converter operation can be found by measuring the electrical transfer function of the device with the input amplifier biased, and the input probe signal power at 0 and maximum levels. This measurement can be performed using a simple optical power meter. Two curves obtained in such a measurement for TAO-WC are shown in Figure 7.17. For these measurements, the bias of the common SOA was fixed, and the other branch’s current was varied.

The input signal will compress the gain of the common SOA, and change the phase response for that branch of the Mach-Zehnder interferometer. The bias points where the distance between the two curves is the largest represent the optimum bias points for non-inverting and inverting mode of operation.

For TAO-PC-WC, first, we need to optimize the gains of the two SOAs, and then, we need to perform the phase adjustment. The bias current of
the common SOA needs to as large as possible, in order to reduce the gain
recovery time. When the input amplifier is biased at its operating level, the
ASE will compress the gain of the common SOA. Therefore, the bias of the
other branch of the MZI needs to be adjusted such that the output power of
the SGDBR-generated CW light is equal coming out of both branches of the
MZI. Finally, using the phase electrode, the phase can be adjusted to shut
off the interferometer. The easiest way to perform this optimization is to use
an optical spectrum analyzer.

7.3.2 Bit Error Rate Characterization

7.3.2.1 TAOMI Wavelength Conversion Results

TAOMI devices were tested using an Agilent photodiode receiver with a sen-
sitivity of -15 dBm for 1 \times 10^{-9} \text{ BER}. The input power to the wavelength
converter was kept at 4 dBm. The output power of the converter was rela-
tively low (-8 dBm) due to the thermal effects on the MZI-SOA gain, as well
as the length of the passive waveguides in the MZI.

For the first set of measurements, one input wavelength (1545 nm) was
chosen, and NRZ 2^{31} – 1 PRBS data at 2.5 Gbps were converted onto 4 dif-
ferent output wavelengths set by the SGDBR laser (21 nm range). Error-free
wavelength conversion was obtained with maximum power penalty of 1 dB,
as shown in Figure 7.18 a). The bias point of the MZI was adjusted for ev-
ery pair of wavelengths in order to maximize the converted signal extinction,
thus minimizing the power penalty.

In the subsequent set of measurements, NRZ 2^{31} – 1 PRBS data streams
at 2.5 Gbps from different input wavelengths were converted onto one device
output wavelength (1571.5 nm). The Mach-Zehnder bias was separately op-
Figure 7.18: TAOMI Device, 2.5 Gbps - Bit error rate measurements for (a) constant output wavelength and variable input wavelength (b) constant input wavelength and variable output wavelength
timized for the best extinction ratio for each input wavelength. BER curves in Figure 7.18 b) indicate error-free operation over 50nm input wavelength range, with a maximum power penalty of 1.6 dB. While the upper limit of the input wavelength was set by cross-phase modulation degradation due to finite SOA gain bandwidth, the lower limit was set by the filters available to us (1535 nm).

Increase in power penalty that was noticed for input wavelengths above 1565 nm can be attributed, in part, to the input signal-to-noise ratio degradation due to our non-optimum L-band amplifier. Gain for the input signal in the L band was achieved by using an additional 10 meter long spool of erbium doped fiber in line with our standard C-band EDFA. This noise did not affect our back-to-back measurements, since those were performed without the EDFA. Another cause for power penalty increase in this wavelength range would be higher ASE noise levels as the laser is tuned away from the SOA gain peak, which directly influence the output signal to noise ratio. Carrier dynamics in the SOAs of the MZI limited the speed of operation to 5 Gbps (for TAOWC).

7.3.2.2 TAO-WC Wavelength Conversion Results

TAO-WC devices were tested using a Nortel photodiode receiver with a built-in electrical amplifier, which had a sensitivity of about \(-18.8 \text{ dBm for } 1 \times 10^{-9}\) BER. The output power of the converter was significantly higher in this case (-2 dBm). The main reason for this power increase would be in the reduced heating of the SOAs in the MZI, due to their larger separation (70 \(\mu\text{m}\) for TAO-\(\text{WC}\), compared to 17 \(\mu\text{m}\) for TAOMI). This issue was addressed in detail in Chapter 6.

For the first set of measurements, one input wavelength (1565 nm) was
Figure 7.19: TAO-WC Device, 2.5 Gbps - Bit error rate measurements for (a) constant input wavelength and variable output wavelength (b) constant output wavelength and variable input wavelength.
Figure 7.20: TAO-WC Device, 2.5 Gbps - Bit error rate measurements for constant output wavelength and variable input wavelength, with device bias optimization for each input wavelength

chosen, and NRZ $2^{31} - 1$ PRBS data at 2.5 Gbps were converted onto 4 different output wavelengths of the device (21 nm range). The resulting BER curves for this case are shown in Figure 7.19 a). BER curves, Figure 7.19 a), indicate error-free operation with little variation in power penalty as a function of the output wavelength. The maximum power penalty measured was 2 dB. This penalty can be in part be explained by the wavelength sensitivity of the SOAs, and could therefore be reduced by optimizing the device bias for every output wavelength, as shown for TAOMI-WC devices.

In the subsequent set of measurements, the NRZ $2^{31} - 1$ PRBS data streams at 2.5 Gbps from different input wavelengths were converted onto one device output wavelength (1572 nm).
This time, TAO-WC was set to a single bias point for optimum performance over the entire wavelength range, and kept in that state for all input wavelengths. The BER results for this measurement are shown in Figure 7.19 b).

Then, for comparison, the device bias was re-optimized for each input wavelength, and the BER curves were measured again, Figure 7.20.

Without separate optimization of the MZI bias point, the best power penalty of 1 dB was obtained for the input signal closest to the gain peak of the SOAs, at 1555 nm. For this wavelength, the on-chip preamplifier SOA would give the highest possible gain at the input and the effects of gain compression and cross phase modulation in the common SOA of the MZI would be the most pronounced. Also, the ASE suppression in all of the SOAs would be the best, therefore giving the best SNR at the output. The power penalty was primarily caused by the SNR and extinction ratio degradation and wavelength dependence, due to finite extinction at the output of \( \lambda \)12dB. The maximum power penalty obtained at far ends of the gain peak was as much as 3 dB, due to further decrease in SNR, conversion efficiency and output extinction ratio.

By re-optimizing the MZI bias and the input preamplifier gain as a function of the input wavelength, the maximum power penalty for these devices obtained over the entire range of operation was reduced to 1.9 dB.

Carrier dynamics in the SOAs of the MZI limited the speed of operation to 7 Gbps (for TAO-WC). The speeds observed were higher than for the TAOMI-WC design due to several differences in the device design. First, the length of the passive sections in the TAO-WC design was shorter than that in the TAOMI-WC design, allowing for higher SGDBR-generated CW light intensities to reach the MZI. This reduced the gain recovery time, as
explained in Chapter 4. The higher speeds were observed in part due to the wider separation of the MZI SOAs which lead to lower heating of these SOAs, causing the differential gain to remain high.

7.3.2.3 TAO-PC-WC Wavelength Conversion Results

TAO-PC-WC devices were tested with the input signal at 1570 nm that was externally modulated using an electro-optic modulator with NRZ $2^{31} - 1$ pseudo-random bit sequence data at both 2.5 and 10 Gbps. The converted output wavelength was filtered using a thin-film tunable filter and detected with a PIN-photodiode based receiver.

Measured BER curves are shown in Figure 7.21. The device sensitivity at the input was -10 dBm for 2.5 Gbps operation and -5 dBm for 10 Gbps operation. The average output power of the wavelength converter was 0 dBm. At 2.5 Gbps, the maximum power penalty measured was 0.8 dB which can be attributed mainly to the ASE noise generated by the on-chip SOAs. At 10 Gbps, the power penalty was measured as low as 1.4 dB for output wavelengths between 1542-1555 nm. The penalty increased to around 3 dB, and the BER slope decreased for longer wavelengths (above 1570 nm), which can be attributed to different SNR redistribution due to optical transfer function change for wavelengths near the band edge.

Improved carrier dynamics properties in the SOAs of the MZI enabled the speed of operation of 10 Gbps (for TAO-PC-WC). The speeds observed were higher than those for the TAOMI-WC and TAO-WC designs due to improved MZI optical pumping, as described in the next section.
Figure 7.21: TAO-PC-WC Device - Bit error rate measurements for constant input and variable output wavelength - (a) 2.5 Gbps (b) 10 Gbps
7.3.3 High Photon Density Mode of Operation

As pointed out in the Chapter 4, one of the ways to reduce the gain recovery time in the SOA is to increase the level of optical pumping. Figure 7.22 illustrates this effect, showing the eye distortion as a function of the total input power into the wavelength converter. Case a) represents an eye from the TAOMI device design, with the SGDBR laser biased at half the maximum power level. Figure b) shows an optimized eye for the TAO-WC device design, where 2 mW of SGDBR power arrive in each branch of the SOA, and the rest comes from the amplifier input signal. Finally, Figure c) represents an eye diagram for the TAO-PC-WC device design, where the SGDBR laser in combination with post-amplifier SOAs provides 12 mW of optical power per branch in the MZI. In this device implementation, the gain recovery time
Figure 7.23: TAO-PC-WC - (a) Power of the SGDBR-generated light that reaches the MZI-SOA as a function of the post-amplifier bias current (b) Gain of the preamplifier SOA measured at the MZI-SOA

is reduced to less than 60 ps and 10 Gbps operation is enabled. Measured SGDBR light power into the MZI-SOAs in function of the SGDBR output power is shown in Figure 7.23 a). The power was measured by reverse biasing the MZI-SOAs and measuring the photocurrent.

Longer preamplifier SOA implemented in TAO-PC-WC devices helps improve the device sensitivity by providing a large amount of gain, and seen in Figure 7.23 b). The total gain shown represents the gain measured at the input to the left MZI-SOA, and therefore includes the propagation loss of
7.3.4 Regenerative Properties

Regenerative properties of the cross-phase modulation SOA-MZI wavelength converters are based on their highly nonlinear optical transfer characteristics, as already discussed in Chapter 3. Regenerative properties of integrated SOA-MZIs devices were demonstrated in To quantify the regenerative properties of the tunable wavelength converter (TAO-WC), the input signal’s extinction ratio was degraded in a controllable manner by adjusting the EOM bias and the polarization of the light at the input of the electro-optic modulator used to encode the data. The power level of the input signal was kept constant for all the input extinction ratio values. Significant improvement in the output extinction ratio was measured - for input ER of 6.33 dB, the converted signal had an extinction of 12.06 dB in the non-inverting and 12.33 dB in the inverting mode of operation, Figure 7.24.
However, decreasing the extinction of the input signal increased the average input power into the common SOA in the MZI and thereby reduced the number of carriers and the gain of the laser signal. Consequently, 6 dBm of input optical power resulted in only -4.4 dBm of the output optical power of the converted signal. On the other hand, device excitation with the high ER signal at the input (12 dB) provided the conversion gain of around 2 dB, with -4dBm at the optical input and -2dBm in the converted signal.

### 7.3.5 Dynamic Range and Converter Sensitivity

In an optical network, signals experience different attenuation thereby introducing variations in the input power to the network nodes. Therefore, it is important for the node components to have as large operating dynamic range as possible.

The input dynamic range of the wavelength converter was defined in Chapter 1 as the range of the input signal power for which the converter will
operate error free with a certain maximum receiver power penalty in dynamic operation.

Different methods for increasing the dynamic range of a wavelength converter have been investigated in [4]. Having an integrated preamplifier as part of the wavelength converter enables us to dynamically adjust the SOA gain and thereby insure proper device operation for a wide range of input powers.

As stated in [4], the dynamic range of operation can be controlled by the input SOA bias, as well as by the bias set point of the MZI. Figure 7.25 shows maximum ER values measured as a function of the data input power. High extinction ratio, greater than 10 dB, can be maintained over more than 16 dB of input signal power variation.

The inset of Figure 7.25 shows the TAO-WC converted eye for -6dBm input power in the fiber, corresponding to the WC output power of -4dB in fiber, thereby reamplifying the signal by 2dB.

The dynamic range for TAOMI and TAO-WC was limited by the passive waveguide propagation losses and available gain of the input SOA. The performance was improved for TAO-PC-WC device, due to its longer preamplifier SOA and lower loss waveguide, increasing the dynamic range to more than 20 db.

7.3.6 Chirp

Chirp is the frequency shift occurring in the output pulses of the wavelength converter. This frequency shift appears mainly at the edges of pulses, and is caused by the refractive index modulation in the MZI SOAs. Output chirp is an important parameter for any type of optical regenerator as it will dictate the dispersion-limited transmission distance and/or number of regenerator
spans. Low chirp or negative chirp is required for long distance transmission over standard single mode fiber. It has been shown that the chirp of SOA-MZI wavelength converters has little dependence on the chirp of the input signal, [5]. Therefore, the chirp of the wavelength converter introduced in the process of data transcription will ultimately determine its performance in transmission systems.

For time resolved chirp measurements, the TAO-WC MZI's bias currents were optimized for maximum extinction ration in either inverting or non-inverting mode of operation at 2.5Gbps. The output of the device was optically filtered and then led into the Advantest time-resolved chirp test instrument. The interferometric method used for chirp measurement is based on frequency and amplitude change measurements on two different slopes of the interferometer, in order to obtain time resolved frequency change [6]. The optical output from the instrument was connected to a high-speed digital oscilloscope, which is used as part of the setup to perform measurements on the data pattern. Time-resolved chirp was measured as a function of the input wavelength, output wavelength (set by the integrated on-chip laser) and the interferometer mode of operation (inverting and non-inverting). Typical results of measurements for non-inverting and inverting mode of operation are shown in Figure 7.26. Little input-output wavelength dependence of chirp parameter values was observed across the entire wavelength range set. For non-inverting operation, the average chirp parameter was measured to be -2 for 40 nm input and 22 nm output wavelength range. For inverting mode of operation, the average chirp parameter was measured to be 1-3 for the same output wavelength range. Thus, the performance of the wavelength converter in transmission should consistently reduce the dispersion power penalty if operated in the suitable mode of operation (based on the fiber
Figure 7.26: Example of time-resolved chirp data for non-inverting and inverting mode of operation

dispersion parameter). As an example, transmission over 480 km of SMF-28 fiber, with power penalty improvement, has been demonstrated using a MZI-SOA WC, [7]. The chirp parameter sign and value measured are consistent with theory and previous results [5] for XPM-SOA based wavelength
converters.

### 7.3.7 Linewidth and RIN Measurements

The tunable wavelength converter linewidth will determine the expected dynamic performance of the device. Measuring the linewidth of the device and direct comparison with the linewidth of a commercial widely-tunable SGDBR laser also provides useful information about potential back reflection issues with the chip. Although optical low coherence reflectometry can be used as a more accurate tool to investigate the origins of particular back reflections on chip, the information on the linewidth represents a good way of verifying whether any detrimental reflection issues are present in the device at all. The linewidth of a light source can be determined by measuring the autocorrelation function of the output light beam. If the electric field from the output of the device is mixed with the version of the same field that is delayed by some time \( \tau \), as long as the phases of two fields are well correlated, the fields will add coherently [8]. The decay of the strength of the autocorrelation of a signal can be described by the coherence time of the device \( \tau_{coh} \),

\[
\langle E(t)E(t-\tau)^* \rangle \propto e^{j\omega t} e^{-\frac{1}{\tau_{coh}}}.
\] (7.1)

The autocorrelation can be related to the frequency spectrum of the mode. If the decay is exponential with constant \( \tau_{coh} \), then the lasing spectrum is a Lorentzian [9].

The schematic of the experimental setup used to measure the linewidth is shown in Figure 7.27. The gain section of the tunable wavelength converter’s laser was biased at 90 mA, the booster–SOAs were biased at 45 mA, and the MZI-SOAs were biased at 200 mA. The light from the output was coupled through a lens with a built in isolator, then modulated with a sinusoidal
signal whose frequency was 1 GHz. Then the light was split between the two branches of the interferometer, de-correlated by passing the signal from one branch through a spool of fiber, and finally detected by a photodiode, amplified by an electrical amplifier and led to an electrical spectrum analyzer. The reason for spectrally shifting the signal is to eliminate the influence of the $1/f$ noise. The two recombined incoherent fields generate a difference frequency signal which contains the combined FM field noise from both light sources. Therefore, the full width at half maximum of the spectrum measured will be twice as wide as the laser linewidth, due to the properties of the Lorentzian lineshape.

Figure 7.28 shows the measured FM noise spectrum for the TAO-PC-WC wavelength converter. The linewidth of the device corresponding to this measurement is 7.85 MHz. For comparison, Figure 7.29 shows the measured FM noise spectrum for an etalon commercial SGDBR laser using the same test setup. The linewidth corresponding to this measurement is 7 MHz. The
Figure 7.28: FM noise spectrum of the TAO–PC–WC device

Figure 7.29: FM noise spectrum of the commercial SGDBR–SOA device
value measured is consistent with the linewidth values that are specified for this type of laser [10]. Therefore, the performance of the tunable wavelength converter is free of any influences from coherent back reflections and it is in no way limited by this factor.

Relative intensity noise (RIN) is an important parameter for both analog and digital communications. It is defined as the ratio of the time averaged squared signal amplitude noise to the average signal power squared, $P_0^2$,

$$\text{RIN} = \frac{\langle \delta P(t)^2 \rangle}{P_0^2}. \quad (7.2)$$

The usefulness of this parameter comes from the fact that in digital optical communications, for the Gaussian noise distribution, RIN can be directly related to the bit error rate [3]. Similarly, RIN can also be related to the signal-to-noise ration for analog signals.

Measuring the electrical power as a function of frequency using an elec-
Figure 7.31: Relative intensity noise for the TAO-PC-WC device (with an optical filter at the device output)

...trical spectrum analyzer, it can be shown that the RIN can be related to the spectral density of the measured signal $S_{\delta P}$ by

$$\frac{\text{RIN}}{\Delta f} = \frac{S_{\delta P}}{P_0^2},$$

(7.3)

where $\delta f$ is the filter bandwidth of the measurement apparatus. Because the measurement bandwidth can vary, it is common to specify the RIN per unit bandwidth, in dB/Hz.

The schematic of the experimental setup used to measure the RIN for TAO-PC-WC devices is shown in Figure 7.27. To get the accurate measured values, a proper system calibration is required, in order to remove the frequency response of the photodiode/amplifier/ESA from the measurement, as well as the thermal and shot noise influences.

The results for RIN are shown in Figure 7.30, and for this measurement,
no output optical filter to suppress the ASE was used after the device. The MZI-SOA bias current were varied between 150 and 250 mA. Figure 7.31 shows the same set of measurements with use of optical filter at the output. The RIN values measured in this case were lower, as expected.

The increase in RIN relative to the values measured for a commercial SGDBR laser, [10] can be attributed to the long MZI-SOAs and their ASE. However, in order to achieve the bit error rate lower $10^{-9}$ at 10 Gbps, the required RIN has to be lower than $-121.5\text{dB}$, [3], which is satisfied by a large margin even at the resonance peak.

### 7.4 Dynamic Performance for Analog Signals

In order to assess the analog performance of wavelength conversion the spurious-free dynamic range (SFDR) was measured as a function of input and output wavelength. A two-tone technique was implemented by directly
modulating a widely tunable integrated EML with two RF tones at frequencies of 1.00 GHz and 1.0001 GHz. The average output power from the EML was 10mW and was coupled into the wavelength converter. The bias point of the wavelength converter was set to minimize the 3rd order IMD terms. The particular TAO-WC device used in these measurements had an average output power of -5 dBm at the optimum set point. After wavelength conversion, the signal was optically filtered, detected by a low noise photo diode, electrically amplified and the resulting signal and 3rd order IMD terms measured using an electrical spectrum analyzer. A typical SFDR measurement result is shown in Figure 7.32, for conversion from 1561 nm to 1550 nm. The results for 2 input - 2 output wavelengths combinations are summarized in table 1. Similar SFDR measurements were taken over a range of RF tone spacing to characterize ∆f dependence. Results of these measurements are shown in the inset of Figure 7.32. The SFDR remained greater than 82.7 dB-Hz2/3. There are several limiting factors in device performance - coupled output power being the most important one. These SFDR measurements were also limited by a noise floor of -130 dBm/Hz at the receiver.
7.5 Optical Wavelength Routing using TAO-WC Device

In Chapter 1, optical wavelength routing function in an optical wavelength switch was mentioned as one of the main applications for all-optical tunable wavelength converters. One of the possible implementations of an optical wavelength switch was shown in Figure 1.1.

In this experiment, we tried to replicate a similar architecture, but without the input demultiplexer. Instead, a single wavelength was transmitted through the fiber. The demonstration of wavelength routing using the TAO-WC was performed through four different ports in an arrayed waveguide grating router, as shown in the experimental setup schematic, Figure 7.33.

7.5.1 Experiment

The transmitter consisted of a tunable laser operating at 1555nm, a polarization controller, and a lithium-niobate electro-optic modulator. An EDFA was placed after the transmitter to amplify the signal for transmission through 50km of dispersion shifted Truewave fiber.

Two conical-tipped lensed-fibers on piezo-controlled translational stages were used to couple light into and out of the device. Four wavelengths (1551.9 nm, 1558.6 nm, 1560.0 nm, 1561.6 nm), each corresponding to a different port on the AWGR, were chosen for their placement in the C-band and for their relation to the input wavelength of 1555 nm. Tuning of the device’s output wavelength was achieved by controlling the mirrors of the on-chip SGDBR laser. The temperature of the device was kept at 18°C using a thermoelectric cooler.
7.5.2 Results

For the experimental demonstration, the data was generated using a BERT with $2^{31} - 1$ PRBS output data at 2.5 Gbps. The optical power measured in fiber at the input to the device was -2.5 dBm. For each output wavelength, the currents injected through the SOAs of the device’s MZI arms were adjusted to maximize the extinction ratio of the wavelength converted signal. The extinction ratio was calculated using the eye diagram obtained by a digital sampling oscilloscope.

Extinction ratios of 12 dB or greater were measured for each of the wavelength converted signals. BER measurements were taken after the transmitter, after the 50 km spool of fiber, and at the output ports of the AWGR for each wavelength using an optically preamplified receiver whose sensitivity was -34.5 dBm. Results of the BER measurements are shown in Figure 7.34. Less than 1 dB of power penalty was measured at a bit-error rate of $10^{-9}$ for
Figure 7.34: BER results for the wavelength routing experiment

each of the wavelength converted signals.

7.6 2-Stage Wavelength Conversion

2-stage wavelength conversion has been suggested as a way of realizing an all-optical tunable wavelength converter that would circumvent the limitations that both XGM and MZI-SOA XPM wavelength converters share - mainly, the inability to perform the wavelength conversion to the same wavelength. Another advantages that this scheme provides are reduced requirements on the output optical filters, higher input dynamic range and polarization insensitivity.

The schematic of the device used in this work is shown in Figure 7.35. The first stage of the wavelength converter utilizes the XGM effect in an SOA to perform wavelength conversion from any input wavelength $\lambda_{\text{in}}$ to a fixed internal wavelength $\lambda_{\text{int}}$ via down conversion, which is the optimal
type of conversion for XGM in SOAs, as already discussed in Chapter 3. The polarization state and the intermediate wavelength can be optimized for maximum performance of the second stage. The second stage consists of the tunable all-optical wavelength converter (TAO-WC in this particular experiment). Incoming data at the fixed wavelength $\lambda_{\text{int}}$ from the first stage is transcribed to the new wavelength, $\lambda_{\text{out}}$ set by the on-chip SGDBR laser.

Examining the filtering needs for this wavelength converter type, no tunable filters are required, but rather two fixed band-blocking filters suffice. The wavelength conversion in the first stage is performed out of band, therefore, the filter after the first stage needs to block the input signal band. After the second stage, data are converted to back to the original output band, which allows the use of a fixed out-of-band filter to filter out the internal wavelength.

The second stage wavelength converter operates in the inverting mode of operation, which is the preferred mode of operation as far as the highest achievable extinction ratio of the converted signal is concerned. This is another advantage of the 2-stage wavelength conversion approach.
Figure 7.36: Spectra of the three signals in the experiment - input wavelength, internal wavelength (out of band) and output wavelength

7.6.1 Performance of the 2-stage Wavelength Converter

Performance through the 2-stage WC was characterized at 2.5 Gbps. The input electro-optic modulator in the transmitter was biased to provide highest extinction. The first-stage SOA was biased at 133 mA and driven in saturation to induce XGM. The input wavelength to the 2-stage WC was 1565 nm at a power of 8.8 dBm and further amplified by an EDFA. The internal wavelength was 1555 nm at a power of -10 dBm at the input to the second stage. Both wavelengths were coupled together and sent through the first-stage SOA and an optical bandpass filter centered at $\lambda_{int}$ to filter the converted signal and reject the input wavelength. The data at the internal wavelength was then subsequently sent through an EDFA and the integrated
wavelength converter. The input wavelength range into the TAO-WC spans 50 nm, covering both C and L bands, while the output wavelength from the SGDBR laser on the integrated WC can be tuned over 22 nm in the L-band and was set to 1573 nm, with a maximum output power of 4 dBm. The TAO-WC MZI’s bias currents were optimized for maximum extinction ratio in the inverting mode of operation. The wavelength converted signal from the TAO-WC was filtered with a 1.2 nm optical band-pass filter and the internal wavelength was rejected. BER measurements were performed on the XGM and XPM wavelength-converted signal and are shown in Figure 7.38. Receiver sensitivity of -17 dBm was achieved without optical preamplification in the receiver. The 2.5 dB power penalty due to XGM can be attributed to the reduced extinction and addition of ASE noise from the SOA. Measured eye diagrams are also included illustrating the extinction ratio degradation of the XGM process as well as extinction ratio and noise improvement of the 2-stage process. Regeneration in the XPM stage is due to the nonlin-
Figure 7.38: **BER curves for the signal at the input, after the first stage and at the output of the second stage**

ear transfer function of the TAO-WC device. The high slope of the transfer function improves the ER from 10.7 dB after the XGM stage to 17.7 dB after the XPM stage.

### 7.7 Chapter Summary

In this chapter, we have presented results of experimental investigation of different tunable all-optical wavelength converter designs.

The first and the second device generations operated at 2.5 Gbps with low power penalties, and with 22 nm output tuning wavelength range. This was improved in the third device generation, for which error-free operation for data rates up to 10 Gbps over 35 nm output tuning range was demonstrated.
The device input sensitivity for error-free operation was -10 dBm at 2.5 Gbps and -5 dBm at 10 Gbps. The average converted signal output power of the device was 0 dBm. Therefore, the device provided for 5-10 dB of signal gain. Improved carrier dynamics properties in the SOAs of the MZI enabled the speed of operation of 10 Gbps (for TAO-PC-WC). The speeds observed were higher than those for the TAOMI-WC and TAO-WC designs due to improved MZI optical pumping.

The extinction ratio of the converted signal was mainly affected by the ability to match the output powers and phases of the interferometer in the OFF state. Therefore, the third device generation with the independent phase control exhibited the best output extinction performance.

No significant linewidth increase was noticed when compared to a commercial widely-tunable SGDBR laser, indicating the low level of coherent back reflections. The linewidth measured was only 10% higher than that of the SGDBR laser.

Finally, the results of experiments using the device for optical wavelength routing, as well as for the second stage of a 2-stage wavelength converter showed the practicability of the device and its robustness that makes its use in the optical networks a real possibility.
References


Chapter 8

Summary and Directions for Future Work

8.1 Thesis Summary

The purpose of this thesis was to explore the possibilities for monolithic integration of widely-tunable all-optical wavelength converters in InP. Tunable wavelength converters represent one of the enabling technologies for future optical networks where the switching and routing functionalities are expected to be pushed into the optical layer in order to circumvent the limitations of electronic processing of ultrafast data rates. In particular, all-optical wavelength conversion technologies, that allow for regenerative transcription of data from one wavelength to another without passing it through electronics, represent an attractive solution due to their better scalability in terms of bit rate, simpler design, low power consumption and potential for monolithic integration, when compared to the classical optical-electronic-optical techniques.

The tunable integrated wavelength converters that were designed, fabri-
cated and tested as part of this work employed Sampled-Grating Distributed Bragg Reflector (SGDBR) lasers as widely tunable light sources, which were monolithically integrated with different Mach-Zehnder interferometer (MZI) semiconductor optical amplifier (SOA) based wavelength converters.

In this work, important aspect of the monolithic integration were studied: the benefits and challenges of monolithic integration, the choice of the optimum integration platform and the tradeoffs in the different component design that originate from the integration platform used. The integration platform used in this work, Offset Quantum Wells (OQW), represents a simple and versatile solution for robust prototyping of the state-of-the-art photonic integrated circuits.

Properties of the main building blocks in this integration, semiconductor optical amplifiers, MZI-SOA-based wavelength converters and SGDBR laser, were studied in detail. Guidelines for their design and performance maximization on the same chip were given. The properties of the semiconductor optical amplifiers critically depend on the active region design. Offset quantum well active regions provide for high differential gain, large gain bandwidth, and large output saturation power. The gain recovery time will be influenced in part by the photon density in the active region. Higher photon densities lead to higher speed of operation, but reduce the efficiency of the phase change in the wavelength converter. Mach-Zehnder interferometer wavelength converter allows for regenerative operation in both inverting and non-inverting modes of operation. The output extinction ratio is critically determined by the ability to cancel the fields of the two interferometer branches in the OFF state. Better results can be achieved using independent phase control of the interferometer.

Special attention in this thesis was dedicated to understanding the re-
quirements and limitations of photonic interconnections, consisting of passive waveguides, light couplers and light splitters, that linked all of the building blocks together into a single photonic integrated circuit. These components are critical, because their improper design (leading to large losses or non-optimized reflection properties) can be detrimental to the whole device performance. Weakly guiding components have better reflection and propagation losses properties, whereas the strongly guiding structures provide for the more compact designs. The dimensions of the bend-waveguides will be determined by the maximum amount of the radiation losses tolerable, and they critically depend on the refractive index contrast between the core and the cladding of the waveguide. Multimode interference components represent an attractive solution for passive light splitters and combiners, due to their low loss, low polarization dependence and compact size. Different types of multimode interference phenomena can be used for different splitter/combiner realizations. The most compact components are based on the symmetric mode interference.

Having an integrated laser on the same chip with other components requires efficient coherent back reflection suppression. Therefore, a comprehensive analysis of possible sources of back reflection, reflection mitigation and influence on the device performance was conducted. Linewidth measurements were performed to assess the amplitude of back reflections into the integrated laser of the wavelength converter, and the values measured were very close to those of the commercial SGDBR lasers. A total of 10% of the linewidth increase is within the range of the acceptable values.

Three different device designs, TAOMI-WC, TAO-WC and TAO-PC-WC were implemented, and chronologically, the designs and their performance improved.
The first and the second device generations operated at 2.5 Gbps with low power penalties, and with 22 nm output tuning wavelength range. This was improved in the third device generation, for which error-free operation for data rates up to 10 Gbps over 35 nm output tuning range was demonstrated. The device input sensitivity for error-free operation was -10 dBm at 2.5 Gbps and -5 dBm at 10 Gbps. The average converted signal output power of the device was 0 dBm. Therefore, the device provided for 5-10 dB of signal gain. Improved carrier dynamics properties in the SOAs of the MZI enabled the speed of operation of 10 Gbps (for TAO-PC-WC). The speeds observed were higher than those for the TAOMI-WC and TAO-WC designs due to improved MZI optical pumping.

The important function of signal regeneration for the tunable wavelength converters was demonstrated at 2.5 GBps. Detailed experimental study of device static and dynamic performance was carried out.

The MZI-SOA wavelength converter allows for wavelength conversion in both inverting and non-inverting mode of operation. Detailed extinction ratio analysis was performed in this thesis and the origins of the performance noticed explained. The device performs better in terms of optical extinction ratio for the inverting mode of operation, although through the proper design, the difference between two regimes can be engineered to become negligible. This was carried out in the TAO-PC-WC device design by introducing the independent phase control of the wavelength converter.

Finally, the feasibility of the optical routing using this device was demonstrated in a simple scheme employing a tunable wavelength converter and an arrayed waveguide grating router.

A new, more complex and robust 2-stage wavelength converter architecture was demonstrated and experimentally investigated. This architecture
allows for polarization insensitivity of the device as well as simplified filtering scheme while enabling the wavelength conversion to the same wavelength.
8.2 Future Work

The future work can lead in several different directions. One direction would be towards improving the existing device performance, while the other would lead to more advanced photonic integration of even higher complexity integration.

Most of the constraints and limitations in the device performance were imposed due to the use of offset quantum well platform used. While this platform showed excellent properties in terms of robustness, simplicity, low reflections etc, the use of an integration platform that would allow for more non-linear SOA designs would be of great benefit. The new platforms and processes based on impurity-free quantum well intermixing are natural candidates for this future work, due to their attractive properties of post growth bandgap control and compatibility with the low reflection requirements.

To achieve polarization independent operation, an integration using butt joint growths would have to be employed, due to the fact that it is beneficial for the laser to have a polarization dependent quantum well region, and the amplifiers on chip to be made using polarization insensitive bulk active regions. It would be of interest to investigate whether such a technology can meet the limits imposed by the desired reflection properties of the MZI-SOA WC.

Integration of spot-size converters would be of great interest, since it would help to significantly reduce the coupling losses from current 4 dB.

Reducing the chip size and area would be of interest in order to make the devices even more economical and to further simplify the requirements for packaging. The use of turning mirrors could help with achieving more compact device.
As discussed in Chapter 3, the speed of operation for the MZI-SOA wavelength converters can be increased by using them in the differential excitation regime with time delay for RZ data conversion. Previously, the differential time delay has never been realized on the same chip with the wavelength converter. We believe that the existing device designs could be adapted to incorporate a monolithically integrated time delay as well.

Finally, from the analysis of the 2-stage wavelength converter design in Chapter 7, it would be of interest to realize a 2-stage all-optical wavelength converter on the same chip, where the second stage would be the tunable MZI-SOA-WC, as realized in this work, Figure 8.1. This task would also require the development of filtering technologies or data separation schemes on the same chip, which is another challenge. However, its successful resol-
tion would push the boundaries of PICs even further, and lead the way to a monolithically-integrated optical router and to the new devices and applications that are yet to come.