All-Optical Buffering Based on Nonlinear Optical Processing with Semiconductor Optical Amplifiers

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de Rector Magnificus, prof.dr. R.A. van Santen, voor een commissie aangewezen door het College voor Promoties in het openbaar te verdedigen op maandag 18 oktober 2004 om 16.00 uur

door

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geboren te Fushun, China
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The work presented in this thesis was performed in the Faculty of Electrical Engineering of Eindhoven University of Technology, and was financially supported by the Netherlands Organization for Scientific Research (NWO), “het Prioriteitslandenfonds” of Eindhoven University of Technology and the COBRA Research Institute.

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NUR 959
Trefw.: optische signaalverwerking / optische geheugens / nietlineaire optica / halfgeleiderversterkers / optische telecommunicatiesystemen / computernetwerken ; packet switching.
Subject headings: buffer storage / optical information processing / optical storage / optical logic / nonlinear optics / semiconductor optical amplifiers / packet switching / optical wavelength conversion.

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Typeset using Microsoft Word, printed in the Netherlands.
All-optical packet switched networks are seriously considered as a future scenario for optical networks. In optical packet switched cross-connects, an essential issue is packet contention. Packet contention arises when packets from different sources arrive at a node simultaneously and have to be routed to the same destination. Packet contention can be solved via buffering.

This thesis addresses the physical realization of all-optical buffers. We demonstrate all-optical buffering by using optical signal processing technology. Our buffering concept contains two building blocks: an all-optical arbiter and an all-optical wavelength routing switch.

In Chapter 3 of this thesis, we introduce an optical threshold function that can act as an optical arbiter to handle two-packet contention. In Chapter 4, we extend this approach by using a laser neural network as an optical arbiter that can handle contention of more than two packets. In Chapter 8, we introduce an optically controlled variable optical delay that can be utilized in optical re-circulating loop buffer.

Our optical wavelength routing switch consists of an optical wavelength converter in combination with an optical demultiplexer. We investigate wavelength conversion by using nonlinear polarization rotation in a semiconductor optical amplifier and in an electro-absorption modulator. The results are presented in Chapters 6 and 7. A theoretical study to nonlinear polarization rotation in a semiconductor optical amplifier is given in Chapter 5.

All-optical flip-flop memories have many potential applications in the context of all-optical buffering and all-optical packet switching. We present a novel optical flip-flop concept based on nonlinear polarization rotation in a semiconductor optical amplifier in Chapter 9. In Chapters 10 and 11, we describe a three-state optical memory that can be realized by using either three coupled ring lasers or by using three coupled nonlinear polarization switches. This concept can be extended to optical memories with a larger number of states. Such multi-state optical memories might form an essential building block in packet switches with multiple output ports.
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Chapter 1
General introduction

1.1 Introduction

Optical networks have become an important part of the global telecommunication infrastructure due to the merits of optical fiber, which is the only medium capable of moving data at multi-gigabit/s commercially. Basically optical networks provide two functions: transmission and switching. The signal is transmitted through the optical fiber, and the optical signal is switched by cross-connects. Driven by the Internet, the demand for bandwidth is constantly increasing. The present-day transmission technologies are sufficient to meet the demand for bandwidth. However, electronic switches in present-day cross-connects are significant bottlenecks that limit the bandwidth. To eliminate this bottleneck, all-optical packet switched cross-connects are a promising technology for future telecommunication networks. In optical packet switched cross-connects, gradually more switching functions are implemented in the optical domain by using photonic integrated circuits. Therefore, all-optical signal processing technology is essential for future optical packet switched cross-connects.

In optical packet switched cross-connects, a key issue is packet contention. The packet contention arises when packets from different sources arrive at one node within the same time slot and have to be routed to the same destination. Packet contention can be solved via buffering. This thesis describes the physical realization of all-optical buffering by using all-optical signal processing technology.

1.2 Optical networks in the telecommunication infrastructure

Optical fiber communication technologies have been widely used in telecommunications since the 1980s. Optical fibers are not susceptible to electromagnetic distortion and offer high bandwidths (more than 50 terabit/s) with low
transmission losses [1]. These properties have led to the rapid adoption of optical fiber communication in the undersea as well as in landline communication networks. Optical transmission technology evolved to meet the globally growing demand for bandwidth, and optical networks became an important part of global telecommunication infrastructure.

We can roughly divide the current global telecommunication network into three kinds of network layers: long-haul networks, metropolitan area networks and access networks [2, 3]. Figure 1.1 shows a schematic representation of the architecture of transport networks. The long-haul communication links form the backbone of the global network, and are primarily optical fiber-based facilities that link different metropolitan areas. The function of the long-haul networks is to move large amounts of data over very long distances. Metropolitan networks are the portions of the global network that link metro traffic aggregation points like exchange centers, data centers, enterprises, and so on. Optical fibers also play a major role in metropolitan area networks. Access networks make the final connections to the end-users, linking between the end-users and metro networks. Many kinds of transmission technologies are currently used in access networks, such as copper wire, cable, satellite, optical fiber, wireless, etc. It should be remarked that currently fiber-to-the-home technology is commercially available, so that the advantages of optical fiber can also be employed in the access network.

![Figure 1.1: The global telecommunication network overlay. (By courtesy of Prof. A.M.J. Koonen)](image-url)
The three network layers contain many nodes, where the transmitted signals are processed. Processing functionalities include amplification, switching, transmitting, receiving, multiplexing. Cross-connects in the nodes are deployed to route and switch the information arriving at a node to its destination via the best possible path, which may be determined by factors such as distance, cost, and the reliability of specific routes.

1.3 Optical cross-connects in the optical networks

The demand for bandwidth is increasing rapidly. This demand is mainly driven by new services in the telecommunication network, such as high-speed Internet, video-on-demand, videoconferencing and videophones. The emergence of dense wavelength division multiplexing (WDM) technology, allows more than one hundred wavelengths to be simultaneously launched into one optical fiber, and the transmission speed per wavelength channel can be increased to more than 10 gigabit/s. A transmission rate of 10.92 terabit/s has been reached by employing 273 wavelength channels at a bit-rate of 40 gigabit/s per channel [4]. Furthermore, the transmission distance is also increased by employing optical amplifiers, such as erbium-doped fiber amplifiers (EDFAs) [5] and Raman amplifiers [6, 7], which can amplify many wavelength channels simultaneously in the optical domain. Optical amplifiers have led to a significant reduction in transmission costs. Today’s transmission technologies are sufficient to meet the demand for increased bandwidth. However, in today’s cross-connects, the signal is processed electronically, which means that the optical signals that arrive from the transmission lines have to be converted into electronic signals before they can be switched. Also, after being switched, the electronic signals have to be reconverted into optical signals before being transmitted through the optical transmission lines. This process is referred to as “optical-to-electronic-to-optical” (OEO) conversion, which has turned out to be a significant bottleneck for transmission bandwidth. The bandwidth mismatch between the fiber transmission systems and the electronic switches is expected to become more complex in future switches that have to handle terabit/s data streams. Electronic cross-connects cannot directly route and switch the future terabit/s data-streams. Therefore cross-connects which can route and switch the data in the optical domain have to be realized.

The migration from electronic cross-connects to optical cross-connects will take place gradually. The first generation of optical cross-connects can already switch the information at the granularity of a wavelength. One of the most common cross-
connect technologies is known as micro-electro-mechanical systems (MEMS) [8, 9]. MEMS consist of up to one thousand micro-mirrors that are moved mechanically. The input light is reflected to the desired output port via the mirrors. MEMS-based cross-connects allow a network reconfiguration time in the order of milliseconds. Although this is not fast enough to allow optical packet switching, this technology represents a significant step in the direction of transparent and configurable optical networking in which the OEO bottleneck is reduced. However, Internet data traffic is “bursty”, and it is hard to predict when a data packet is transmitted [10]. One can imagine that an Internet user triggers the information flow by a simple click of a mouse, which can result in a huge data stream that needs to be transmitted across a continent, passing through many nodes. Thus a large bandwidth demand from a single end-user could suddenly arise. The optical networks have to support all the end-users in the world. Therefore, network reconfigurations are necessary to create bandwidth in real time between end-users to accommodate dynamically changing traffic demands. MEMS-based technology cannot meet this demand. As a result, in the longer term optical packet switching has to be deployed.

In Internet data streams, the transferred data are split into some small data-packets. Using data-packets instead of a continuous data-stream provides more flexibility and allows more efficient use of the network [11-17]. In an Internet environment, the data-packets consist of two parts: header and payload. The header contains the destination information and the payload contains the content of the data that needs to be transferred. At each node, the optical date-packets are switched individually. When an optical packet arrives at a node, the optical cross-connect will process the destination information contained in the header, and switch the packet to its desired destination. In optical packet switched cross-connects, the network reconfiguration time is determined by the routing time on a per-packet basis, which is typically in the order of nanoseconds. This kind of optical packet switched cross-connects can provide almost arbitrarily fine switching granularity, ensuring more efficient use of the bandwidth and that optical networks are flexible enough to support diverse services [11-17].
Figure 1.2 is a functional representation of a typical optical packet switched cross-connect, as used in the European ACTS (Advanced Communications Technologies and Services) KEOPS (Keys to Optical Packet Switching) project [11, 12]. This optical packet switched cross-connect consists of three functional blocks: an input interface, a switching matrix and an output interface. The input interface is to synchronize the incoming packets so that the packets are in a specific time slot when the packets are processed. The second functional block is the switching matrix, which is used to route the packets and to solve packet contention. Packet contention will take place when one or more packets from different inputs arrive at the same time slot and have to be routed to the same outputs. Packet contention can be solved via buffering [18], where one or more packets are stored while others are transmitted to the desired output. The third block, the output interface, is used to regenerate the signal for consistent quality as the packet passes through multiple nodes.

### 1.4 All-optical signal processing in the optical cross-connects

In all-optical packet switched cross-connects, several key technologies play an essential role [19], such as optical buffering, optical header processing, and wavelength conversion. Due to the lack of reliable optical logic devices, the signal processing technology used in current optical packet switched cross-connects (such as in the KEOPS project [11,12]) is based on a combination of electronic and optical technology. The header processing is carried out in electronics while the payload remains in the optical domain. Optical packets are buffered in the optical domain by using an optical fiber delay but the buffering is controlled electronically.
Current electronic signal processing technologies are cheap, commercially available, and mature. However, compared to optical technology, electronic technologies have limitations in terms of data-format transparency, power consumption, and speed [20]. Optical signal processing technologies are promising due to several reasons. Firstly, at high bit-rates (> 40 gigabit/s) optical signal processing can be cheaper and is simpler to implement compared to electronics. Current examples are optical add/drop multiplexing, optical regeneration, clock recovery, and optical short pulse generation. Electronic solutions need opto-electronic conversion, resulting in a bottleneck for the operating speed. Moreover, devices for high-speed opto-electronic conversion are not cheap, and are hard to implement. This can make electronic solution expensive and complicated. Secondly, optical signal processing can reach a higher operating speed than electronics due to the inherent properties of light [21]. Electronic signal processing has an operating speed bottleneck, which is limited by the undesirable stray capacitance that always exists in electronic devices. Optical signal processing does not have this limitation. In contrast to electronic currents, optical light paths can cross each other without interacting, which are advantageous for photonic integration. Therefore, future optical signal processing can achieve higher operating speed compared to electronics [22, 23]. In order to achieve high operating speeds and stable operation, the optical signal processing should be carried out in integrated devices [24].

Photonic integrated circuits (PICs) are the photonic equivalent of microelectronic integrated circuits. However, PICs route lightwaves instead of electronic currents. PICs can be realized as integrated discrete passive devices or as active optical devices. Examples of passive devices are the integrated arrayed waveguide grating (AWG), sometimes referred to as Phased Array (PHASAR) demultiplexers [25-28], which form a key component in WDM systems. A single photonic chip can also contain some sophisticated devices, such as tunable lasers and optical wavelength converters [29, 30]. Optical components are slowly migrating from manual assembly of discrete optical devices to automated, semiconductor wafer-processing techniques and single-chip solutions. Ultimately, the signal processing in major optical networks, such as amplification, buffering, switching, multiplexing and demultiplexing, transmitting and receiving, will all be performed in the optical domain at high speed by using photonic integrated devices. Therefore, all-optical signal processing technologies are essential for future all-optical packet switched cross-connects.
1.5 Outline of this thesis

The topic of this thesis is all-optical signal processing in optical packet switched cross-connects, with an emphasis on all-optical buffering. Semiconductor optical amplifiers (SOAs) are used for all-optical signal processing. Some key technologies for realizing all-optical buffering systems are discussed, including all-optical arbiters, all-optical wavelength converters, and all-optical flip-flop memories.

An optical arbiter is a crucial building block of our all-optical buffering approach. The role of the arbiter is to judge the traffic situation, and to control the optical switch. All-optical arbiters that can handle the contention of two or three packets are discussed in this thesis.

The optical switch in our buffering concept can be realized by using an all-optical wavelength converter in combination with an optical demultiplexer. In this thesis, we call it a wavelength routing switch. The optical demultiplexer is a passive device, which can be an AWG. All-optical wavelength conversion is an important part of the wavelength routing switch. Two all-optical wavelength converter concepts are discussed in this thesis.

Optical memories have many potential applications in the field of all-optical buffering as well as all-optical packet switching. A novel all-optical flip-flop memory is presented in this thesis. We also give experimental proof for a three-state all-optical memory concept.

The thesis work is described in twelve chapters.

In Chapter 2, an overview of several all-optical buffering technologies is given. Our all-optical buffering concept is explained, and the key technologies in our all-optical buffering concept are discussed.

Chapter 3 introduces an all-optical buffering concept that is made up of optical arbiters and wavelength routing switches. It is experimentally shown that an optical threshold function can be employed as an optical arbiter to avoid two-packet contention.

Chapter 4 shows that the all-optical buffering concept in Chapter 2 can be extended to handle the contention of more than two packets. A laser neural network acts as an optical arbiter, and performs the role of the optical threshold function.

In Chapter 5, a model for nonlinear polarization rotation in strained bulk semiconductor optical amplifiers (SOAs) is presented. The model is applied to a nonlinear polarization switch. The simulation results are in good agreement with
experimental data. This model is essential for understanding wavelength conversion (Chapter 6) and optical flip-flop memories (Chapter 9) based on nonlinear polarization rotation in an SOA.

In Chapter 6, wavelength conversion based on nonlinear polarization rotation in an SOA is investigated. The performance of inverted and non-inverted wavelength conversion is presented.

Chapter 7 shows that wavelength conversion based on nonlinear polarization rotation can also be realized by using an electro-absorption modulator instead of an SOA. We investigate the performance of wavelength conversion based on nonlinear polarization rotation in an electro-absorption modulator.

Chapter 8 focuses on a variable optical delay for a re-circulating buffer. We demonstrate a variable optical delay by employing a re-circulating loop that is controlled by using all-optical signal processing technology. The variable optical delay concept can be utilized in all-optical re-circulating buffers. Re-circulating buffering systems can reduce the physical size of the buffer systems. We experimentally show that in case of packet contention one optical packet is re-circulated four times in the loop and when the contention disappears, the packet is routed out of the optical loop.

In Chapter 9, we investigate an optical flip-flop memory concept, which can be used for all-optical buffering and optical packet switching. An all-optical flip-flop memory with separate set and reset inputs is presented. The flip-flop is realized from two coupled polarization switches. The concept is explained and experimental results are presented.

In Chapter 10, we demonstrate that it is possible to make an all-optical memory with three states, by using three coupled ring lasers. Each state of the all-optical memory can be distinguished by a specific wavelength. This concept can be extended to form an optical memory with multiple states.

In Chapter 11, it is shown that the concept in Chapter 10 can be extended to form a three-state optical memory by using coupled polarization switches instead of coupled ring lasers.

Finally, conclusions are presented in Chapter 12.
Chapter 2

All-optical buffering

2.1 Introduction

Optical packet switched cross-connects have been considered as an important function block in future optical networks [11-17]. In optical packet switched cross-connects, a key issue is packet contention [18]. The packet contention takes place when packets from different sources arrive at one node simultaneously and have to be routed to the same destination. To solve the packet contention, several optical buffering strategies have been proposed [18, 31-42].

In this chapter, firstly an overview of some important all-optical buffering systems is given. In Section 2.2 our all-optical buffering concept is explained and in Section 2.3 the key technologies (including all-optical arbiters, all-optical wavelength converters, and all-optical memories) for realizing our optical buffers are discussed.

2.2 All-optical buffering strategies

2.2.1 Deflecting routing

In this buffering strategy, packet contention is resolved by routing one packet to the correct output port, while the others will be routed to any other available output ports [31]. The deflected packets follow alternative, maybe longer, paths to the destination. This method is suitable for nodes that have limited buffer capacity. However, when the traffic load becomes heavy, the end-to-end delay for packets may be unacceptably high, and the packets may arrive out of sequence at the destination.
2.2.2 Buffering by using optical fiber delay lines

The major constraint for optical buffering is currently the lack of optical random access memory. Alternatively one can use optical delay lines in combination with other optical components such as optical gate switches, optical wavelength converters, optical multiplexers/demultiplexers, and optical amplifiers to realize optical buffering. In general, there are two types of optical buffers implemented with fiber delay lines: traveling buffers and re-circulating buffers [32], as shown in Figure 2.1.

![Figure 2.1: Basic configuration of optical buffers based on optical fiber delay lines. (a) Traveling buffer, (b) Re-circulating buffer.](image-url)
Figure 2.1(a) shows a traveling-type buffer that generally consists of multiple optical fiber delay lines whose lengths are equivalent to multiples of the packet duration $T$, and optical switches to select a particular delay time. In a traveling type buffer, the storage time of a packet is simply determined by the duration of a packet propagating through a length of optical fiber.

Figure 2.1(b) schematically shows a re-circulating type buffer, which consists of variable optical delay units and a $1\times N$ optical switch. The variable optical delay unit contains a fiber optical delay loop, with one circulation time equal to one packet duration $T$. The delay time of the packet is determined by the number of circulations of the packet in the loop. An optical amplifier is used to compensate for the transmission loss during each circulation. The amplified spontaneous emission noise from the optical amplifier will accumulate and substantially degrade the signal, which eventually limits the maximum number of circulations [43].

Traveling buffers have a simple structure, and are easy to implement. However, in practical optical packet networks, the buffer needs to have a certain buffer-depth to avoid packet loss. For traveling buffers, a large number of fiber delay lines needs to be implemented, which makes traveling buffers bulky. For re-circulating-type buffers, the delay time is determined by the length of the loop and the circulation number. Hence, a single delay line can be used to realize a large delay by increasing the number of circulations. Therefore, the physical size of the buffer is reduced. The re-circulating-type buffers are flexible, but require more complicated control systems. For example, each variable delay unit needs one $2\times 2$ optical switch.

In fiber buffers, the buffer size can be reduced, since a large number of optical packets at different wavelengths can share one optical fiber. This is shown in the Wavelength Switched Packet Network (WASPNET [33, 34]). In [35] a traveling-type buffer is realized by cascading a large number of electronically controlled $2\times 2$ switch modules with a moderate amount of buffering. When the packet traffic becomes too heavy, it is necessary to increase the buffer depth to reduce packet loss. This was shown by using a Switch with Large Optical Buffers (SLOB [36]), which cascades many small electronically controlled switching elements, forming a larger switch with an increased buffer depth.

In [37, 38], a variable optical delay for re-circulating buffering is demonstrated in an optical fiber loop that is controlled by wavelength converters or wavelength shifters, respectively. It is shown that a variable optical delay can be achieved.
In [39, 40], the packet contention is solved by using a small number of buffers in combination with deflection routing. If the buffer overflows, the packets will be sent to an alternative output to reach its final destination node via another route (see deflection routing).

However, buffering by using optical delay lines has some limitations. Firstly, it is difficult to adjust delay time. Once the optical packet is sent into the optical delay line, the optical packet cannot be retrieved until it emerges on the other side of the delay line. In addition, the delay efficiency of the fiber delay line still needs to be improved. For example, to store a packet with length of 1.646 µs (the packet length used in the KEOPS project [11,12]), a 330-meter fiber delay line is required, which is too long to be integrated into a photonic integrated circuit. To solve these limitations, an alternative buffering concept is proposed by using semiconductor quantum dot devices, which are discussed in the next section.

### 2.2.3 Buffering by using semiconductor quantum dot devices

A semiconductor-based all-optical buffering concept [41, 42] is proposed by employing a semiconductor quantum dot waveguide as a delay medium, instead of optical fiber delay lines. The group velocity of a signal in the waveguide will slow down when a strong pump light is launched simultaneously into the waveguide due to the electromagnetically-induced transparency effect [44, 45]. Simulation results indicate that this approach can slow down the group velocity by a factor of 55, and the group velocity slow-down is adjustable by changing the pump power, which makes this approach flexible. Furthermore, this buffering concept can be integrated. Therefore, this semiconductor device is interesting for realizing optical buffers within a photonic chip. Experimental results using this approach have not yet been published.

### 2.2.4 Buffering by using optical memories

The most direct way to realize optical buffering is to store the packet bit by bit via optical memories, similarly to electronic packet buffers. Currently, large scale optical memories are not yet available. In this thesis, the nonlinearity produced by semiconductor optical amplifiers is utilized to construct optical flip-flop memories. The aim of the optical flip-flop research is to find a way to realize optical memories that can store a large number of signals.
2.3 The proposed all-optical buffering structure

It has been discussed in Chapter 1 that it is likely that eventually signal processing in all-optical packet switched cross-connects will be carried out by using photonic chips. In our research, we investigate all-optical packet switched cross-connects by using all-optical signal processing technology. Figure 2.2 presents a generic node structure of an all-optical packet switch [46]. A hybrid electro-optical packet-switching concept that used this node structure was investigated in the ACTS-KEOPS project [11,12] and the WASPNET project [34]. As shown in Figure 2.2, the WDM channels are initially demultiplexed. In the switching fabric three important steps take place, synchronization of the packets, buffering of the packets and switching of the packets. Afterwards, the packets are multiplexed and fed into the optical transmission line.

![Diagram](image)

**Figure 2.2:** Generic node structure for all-optical packet switched cross-connects.

In the ACTS-KEOPS project [11,12] routing of optical packets was demonstrated by using electronically controlled wavelength routing switches (1×N switches). All-optical packet switching can potentially lead to the routing of optical data packets at ultrahigh speeds. An example of a 1×2 all-optical packet switch in which the processing of the header information is carried out in optics is presented in [46, 47]. In order to fully exploit the advantages of all-optical packet switching, all-optical buffering has to be investigated. We concentrate on the buffering of packets in the time domain, which means that one packet has to be delayed in the case that two packets compete (within the same timeslot) for the same output. An additional reason to use time-domain buffering is that our optical packet switch is a 1×N structure, which can route and switch only one optical packet at one timeslot.
Currently there are two all-optical buffering research fields. The first one focuses on sophisticated networking design and protocols. The second deals with the physical realization of optical buffers. The focus in this thesis is on the physical realization of all-optical buffers by using all-optical signal processing. Our all-optical buffering concept consists of two functional blocks: an optical arbiter and an optical switch.

![Figure 2.3: The structure of an optical wavelength routing switch.](image)

The first functional block in our buffering concept is an optical switch. This switch can be a space switch, a wavelength routing switch or another type of all-optical switch. In the experiment, we have chosen a wavelength routing switch since it is an all-optical switching concept that allows photonic integration. The wavelength routing switch is comprised of an optical wavelength converter and an optical demultiplexer, as shown in Figure 2.3. The wavelength converter can transfer the signal from one wavelength to another wavelength in the optical domain [48-53] by injecting two optical beams simultaneously into the wavelength converter. One beam is continuous wave (CW) light at wavelength \( \lambda_i \), and the other beam is an amplitude-modulated optical data packet at wavelength \( \lambda_p \). After the wavelength conversion, the modulated information in the packet at wavelength \( \lambda_p \) is transferred to \( \lambda_i \). The optical demultiplexer is used to route packets to a specific port, depending on the wavelength of the packets. Therefore, the optical packet with wavelength \( \lambda_i \) is routed to port i, as shown in Figure 2.3. The routing of the optical packet is determined by the wavelength of the CW light. Thus by tuning the wavelength of the CW light, the optical packet can be switched into different output ports.

The second functional block in our buffering concept is an optical arbiter. The role of the optical arbiter is to judge the traffic contention and control the optical switch. The optical arbiter outputs CW light at a specific wavelength, which is determined by the traffic situation. The CW light from the optical arbiter is sent into
the wavelength routing switch, so that the optical arbiter controls the wavelength of the CW light at the input of the wavelength converter, and thus the routing of the optical packet.

![Diagram of optical wavelength routing switch](image)

**Figure 2.4:** The configuration of the optical wavelength routing switch.

The all-optical buffering concept for handling the contention of two-packets is presented schematically in Figure 2.4. The optical arbiter emits CW light at wavelength $\lambda_1$ or $\lambda_2$, outputting CW light at $\lambda_1$ if no external optical light is injected into the optical arbiter, and outputting CW light at $\lambda_2$ if an external light is sent into it. We assume that the packets arrive in a synchronized fashion and that Packet 1 has a higher priority than Packet 2. The optical power of Packet 1 is first split into two parts. The first part passes the node directly and is not delayed. The second part is injected into an optical arbiter to decide if packet contention occurs. When two packets are present, contention arises. If packet contention occurs, Packet 2 is delayed. The packet contention is resolved, since in this case, the optical arbiter emits CW light at wavelength $\lambda_2$ due to the presence of Packet 1. Thus Packet 2 will be routed to the port 2, having one period of time delay. Packet 1 can pass through the node directly. When Packet 1 is absent, the optical arbiter will emit CW light at wavelength $\lambda_1$. As a consequence, Packet 2 will be switched to Port 1, and pass through the node without delay.

This buffering concept for two-packet contention is described in detail in Chapter 3. This concept can be extended to handle the contention of three packets, as explained in Chapter 4. Later in Chapter 8, we show it is possible to realize a variable
optical delay for re-circulating buffers by using an optical arbiter in combination with a wavelength routing switch.

### 2.4 Key technologies in the all-optical buffering concept

To realize the all-optical buffers, three key technologies are investigated in this thesis. The three key technologies are all-optical arbiters, all-optical wavelength converters, and all-optical memories.

In this research, semiconductor optical amplifiers (SOAs) are used for all-optical signal processing [54, 55]. SOA-based technologies are promising because SOAs can provide high nonlinearity. In the SOAs, the refractive index changes induced by the pump-light are $10^8$ times larger than pump-light induced refractive index changes in an equivalent length of silica fiber [23]. In addition, in SOAs, the signals are amplified. Furthermore, the SOA-technology can be integrated into a photonic chip.

#### 2.4.1 Optical arbiters

The optical arbiter is essential in our buffering concept. The optical arbiter is an all-optical logic device that emits CW light at a specific wavelength. This wavelength is variable and determined by the signals at the arbiter input. In the experiment, two-coupled ring lasers are used to form an optical threshold function that acts as an optical arbiter [47]. This optical threshold device can be used to handle the contention of two packets. To extend this buffering concept to handle the contention of a larger number of packets, a laser neural network [66] is employed to replace the role of the optical threshold so that the laser neural network acts as an optical arbiter for handling contention of more than two packets. The feasibility of the buffering concept has been demonstrated by using commercial pigtailed components.

#### 2.4.2 All-optical wavelength converters

All-optical wavelength converters form an essential part of the wavelength routing switch that is employed in the all-optical buffering concept. All-optical wavelength conversion can be realized by utilizing fiber nonlinearities [53] or by utilizing nonlinearities in semiconductor devices [48-52]. We focus on technology that allows photonic integration since our ultimate aim is to realize buffering within a photonic chip.
chip. Therefore, semiconductor-based technology is investigated. We investigate an all-optical wavelength converter based on nonlinear polarization rotation in a semiconductor optical amplifier. We show inverted and non-inverted conversion can be realized in a single semiconductor optical amplifier. The reshaping function in the non-inverted conversion is also demonstrated. The details are reported in Chapter 6. The theoretical analysis is presented in Chapter 5.

This wavelength conversion concept can also be employed in an electro-absorption modulator. The electro-absorption modulator can also achieve cross-polarization modulation. The advantage of using an electro-absorption modulator is that the wavelength conversion in electro-absorption modulators can operate at higher speeds than in semiconductor optical amplifiers. Chapter 7 describes the details.

2.4.3 All-optical memories

All-optical memories have many potential applications in optical communication systems and optical computing [56]. As discussed in Section 2.2.4, one possible strategy to realize optical buffering is to employ bit-wise storage of the data-packet. Moreover, optical flip-flop memories have been shown to be essential for all-optical packet switches [46, 47].

In this research, we use optically induced nonlinearities in semiconductor optical amplifiers to realize all-optical memories. It has been shown that it is possible to form an optical memory by using two coupled lasers [57]. The state of the optical memory is determined by the wavelength of the memory’s output light. This concept can be extended by using other nonlinear optical elements, such as two coupled Mach-Zehnder interferometers [58] instead of lasers. We show in Chapter 9 that an optical memory can also be made by using two coupled nonlinear polarization switches.

Since the wavelength can be used to represent the state of an optical memory, the number of states is not restricted to two. In Chapters 10 and 11, we present a three-state optical memory based on three coupled ring lasers and three coupled nonlinear polarization switches, respectively.

2.5 Conclusion

We have introduced several all-optical buffering solutions for packet contention in optical packet switched cross-connects. All-optical buffering can be realized by using
optical fiber delay lines, semiconductor quantum dot devices or optical memories. The current all-optical buffering systems mainly utilize optical fiber delay lines as a buffer medium. Semiconductor quantum dot devices and optical memories are still confined to research laboratories.

We have also proposed an all-optical buffering concept that is comprised of one optical arbiter, optical delay lines and optical wavelength converters. The key element in the buffering concept is SOAs that are utilized for all-optical signal processing. We have discussed three key SOA-based technologies for realizing our optical buffers, including all-optical arbiters, all-optical wavelength converters, and all-optical memories.
Chapter 3

All-optical buffering by using optical threshold functions

3.1 Introduction

All-optical packet switched networks, in which routing and switching are performed in the optical domain, are seriously considered as a possible long-term route in the evolution of the present telecommunication networks [11-17]. A severe complication is a contention that takes place when two or more optical packets arrive simultaneously at the same packet switch. Optical buffering has to be used to handle this problem [18, 31-42]. Several techniques for optical buffering have been proposed and some promising results have been achieved [11, 12]. In these approaches, optical buffering was realized by using electronically controlled wavelength routing switches and optical delay lines. Since optical technologies demonstrate remarkable improvement in speed compared to electronic technologies [21-23], it appears to be an inevitable trend that buffering will be implemented in the optical domain.

In this chapter, we present an all-optical buffering concept by using all-optical signal processing techniques. Similarly, as in [11,12], optical buffering is realized by using a combination of optical delay lines and wavelength routing switches. We demonstrate experimentally how all-optical techniques can be employed for optical buffering purposes. In particular, we show that an optical packet can be routed in an optical fiber buffer by using a wavelength converter that is controlled by an arbiter.

This Chapter is based on the results published in [59]:

that is realized from an optical threshold function (OTF). The OTF has two functions: first, it decides the potential contention of two packets. In addition, it controls a wavelength routing switch to route one packet into buffer in case of packet contention. Our results suggest that it is not necessary to recognize and process optical packet headers for buffering purposes.

This chapter is organized as follows. In Section 3.2 all-optical buffering concept is explained. Experimental results are given in Section 3.3.

![Figure 3.1: System concept for all-optical buffering. FDL: fiber delay line.](image)

### 3.2 All-optical buffering concept for handling two-packet contention

An all-optical buffering concept is presented schematically in Figure 3.1. We assume that packets arrive in a synchronized way and that Packet 1 has a higher priority than Packet 2. The optical power of Packet 1 is firstly split into two parts: the first part passes the node directly and is not delayed. The other part is injected into an OTF [57] that acts as an optical arbiter to decide if a packet contention takes place. If packet contention takes place, Packet 2 is delayed. By resetting the wavelength and combining the signals, Packet 2 leaves the optical fiber buffer after Packet 1 (not displayed in Figure 3.1).

The OTF that we use is based on two coupled ring lasers. The device is depicted in Figure 3.2. The semiconductor optical amplifiers (SOAs) act as the gain mediums and the Fabry-Perot filters act as wavelength selective elements. The operation of the OTF is similar to an optical flip-flop memory that is described in detail in [57, 66]. For specific injection currents and amount of coupling between the lasers the system
can form a threshold function rather than a flip-flop memory. In [57, 66] it is shown that a system of two coupled lasers can have two possible states. In State 1, light from Laser 1 (lasing at wavelength $\lambda_1$) suppresses lasing in Laser 2. Therefore, $\lambda_1$ dominates the output of the OTF. Conversely, in State 2, light from Laser 2 (lasing at wavelength $\lambda_2$) suppresses lasing in Laser 1, $\lambda_2$ is dominant. The SOA currents are biased asymmetrically so that the system is in State 1 if no external light is injected. To change states, lasing in the dominant laser is stopped by injecting light, not at the dominant laser’s lasing wavelength, into the dominant laser [57, 66]. Hence, Laser 2 becomes the dominant laser (State 2). However, the asymmetrically biased SOA currents ensure that the system returns to State 1 if injection of external light is stopped.

The output light of the OTF is used to control a wavelength converter that converts the wavelength of Packet 2. A demultiplexer is used to route Packet 2 into a pass-port or a buffer-port, depending on the converted wavelength of Packet 2. The optical buffer that is described in Figure 3.1 could have three different non-trivial input cases that are described below:

**Case 1:** Packet 1 and Packet 2 are present and a collision could take place. Due to the presence of Packet 1, the OTF is forced into State 2 and emits continuous wave (CW) light at wavelength $\lambda_2$. Hence, the wavelength of Packet 2 is converted to $\lambda_2$ and Packet 2 is routed into the fiber buffer. Packet 1 can pass the node directly.

**Case 2:** Packet 1 is present while Packet 2 is absent (no contention). Packet 1 can pass the node directly. Part of the power of Packet 1 is fed into the OTF forcing the OTF into its State 2, emitting CW light at wavelength $\lambda_2$.

**Case 3:** Packet 1 is absent while Packet 2 is present (no contention). The OTF outputs CW light at wavelength $\lambda_1$ due to the absence of Packet 1. Thus Packet 2 is directed into the pass-port after wavelength conversion.

In [11, 12], it is shown that the wavelength of Packet 2 can be reset by using interferometric wavelength converters. Network architectures in which this optical buffering concept can be applied are given in [11, 12].

### 3.3 Experiment and results

The experimental setup for the demonstration of all-optical buffering by using an OTF that controls a wavelength routing switch is presented schematically in Figure 3.2.
external modulator is used to generate optical packets. The bit rate is 2.48832 Gbit/s, and the wavelength is 1560.61 nm. The bit patterns in the packets have a data format of $2^{15} - 1$ non-return-to-zero pseudorandom binary sequence. The packets are then amplified by an EDFA and subsequently filtered by a tunable band pass filter with 3 nm bandwidth. An optical splitter is used to direct half of the optical power of the packet into the OTF via an optical circulator, representing Packet 1 that is coupled into OTF (see Figure 3.1). The other half of the optical power is coupled into a 90/10 coupler.

Figure 3.2: Experimental setup. MOD: external optical modulator, EDFA: erbium-doped fiber amplifier, BPF: optical bandpass filter, SOA: semiconductor optical amplifier, ISO: optical isolator, FPF: Fabry-Perot filter, Demux: optical demultiplexer.

The 90/10 coupler splits the optical power of the packet into two parts: one part goes directly to the output, representing Packet 1 that passes the node directly (see Figure 3.1). Another part, representing Packet 2 (see Figure 3.1), is firstly delayed by 1.95 μs (390 meter of fiber) corresponding to the time that is needed to let the OTF change states, and is then fed into the wavelength converter. The wavelength of the packet is converted via cross-gain modulation (XGM) in an SOA. The demultiplexer
spatially directs the packet into a different port based on the wavelength of the packet. In the buffer-port, 9.95 km fiber is employed for buffering purposes. This corresponds to a delay of 49.75 µs for the packet.

In the first experiment we demonstrate the operation principle of the OTF. As shown in Figure 3.2, the OTF is implemented by using two coupled ring lasers. The injected currents to the SOAs in the OTF are 177 mA (the threshold current is 82 mA) for Laser 1 and 192 mA for Laser 2 (the threshold current is 117 mA) respectively. The wavelength of each laser is \( \lambda_1 = 1549.32 \text{ nm} \) and \( \lambda_2 = 1552.52 \text{ nm} \). The spectrum of the OTF is presented in Figure 3.3. It can be observed from Figure 3.3 that the contrast ratio between the two states in the OTF is over 45 dB. In Figure 3.4 the switching characteristics of the OTF are presented. The upper panel of Figure 3.4 shows the optical packet. The dynamic behavior of the OTF is presented in the middle and lower panel of Figure 3.4. It can be observed from Figure 3.4 that the state (the output wavelength) of the OTF changes if an optical packet is injected. As soon as injection of the packet is stopped the OTF switches back to its original state.

![Figure 3.3: Spectral output of two states of the OTF. The solid curve (-) represents State 1 (Laser 1 dominant), and the dotted curve (.) represents State 2 (Laser 2 dominant).](image)

In the second experiment we demonstrate that an OTF in combination with a wavelength routing switch can be used for buffering purposes. An optical packet, representing Packet 1 (see Figure 3.1), is injected into the OTF and changes the state of the OTF into State 2 (Laser 2 dominant). Thus, the dominant wavelength of the OTF is \( \lambda_2 \). Meanwhile, another packet, representing Packet 2 (see Figure 3.1) is coupled into the wavelength converter and its wavelength is converted to \( \lambda_2 \) via XGM. To simplify the configuration of the wavelength converter, the pump- and the probe light counter-propagate. The SOA for wavelength conversion is biased to 350 mA.
The result is shown in Figure 3.5, which indicates that the packet is converted into wavelength $\lambda_2$ for the time that the OTF is in State 2. The optical power of the packet is relatively small due to gain saturation in the wavelength conversion. The eye pattern of converted pulses in the packet after the wavelength conversion is also presented in Figure 3.5. The widely open eye without spikes indicates that error-free propagation through the wavelength converter is possible.

**Figure 3.4:** Dynamic output of the OTF with and without the presence of packet input. The upper panel is the traces of the external optical packet. The middle and lower panel are the dynamic output of OTF at each wavelength.

**Figure 3.5:** Oscilloscope trace after wavelength conversion showing that the whole packet is converted to wavelength $\lambda_2$ within the duration of wavelength $\lambda_2$. 
All-optical buffering by using optical threshold functions

3.4 Discussion

We have presented a new method for all-optical buffering. It has been demonstrated experimentally that an optical packet is all-optically routed into an optical fiber buffer in the case of contention between two optical packets. This method is advantageous since we need no complicated header recognition techniques to route an optical packet into a buffer.

Crucial in our method is the OTF that controls a wavelength routing switch. Experimental results indicate that a contrast ratio of more than 45 dB between the output states in the OTF can be obtained. Moreover, a clear open eye-diagram through the wavelength converter can be achieved.
In our experiment the wavelength conversion utilizes XGM in a single SOA, leading to a strong degradation of the extinction ratio. However, a better extinction ratio could be achieved by using an interferometric wavelength converter based on cross-phase modulation.

The duration of the packet is related to the particular implementation of the OTF used in the experiment. The lasers that are used to form the OTF were constructed from standard commercially available fiber pigtailed components having cavity lengths of many meters. Thus the component lasers had low intrinsic modulation bandwidth, which implies that several microseconds are required to change the states of the OTF. However, integrated versions of the OTF having cavity lengths of several millimeters could attain speeds in the GHz range.

Finally, this buffering concept can be extended to handle the contention of more than two packets. In the next Chapter, we show that a laser neural network can replace the role of the OTF, and act as an optical arbiter to solve the contention of three packets.
Chapter 4

All-optical buffering concept by using laser neural networks

4.1 Introduction

Optical buffering technology is receiving considerable attention as a result of the development of optical packet switches [19]. Examples are presented in [11, 12] where optical buffering was realized by using electronically controlled wavelength routing switches in combination with optical delay lines. In Chapter 3, an all-optical buffering concept is demonstrated in which buffering is realized by using an optical threshold function, in combination with a wavelength routing switch [59]. The functionality of the optical threshold function is twofold: it acts as an arbiter to decide whether packet contention takes place, and it also controls a wavelength routing switch that is made from a wavelength converter in combination with a demultiplexer. The optical threshold function that was used in [59] can only handle the contention of two packets.

In this chapter, we present an all-optical buffering concept that can handle multi-packet contention, by using an all-optical arbiter that is based on a Laser Neural Network (LNN) [61-66]. The LNN replaces the role of the optical threshold function in [59] and acts as a nonlinear wavelength controller. We demonstrate experimentally that it is possible to route optical packets into optical buffers by using a LNN that controls a wavelength routing switch.

This Chapter is based on the results published in [61]:

This chapter is organized as follows. In Section 4.2 our all-optical buffering concept is presented. The operation principle of the LNN is explained in Section 4.3. Experimental results are given in Section 4.4. The chapter is concluded with a discussion.

4.2 All-optical buffering concept

The optical buffering concept is presented schematically in Figure 4.1. Suppose that a maximum of three synchronized optical packets arrive simultaneously at the packet switch, and assume that the priority of the packet to pass the node decreases from Packet 1 to Packet 3. That is Packet 1 has the highest priority and Packet 3 has the lowest priority. It should be noted that synchronization of the packets is required for the buffer to operate properly. The routing of Packet 1 and Packet 2 is shown in [59]. An optical threshold function that is driven by Packet 1, controls a wavelength routing switch, so that (in the presence of Packet 1) Packet 2 is delayed for one packet period [59]. Similarly, the routing of Packet 3 is determined by the presence of Packet 1 and Packet 2. An optical arbiter that drives a wavelength routing switch is employed to decide whether packet contention takes place. The wavelength routing switch is operated by wavelength conversion in combination with a demultiplexer. We use a winner-take-all LNN as an optical arbiter, which is suitable for all-optical processing of telecommunication data [63-66]. Since wavelength conversion requires continuous wave (CW) light to be injected into the wavelength converter simultaneously with the data packet, the first function of the LNN is to generate CW light at a specific wavelength. Table I shows the truth table of the LNN that acts as an optical arbiter. The wavelength of the CW output of the LNN controls the wavelength routing switch, and thus the buffer output.
All-optical buffering concept by using laser neural networks

Figure 4.1: Functional scheme of the all-optical buffer concept and the truth table of the optical arbiter (Laser Neural Network) that is required to handle three-packet contention. FDL: fiber delay line. T: the delay time equal to one packet length.

### TABLE I

Truth Table of LNN for the Buffering Purpose

<table>
<thead>
<tr>
<th>Packet 1</th>
<th>Packet 2</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>$\lambda_1$</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>$\lambda_2$</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>$\lambda_2$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>$\lambda_3$</td>
</tr>
</tbody>
</table>

"1" --- presence of packet
"0" --- absence of packet
LNN: Laser Neural Network
Firstly, assume that only Packet 3 arrives at the buffer and that Packet 1 and Packet 2 are absent. Thus no packets are input to the LNN (see Figure 4.1). It follows from Table I, that the LNN should be trained in such a way that CW light at wavelength $\lambda_1$ outputs from the arbiter. Therefore, the wavelength of Packet 3 is converted to $\lambda_1$, and Packet 3 is routed into Port 1, passing the buffer without any delay (see Figure 4.1).

In the second case, only one data packet (either Packet 1 or Packet 2) is input to the LNN. Crucial in our buffering concept is that the LNN can be trained in such a way, that the output state only depends on the number of packets that are input to the LNN and not on the specific input ports [66]. According to Table I, the LNN has to output CW light at wavelength $\lambda_2$, if only one packet is injected. Hence, Packet 3 is routed into Port 2, undergoing one packet period of delay.

Finally, both Packet 1 and Packet 2 arrive simultaneously at the LNN. In this case the LNN has to output CW light at wavelength $\lambda_3$ (see Table I). Hence, Packet 3 is routed into Port 3, undergoing two packet periods of delay. Below we describe a LNN that has the functions described above, and we show that the concept can be used for buffering of telecommunication date packets.

4.3 Operation principle of laser neural networks

The concept of the neural networks was inspired by the operation of the human brain. The artificial model of a human nerve cell, called a neuron, is shown in [63]. A neuron has some input ports and one output port. The inputs are weighted, and then added together. The sum of the weighted inputs is compared to a threshold value. If the weighted sum is higher than the threshold, the neuron sends out a signal via the output port. It can be seen that a neuron is made up of two parts: a sum of weighted inputs and a nonlinear threshold decision. A number of the neurons can be connected to form a neural network. In such a neural network, thresholds for neurons can be achieved by the interaction between each neuron, and each neuron may have a different threshold value [63-66].

Various logic functions can be obtained with a neural network. Different weights in combination with different threshold values can lead to different logic functions [63-66]. The concept of a neural network can be used to form a winner-take-all optical neural network that is based on coupled lasers [66]. This is called a laser neural network (LNN). Each laser in the network lases at a specific wavelength,
representing one neuron. The network status is determined by the wavelength of the network’s light output. The LNN that acts as the optical arbiter is depicted in the two upper-dashed boxes of Figure 4.2. The LNN is made out of two parts. In the first part, the optical inputs are weighted. Weighting of the LNN inputs is carried out by a system of variable optical attenuators and couplers. The second part of the LNN is a nonlinear threshold decision part, which is realized optically by the interaction between lasers [66]. In each laser, semiconductor optical amplifiers (SOAs) act as the laser gain media. The wavelengths are selected by Fabry-Perot filters. Optical isolators are used to allow the light to travel in only one direction, thus ensuring lasing in one direction. External light is injected into the coupled laser cavities through this system of input weights. The choices of the input weights and thresholds determine the truth table of the LNN, i.e. different weights and thresholds lead to different logic operations. The weights can be determined by using the stochastic learning algorithm of [64-66], and thresholds can be determined by the property of the coupled lasers. Since our LNN is a winner-take-all system, in each state, only one laser is lasing while the other lasers are suppressed. Our LNN consists of three coupled ring lasers and has three states. In State 1, light from Laser 1 suppresses lasing in Laser 2 and Laser 3, thus Laser 1 is dominant. In State 2, Laser 2 is dominant and suppresses lasing in the other two lasers, and in State 3, only Laser 3 is lasing and suppresses Laser 1 and Laser 2. Laser 1 has the highest output power, and suppresses lasing in the other two. Thus if no external light is injected, the system is in State 1. Injection of external light changes the states of the arbiter.

The LNN can realize various logic functions. The truth Table I that is required for buffering (see Figure 4.1) can be realized by optimizing the system. Actually in this truth table, Laser 1 performs a NOR function for two binary inputs, Laser 2 performs an XOR and Laser 3 performs an AND logic function. In the next section, we will demonstrate this truth table can be achieved.
Figure 4.2: Experimental setup of a LNN that can be used as an all-optical arbiter. MOD: external modulator, BPF: bandpass filter, ATT: variable optical attenuator, FPF: Fabry-Perot filters, PC: polarization controller, ISO: isolator, CIR: circulator, Demux: demultiplexer.
4.4 Experiment and results

The experimental realization of a LNN with the properties that are described above is presented schematically in Figure 4.2. The LNN that acts as the optical arbiter is depicted in the two upper dashed boxes of Figure 4.2.

In the experimental setup, a laser and an external modulator (MOD) are used to generate optical packets. The laser has a coherence length of several meters and the wavelength is 1560.61 nm. The bit rate of the packets is 2.48832 Gbit/s, and the bit patterns in the packets have a non-return to zero data format and form a $2^{15}-1$ pseudorandom binary sequence. The packets are then amplified by an EDFA and subsequently filtered by a tunable bandpass filter (BPF) with 3 nm bandwidth. An optical splitter is used to split the optical power of the packet into two parts. The first part, representing Packet 3 in Figure 4.1, is fed directly into the wavelength converter. The second part is firstly split by a 3 dB coupler, representing Packet 1 and Packet 2 respectively (see Figure 4.1). Packet 1 and Packet 2 enter the LNN, and are then weighted. The light that is injected into the LNN through Input 1 and Input 2, is decorrelated by using two optical fibers of 10 meter each. However, in a realistic situation, the 10 meters of fiber are redundant because the contending packets are not coherent. The weights are determined by the coupler ratios and the amount of attenuation in the variable attenuators. The weighted inputs are coupled into the coupled laser cavities via circulators. The external optical power injected into Laser 1 via the circulator is higher than the optical power injected into Laser 2, so asymmetric couplers (80/20) are used in the experiment. Polarization controllers (PCs) are used to correct for polarization changes in the connecting fiber. SOA 4 is used to increase the output power of the arbiter. There are no attenuators in the coupled ring lasers to adjust relative thresholds and output powers. The relative output powers of the coupled ring lasers are controlled by the injection current of each SOA (SOA 1 to SOA 4). It is noted that controlling just the output power of each individual laser is sufficient to obtain the required functionality [66]. The output of the LNN is fed into SOA 5, which acts as a wavelength converter operated by cross-gain modulation. The demultiplexer spatially directs the packet into a specific port based on the wavelength of the packet.

In the first experiment we demonstrate the static operation of the arbiter. The wavelength of the three lasers are $\lambda_1=1549.32$ nm, $\lambda_2=1550.92$ nm, and $\lambda_3=1552.52$ nm. The spectral output of the LNN is presented for different inputs in Figure 4.3. It follows from Figure 4.3(a) that Laser 1 (1549.32 nm) is dominant if no external light is injected. In Figure 4.3(b) and Figure 4.3(c) the spectrum of the arbiter is shown if
8.2 dBm of external light is injected either at Input 1 or at Input 2. It can be seen that Laser 2 (1550.92 nm) is dominant if external light is injected at one of the two input ports. Finally, Figure 4.3(d) shows the spectrum if 8.2 dBm of external light is injected into Input 1 and Input 2 simultaneously. In this case only Laser 3 is lasing, at a wavelength of 1552.52 nm. It is shown in Figure 4.3 that the truth table of Table I, which is required for buffering purposes, is indeed realized. The contrast ratio among the different states in the LNN is over 30 dB. Moreover, an eye diagram after the wavelength conversion at output $\lambda_3$ is presented in Figure 4.3. The open eye indicates that the LNN output can be used to drive a wavelength routing switch so that error-free data transmission is possible.

**Figure 4.3:** The measured spectral output of the LNN for different input cases, as well as an eye-diagram of the converted output data when the input case is “11”. The input case is related to the truth table in Figure 4.1. For instance, the Input case “10” represents that Packet 1 is present while Packet 2 is absent.
In the second experiment the dynamic operation of the arbiter is demonstrated. Firstly an optical packet is injected into the arbiter via Input 1 while no packet is injected into Input 2 (this corresponds to the “10” case in Table I). If no external light is injected, Laser 1 is lasing while the others are suppressed. According to the results presented in Figure 4.3, if external light is injected into one of the inputs, Laser 2 (1550.92 nm) becomes dominant. It can be observed from Figure 4.4(a) that if an optical packet is injected in Input 1, Laser 1 switches off and Laser 2 switches on. Laser 3 remains switched off. A similar result can be obtained if light is only injected into Input 2. As soon as injection of the packet is stopped, the arbiter switches back to its original state, outputting CW light at wavelength $\lambda_1$. The packets we used have duration of 50 µs. In Figure 4.4(b), the dynamic operation is demonstrated if optical packets are simultaneously injected into Input 1 and Input 2 (this corresponds to the “11” case in Table I). According to Figure 4.3, in this case Laser 3 should switch on. This is clearly visible in Figure 4.4(b), where it can be observed that Laser 1 switches off and Laser 3 switches on, as long as there is a packet injected at Input 1 and Input 2.

![Figure 4.4: Dynamic output of the LNN with and without the presence of injected packets at the input for the “10” input case (a) and the “11” input case (b). The upper panel shows the external optical packet. The middle and lower panel are the dynamic output of LNN at each wavelength.](image-url)
It is noted that the variability of the CW output power of the ring lasers leads to a variability in the packet output power. However, interferometric wavelength converters at the output of the buffer (not shown in this paper) can be used to reset the wavelength of the packet and to reshape the packet simultaneously [11]. Network architectures in which this optical buffering concept is applied are given in [11].

4.5 Discussion

We have proposed an all-optical buffering concept that can be used to resolve packet contention in the case that three synchronized packets arrive at an optical packet buffer. The crucial component in this concept is an all-optical arbiter that decides whether packet contention takes place and that drives a wavelength routing switch. We have employed a LNN as an optical arbiter. Experimental results indicate that a LNN made from three coupled lasers is suitable as an optical arbiter. The LNN shows a contrast ratio of more than 30 dB between the output states. Moreover, the LNN output is suitable for driving a wavelength converter switch. We obtained a clear open eye after wavelength conversion.

The packet length is determined by the particular implementation of the LNN used in the experiment. The lasers used to form the LNN were constructed from standard commercially available fiber pigtailed components. Therefore the length of the laser cavities are several tens of meters. Thus the component lasers had low intrinsic modulation bandwidths, which limited the speed. However, integrated versions of the laser neural network could attain speeds in the order of a gigahertz, indicating that the guardband between the packets could be reduced to several nanoseconds. In principle the LNN can be extended further, so that it could be used in a system that is capable of handling the contention of more than 3 packets. The extended LNN requires more coupled lasers and more complex weighted inputs connection, which will slow down the operating speed of the LNN.
Chapter 5

Theory of nonlinear polarization rotation in semiconductor optical amplifiers

5.1 Introduction

The use of polarization switches based on nonlinear polarization rotation in Semiconductor Optical Amplifiers (SOAs) in optical signal processing applications is receiving considerable interest by many research groups. Applications of polarization switches to wavelength conversion are presented in [68-72]. Applications of polarization switches to optical time domain demultiplexing are presented in [73, 74]. Recently, the importance of polarization switches for all-optical logic has also been recognized [75-77]. Despite the large amount of experimental results that are published on polarization switches, the underlying concepts are not well understood [76]. In [78] theoretical results are published on polarization-dependent gain in SOAs in the context of optical switching and optical bi-stability, but their results are based on a microscopic model that is impractical as a design-tool for optical switching configurations. We present a simple rate-equation model that can be used to model the switching characteristics of a polarization switch.

Our model is based on the decomposition of the polarized optical field into a transverse electric (TE) and transverse magnetic (TM) component. These modes propagate “independently” through the SOA, although they have indirect interaction with each other via the gain saturation. We have accounted for different TE and TM gains by assuming that these polarizations couple to different hole reservoirs. This

This Chapter is based on the results published in [67]:

assumption is justified by the fact that the optical transitions occur between the j=1/2 type conduction band states and the j=3/2 type valence band states, where the latter correspond to the light-hole and heavy-hole valence bands. Two out of the three possible transition types are selected by the TE and TM polarizations, which define two corresponding inversions. In the isotropic bulk situation, these two transitions occur in a fully symmetric manner, but we are now interested in the case where tensile strain is built into the bulk medium, causing an asymmetry between the two transition types, such that TM will be favoured over TE transitions. This will be modelled by introducing a population imbalance factor $f$.

Our rate equation model is applied to describe the switching characteristics of a polarization switch that is based on these principles. We find excellent agreement between our model and experimental data. Our results also reveal that there is an interesting similarity between the switching properties of a polarization switch and those of a Mach-Zehnder switch, which indicates that the polarization switch acts as a Mach-Zehnder switch, where the roles of the different light paths are now played by the independently operating TE and TM modes of the optical field.

In Section 5.2 of this chapter, we present the rate equation model that is based on the assumptions given above. Experimental results show that this model can explain the polarization-dependent gain saturation of an SOA. In Section 5.3, we point out how our results can explain polarization switching in systems employing SOAs. We find excellent agreement between our model and experimental results. The chapter is concluded with a discussion.

5.2 Model

We decompose the incoming arbitrarily polarized electric field in a component parallel to the layers in the waveguide (TE mode) and a perpendicular component (TM mode). These two polarization directions are along the principal axes that diagonals the wave propagation in the SOA. In fact, apart from their indirect interaction through the carrier dynamics in the device, these two polarizations propagate independently from each other. It is our aim to develop a model capable of describing the polarization behaviour up to speeds of a few tens of gigahertz. In this case, we can use relatively simple propagation and rate equations, i.e. without necessity of taking into account the ultrafast (sub-picosecond time-scale) intra-band relaxation dynamics.
The propagation equation for the TE-polarized electric field component $A_{TE}^{TE}(z,t)$ is given by:

$$
\left( \frac{\partial}{\partial t} + V_{g}^{TE} \frac{\partial}{\partial z} \right) A_{TE}^{TE}(z,t) = \frac{1}{2} \Gamma_{TE}^{*} (1 + i \alpha_{TE}^{TE}) g_{TE}^{TE}(z,t) A_{TE}^{TE}(z,t) - \frac{1}{2} \alpha_{\text{int}}^{TE} A_{TE}^{TE}(z,t)
$$

(1)

Here, $A_{TE}^{TE}(z,t)$ is the weakly time- and space- dependent complex envelope of the optical field, $V_{g}^{TE}$ is the corresponding group velocity taken at the central frequency of the wave, $\Gamma_{TE}$ is the confinement factor, $g_{TE}^{TE}(z,t)$ is the (real) gain function, $\alpha_{TE}$ is the phase-modulation parameter and $\alpha_{\text{int}}^{TE}$ is the modal loss. A similar rate equation holds for the complex field envelope $A_{TM}^{TM}(z,t)$ corresponding to the TM mode:

$$
\left( \frac{\partial}{\partial t} + V_{g}^{TM} \frac{\partial}{\partial z} \right) A_{TM}^{TM}(z,t) = \frac{1}{2} \Gamma_{TM}^{*} (1 + i \alpha_{TM}^{TM}) g_{TM}^{TM}(z,t) A_{TM}^{TM}(z,t) - \frac{1}{2} \alpha_{\text{int}}^{TM} A_{TM}^{TM}(z,t)
$$

(2)

where $A_{TM}^{TM}(z,t)$ is the weakly time- and space- dependent complex envelope of the optical field, $V_{g}^{TM}$ is the corresponding group velocity, $\Gamma_{TM}$ is the confinement factor, $g_{TM}^{TM}(z,t)$ is the (real) gain function, $\alpha_{TM}$ is the phase-modulation parameter and $\alpha_{\text{int}}^{TM}$ is the modal loss. The envelopes for each polarization can be expressed as:

$$
A_{TE}^{TE}(z,t) = \sqrt{S_{TE}^{TE}(z,t)} e^{i \phi_{TE}^{TE}(z,t)} \quad A_{TM}^{TM}(z,t) = \sqrt{S_{TM}^{TM}(z,t)} e^{i \phi_{TM}^{TM}(z,t)}
$$

(3)

where $S_{TE}^{TE}(z,t)$ and $S_{TM}^{TM}(z,t)$ are the photon numbers and $\phi_{TE}^{TE}(z,t)$ and $\phi_{TM}^{TM}(z,t)$ are the phases for the TE and TM components.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confinement factor</td>
<td>$\Gamma_{TE}, \Gamma_{TM}$</td>
<td>0.2, 0.14</td>
<td></td>
</tr>
<tr>
<td>Phase modulation coefficients</td>
<td>$\alpha_{TE}, \alpha_{TM}$</td>
<td>5, 5</td>
<td></td>
</tr>
<tr>
<td>Modal loss</td>
<td>$\alpha_{int}^{TE}, \alpha_{int}^{TM}$</td>
<td>0.27, 0.27</td>
<td>ps⁻¹</td>
</tr>
<tr>
<td>Gain coefficient</td>
<td>$\xi_{TE}, \xi_{TM}$</td>
<td>7.0, 6.5</td>
<td>$10^9$ ps⁻¹</td>
</tr>
<tr>
<td>Hole population imbalance factor</td>
<td>$f$</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Electron-hole recombination time</td>
<td>$T_1$</td>
<td>500 ps</td>
<td></td>
</tr>
<tr>
<td>Hole-hole relaxation time</td>
<td>$T_2$</td>
<td>0.1 ps</td>
<td></td>
</tr>
<tr>
<td>Optical transition state number</td>
<td>$N_0$</td>
<td>$10^8$</td>
<td></td>
</tr>
<tr>
<td>Group velocity</td>
<td>$v_g$</td>
<td>100 μm/ps</td>
<td></td>
</tr>
<tr>
<td>Electrical current</td>
<td>$I$</td>
<td>160 mA</td>
<td></td>
</tr>
<tr>
<td>SOA length</td>
<td>$L$</td>
<td>800 μm</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5.1:** Waveguide structure and definition of coordinate frame.
The two optical modes have indirect interaction via the carriers. We assume that the TE and TM polarizations couple the electrons in the conduction band with two distinct reservoirs of holes. This assumption is justified by the fact that in zincblende structures such as GaAs and InP, optical transitions occur between \( j=1/2 \) type conduction band states and the \( j=3/2 \) type valence band states, where the latter are subdivided into light-hole and heavy-hole band states. In principle, three types of transitions can occur, but for the waveguide structure shown in Figure 5.1, with the optical field propagating in the z-direction, the transitions with z-polarization are not activated. The remaining two transitions with x and y polarizations correspond to TE and TM polarizations, respectively. Hence, two out of the three possible transition types are selected by the TE and TM polarizations and these transitions define two relevant hole reservoirs, with corresponding numbers \( n_x \) and \( n_y \), respectively. In the isotropic bulk situation, the two transitions will occur in a fully symmetric manner, but we are now interested in the case where tensile strain is built into the bulk medium, causing an asymmetry between the two transition types, such that TM will be favoured over TE transitions [83]. This compensates for extra TM waveguide losses and confinement factor differences so as to make the gain of the SOA polarization independent.

The number of electrons in the conduction band is denoted by \( n_c(z,t) \), while the number of holes involved in the x and y transitions is denoted by \( n_x(z,t) \) and \( n_y(z,t) \). A more in-depth analysis shows that \( n_y \) is just the number of holes in the light-hole band, while \( n_x \) is made up of a mixture of light (25%) and heavy (75%) holes. In fact, due to tensile strain the light-hole population can be enhanced over the heavy holes, leading to enhanced TM transitions. This latter effect will be accounted for by an imbalance factor \( f \) (see (8)-(10)). The (linearized) gain \( g^{TE}(z,t) \) for TE polarization is given by:

\[
g^{TE}(z,t) = \xi^{TE} [n_c(z,t) + n_x(z,t) - N_0] \tag{4}
\]

where \( \xi^{TE} \) is the gain coefficient for the TE mode and \( N_0 \) is the total number of electronic states involved in the optical transition. Similarly, the gain \( g^{TM}(z,t) \) can be expressed as:

\[
g^{TM}(z,t) = \xi^{TM} [n_c(z,t) + n_y(z,t) - N_0] \tag{5}
\]
where $\xi_{TM}$ is the gain coefficient for the TM mode. In cases of high-intensity optical beams, one should correct $\xi_{TE/TM}$ for saturation due to the carrier heating according to:

$$\xi_{TE/TM} = \frac{\xi_{TE/TM}}{\xi_0 + \xi_{S_{TE/TM}}}$$

where $\xi$ is typically $10^{-7}$ per photon present in the SOA [79]. In the experiments that follow, we use optical fields that have a much lower intensity so that in good approximation $\xi_{TE/TM} = \xi_{0_{TE/TM}}$. In writing down (4) and (5), we tacitly assumed that the semiconducting medium in the active layer gives rise to anisotropic gain, such as can be realized in a bulk layer with tensile strain [80]. If we assume that the total number of holes is equal to the number of electrons:

$$n_e(z,t) = n_x(z,t) + n_y(z,t)$$

(6)

and substitute this into (5) and (6), we can express $g^{TE}(z,t)$ and $g^{TM}(z,t)$ as:

$$g^{TE}(z,t) = \xi^{TE}[2n_x(z,t) + n_y(z,t) - N_0]$$

$$g^{TM}(z,t) = \xi^{TM}[2n_y(z,t) + n_x(z,t) - N_0]$$

(7)

The rate-equation for $n_x(z,t)$ can be written as:

$$\frac{\partial n_x(z,t)}{\partial t} = -\frac{n_x(z,t) - \bar{n}_x}{T_1} - \frac{n_x(z,t) - f n_y(z,t)}{T_2} - g^{TE}(z,t) S^{TE}(z,t)$$

(8)

and similarly for $n_y(z,t)$:

$$\frac{\partial n_y(z,t)}{\partial t} = -\frac{n_y(z,t) - \bar{n}_y}{T_1} - \frac{f n_y(z,t) - n_x(z,t)}{T_2} - g^{TM}(z,t) S^{TM}(z,t)$$

(9)

where $\bar{n}_x$ and $\bar{n}_y$ are the respective equilibrium values determined by the applied pump current as will be discussed below, $T_1$ is the electron-hole recombination time
and $T_2$ is the inter-hole relaxation time. The last terms in the right hand sides of (8) and (9) account for the stimulated recombinations. It should be noted that the inter-hole relaxation time $T_2$ (∼100 fs) is much shorter than the electron hole recombination time $T_1$ (∼500 ps). Since we do not consider here applications that involve ultrafast dynamics, the two populations $n_x$ and $n_y$ will be clamped tightly together i.e.

$$n_x(z,t) = fn_y(z,t)$$  \hspace{1cm} (10)

In case of unstrained bulk material, the gain will be isotropic and $f=1$. In case of tensile strain, TM gain will be larger than TE, i.e., $f<1$. For the equilibrium values, consistent with (10), we can write

$$\bar{n}_x = \frac{\bar{n}f}{1+f} \quad \bar{n}_y = \frac{\bar{n}}{1+f}$$  \hspace{1cm} (11)

where:

$$\bar{n} = \frac{I}{e} T_1$$  \hspace{1cm} (12)

and $I$ is the electric current and $e$ is the electric unit charge. In (8)-(11) $f$ expresses the magnitude of the anisotropy.

The equations (1)-(12) form a closed set of equations. First we will calculate the small-signal gain. To this end, we substitute the equilibrium values (11) in the gain expressions (7) and obtain the small signal gain $g_0^{TE/TM}$:

$$g_0^{TE} = \xi^{TE} \left[ \frac{1+2f}{1+f} \bar{n} - N_0 \right] \quad g_0^{TM} = \xi^{TM} \left[ \frac{2+f}{1+f} \bar{n} - N_0 \right]$$  \hspace{1cm} (13)

These expressions are quite general, but derived under the assumption of linear relationship between gain and carrier numbers. This implies that (13) can only be used in a small interval of the pump current. Within this given interval the parameter values occurring in (13) can be determined, but for different intervals, different parameter values will be obtained.

According to (1) and (2) the net amplifications by the SOA (in decibels), in absence of spatial inhomogeneity, are given by:
\[ 4.343 \times (\Gamma^{TE} g^{TE} - \alpha^{TE}_{int}) \frac{L}{v^{TE}_g} \]  
For TE \hspace{1cm} (14)

and

\[ 4.343 \times (\Gamma^{TM} g^{TM} - \alpha^{TM}_{int}) \frac{L}{v^{TM}_g} \]  
For TM \hspace{1cm} (15)

where \( L \) is the length of the SOA. The small-signal amplification can be obtained by replacing \( g^{TE} \) by \( g^{TE}_0 \) and \( g^{TM} \) by \( g^{TM}_0 \) in (14) and (15).

The experimental setup that is used to measure the polarization-dependent gain of the SOA is shown in Figure 5.2. A laser source emits a Continuous Wave (CW) probe beam at a wavelength 1552.60 nm. This probe beam is fed into the SOA via an attenuator and an isolator. The SOA was manufactured by JDS-Uniphase and employs a strained bulk active region with a length of 800 \( \mu \)m. An attenuator is used to assure the light that enters the SOA has a low intensity (-15.24 dBm) so that the SOA is operated in the linear regime (with this, we mean that no gain saturation is introduced by the probe beam). The SOA can be saturated by a high-intensity CW pump beam at a wavelength of 1550.92 nm that enters from the opposite direction. The SOA output is fed into a power meter via a circulator. A tuneable band pass filter with a bandwidth of 2 nm is used to filter out the spontaneous emission that is produced by the SOA. The polarization controllers are used to adjust polarization of the input signals (pump and probe) to the orientation of the SOA layers.

![Figure 5.2: Experimental setup that is used to measure the polarization-dependent SOA gain. SOA: Semiconductor Optical Amplifier, PC: Polarization controller, ATT: Attenuator, CIR: Circulator, BPF: Band Pass Filter.](image-url)
As a first experiment, the polarization-dependent gain is measured as a function of the injected current $I$ in the absence of a saturating control beam. This is done by adjusting the polarization of the small-signal probe beam in such a way that the minimum and maximum amplification is measured. The results are presented in Figure 5.3(a) where the curve with the maximum amplification is attributed to the TE mode and the curve with minimum amplification is attributed to the TM mode. If we compensate for the coupling losses, estimated to be 5.6 dB (this includes two times 2.5-dB facet losses and two times 0.3-dB connector losses), it follows from Figure 5.3(a) that for a current $I = 160$ mA, the gain of the TE mode equals to 18.1 dB and that of the TM mode 13.6 dB. Moreover, if we use the following parameter values: $\alpha_{\text{int}}^{\text{TE}} = \alpha_{\text{int}}^{\text{TM}} = 0.27 \text{ ps}^{-1}$, $f = 0.5$, $N_0 = 10^8$, $T_1 = 500 \text{ ps}$, $e = 1.6 \times 10^{-19} \text{ C}$, $v_g^{\text{TE}} = v_g^{\text{TM}} = 100 \mu \text{m} / \text{ps}$, $g^{\text{TE}} = 0.2$ and $g^{\text{TM}} = 0.14$ [81, 82], it follows from (14) and (15) that $\xi^{\text{TE}} = 7.0 \times 10^{-9} \text{ ps}^{-1}$ and $\xi^{\text{TM}} = 6.5 \times 10^{-9} \text{ ps}^{-1}$.

![Figure 5.3](image_url)

**Figure 5.3:** (a). Measured polarization dependent small signal gain for the TE mode and TM mode as a function of the injected current $I$. (b) Similar as in (a), but now with a saturating control signal. The intensity of the control signal is 0.32 dBm.

If a saturating control beam is also injected into the SOA, the gain can be computed by using (7), (8), (9), (14) and (15). The optical power $P_{\text{TM}}^{\text{TE/TM}}$ for each mode is related to the intensity $S_{\text{TE/TM}}^{\text{TE/TM}}$ according to:
where $h$ is Planck’s constant and $\omega$ is the optical frequency. In Figure 5.3(b), the saturated gain is plotted as a function of the injected current if a saturating pump signal with an intensity of 0.32 dBm is applied. The polarization of the pump beam was adjusted in such a way that maximum gain saturation for both the TE and TM modes was obtained. In Figure 5.4, the computed gain saturation is presented for the two modes as a function of the injected optical power at a bias current of 160 mA, while it is assumed that 50% of the injected power is used to saturate the TE mode and the other 50% of the injected power is used to saturate the TM mode. If we correct for 2.8-dB coupling losses of the pump beam, and if we use that $h\omega = 0.8$ eV, it follows from (16) that under these circumstances a pump beam with an intensity of 0.32 dBm leads to a saturated gain of 13.4 dB for the TE mode and 10.5 dB for the TM mode. This is in agreement with the experimental data that are presented in Figure 5.3(b).

![Figure 5.4: Computed SOA gain for the TE mode (solid line) and the TM mode (dashed line) as a function of the intensity of a saturating control signal. The SOA was pumped with 160 mA.](image-url)

We have also compared the experimental gain saturation and the computed gain saturation for other intensities of the saturating control beam, and we find that the experimental results are in good agreement with the theoretical results. It should be
remarked however, that from an experimental point of view, it is difficult to control the intensities of the light that is injected in each mode.

We have shown that our SOA model can accurately describe the polarization-dependent gain saturation. It should be noted however that the SOA parameters $N_0$, $T_1$, $I^{TE/TM}$, $\alpha_{init}^{TE/TM}$, $\nu_g^{TE/TM}$ cannot be estimated accurately. We solve this problem by compensating the combined uncertainties in these parameter values by assigning values to $f$ and $\zeta^{TE/TM}$ in such a way that the (measured) fiber-to-fiber gain is reproduced. In the most simple approach, one would choose $\zeta^{TE} = \zeta^{TM}$, as would be exact in the case of isotropic gain, so that $f$ can be estimated from the measured TE and TM gain curves by using (14) and (15). In this case the polarization-dependent gain would be totally explained by the band-filling effects that are represented by the factor $f$. However, this leads to gain saturation that is not in agreement with experimental data. We have, therefore, chosen to allow for a small difference in the values for $\zeta^{TE}$ and $\zeta^{TM}$ (as this could be due to a small difference in effective transition strength). This approach leads to a gain saturation that is in good agreement with experimental data. The value of $f$ in Table I is obtained from experimental data (Figure 5.3) when the SOA is pumped with 160 mA of current. It should be noted that the value of $f$ depends on the SOA pump current. The difficulties in estimating $f$ and $\zeta^{TE/TM}$ may be inherent to our modeling the SOA strain in terms of a population imbalance factor $f$. In a more accurate, but also much more complicated model, one can calculate the band structure and transition matrix elements in the presence of tensile strain and keep track of the different optical transitions involved as well as the relevant populations. This would, however, extend beyond the scope of the present approach.

![Figure 5.5: Schematic setup of a non-linear polarization switch. ATT: Attenuator, PC: Polarization controller, SOA: Semiconductor optical Amplifier, PBS: Polarizing Beam Splitter.](image-url)
5.3 Nonlinear polarization switching

The principle of polarization-dependent SOA gain discussed in the previous section will now be applied to a nonlinear polarization switch (PSW) schematically indicated in Figure 5.5. The PSW is made from two laser sources, a SOA, three polarization controllers and a polarization beam splitter (PBS) [73]. The first laser (Laser 1) emits a CW probe beam at wavelength $\lambda_1$ that is fed into the SOA. The SOA output is sent into the PBS. One polarization controller (PC\textsubscript{1}) is used to adjust the polarization direction of the input signal at approximately 45 degrees to the orientation of the SOA layers, while the second polarization controller (PC\textsubscript{2}) adjusts the polarization of the (amplified) output light to the orientation of the PBS. The SOA gain can be saturated by injection of a high-intensity pump (control) signal produced by the second laser (Laser 2). The wavelength $\lambda_2$ of the pump beam should be distinguishable from the wavelength of the probe beam if the two beams co-propagate. If the control light counter-propagates with the probe signal, the two wavelengths may be identical. The polarization of the light from Laser 2 is controlled by the third polarization controller (PC\textsubscript{3}).

![Figure 5.6: Output of the setup of Figure 5.5. The horizontal axis represents the switching intensity. The vertical axis represents the output intensity of the polarization switch. The solid curve: experimental result. The dashed curve: theoretical result.](image)

The solid curve in Figure 5.6 shows the experimental PBS output as a function of the intensity of the saturating control light. The system is tuned in such a way that the maximum output intensity of the polarization switch is equal to the intensity of the
control light that is required to suppress the output of the polarization switch. The SOA used in this experiment was pumped with 162 mA of current. Figure 5.6 clearly demonstrates that a control beam of sufficient intensity suppresses the output of the PSW. This effect is a consequence of the polarization-dependent gain saturation described in Section 5.2. The gain saturation generally leads to different refractive-index changes for TE and TM, which results in a saturation-induced phase difference between these modes. If this phase difference is an odd multiple of \( \pi \), the output from the PBS is suppressed, i.e. switched off.

In the experiment, the polarization direction of the input probe light is approximately at 45 degrees to the layers of the SOA, but not exactly. This is because our SOA had a polarization sensitivity of almost 4 dB at 1550nm, implying a difference in the saturation properties of TE and TM modes also. The input angle is carefully adjusted to compensate for this, thus achieving more than 20-dB switching contrast ratio.

The phase difference \( \theta \) between the TE and TM modes can be computed from (1) and (2):

\[
\theta = \phi^{TE} - \phi^{TM} = \frac{1}{2} \left( \frac{\alpha^{TE} \Gamma^{TE} g^{TE}}{v_g^{TE}} - \frac{\alpha^{TM} \Gamma^{TM} g^{TM}}{v_g^{TM}} \right) L \quad (17)
\]

where spatial inhomogeneity is neglected altogether. Such effects can be taken into account, but then the propagation equation should be numerically integrated. In the cases considered here, (17) turns out to be an adequate approximation. The intensity \( S_{out} \) of the light that outputs the PBS is given by:

\[
S_{out} = S^{TE} + S^{TM} + 2\sqrt{S^{TE} S^{TM}} \cos \theta \quad (18)
\]

where

\[
S^{TE} = S^{TE}_{in} e^\left( \Gamma^{TE} \frac{g^{TE}}{v_g^{TE}} \frac{L}{v_g^{TE}} \right)
\]

\[
S^{TM} = S^{TM}_{in} e^\left( \Gamma^{TM} \frac{g^{TM}}{v_g^{TM}} \frac{L}{v_g^{TM}} \right)
\]

where...
and $S_{\text{in}}^{\text{TE/TM}}$ in (19) represent the intensities of the TE and TM components of the probe beam at the SOA input. The gains $g^{\text{TE/TM}}$ can be computed from (7) and (9). Once the gain for each mode is known, the phase difference can be computed by using (17).

If we use the SOA parameters that are presented in Section 5.2, we can compute $S_{\text{out}}$ as a function of the intensity of a control beam by using (17)-(19). The result is shown by the dashed curve in Figure 5.6, if we use that $\alpha_{\text{TE}} = \alpha_{\text{TM}} = 5$. It is clearly visible in Figure 5.6 that our SOA model leads to results that are in excellent agreement with the experimental data. Note that curves in Figure 5.6 are similar to the ones presented in [58] in which the suppressed output of an active Mach-Zehnder interferometer is discussed. This reflects that the nonlinear polarization switch operates in a similar fashion as a Mach-Zehnder interferometer, since in the PSW, the role of the different light paths is played by the different polarizations.

### 5.4 Conclusion

We have presented a simple rate-equation model that is capable of describing the behavior of polarization switches based on nonlinear polarization rotation in strained bulk SOAs. This model is based on the assumption that TE and TM components of the light correspond to the two principle axes of the SOA while the carriers establish an indirect coupling between the components. The effect of tensile strain is accounted for by a population imbalance factor $f$ and a small difference in gain coefficients for TE and TM.

The polarization-dependent gain saturation of the SOA can be explained with our model. The TE and TM modes experience different refractive indexes, which leads to a phase difference between the two modes. The operation of a nonlinear PSW is based on this principle, in which the phase difference is used to suppress the output of the PSW. The nonlinear polarization switch turns out to behave similarly as a Mach-Zehnder interferometer, in which the roles of the different light paths are taken by the independently propagating TE and TM modes.
Chapter 6

Wavelength conversion using nonlinear polarization rotation in a single semiconductor optical amplifier

6.1 Introduction

All-optical wavelength converters based on nonlinearities in Semiconductor Optical Amplifiers (SOAs) are considered as important building blocks for wavelength division multiplexed networks [48-50]. Several SOA-based wavelength conversion techniques have been demonstrated. Wavelength conversion utilizing four-wave-mixing in an SOA is independent of the modulation format but it has low conversion efficiency and also the input light needs to be polarization matched [50]. Inverted wavelength conversion based on cross-gain modulation (XGM) in a single SOA has been demonstrated at 100 Gbit/s, but this approach also leads to a degradation of the extinction ratio [48, 84]. Interferometric wavelength converters based on cross-phase modulation in combination with XGM in SOAs lead to an improved extinction ratio and can also be used to realize inverted and non-inverted conversion. Furthermore, this concept can be utilized for signal reshaping [48-50].

In this chapter, we focus on wavelength conversion based on nonlinear polarization rotation in a single SOA. Although the principle of wavelength conversion based on nonlinear polarization rotation has already been demonstrated by others [68, 70], we present new results that clearly demonstrate the potential of this concept within a telecommunication systems context. We demonstrate that error-free

This Chapter is based on the results published in [71]:

inverted and non-inverted wavelength conversion at data-rates up to 10 Gbit/s can be realized in a single SOA. The stable operation is obtained by using a commercially available pigtailed SOA. We note that there is a remarkable similarity between the characteristics of a wavelength converter based on nonlinear polarization rotation in a single SOA and Mach-Zehnder Interferometric (MZI) wavelength converters. This similarity can be explained by the fact that wavelength converters based on nonlinear polarization rotation operate by interferometric principles, since the transverse electric (TE) and transverse magnetic (TM) modes that independently propagate through the SOA play the roles of the different light paths in the MZI. Hence, important properties of interferometric wavelength converters also apply to this concept. A clear advantage of this wavelength converter is that it allows inverted and non-inverted wavelength conversion as well as reshaping using a single SOA. A similar approach has already been used for demultiplexing from 40Gbit/s to 10Gbit/s [73].

![All-optical Wavelength Converter](image)

**Figure 6.1:** The configuration of the all-optical wavelength converter based on nonlinear polarization rotation. PC: polarization controller, SOA: semiconductor optical amplifier, PBS: polarization beam splitter, BPF: optical band pass filter.

### 6.2 System concept

The all-optical wavelength converter is depicted in Figure 6.1. As shown in the dashed box of Figure 6.1, the wavelength converter is made from an SOA, two polarization controllers (PCs), an optical isolator, an optical circulator, an optical band pass filter and a polarization beam splitter (PBS). PC1 and PC2 are conventional polarization
controllers, which are based on stress-induced birefringence in a fiber [91]. A laser emits a continuous wave (CW) probe beam at wavelength $\lambda_{\text{probe}}$ that is fed into an SOA. The SOA output is sent into a PBS. The system contains two polarization controllers. The first polarization controller is used to adjust polarization of the input signal to be approximately 45 degrees to the orientation of the SOA layers, while the second polarization controller is used to adjust the polarization of the amplified SOA output with the orientation of the PBS. The SOA can be saturated by injecting a high-intensity pump signal at a different wavelength ($\lambda_{\text{pump}}$). The injected pump light introduces additional birefringence in the SOA [76], which causes the TE and the TM modes of the probe beam to experience a different refractive index. At the PBS, the two modes coherently combine.

In the first case, the polarization controllers are set in such a way that the probe beam cannot pass through the PBS when only the probe beam is present. If a saturating pump beam is coupled into the SOA, the additional birefringence in the SOA leads to a phase difference between the TE and TM modes of the probe signal, causing the polarization of the probe light to be rotated [68, 70]. As a consequence, some probe light can pass through the PBS. Hence, an increase in the intensity of the pump light leads to an increase in the intensity of the probe light that outputs through the PBS. Thus non-inverted wavelength conversion is obtained.

Conversely, the polarization controllers can also be adjusted so that initially a maximum amount of probe light can pass through the PBS. If a saturating pump beam is applied, the phase change between the TE and TM modes leads to a lower intensity at the PBS output. Thus, an increase in the pump intensity leads to a decrease in the probe intensity at the PBS output. Thus inverted wavelength conversion is realized.

### 6.3 Experiment and results

The experimental setup is shown in Figure 6.1. The CW probe light is sent into the SOA via PC1 and an optical isolator. The SOA (manufactured by JDS Uniphase) has an active length of 800 $\mu$m and employs a strained bulk active region. The pump beam (1550.92 nm) is firstly modulated by a 10 Gbit/s external modulator, and then coupled into the SOA via a circulator. The bit patterns have a data format of a $2^{31}-1$ non-return-to-zero pseudorandom binary sequence. The PBS has an extinction ratio of 30 dB. A band pass filter (1 nm bandwidth) is used to suppress the spontaneous emission noise of the SOA.
The static operation of the wavelength converter is measured by an optical power meter, as presented in Figure 6.2. In Figure 6.2 the (measured) power of the probe light that outputs the PBS is plotted versus the power of the pump light, for both the inverted and the non-inverted case. The intensity of the probe light that enters the SOA is 2 dBm. The SOA is pumped with 237 mA of current. However, it is not essential to drive the SOA at this current. By adjusting the setting of the two polarization controllers (PC1 and PC2), similar curves can be obtained when the SOA is biased at a higher current (for example 392 mA or 399 mA as used in later experiments). It can be seen from Figure 6.2 that the extinction ratio of the converted signal can be over 20 dB. In the wavelength converter, high-intensity pump light is required to saturate the SOA. Therefore, XGM takes place simultaneously with nonlinear polarization rotation. XGM opposes the effect of non-inverted wavelength conversion, but enlarges the effect of inverted wavelength conversion. As a consequence, the slope of the curve for the inverted case is sharper than the one for the non-inverted case.

Figure 6.3 shows the measured penalty for conversion from 1520 nm to 1570 nm at a bit-rate of 4.97664 Gbit/s. The wavelength of modulated pump light is 1550.92 nm. The intensity of the input CW probe light is 1.58 dBm and the average power of the pump light is 0.53 dBm. The SOA is biased with 392 mA of current. It can be observed from Figure 6.3 that this wavelength conversion concept can operate over a large wavelength range (50 nm) with a small penalty. Figure 6.3 shows that the
penalty for non-inverted conversion reaches a maximum when the pump and probe light have the same wavelength. This is due to the reflected pump light at the SOA facet, which has the same wavelength as the probe light. For inverted wavelength conversion effects of nonlinear polarization rotation and XGM enlarge each other. XGM however has a larger penalty for up-conversion than for down-conversion, so the total penalty for inverted conversion increases if the probe wavelength is increased. Finally, we mention that this wavelength converter can also convert information to the same wavelength, which is important for applications in WDM switching blocks [85].

![Figure 6.3: The measured penalty after wavelength conversion versus the CW wavelength of probe light at a bit-rate of 5 Gbit/s.](image)

Figure 6.4(a) shows the Bit-Error-Rate (BER) curves of the converted signal for both inverted and non-inverted operation, together with back-to-back measurement at a bit-rate of 9.95328 Gbit/s. The input power of the CW probe light (1552.52nm) is 3.82 dBm and the average power of modulated pump light (1550.92 nm) is 3.80 dBm. The SOA is pumped with 399 mA of current. The BER measurements are optimized for an input power that corresponds to a BER of $10^{-9}$. It can be seen in Figure 6.4(a) that non-inverted conversion leads to a penalty of 3 dB at a BER of $10^{-9}$. Moreover, it is visible that no BER floor is observed up to BERs as low as of $10^{-12}$, which indicates excellent performance of the wavelength converter. The eye diagram is presented in Figure 6.4(b), having an extinction ratio of 12.3 dB and a Q-factor of 11.1. The eye
pattern for an inverted conversion is presented in Figure 6.4(c), having an extinction ratio of 4.7 dB and a Q-factor of 7.3. The eye-diagram for the inverted conversion has a fast fall time but slow rise time, which can be explained by the nonlinear slope in the transfer curve (see Figure 6.2) in combination with the slow carrier recovery time of the SOA. The oscilloscope traces of 10 Gbit/s input pump signal as well as converted signals (non-inverted and inverted) are shown in Figure 6.5. The eye-diagrams are measured on a HP 83480A Digital Communication Analyzer with a 30GHz O/E converter (83482A). The stability of the system has also been investigated. It appears that the system is stable for several hours.

![Figure 6.4: Bit-Error-Rate curves for wavelength conversion at 10 Gbit/s (a) and related eye-diagrams. (b) non-inverted and (c) inverted signal.](image)

The extinction ratio of the converted signal is degraded from 20 dB in the static measurement to 12 dB in the dynamic measurement. There are two reasons for the degradation. Firstly, the SOA carrier number can reach a steady state value in the static tests, leading to a small output value in the “0” level. However, in dynamic operation, the SOA carrier number does not reach this steady state value due to the finite carrier lifetime, hence, the small output value in the “0” level is not reached. Secondly, noise in the O/E converter (30GHz bandwidth) and the oscilloscope limits the smallest signal that can be seen, thus further degrading the extinction ratio. In the dynamic measurement, a higher current is applied to the SOA in order to reduce the
carrier lifetime of the SOA, so that a better extinction ratio of converted signal can be obtained.

Figure 6.5: The oscilloscope traces of the 10 Gbit/s input and converted signals. (a) input pump signal, (b) non-inverted and (c) inverted signal.

Finally, we have investigated the reshaping functionality of the wavelength converter. We have found that for non-inverted conversion at a data-rate of 4.97664 Gbit/s, a modulated pump signal with an extinction ratio of 6.6 dB leads to a converted signal with an extinction ratio of 12.1 dB.

As in other interferometric wavelength converters, the reshaping capability of the wavelength converter is based on the input to output transfer curve (Figure 6.2). The shape of the transfer curve in this system is determined by the drive current of the SOA and the setting of the two polarization controllers (PC1 and PC2).

6.4 Conclusion

We have investigated wavelength conversion based on nonlinear polarization rotation in an SOA. We have shown that inverted and non-inverted wavelength conversion can be obtained by using a single SOA. The selection for inverted or non-inverted operation is achieved by using polarization controllers. The static extinction ratio of the converted signal is more than 20 dB. It is demonstrated that this approach can
convert signals over a large wavelength range (50 nm) with a small conversion penalty. Error-free wavelength conversion at 10 Gbit/s is obtained. No error floors are observed. Moreover, the reshaping ability is investigated.

Our results indicate that the operation of the wavelength converter based on nonlinear polarization rotation in an SOA is comparable with the operation of MZI wavelength converters. In fact, the wavelength conversion based on nonlinear polarization rotation operates as a MZI since the independently propagating TE and TM modes in an SOA play the roles of the different paths in the MZI.
Chapter 7

Wavelength conversion using cross-polarization modulation in an electro-absorption modulator

7.1 Introduction

All-optical wavelength converters based on nonlinearities in electro-absorption modulators (EAMs) are attractive due to the fast recovery time of EAMs compared to semiconductor optical amplifiers (SOAs) [51-52, 86-89]. This indicates that EAM-based wavelength converters can operate at higher bit rates than SOA-based wavelength converters. Several EAM-based wavelength conversion techniques have been demonstrated. Cross-absorption modulation (XAM) in an EAM has been utilized to obtain non-inverted wavelength conversion, but this approach also leads to a degradation of the extinction ratio [86, 87]. Delayed-interferometric wavelength conversion using cross-phase modulation in an EAM has been demonstrated at bit-rate of 40 Gbit/s [88] and 80 Gbit/s [89]. This approach achieves an improved extinction ratio compared to XAM-based wavelength conversion, and the delayed-interferometric structure is suitable for return-to-zero bit streams.

In this chapter, we present a wavelength converter based on cross-polarization modulation in combination with XAM in an EAM utilizing the birefringence of the EAM. Cross-polarization modulation and XAM take place simultaneously, and operate at the same direction in non-inverted conversion. We will show that wavelength converters based on cross-polarization modulation in an EAM operate by interferometric principles, since the transverse electric (TE) and transverse magnetic

This Chapter is based on the results published in [90]:

(TM) modes that propagate independently through the EAM play the roles of the different light paths in a conventional interferometer. Therefore, important properties of interferometric wavelength converters also apply to this concept. We demonstrate that error-free non-inverted wavelength conversion at 10 Gbit/s non-return-to-zero (NRZ) can be realized in a single EAM. A better extinction ratio of converted signal is obtained compared to XAM-based conversion and a 3-dB penalty improvement is achieved. The stable operation is obtained by using a commercially available pigtailed EAM.

![Figure 7.1: The configuration of the all-optical wavelength converter based on cross-polarization modulation in an EAM. PC: polarization controller, EAM: electro-absorption modulator, PBS: polarization beam splitter, BPF: optical band pass filter.](image)

**7.2 System concept**

The all-optical wavelength converter is depicted in Figure 7.1. As shown in the dashed box of Figure 7.1, the wavelength converter is made from an EAM, two polarization controllers (PCs), an optical band pass filter (BPF) and a polarization beam splitter.
Wavelength conversion using cross-polarization modulation in an EAM

The PC1 and PC2 are ordinary polarization controllers that are based on stress-induced birefringence in the fiber [91]. A laser emits a continuous wave (CW) probe beam at wavelength $\lambda_{\text{probe}}$ that is fed into the EAM. The EAM output is sent into the PBS.

An injection of modulated pump light can lead to XAM [86, 87]. If a high-intensity pump light is injected into the EAM, the injected high-intensity pump light saturates absorption of the EAM, and substantially reduces the loss of the EAM. As a result, the probe light that passes through the EAM experiences a small loss. If the injection of high-intensity pump light is stopped, the photon-generated carriers are swept away by the external electric field that is applied to the EAM, thus the probe light will pass through the EAM with a large loss. It can be seen that a non-inverted wavelength conversion is realized by XAM. On the other hand, the injection of the pump light modulates the absorption of the EAM, and simultaneously modulates the refractive index of the EAM according to the Kramers-Kroning relations. Since the refractive indices of TE and TM modes are different, the injected pump light introduces additional birefringence in the EAM, causing the polarization of the probe light to be rotated. The PBS is used to discriminate the rotated probe light. Thus cross-polarization modulation is realized.

In the first case, the PC1 and PC2 are set in such a way that the probe beam cannot pass through the PBS when only the probe beam is present. The injection of a saturating pump light causes the polarization of the probe light to be rotated. As a consequence, some probe light can pass through the PBS. Hence, an increase in the intensity of the pump light leads to an increase in the intensity of the probe light that outputs through the PBS. This indicates that non-inverted wavelength conversion is obtained.

Conversely, the PC1 and PC2 can also be adjusted so that initially a maximum amount of probe light can pass through the PBS. If a saturating pump beam is applied, the phase change between the TE and TM modes leads to a lower intensity at the PBS output. Thus, an increase in the pump intensity leads to a decrease in the probe intensity at the PBS output. Thus inverted wavelength conversion is realized. The description of cross-polarization modulation in an EAM is similar to the one in [71] where wavelength conversion is realized by using cross-polarization modulation in an SOA. In this chapter, we demonstrate that cross-polarization modulation operates by interferometric principles.

As shown in Figure 7.1, “A” is the amplitude of the electric field of the input probe light. The PC1 adjusts polarization of the input probe light at a certain angle $\theta$
to the orientation of the EAM layers. Due to the birefringence in the EAM, the TE and TM probe light polarizations have different refractive indices: $n_{\text{TE}}$ and $n_{\text{TM}}$, and have different optical power absorption coefficients: $a_{\text{TE}}$ and $a_{\text{TM}}$, respectively. $\beta$ is the angle between the orientation of the PBS and the EAM layers, as shown in the upper panel of Figure 7.1. At the PBS, the two modes’ components that are parallel to the PBS orientation combine together. Since these components are coherent, they will interfere with each other. Therefore, the optical power of probe light that passes through the PBS is given by

$$P_{\text{out}} = A^2 a_{\text{TE}} \cos^2 \theta \cos^2 \beta + A^2 a_{\text{TM}} \sin^2 \theta \sin^2 \beta$$

$$+ \frac{1}{2} A^2 \sqrt{a_{\text{TE}} a_{\text{TM}}} \sin 2\theta \sin 2\beta \cos \left( \frac{2\pi}{\lambda_{\text{probe}}} (n_{\text{TE}} - n_{\text{TM}}) l + \phi_{\text{pc}} \right) \quad (7.1)$$

In formula (7.1), $l$ is the active length of the EAM. $\phi_{\text{pc}}$ is a phase induced by the PC1 and PC2. The third item in formula (7.1) clearly shows that the components of TE and TM modes that are parallel to the PBS orientation produce interference. The PC1 and PC2 in Figure 7.1 play important roles in the system. The PC1 is used to control the input angle $\theta$ to be approximately 45°, so that the maximum birefringent effect can be obtained. The function of the PC2 is twofold: firstly, it determines $\beta$ in formula (7.1) because the PC2 can change the polarization of the EAM output into any desired polarization [91]. In addition, it induces an extra phase $\phi_{\text{pc}}$. $\phi_{\text{pc}}$ can be changed by adjusting the PC2 (by changing the stress to the fiber in the PC2) [91]. At this point, the PC2 acts as a phase compensator.

In our wavelength conversion, the modulated pump light creates a modulated phase difference ($\Delta \phi$) between TE and TM modes of probe light, and $\phi_{\text{pc}}$ is used as a phase bias to control the offset of $\Delta \phi$. From an interferometer transfer curve (output power versus phase) that is based on formula (7.1), it can be obtained that changing $\phi_{\text{pc}}$ alters the offset of $\Delta \phi$, thus alters the extinction ratio of the converted probe light. Moreover, the offset of the $\Delta \phi$ can be set in an either rise or fall slope in the interferometer transfer curve, as a consequence, non-inverted or inverted conversion is achieved.
7.3 Experiment and results

The experimental setup is shown in Figure 7.1. The EAM we used is a commercial polarization dependent device, manufactured by OKI. The EAM allows maximum injected optical power of 13 dBm. The pump beam is firstly modulated by a 10 Gbit/s external modulator, and then coupled into the EAM via a 3-dB coupler. The bit patterns have a data format of a $2^{31}-1$ NRZ pseudorandom binary sequence. The PC3 that controls the polarization of pump light is optimized to achieve maximum absorption saturation of the EAM. A band pass filter (0.5 nm bandwidth) between the EAM and PC2 is used to filter out the pump light. The PBS has an extinction ratio of 30 dB.

![Graph showing static output power of CW probe light versus the EAM bias voltage.](image)

**Figure 7.2**: Static output power of CW probe light versus the EAM bias voltage. Input probe power is 5.1 dBm. The curves are measured at the output of the EAM and the output of the PBS, respectively.

The static output power of CW probe light versus biased voltage to the EAM is presented in Figure 7.2. The input power of probe light is 5.1 dBm and the wavelength of probe light is 1552.52 nm. The curve that is measured at the output of the EAM shows the absorption characteristic of the EAM at 1552.52 nm. It is shown that the output power reduces with the increasing biased voltage to the EAM. In the curve that is measured at the output of the PBS, it is shown that with the increasing biased voltage, the measured output power first increases and then decreases. This is because the varied voltage applied to the EAM leads to the changes of absorption of the EAM,
causing the changes in refractive index of the EAM. Therefore, the phase difference between TE and TM modes is also changed. This varied phase dominates the output of formula (7.1) when the absorption of the EAM is less than one certain level (biased voltage $-1.8 \text{ V}$ in Figure 7.2). However, when the reverse biased voltage to the EAM is further increased, the absorption of the EAM is so strong that the attenuated amplitude becomes to dominate the output of formula (7.1). Hence, the output power of the PBS decreases.

![Figure 7.3: Bit-Error-Rate curves for non-inverted wavelength conversion at 10 Gbit/s (a) and related eye-diagrams: (b) Back to back input signal, (c) converted signal based on cross-polarization modulation, and (d) converted signal based on XAM.](image)

Figure 7.3 shows the dynamic operation of the proposed wavelength converter at a bit-rate of 9.95328 Gbit/s. The power of the CW probe light that is injected into the EAM equals to 5.1 dBm. The average power of the modulated pump light that is injected into the EAM is 8.8 dBm. The EAM is biased at $-1.6 \text{ V}$. Figure 7.3(a) shows
the Bit-Error-Rate (BER) curves of the non-inverted signal based on cross-polarization modulation and non-inverted signal based on XAM, together with back-to-back measurement. The converted signal is optimized to achieve good BER performance. It can be seen from Figure 7.3(a) that wavelength conversion based on cross-polarization modulation leads to a 3-dB penalty at a BER of $10^{-9}$, and XAM-based wavelength conversion leads to a 6-dB penalty. This indicates that a 3-dB penalty improvement by using cross-polarization modulation. Moreover, it can be seen that no BER floor is observed up to BERs as low as of $10^{-12}$, which indicates excellent performance of the wavelength converter. The eye diagrams are presented in Figure 7.3(b), 7.3(c) and 7.3(d). It can be seen that the eye pattern by using cross-polarization modulation (Figure 7.3(c)) has an improved extinction ratio compared to the eye pattern in XAM-based conversion (Figure 7.3(d)).

It is measured that the eye patterns in Figure 7.3(c) (using cross-polarization modulation) and Figure 7.3(d) (using XAM) have a same rise time of 38 ps and a same fall time of 39 ps. This shows that the wavelength conversion based on cross-polarization modulation can reach the same operating speed as the wavelength conversion based on XAM. Compared to the back-to-back eye pattern (see Figure 7.3(b)) that has a 32 ps rise time and 33 ps fall time, the rise and fall time in Figure 7.3(c) only adds an extra 6 ps. This clearly proves the high-speed property of the proposed scheme.

![Figure 7.4](image_url)

**Figure 7.4:** The oscilloscope traces of the 10 Gbit/s converted signals: (a) non-inverted and (b) inverted signal.
Furthermore, we observed that by adjusting the PC2 the extinction ratio of the converted signal can be changed, and even inverted conversion could be obtained. This is in agreement with the analysis in Section 7.2. Figure 7.4 shows the oscilloscope traces of the 10 Gbit/s non-inverted and inverted signals. It is noted that the output power of the non-inverted signal is larger than the output power of the inverted signal. This is because XAM takes place simultaneously with cross-polarization modulation in the wavelength conversion. XAM and cross-polarization modulation operate in the same direction in non-inverted conversion, but in the opposite directions in inverted conversion. Moreover, the obtained inverted conversion indicates that cross-polarization modulation is stronger than XAM, because XAM always leads to a non-inverted conversion.

The EAM we used allows only 13 dBm peak optical power to be injected into it. In the experiment, the average power of the modulated pump light is 8.8 dBm, which is much smaller than the pump power used in [88] (14.8 dBm) or in [89] (18.7 dBm). This relative small pump light (8.8 dBm) creates $0.12\pi$ phase difference between the TE and TM modes of the probe light. The created small phase difference is not strong enough to achieve penalty free conversion. A 3-dB conversion penalty is observed in the proposed wavelength conversion when the system is optimized to obtain good BER measurement. It can be seen from Figure 7.3(c) that the extinction ratio of the converted signal is not perfect because the system operates at the linear region of the interferometer transfer curve (output power is proportional to phase) in order to get more output power. The system can also be adjusted to obtain a good extinction ratio. We observe a BER-floor at $10^{-11}$ in this case because the system operates in a nonlinear regime (the output power is proportional to the square of the phase), so that the small phase difference ($0.12\pi$) leads to a much weaker output power compared to the system operating in the linear regime. Therefore, the optical signal noise ratio (OSNR) of the converted light (after the EDFA shown in Figure 7.1) is not sufficient to obtain error-free conversion. However, the pump light with higher power can create a larger phase difference, hence the converted signal can have higher optical power with a better OSNR when the system operates in the nonlinear regime in order to attain a good extinction ratio. Thus, a better performance of the proposed wavelength converter could be obtained. It is estimated that more than 20 dBm optical power needs to be injected into the EAM, and the reliability of the EAM at such a high optical power injection should be considered.

In [71], a similar conversion penalty (3 dB) at 10 Gbit/s NRZ signal is obtained in a wavelength converter based on cross-polarization modulation in an SOA, instead of an EAM. Although the conversion penalty is similar, the reason is different. In the
SOA-based wavelength conversion [71], the extinction ratio of the converted signal is quite good. The 3-dB conversion penalty is due to the slow recovery time of the SOA (several hundreds of ps). A strongly distorted eye-diagram of the converted signal is observed. It should be noted that in [71] more than $0.4\pi$ phase difference between the TE and TM modes of probe light is obtained when 3 dBm optical pump light is injected into the SOA, indicating that the operating optical power for cross-polarization modulation in an SOA is much smaller than for the EAM. However, the advantage of using EAMs is that the recovery time of the EAM can reach several ps [92], which is much faster than for an SOA, indicating that up to 40 Gbit/s wavelength conversion can be achieved.

7.4 Conclusion

We have demonstrated wavelength conversion based on cross-polarization modulation in an EAM. We have shown that the wavelength converter based on cross-polarization modulation can achieve a better performance than XAM-based wavelength conversion. Cross-polarization modulation and XAM take place simultaneously, and operate in the same direction in non-inverted conversion. Error-free wavelength conversion at 10 Gbit/s is obtained and no error floors are observed.

We have also shown that wavelength converters based on cross-polarization modulation in an EAM operate by interferometric principles. The independently propagating TE and TM modes in the EAM play the roles of the different paths in a conventional interferometer. Therefore, important properties of interferometric wavelength converters, such as controllable extinction ratio and the selection of converted polarity also apply to this concept.
Chapter 8

Demonstration of a variable optical delay for a recirculating buffer by using optical signal processing

8.1 Introduction

Optical buffering technologies are crucial to avoid optical packet contention in all-optical switched networks [18]. In these buffering configurations the data packets are stored in fiber delay lines. In general two types of buffers are used: travelling buffers and re-circulating buffers [32]. In travelling buffers, the delay time is determined by the length of the optical delay line. Such configurations are investigated in [11, 12] where optical travelling buffering is realized by using electronically controlled wavelength routing switches, and in [59] where an all-optical travelling buffer concept is realized by using all-optical signal processing. In the concept presented in [59] an optical threshold function is used as an optical arbiter to decide whether packet contention takes place. The optical threshold function drives a wavelength routing switch that sends the packet into a desired buffer when packet contention occurs. This is described in Chapter 3. The concept presented in [59] is extended in [61] in which a laser neural network is used to replace the optical threshold function. The configuration in [61] has been successful to handle contention of three packets, which is explained in detail in Chapter 4.

Travelling buffers have a disadvantage since a large number of delay-lines are required to avoid packet loss under heavy traffic load. This makes travelling buffers

This Chapter is based on the results published in [93]:

bulky. In re-circulating buffers however, the delay time is determined by the length of
the loop and the circulation number. Hence, a single delay line can be used to realize a
large delay by increasing the number of circulations. An important advantage of re-
circulating buffers over travelling buffers is that the physical size of the buffer is
reduced. In [37], a variable optical delay is demonstrated by using optical delay lines
and wavelength converters. After each circulation, the optical signal is converted to a
new wavelength. A disadvantage of the approach presented in [37] is that for each
circulation a wavelength converter is required. To realize a large number of
circulations, the same number of wavelength converters is required. This makes the
system complicated and expensive. In [38], a variable optical delay is realized by
using an optical delay line and one wavelength shifter. After each circulation, the
wavelength of the optical signal is shifted a uniform step. The number of circulations
is determined by the initial wavelength of the optical input signal, the final output
wavelength and the wavelength shift in each circulation. The wavelength shifter is
made out of two wavelength converters based on four-wave mixing in highly
nonlinear fiber. This scheme requires a high power pump light (28.9 dBm) that is
phase modulated [38].

In this chapter, we demonstrate a variable optical delay by employing a re-
circulating loop that is controlled by using all-optical signal processing technology.
This variable optical delay concept can be utilized in the architecture of a re-
circulating buffer as shown in Figure 2.1 (see Chapter 2, and [32]). We show that an
optical threshold function (as presented in Chapter 3) in combination with a single
optical wavelength converter based on nonlinear polarization rotation in a
semiconductor optical amplifier (SOA) can be used to realize a variable optical delay.
The variable delay time is achieved by altering the number of circulations of the
packet in the loop. In our approach, the circulation number is determined by the
traffic situation. Thus the delay time of the packet depends on the traffic, which makes
the system flexible, and suitable for re-circulating buffers. We demonstrate that an
optical packet is re-circulated in an optical loop four times when packet contention
occurs. When the contention disappears, the packet is routed out of the optical loop.

This chapter is organized as follows. In Section 8.2 our variable optical delay
concept is presented. Experimental results are given in Section 8.3. The chapter is
concluded with a discussion.
8.2 Operation principle

The variable optical delay concept is presented schematically in Figure 8.1. We assume that the packets arrive in a synchronized fashion and also that the packets in channel 2 (CH2) have the lowest priority to pass the node. The packets in channel 1 (CH1) have the highest priority to pass the node. Thus if packet contention takes place, the packets in CH2 have to be sent into the loop. The packets in CH2 can only pass through the node if there is no packet in CH1 that causes packet contention in a specific timeslot. The packets in CH1 are injected into an OTF that acts as an optical arbiter to decide if packet contention occurs.

![Figure 8.1](image)

Figure 8.1: Functional scheme of the variable optical delay concept. T: the delay time equal to one timeslot, Demux: demultiplexer.

The first essential building block of this concept is an optical threshold function (OTF). The OTF is made out of two coupled lasers and is described in detail in [57, 59]. The OTF is depicted in Figure 8.2. It is shown in [57, 59] that the OTF can have two possible states. In State 1, light from Laser 1 (lasing at wavelength $\lambda_1$) suppresses lasing in Laser 2 (lasing at wavelength $\lambda_2$). This means that the OTF outputs continuous wave (CW) light at wavelength $\lambda_1$. Conversely, in State 2, light from Laser 2 suppresses lasing in Laser 1, thus the OTF outputs CW light at wavelength $\lambda_2$. The system is asymmetrical so that the OTF is in State 1 if no external light is injected. If external light is injected into Laser 1, lasing in Laser 1 is stopped and the OTF
Chapter 8

switches to State 2. The OTF remains in State 2 as long as external light is injected in Laser 1. If the injection of external light is stopped, the OTF switches back to State 1 [57, 59].

The second essential building block is a wavelength converter. The wavelength converter that we used is based on nonlinear polarization rotation in a single SOA, which is described in detail in Chapter 6 as well as in [71]. The configuration is shown in Figure 8.2. It has been demonstrated in Chapter 6 that this wavelength converter can realize non-inverted conversion with reshaping ability, and also can convert the signal into the same wavelength.

The system shown in Figure 8.1 can function as a variable optical delay in a recirculating loop as follows. Firstly, we assume that the synchronized data packets arrive at the packet buffer in distinct timeslots. The delay time introduced by the fiber delay line is exactly one timeslot. The CW light outputting from the OTF controls a wavelength converter that in turn converts the wavelength of packets that arrive in CH2. The optical demultiplexer is used to route packets into a specific port, depending on the wavelength of the packets. Suppose that in timeslot I, packets in CH1 and CH2 are present, so that packet contention takes place. The packet in CH1 is injected into the OTF, thus the OTF switches its state to output CW light at wavelength $\lambda_2$. Hence, the wavelength of Packet I is converted into $\lambda_2$ so that Packet I is routed into an optical loop which delays the packet for the duration of one timeslot. In timeslot II, the OTF also outputs CW light at wavelength $\lambda_2$ due to the presence of a packet in CH1. Thus, Packet I, which was already converted to wavelength $\lambda_2$ and delayed by one timeslot, is reconverted to wavelength $\lambda_2$ and delayed for another timeslot in the delay loop. A similar situation takes place in timeslot III and IV, but in timeslot V, the OTF outputs $\lambda_1$ due to the absence of a packet in CH1. Hence, Packet I is reconverted from wavelength $\lambda_2$ into $\lambda_1$ and is routed out of the loop.

It can be observed that the delay time of the packets in CH2 is determined by the traffic situation. This variable optical delay concept can be applied in [32], where a number of variable optical delay units are employed to construct a re-circulating buffer. The configuration of the re-circulating buffer is also presented in Figure 2.1 (see Chapter 2).
8.3 Experiment and results

The experimental setup is shown in Figure 8.2. The bit rate of the data stream is 2.73 Gbit/s, and the wavelength is 1560.61 nm. The bit patterns in the data stream have a non-return to zero (NRZ) data format and form a $2^{15}-1$ pseudorandom binary sequence (PRBS). The external modulators (MODs) are used to generate optical packets. The packets that are generated by MOD1, represent the packets in CH1 (shown in Figure 8.1), and are injected into the OTF via a circulator. The packets that are generated by MOD2, represent the packets in CH2 (shown in Figure 8.1), and are directed to an optical wavelength converter via a 3 dB coupler and a circulator. The packets have a duration of 57.5 $\mu$s, and the guard time between each packet is 20 $\mu$s.

![Figure 8.2: Experimental setup. MOD: external modulator, BPF: bandpass filter, FPF: Fabry-Perot filter, PC: polarization controller, ISO: isolator, CIR: circulator, PBS: polarization beam splitter, Demux: demultiplexer.](image-url)
The output of the OTF is fed into the optical wavelength converter. The injection current of SOA 3 in the wavelength converter is 300 mA. The optical power of the probe light that outputs from the OTF is 1 dBm and the average optical power of a packet that is injected into SOA 3 is 1 dBm. The length of the optical loop is about 15.5 km, which is equivalent to a delay of 77.5 µs for the packets. An EDFA in the loop provides 19 dB gain for the packet.

The OTF is depicted in the upper dashed box of Figure 8.2. The OTF consists of two coupled ring lasers, in which SOAs act as laser gain media. The wavelengths are selected by Fabry-Perot filters. Optical isolators are used to ensure lasing in one direction. The lasers in the OTF are constructed from standard commercially available fiber pigtailed components, which makes that the total length of each laser cavity is over ten meters. The wavelength of each laser is \( \lambda_1 = 1550.92 \text{ nm} \) and \( \lambda_2 = 1554.05 \text{ nm} \). The SOA injection currents are set in such a way that the system is asymmetric. The SOA injection currents were 354 mA for SOA 1 (the threshold current of Laser 1 is 71 mA) and 247 mA for SOA 2 (the threshold current of Laser 2 is 85 mA), respectively.

The spectral output of the OTF is presented in Figure 8.3. It follows from Figure 8.3(a) that Laser 1 (1550.92 nm) is dominant if no external light is injected. In Figure 8.3(b) the spectrum of the OTF is shown if 10 dBm of external light (1560.61 nm) is injected into Laser 1, it follows that Laser 2 (1554.05 nm) is dominant. However, the OTF returns to State 1 if the external injection is stopped. It can be observed from Figure 8.3 that the contrast ratio between the two states in the OTF is over 50 dB.

![Figure 8.3: The measured spectral output of the OTF without (a) and with (b) the presence of external light.](image-url)
We demonstrate a variable optical delay that has the same traffic situation as discussed in Section 8.2. Optical packets are created in repeated five distinct timeslots. In timeslots I to IV, the optical packets that are created in CH1 are injected into the OTF. As explained before, these packets cause the OTF to switch its state to State 2. Thus in timeslots I to IV, the OTF outputs CW light at wavelength $\lambda_2$. As a result, Packet I is converted in these timeslots into wavelength $\lambda_2$ and routed into the optical loop where it remains for four circulations. It is shown in Figure 8.4(a) (via the loop monitoring output), that Packet I circulates in the loop for four timeslots (from timeslot I to IV). In timeslot V, no packet is present in CH1 and thus the OTF switches back to output CW light at wavelength $\lambda_1$. Hence, Packet I is converted into $\lambda_1$ (inverted conversion) and passes through the node, as shown in Figure 8.4(b). The inset picture shows the eye pattern of the packet after the packet has been switched out of the loop. A widely open eye is obtained.

**Figure 8.4:** (a) Oscilloscope trace showing that the packet circulates in the loop four times. (b) Oscilloscope trace showing that the packet is converted to $\lambda_1$ and routed out of the loop after re-circulating in the loop four times. The inset picture is an eye-diagram of the converted output data in Figure 8.4(b).
Figure 8.4(a) shows a different wavelength conversion polarity compared to Figure 8.4(b). This is because the conversion polarity of our wavelength conversion is related to the polarization of the CW light that outputs from the OTF. In the OTF, the polarization of the lasing light in each state is different due to the long laser cavities. The wavelength converter is optimized to realize non-inverted conversion at wavelength $\lambda_2$ (see Figure 8.4(a)) to fully benefit from the reshaping ability [37]. This is important to prevent the packet from signal degradation due to accumulated ASE noise generated by the EDFA in the loop [37, 38]. When the OTF outputs light at wavelength $\lambda_1$, the polarization of the OTF output light is changed so that inverted conversion takes place (see Figure 8.4(b)). The long cavities also make that it takes several $\mu$s for the OTF to change state so that the guard time between the packets is 20 $\mu$s. The slow switching time causes the large spikes in the guard time as shown in Figure 8.4(a). Photonic integration of the OTF could prevent both unwanted effects, since an integrated OTF can output purely TE polarized light in both states. As a result, wavelength conversion in Figure 8.4(a) and Figure 8.4(b) can both be non-inverted. If no packet is sent into the wavelength converter, non-inverted wavelength conversion ensures that no optical power will appear at the output of the loop. Also, the integrated OTFs could attain speeds of about a few gigahertz, so that the large spikes in Figure 8.4(a) will be eliminated and the packet length could be reduced to within a hundred nanoseconds.

In the experiment, only four circulations have been demonstrated because the pulse pattern generator we used can only generate five pre-programmed data packets (since the packet is very long). The maximum circulation number is determined by the quality of the OTF, the reshaping ability of the wavelength converter, the noise figure of the EDFA, the packet length and the polarization state of the light in the loop. We have observed that a packet with a length of 9 $\mu$s has been successfully circulated in the loop fifteen times by using electronically controlled DFB lasers instead of the OTF. We believe that at least several tens of circulations can be achieved by using integrated versions of the OTF and reducing the packet length to hundreds of nanoseconds. The wavelength converter in our concept can be replaced by an integrated MZI wavelength converter, which has shown remarkable reshaping ability [37]. Thus the maximum circulation time can be further increased.

A particular bit-rate (2.73 Gbit/s) is used because the sum of the packet length and the guard time between each packet needs to be equal to one timeslot. In principle, the bit-rate is only limited by the wavelength converter, and could reach more than 10 Gbit/s [71].
8.4 Discussion

We have proposed a variable optical delay in a re-circulating loop by using entirely all-optical signal processing technology. This concept can be utilized in all-optical re-circulating buffers. We have shown that an optical threshold function (OTF) in combination with an optical wavelength converter can realize a variable optical delay. Experimental results indicate that the OTF made from two coupled ring lasers in combination with the wavelength converter based on nonlinear polarization rotation was suitable to demonstrate the concept. The OTF showed a contrast ratio of more than 50 dB between the output states. An optical packet was circulated in an optical loop four times when packet contention occurred, and was routed out of the loop when the contention disappeared. A clear open eye after the re-circulating loop was obtained.
Chapter 9

All-optical memory by using two coupled nonlinear polarization switches

9.1 Introduction

All-optical memories have many potential applications in optical communication systems and optical computing [56]. It has been discussed in Chapter 2 that all-optical memories can be used for all-optical buffering. In this chapter, we show that the all-optical memory is also a very important component in the structure of all-optical packet switches, which have been considered as an important part for the future all-optical access node [11-17].

The optical memories based on bistable laser diodes (BLD) have been extensively studied, and has been reported in [94] as a review paper. In the normal BLD, the bistability operation is performed in the ‘S-shaped’ hysteretic region and needs trigger pulses to change the memory state. In all-optical set and reset operation, one difficulty is that the optical reset operation needs a ‘negative’ optical pulse to switch the laser off. To overcome this problem, BLDs with separate optical set and reset inputs are proposed [95, 96]. The output states of BLDs can be distinguished by different output power or different polarization states, but in BLDs it is difficult to have output states that have a large wavelength range, and can be used in WDM system. In [97, 98], a bistable semiconductor fiber ring laser that has optical spectral bistability is proposed. In one of the bistable states, one wavelength is dominant. However, in another state, two wavelengths are dominant, including the wavelength

This Chapter is based on the results published in [100]:

that was dominant in the previous state. This makes the optical memory in [97, 98] difficult to be implemented in all-optical packet switches.

Optical flip-flop memories can be realized from two coupled nonlinear optical elements [99]. An all-optical flip-flop memory that is made from two coupled lasers is published in [57]. The state of the optical flip-flop is determined by the wavelength of the flip-flop output light. In each state, only one wavelength is dominant. The optical flip-flop presented in [57] has a number of advantages. Firstly, it can provide high contrast ratios between the states. Moreover, it has separate optical set and reset operation. Furthermore, the wavelength range of the input light and the output light can be large and the flip-flop has controllable and predictable switching thresholds. The general concept in [57] can be used to form an all-optical flip-flop memory based on two coupled Mach-Zehnder interferometers (MZIs) [58], which allows ultra-fast operation.

In this chapter, an all-optical flip-flop memory with separate optical set and reset inputs is described. We demonstrate an all-optical flip-flop memory that is made from two coupled nonlinear polarization switches that are operated by utilizing the nonlinear polarization rotation in semiconductor optical amplifiers (SOAs). The theory of nonlinear polarization rotation in SOAs has been presented in Chapter 5. This all-optical flip-flop implementation has a simple structure, separate set and reset inputs and large input wavelength range. Moreover, this all-optical flip-flop has similar properties as the one that is based on two coupled MZIs [58]. However this implementation is easy to realize by using commercially available pigtailed components and shows stable operation without photonic integration. We demonstrate the feasibility of the concept and we show that the contrast ratio between the output states of the flip-flop is over 20 dB while the switching power is less than –3 dBm.

This chapter is organized as follows. In Section 9.2 the concept of a 1×2 optical packet switch is explained, which shows that the optical memory is a very important part in this 1×2 optical packet switch. The operation principle of our optical memory is presented in Section 9.3. Experimental results are given in Section 9.4. This chapter is concluded with a discussion.
9.2 System concept of a 1×2 optical packet switch

The concept of our optical packet switch is presented schematically in Figure 9.1. The optical packet switch is realized by using entirely all-optical signal processing. The all-optical packet switch is made out of three functional blocks: the all-optical header processing block, the all-optical flip-flop memory block, and the wavelength conversion block. The packets that we used have a fixed duration and consist of an optical header and optical payload. The header contains the routing information of the packet while the payload contains the information content. Both the header and the payload consist of amplitude modulated data bits. When an optical packet arrives at the optical packet switch, the optical power of the packet is split into two parts. Half of the optical power of the packet is delayed and injected into a wavelength converter. Some delay is required to compensate for the time taken to carry out the header processing function.

The header processing function block translates the optical header pattern into an optical pulse. This pulse triggers the flip-flop memory to generate continuous wave (CW) light with a specific wavelength. Hence, different header information forces the optical memory to output CW light with a different wavelength. The output light from the optical memory is fed into the wavelength converter to convert the packet into the desired wavelength. Afterwards, a demultiplexer is used to route the packet into a specific port, depending on the wavelength of the packet. Thus the routing of the packet is determined by the wavelength of the optical memory output light, in turn, determined by the header information. Thus an optical packet switch is realized.

A 1×2 optical packet switch [46, 47] is achieved by using entirely all-optical signal processing. The header processing is realized by using two-pulse correlation.
principles in a Semiconductor Laser Amplifier in Loop Optical Mirror (SLALOM) configuration [101-103]. The optical memory is realized by using two-coupled laser diodes [57]. The wavelength conversion is based on the cross-gain modulation in an SOA.

In principle, the concept of the $1 \times 2$ all-optical packet switches presented in [46, 47] can be generalized to a $1 \times N$ all-optical packet switch. As a consequence, the header processing technique can recognize multiple headers corresponding to multiple output ports [104]. In addition, the optical memory needs to have more output states because the number of output states of the memory determines the number of output ports of the optical packet switch. In the next two chapters, we will show it is possible to make an all-optical memory with multiple states.

![Figure 9.2: The configuration of the all-optical flip-flop based on two polarization switches. PSW: polarization switch, PC: polarization controller, PBS: polarization beam splitter, $P_{out 1}$ is the output of PSW$_1$ and $P_{out 2}$ is the output of PSW$_2$.](image)

**9.3 Operation principle**

The all-optical flip-flop concept is depicted in Figure 9.2. It consists of two coupled polarization switches (PSWs). The PSW, that acts as a logic AND gate [105], is made from a laser source, a semiconductor optical amplifier (SOA), two polarization controllers and a polarization beam splitter (PBS). A laser emits a continuous wave (CW) probe beam at wavelength $\lambda_1$ that is fed into an SOA. The SOA output is sent into a PBS. The system contains two polarization controllers. The first polarization
controller is used to adjust polarization of the input signal to be approximately 45 degrees to the orientation of the SOA layers, while the second polarization controller is used to adjust the polarization of the amplified SOA output with the orientation of the PBS. The SOA can be saturated by the injection of a high intensity pump (control) signal. The solid curve in Figure 9.3 shows the typical (experimental) PBS output as a function of the intensity of the saturating control light. It follows that a control beam of sufficient intensity, can suppress the PSW output. This effect is caused by the additional birefringence that is introduced in the SOA by the control light [76], which causes the TE and the TM modes of the probe beam to experience a different refractive index. At the PBS, the two modes combine coherently. If the phase difference between the two modes is $\pi$, the PSW output is suppressed. Note that the curve of Figure 9.3 is similar to the one presented in [58] in which the suppressed output of an active MZI is discussed.

![Figure 9.3: Intensity $P_{\text{out}1}$ of the light that outputs PSW$_1$ as a function of the intensity $P_{\text{out}2}$ of the light that outputs PSW$_2$ (solid curve). Intensity $P_{\text{out}2}$ of the light that outputs PSW$_2$ as a function of the intensity $P_{\text{out}1}$ of the light that outputs PSW$_1$ (dashed curve). It is clear that the two curves are complementary.](image)

Similar as in [57], an optical flip-flop can be realized by coupling two identical PSWs as shown in Figure 9.2. The first PSW, hereafter to be called PSW$_1$, outputs light that is injected into the second PSW (to be called PSW$_2$). Hence, the light that outputs PSW$_1$ acts as a saturating control signal that can suppress PSW$_2$ and the light that outputs PSW$_2$ can act as a saturating control signal to suppress PSW$_1$. The solid curve in Figure 9.3 represents the intensity $P_{\text{out}1}$ of the light that outputs PSW$_1$ as a
function of the intensity $P_{out\,2}$ of the light that outputs PSW$_2$. The system is set in such a way that the maximum output intensity $P_{out\,1}$ equals the intensity of the control light $P_{out\,2}$ that is required to suppress PSW$_1$. Since the PSWs are identical, the solid curve is complementary to the dashed curve that represents the intensity of the light that outputs PSW$_2$. At point A, PSW$_1$ is dominant and PSW$_2$ is suppressed while at Point B, PSW$_1$ is suppressed and PSW$_2$ is dominant. Both A and B can be shown stable states of the system, Point S can be shown to be an unstable point [57].

The system of two coupled PSWs can function as an optical flip-flop as follows. The state of the flip-flop can be determined by observing the amount of light at the PSW outputs. In State 1, PSW$_1$ dominates and suppresses PSW$_2$, while in State 2 PSW$_2$ dominates and suppresses PSW$_1$. To switch the flip-flop between the states, light can be injected into the PSW that dominates (that is the one injecting the most light into the other PSW) via the set state or the reset ports. The injected light reduces the light exiting the dominant PSW, which allows the suppressed PSW to increase its light output and become the dominant PSW.

### 9.4 Experiment and results

The all-optical flip-flop is implemented as in Figure 9.2. Laser 1 and Laser 2 emit CW light at wavelength $\lambda_1=1549.32$ nm and $\lambda_2=1550.92$ nm respectively, however, it is not essential to bias the PSWs with light at different wavelengths. The output power is $-3.34$ dBm for Laser 1 and $-3.05$ dBm for Laser 2. The SOAs were manufactured by JDS Uniphase and employ a strained bulk active region. SOA$_1$ is biased with 163.97 mA of current and SOA$_2$ is biased with 161.86 mA of current. The PBS has four ports and an extinction ratio of 30 dB. PSW$_1$ and PSW$_2$ are coupled to each other via the PBS.

The steady state PSW output intensity versus the intensity of the input light is presented in Figure 9.3 as discussed in the previous section. The two states of the flip-flop are shown as point A and point B.

The spectral output of the all-optical memory at each state is presented in Figure 9.4, measured by an optical spectrum analyzer. Figure 9.4(a) and 9.4(b) correspond to State 1 and State 2, respectively. It is shown that the contrast ratio between each state of the memory is over 20 dB.
All-optical memory by using two-coupled PSWs

Figure 9.4: Spectral output at each state of the flip-flop. (a) represents State 1 ($\lambda_1$ dominant), and (b) represents State 2 ($\lambda_2$ dominant).

Figure 9.5: Dynamic output of the flip-flop showing switching between states every 1.85 $\mu$s. The upper panels (a) and (b) are the traces of the external optical pulses at wavelength 1552.52 nm. The lower panels (c) and (d) are the dynamic output of flip-flop at each wavelength $\lambda_1$ (1549.32 nm) and $\lambda_2$ (1550.92 nm).

The dynamic operation of the flip-flop is demonstrated by toggling the state of the flip-flop by injecting a regular sequence of optical pulses into the PSW that is currently the master. The pulses have a wavelength of 1552.52 nm and duration of 150 ns. The pulses are injected into the master once every 1.85 $\mu$s through the set and reset
port (see Figure 9.2). Figure 9.5 shows the oscilloscope traces of the optical pulses and the optical output power of the flip-flop at each wavelength. In Figure 9.5(a), optical pulses are injected into PSW\textsubscript{1} via Port I of the PBS (see Figure 9.2) to set the flip-flop to State 2. Figure 9.5(b) shows the optical pulses that are injected into PSW\textsubscript{2} via Port II of the PBS (see Figure 9.2) to reset the flip-flop to State 1. The optical peak power of the pulses in Figure 9.5(a) is –3.91 dBm and –4.35 dBm in Figure 9.5(b). Figure 9.5(c) and Figure 9.5(d) present the dynamic output of the flip-flop at output\textsubscript{1} and output\textsubscript{2}. The switching between flip-flop states every 1.85 µs can clearly be observed. Furthermore, it is visible that the flip-flop state is stable in the time between changing states.

It should be noted that the polarization state of the external optical pulses needs to be controlled since the external pulses are coupled into the system via two ports of the PBS. To avoid the control of the polarization state of the external light, one could also couple the external light into the system via additional couplers. However, this will cause coupling losses and introduce more complexity in the system.

### 9.5 Conclusion

An all-optical flip-flop memory based on two coupled polarization switches has been demonstrated. The contrast ratio between the output states of the flip-flop is over 20 dB and the optical switching power is less than –3 dBm. The speed of this flip-flop is determined by the speed of the PSW and the propagation distance between the two SOAs. In the experimental setup, approximately 12 meters of fiber is used between the two SOAs, which implies that about 100 ns are required for the states of the flip-flop to change. However, integrated versions of the flip-flop could reduce the distance between the two SOAs to several millimeters. In this case, the speed of the flip-flop would be dominated by the speed of the PSW. It has been demonstrated that the PSW can operate at 10 GHz [73], thus we expect the flip-flop can reach similar speeds. Finally, we note that the curves presented in Figure 9.3 are similar to the ones presented in [58] which reveals that a PSW acts as a Mach-Zehnder interferometer where the role of the different light paths is now realized by independently operating TE and TM modes of the optical field.
Chapter 10

Three-state all-optical memory based on coupled ring lasers

10.1 Introduction

All-optical packet switches are considered as important building blocks for future all-optical telecommunication nodes [11-17]. In [46, 47] a 1×2 all-optical packet switch was presented. A key component of this packet switch is a two-state all-optical memory. In principle, the number of output states of the memory determines the number of output ports of the optical packet switch. Therefore, all-optical memories with more states are crucial for extending the 1×2 all-optical packet switch of [46, 47] to a larger dimension (1×N). This has been discussed in Section 9.2 in Chapter 9. The overview of two-state optical memory has been shown in Section 9.1 in Chapter 9.

In this chapter, we describe an all-optical memory that has three states. We demonstrate that it is possible to construct a three-state optical memory based on three coupled identical ring lasers. The state of the optical memory is determined by the wavelength of the memory’s light output. In each state, only one laser lases and the other lasers are suppressed, thus only one wavelength is dominant. This all-optical memory implementation has separate inputs to set the memory to a particular state. We demonstrate the feasibility of the concept and we show that the contrast ratio between output states of the memory is over 40 dB. This three-state memory concept can be extended to create an all-optical memory with an arbitrary number of states.

This Chapter is based on the results published in [106]:

10.2 System concept

The three-state all-optical memory concept is depicted in Figure 10.1. It consists of three coupled identical ring lasers. As shown in Figure 10.1, in each single ring laser a Semiconductor Optical Amplifier (SOA) acts as the laser gain medium. The wavelengths are selected by Fabry-Perot filters (FPFs). Optical isolators (ISOs) are used to allow the light to travel in only one direction, thus ensuring lasing in one direction. The operation principle of a single ring laser is described in [66]. If the gain of the SOA is higher than the threshold of the ring laser, lasing starts. However, the SOA can be saturated by injection of high-intensity external light, which causes the gain at the lasing wavelength to be reduced. If the reduced gain at the lasing wavelength is below the threshold value, lasing stops. Figure 10.2 shows the typical (experimental) ring laser output as a function of the intensity of the saturating external light. It is clearly visible that external light with sufficient intensity can suppress lasing.
Three-state all-optical memory based on coupled ring lasers

Two identical lasers can be coupled to make a two-state all-optical memory [57]. The output of the first laser (Laser 1) is coupled into a second identical laser (Laser 2), and the output of Laser 2 is coupled into Laser 1. In such a configuration one laser can act as the master laser, which suppresses lasing in the other laser (the slave). Due to the symmetry of this master-slave configuration, the role of master and slave can be interchanged. Thus two states are possible. In state 1, Laser 1 is lasing and Laser 2 is suppressed and in state 2, Laser 2 is lasing and Laser 1 is suppressed. To change the states, lasing of the dominant laser can be stopped by injecting external light, which has a different wavelength from the dominant laser, into the dominant laser cavity [57].

The concept in [57] can be extended to a three-state optical memory. In Figure 10.1, three identical ring lasers are coupled to each other to construct a three-state optical memory. The output of each ring laser has to be coupled into the other two lasers, but not into its own cavity. To realize this, the outputs of each ring laser are firstly combined by using a multiplexer. 10% of the combined light is coupled out of the system by using a 90/10 coupler. This is the memory output. The other 90% of the combined light is firstly fed into SOA 4 to be amplified and then fed back into each ring laser through a system of Fiber Bragg Gratings (FBGs). FBGs are used to prevent light at the lasing wavelength re-entering the ring laser cavity. Thus, the output of each laser is coupled into the other lasers but not into its own cavity due to the FBGs. The amplification by SOA 4 ensures that the light injected into each laser is sufficient
to suppress the lasing mode. Since the system is symmetric, all the lasers can suppress lasing in the other lasers, and thus each laser can become dominant. Therefore, the memory has three possible states, depending on which laser is lasing. The state of the memory is determined by the wavelength of the memory’s output light. In each state, only one laser lases and the other lasers are suppressed, thus only one wavelength is dominant. In State 1, Laser 1 dominates and suppresses the lasing in the other lasers, thus $\lambda_1$ is dominant. In State 2, Laser 2 is dominant and suppresses lasing in the other two lasers, therefore, $\lambda_2$ is dominant. In State 3, only laser 3 is lasing and suppresses Laser 1 and Laser 2, thus $\lambda_3$ is dominant.

To select the state of the memory, external light is injected via one of the set ports, as shown in Figure 10.1. The external light, which is used to change the state of the memory, is firstly sent through a small network that is made from 3 dB couplers. (See the dashed-box on the left-hand side in Figure 10.1). The function of this network is to dispense the external light into some specific lasers, depending on which input port is used. External light injected into one set port can set the memory to a particular state. For instance, external light injected into Set 1 Port can set the memory to State 1 (Laser 1 dominates). In this case, the external light suppresses Laser 2 and Laser 3. Thus the external light is distributed over the all the lasers except Laser 1. The saturating external light stops or reduces the light exiting from the lasers in which the external light is injected, irrespective of whether these lasers are dominant or suppressed. As a consequence, Laser 1, in which no external light is injected, can increase its output light and thus become the dominant laser (i.e. suppress the other lasers). This state remains after the external light is removed.

The state of the memory can be changed by injection of external light with arbitrary polarization that has sufficient power, since the switching principle is based on SOA gain saturation [57].

10.3 Experiment and results

The three-state all-optical memory is implemented as in Figure 10.1. All the couplers in the experiment are 50/50 couplers except one 90/10 coupler that is indicated in Figure 10.1. The wavelengths of the lasers are $\lambda_1=1552.18$ nm, $\lambda_2=1554.17$ nm and $\lambda_3=1555.78$ nm respectively. The SOAs were manufactured by JDS Uniphase and employ a strained bulk active region. The SOA injection currents are set in such a way that the system is symmetric. The SOA injection currents were 200 mA for Laser 1.
Three-state all-optical memory based on coupled ring lasers

(the threshold current is 152 mA), 151 mA for Laser 2 (the threshold current is 87 mA) and 186 mA for Laser 3 (the threshold current is 96 mA) respectively. SOA 4 is biased with 300 mA of current, providing an optical power of 13 dBm at the output of SOA 4. We have used commercially available FBGs with 0.5 nm bandwidth and −30 dB transmission at its center wavelength.

The output power of Laser 2 at Port B is plotted versus the input power via Port C (See Figure 10.1) in Figure 10.2. Figure 10.2 shows that for such a ring laser, it is sufficient to inject 3.98 dBm (2.5mw) of light to suppress lasing in the ring laser.

The dynamic operation of the memory is demonstrated by toggling the state of the memory by injecting a regular sequence of optical pulses into each of the set ports (see Figure 10.1). The injected pulses have a wavelength of 1550.92 nm and duration of 2.5 µs. The pulses are injected once every 12.7 µs to change the state of the memory, as shown in the upper panels of Figure 10.3 (Figure 10.3(a), 10.3(b) and 10.3(c)). The optical peak power of pulses is 15 dBm at each input port of the memory. These optical pulses only have around 6 dBm peak power left when they are injected into the ring lasers due to 9 dB of coupling loss in the input network. Figures 10.3(d), 10.3(e) and 10.3(f) show the oscilloscope traces of the optical output power of the memory for each state. In Figure 10.3, regular toggling between memory output states every 12.7 µs is visible. Furthermore, it can be observed that the memory’s state is stable in the time between changing states. The contrast between each state of the memory was investigated by using an optical spectrum analyzer, which has a resolution of 0.02 nm. It is shown in Figure 10.4 that the contrast ratio between each state of the memory is over 40 dB. In Figure 10.4, the spectrum of Laser 1 is broader than the other two lasers due to the bandwidth of the Fabry-Perot filter (0.5 nm) in Laser 1, which is wider than the bandwidth of the Fabry-Perot filters in the other two lasers (0.2 nm). However, a better experimental result can be obtained if the filters are identical.

The SOAs used in the experiment are polarization-insensitive. Hence, external light of arbitrary polarization can switch the state of the memory, ensuring that the optical memory is polarization-independent.
Figure 10.3: Dynamic output of the memory showing switching between the states every 12.7 µs. The upper panels (a)-(c) are the traces of the external optical pulses. The lower panels (d)-(f) are the dynamic output of the memory at each wavelength ($\lambda_1$, $\lambda_2$, $\lambda_3$).

Figure 10.4: Spectral output at each state of the memory. (a) represents State 1 ($\lambda_1$ dominant), (b) represents State 2 ($\lambda_2$ dominant), (c) represents State 3 ($\lambda_3$ dominant).
10.4 Conclusion

A three-state all-optical memory based on coupled ring lasers has been demonstrated. The state of the memory is determined by the wavelength of the memory’s light output. In each state, only one wavelength is dominant. This all-optical memory implementation has separate inputs to set the memory to a particular state, and the contrast ratio between output states of the memory is over 40 dB.

The speed of this memory is determined by the cavity length of the ring laser and the propagation distance between each laser. The experimental setup was constructed from standard commercially available fiber pigtailed components, thus each laser has a cavity length of around 16 meters, and approximately 13 meters of fiber is used between each laser, which implies that about several microseconds are required to change the states of the memory. However, in integrated versions of the memory, the laser would have a cavity length of only several millimeters and the distance between each laser would also be reduced to several millimeters, indicating that integrated versions of the memory could attain speeds in the GHz range.

The concept of this three-state memory can be extended to create all-optical memories with a larger number of states. However, the operating speed of the extended multi-state memory will decrease since the distance between the coupled lasers will increase. Furthermore, more optical switching power and more amplification of the combined light (the role of SOA 4 in Figure 10.1) are required, due to the increasing coupling loss in the extended multi-state all-optical memory.
Chapter 11

Three-state all-optical memory based on coupled nonlinear polarization switches

11.1 Introduction

All-optical memories, which are key components in all-optical packet switches, are currently an important research topic [11-17]. We have shown in Chapter 9 and Chapter 10 that the states of an optical memory can be represented by different wavelengths. Unlike electronic memory, optical memory can have many states, distinguished by different wavelength. In Chapter 10, a three-state optical memory was demonstrated.

In this chapter, we show that the concept in Chapter 10 can be generalized to construct a three-state optical memory based on three coupled identical nonlinear polarization switches [107]. The state of the optical memory is determined by the wavelength of the memory’s light output. In each state, only one wavelength is dominant. This all-optical memory implementation has separate inputs to set the memory to a particular state. We demonstrate the feasibility of the concept and we show that the contrast ratio between output states of the memory is over 20 dB and the switching power is around 8 dBm.

This Chapter is based on the results published in [107]:

11.2 System concept

The all-optical memory concept is depicted in Figure 11.1. It consists of three-coupled nonlinear polarization switches (PSWs). Each PSW consists of a laser source, a semiconductor optical amplifier (SOA), two polarization controllers (PCs) and a polarization beam splitter (PBS). A PBS is shared by the three PSWs as shown in Figure 11.1. In each PSW, a laser emits a continuous wave (CW) probe beam that is fed into a SOA. The SOA output is sent into the PBS.

The operation principle of a single PSW is described in [67, 100]. Figure 11.2 shows the typical (experimental) PBS output as a function of the intensity of the saturating external light. It follows that an external light with sufficient intensity, can suppress the PSW output. This effect is caused by the additional birefringence that is introduced in the SOA by the external light [76], which causes the TE and the TM modes of the probe beam to experience different refractive indexes. If the phase difference between the two modes is $\pi$, the PSW output is suppressed.
Two identical PSWs can be coupled to each other to make a two-state all-optical memory [100]. In such a configuration one PSW acts as the master PSW, which suppresses the output of the other PSW (the slave). Due to the symmetry of the master-slave configuration, the role of the master and the slave can be interchanged by injecting external light into the dominant PSW.

The concept in [100] can be extended to a three-state optical memory. In Figure 11.1, three identical PSWs are coupled to each other to construct a three-state optical memory. The output of each PSW has to be coupled into the other two PSWs, but not into itself. To realize this, each PSW outputs a different wavelength and they are combined at the PBS output. 20% of the combined light is coupled out of the system by using an 80/20 coupler, which acts as the memory output. The other 80% of the combined light is firstly fed into SOA4 to be amplified and is then separated by a demultiplexer (DEMUX). The outputs of the demultiplexer with different wavelengths are combined and dispensed to each PSW via a small network that is made from 3 dB couplers, as shown in the dashed-box on the right-hand side in Figure 11.1. This small network is set in such a way that the output of each PSW is fed back into the other PSWs but not into itself. The amplification by SOA4 ensures that the light injected into each PSW is sufficient to suppress the PSW output. Since the system is symmetric, all the PSWs can suppress the outputs of the other PSWs, and thus each PSW can become dominant. Therefore, the memory has three possible states, depending on which PSW is dominant. In each state, only one PSW dominates and the
other PSWs are suppressed, thus only one wavelength is dominant. For instance, in State 1, PSW₁ dominates and suppresses the output of the other PSWs.

To select the state of the memory, external light can be injected via one of the set ports, as shown in Figure 11.1. The external light is firstly sent through the small network that is described above. This network can dispense the external light into specific PSWs, depending on which input port is used. The external light from one set port can set the memory in a particular state. For instance, the external light from Set 1 Port can set the memory to State 1 (PSW₁ dominates and $\lambda₁$ is dominant). The external light that is injected into Set 1 Port, is distributed into all the PSWs except PSW₁. Thus the saturating external light stops or reduces the light exiting from the PSWs in which the external light is injected, irrespective of whether these PSWs are dominant or suppressed. As a consequence, PSW₁, into which no external light is injected, increases its output light and becomes dominant to suppress the other PSWs. This state remains after the external light is removed.

11.3 Experiment and results

The three-state all-optical memory is implemented as in Figure 11.1. All the couplers in the experiment are 50/50 couplers except one 80/20 coupler that is indicated in the figure. Laser 1, Laser 2 and Laser 3 emit CW light at wavelength $\lambda₁$=1550.92 nm, $\lambda₂$=1552.52 nm and $\lambda₃$=1554.13 nm respectively. The output power is –4.71 dBm for Laser 1, –4.75 dBm for Laser 2 and –4.65 dBm for Laser 3. The SOA (JDS Uniphase) injection currents were 157 mA for SOA₁, 151 mA for SOA₂ and 150 mA for SOA₃. SOA₄ is biased with 300 mA of current.

The output power of PSW₁ at the PBS versus the input power to the pigtail of SOA₁ (see Figure 11.1) is presented in Figure 11.2. It is shown that for this PSW, it is sufficient to inject –2.2 dBm (0.6 mw) of light to suppress the PSW output.

The spectral output of the all-optical memory at each state is presented in Figure 11.3. Figure 11.3(a), 11.3(b) and 11.3(c) correspond to State 1, State 2 and State 3 respectively. It is shown that the contrast ratio between the each states of the memory is over 20 dB.
Three-state all-optical memory based on coupled PSWs

Figure 11.3: Spectral output of the all-optical memory at each state. (a) represents State 1 ($\lambda_1$ dominant), (b) is State 2 ($\lambda_2$ dominant), (c) is State 3 ($\lambda_3$ dominant).

Figure 11.4: Dynamic output of the memory showing switching between the states every 2.8 $\mu$s. The upper panels (a), (b) and (c) are the traces of the external optical pulses. The lower panels (d), (e) and (f) are the dynamic output of memory at each wavelength ($\lambda_1$, $\lambda_2$, $\lambda_3$).
The dynamic operation of the memory is demonstrated by toggling the state of the memory by injecting a regular sequence of optical pulses into each of the set ports (see Figure 11.1). The injected pulses have a wavelength of 1557.36 nm and duration of 480 ns. The pulses are injected once every 2.8 µs to change the state of the memory, as shown in the upper panels of Figure 11.4 (Figure 11.4(a), 11.4(b) and 11.4(c)). The optical peak power of the pulses was 8 dBm at each input port of the memory. Figures 11.4(d), 11.4(e) and 11.4(f) show the oscilloscope traces of the optical output power of the memory for each state. In Figure 11.4, regular toggling between the memory output states every 2.8 µs is visible. Furthermore, it can be observed that the memory’s state is stable in the time between changing states. It can be seen in Figure 11.4 that small spikes appear at the output of the suppressed PSW when external switching pulses are injected. This is because the suppressed PSW starts to output a small amount of light when the power of the external light exceeds the threshold level at which the output of the PSW is completely suppressed (see Figure 5.6.).

11.4 Conclusion

A three-state all-optical memory based on three coupled nonlinear polarization switches has been demonstrated. The state of the optical memory is determined by the wavelength of the memory’s light output. In each state, only one wavelength is dominant. The contrast ratio between output states of the memory is over 20 dB and the optical switching power is around 8 dBm.

In the experimental setup, approximately 40 meters of fiber is used between each SOA, which implies that about 400 ns are required to change the states of the memory. However, integrated versions of the memory could reduce the distance between the SOAs to several millimeters, indicating that the memory could reach a few GHz [100]. Finally, we remark that the concept of this three-state memory can be extended to an all-optical memory with a large number of states.
Chapter 12

Conclusions

This thesis reports on the physical realization of optical packet buffers, by only utilizing all-optical signal processing technology. We have shown that it is possible to realize all-optical buffering by employing optical arbiters, optical wavelength routing switches and optical fibre delay lines. Several optical buffering concepts have been demonstrated. Our experimental set-ups were bulky because they were constructed out of commercially available fiber-pigtailed components. To solve this issue, one must realize photonic integrated packet buffers, which are more compact and have better performance with respect to speed, power consumption, reliability and costs.

As shown in this thesis, the optical packets are routed into the buffers via an optical wavelength routing switch which is composed out of a wavelength converter and a demultiplexer. Integrated wavelength converters and demultiplexers are available in a variety of technologies. Photonic integrated circuits that combine wavelength converters and AWGs can be realized in research laboratories [29].

The optical packet buffers that are discussed in this thesis are based on all-optically controlled fiber buffers. The buffer control was implemented by using an all-optical threshold function or a laser neural network, both implemented by using coupled lasers. Integrated bi-stable devices that could act as an optical threshold function have recently been demonstrated [108]. Photonic integration of the laser neural network is a challenge on its own, but the fact that all available packet buffers are based on fiber delay lines forms a more serious issue. Using optical delay lines as a packet buffer is interesting from a research point of view, but it is not promising for real situations. The optical fiber delay lines cannot be integrated into photonic chips. It is unlikely that the real optical packet switch cross-connects will contain many kilometres fiber in each node for optical buffering. However, monolithically integrated delay lines might be obtained by employing a semiconductor quantum dot waveguide as a delay medium [41, 42]. The group velocity of a signal in the waveguide will slow down when a strong pump light is launched simultaneously into
the waveguide due to the electromagnetically induced transparency effect. Simulation results indicate that this approach can slow down the group velocity of light by a factor of 55.

The use of delay-lines could be avoided in buffer functionalities, if integrated optical shift registers were available. All-optical flip-flops could act as a fundamental building block for an optical shift register. Such optical flip-flop memories should have fast (optical) switching time, operate at low power, have a high contrast ratio and should have sufficiently small dimensions. An integrated optical flip-flop memory based on laser operation is presented in [95], but the power consumption, the size, and the switching speed of these devices remain an issue. It is difficult to couple them in large quantities as required in optical shift registers. A more promising all-optical flip-flop concept based on two coupled micro-lasers is presented in [109]. This flip-flop concept has the potential to have the dimensions in the order of the wavelength of light, a switching speed of a picosecond and a switching energy below a femtojoule. If one succeeds in interconnecting these flip-flops, densely integrated digital optical logic operating at high speed and low power can be realized.

One should realize however that the development of digital optical logics is still in its infancy. Many available devices are still confined to research laboratories. This means that the current stage of photonics development is probably equivalent to that of the vacuum tube used in the electronic systems in the 1940s [110]. It is however remarkable that it is possible to realize sophisticated optical signal processing systems that out-perform electronics, at least with respect to its operating speed, from these “infant” building blocks. New developments that take place in the coming years will undoubtedly contribute to the realization of more mature signal processing systems that will find their way to the market.
References


Conference on Optical Communications (ECOC’2003), Rimini, Italy, We4.P.78, Sept. 2003.


# Appendix A

## List of abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ACTS</td>
<td>Advanced Communications Technologies and Services</td>
</tr>
<tr>
<td>ATT</td>
<td>ATTenuator</td>
</tr>
<tr>
<td>AWG</td>
<td>Arrayed Waveguide Grating</td>
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<tr>
<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>BLD</td>
<td>Bistable Laser Diodes</td>
</tr>
<tr>
<td>BPF</td>
<td>Band-Pass Filter</td>
</tr>
<tr>
<td>CIR</td>
<td>CIRculator</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>dBm</td>
<td>Decibel milliwatt</td>
</tr>
<tr>
<td>DEMUX</td>
<td>DEMUltipleXer</td>
</tr>
<tr>
<td>EAM</td>
<td>Electro Absorption Modulator</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium Doped Fiber Amplifier</td>
</tr>
<tr>
<td>FDL</td>
<td>Fiber Delay Line</td>
</tr>
<tr>
<td>FPF</td>
<td>Fabry-Perot Filter</td>
</tr>
<tr>
<td>ISO</td>
<td>ISOlator</td>
</tr>
<tr>
<td>KEOPS</td>
<td>Keys to Optical Packet Switching</td>
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<tr>
<td>LAN</td>
<td>Local Area Network</td>
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<tr>
<td>LNN</td>
<td>Laser Neural Network</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro Electro-Mechanical Systems</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>-------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>MOD</td>
<td>MODulator</td>
</tr>
<tr>
<td>MUX</td>
<td>MultipleXer</td>
</tr>
<tr>
<td>MZI</td>
<td>Mach-Zehnder Interferometer</td>
</tr>
<tr>
<td>NOE</td>
<td>Nonlinear Optical Element</td>
</tr>
<tr>
<td>NRZ</td>
<td>Non-Return-to-Zero</td>
</tr>
<tr>
<td>OEO</td>
<td>Optical-Electrical-Optical (conversion)</td>
</tr>
<tr>
<td>OSNR</td>
<td>Optical Signal Noise Ratio</td>
</tr>
<tr>
<td>OTF</td>
<td>Optical Threshold Function</td>
</tr>
<tr>
<td>PBS</td>
<td>Polarization Beam Splitter</td>
</tr>
<tr>
<td>PC</td>
<td>Polarization Controller</td>
</tr>
<tr>
<td>PHASAR</td>
<td>PHAsed Array (=AWG)</td>
</tr>
<tr>
<td>PIC</td>
<td>Photonics Integrated Circuits</td>
</tr>
<tr>
<td>PSW</td>
<td>Polarization Switch</td>
</tr>
<tr>
<td>PRBS</td>
<td>Pseudo-Random Binary Sequence</td>
</tr>
<tr>
<td>SOA</td>
<td>Semiconductor Optical Amplifier</td>
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<tr>
<td>TE</td>
<td>Transverse Electric</td>
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<tr>
<td>TM</td>
<td>Transverse Magnetic</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
</tr>
<tr>
<td>XAM</td>
<td>Cross Absorption Modulation</td>
</tr>
<tr>
<td>XGM</td>
<td>Cross Gain Modulation</td>
</tr>
<tr>
<td>XPM</td>
<td>Cross Phase Modulation</td>
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Appendix B

List of publications

Journal papers


International conference papers


Regional conference papers


Samenvatting

Een geheel optisch pakket-geschakeld netwerk kan serieus worden beschouwd als een toekomstig scenario voor optische telecommunicatie netwerken. In optische pakket-geschakelde kruisschakelaars (Optical Cross-Connects, OXCs) is de “contention” een essentieel probleem. Het overlappen van pakketten in een pakket-geschakeld netwerk doet zich voor wanneer de pakketten uit verschillende richtingen gelijktijdig bij een knooppunt aankomen en naar dezelfde bestemming moeten worden geleid. Het overlappen van pakketten in pakket-geschakelde netwerken kan door buffering worden opgelost.

Dit proefschrift richt zich op de fysische realisatie van een geheel optische buffer. Wij demonstreren optische buffering met behulp van optische signaalverwerking technologie. Ons concept voor de buffering bevat twee bouwstenen: een geheel optische arbiter en een geheel optische golflengte “routing” schakelaar.

In hoofdstuk 3 van deze thesis, introduleren wij een optische drempelfunctie die als optische arbiter kan dienen om het overlappen van twee pakketten te behandelen. In hoofdstuk 4, breiden wij deze benadering uit door een laser neurale netwerk als een optische arbiter te gebruiken die het overlappen van van meer dan twee pakketten kan behandelen. In hoofdstuk 8, introduleren wij een optisch gecontroleerde variabele optische vertraging die kan worden gebruikt in een optische re-circulerende lijnbuffer.


Geheel optische flip-flop geheugens hebben vele potentiële toepassingen in de context van geheel optisch bufferen en geheel optisch pakket schakelen. Wij introduceren een nieuw concept voor een optische flip-flop in hoofdstuk 9 dat is gebaseerd op niet-lineaire polarisatiedraaiing in een halfgeleider optische versterker. In
hoofdstukken 10 en 11, beschrijven wij een drie-niveau optisch geheugen dat kan worden gerealiseerd door drie gekoppelde ring lasers te gebruiken of door drie gekoppelde niet-lineaire polarisatieschakelaars te gebruiken. Dit concept kan tot een optisch geheugen met een groter aantal niveaus worden uitgebreid. Dergelijke multi-niveau optische geheugens zouden essentiële bouwstenen in pakket schakelaars met meerdere uitgangen kunnen zijn.
Acknowledgements

It is a pleasure for me to thank many people who in different ways have helped me to carry out my Ph.D. research and complete this thesis.

This thesis was not possible without financial support of the Netherlands Organization for Scientific Research (NWO), “het Prioriteitslandenfonds” of Eindhoven University of Technology, the COBRA Research Institute, and the Department of Electrical Engineering of Eindhoven University of Technology. I would like to thank Prof. G.D. Khoe for providing me an opportunity to complete the research in this thesis. I am also grateful for his advice on my research and his reviews of this thesis.

I would like to thank my supervisor, Dr. Harm Dorren, who continuously encouraged me and coached me in my research and writing. I am also grateful for his attention to all aspects of my personal well-being. I would like to express my gratitude to Dr. Martin Hill who is one of the most creative researchers in my group. His original advice and pioneering publications provide inspiration to my research. Without the considerable help from Harm and Martin, this thesis would not have been completed in time.

I want to thank Dr. Huug de Waardt for arranging the experimental equipment and sharing his research expertise. Special thanks go to Prof. Daan Lenstra for his wise advice. Due to his optimistic research attitude, I have learnt that research work is enjoyable. I am also grateful to Prof. Ton Koonen for his fruitful discussions and for providing a nice figure for my thesis.

I am pleased to express my gratitude to Prof. Patrice Megret and Prof. Ivan Andonovic for their willingness to be a member of my doctoral core committee and for their critical reviews of the thesis.

I want to thank Nicola Calabretta for his cooperation and valuable discussions. In particular, I am grateful for his kindness to me during the time I was a freshman in this group. I would like to thank Dr. Idelfonso Tafur Monroy for his kindly cooperation and help.
I am indebted to Dr. Eduward Tangdiongga for sharing his fruitful research and writing experience, for his experimental help and for his patient translating service.

I would like to express my gratitude to my “Beugelen” mates Susan and Henrie for their tolerance when I pushed my own ball into the ditch, which ended our hope of the championship. Apart from that, Susan has helped me to correct the English grammar of this thesis.

I would like to thank Frans Huijkens, Peter Bennekom, Johan van Zontvoort, René Jonker, Laurens Bakker and Ronald Schimmel for their experimental assistance.

I am thankful also to all my colleagues in the Electro-Optical Communication group for their warm cooperation, patient assistance and valuable discussions. Special thanks go to Dr. Yang Xuelin, Zhang Shaoxian, Ronelle, Arvind, Li Zhonggui, H. Ju, Zhao Yongpeng, A. Delphinanto, Zeng Jianming, C. Tsekrekos, Nan Ji, B. Huiszoon, J.P.A. van Berkel, E. Gerritsen, G.D.P. Petkov, S.L.Jansen, M. Garcia Larrode, Vegas Olmos JJ, Anthony, Jakek and Erwin Verdurmen. In particular, Ronelle has corrected the English grammar of this thesis. Jakek has guided me touring around Portugal. Erwin has translated the summary of this thesis into the Dutch “Samenvatting”.

I am equally thankful to all my colleagues in the COBRA research institute. In particular, R.G. Broeke, J.J.G.M. van der Tol and E. Patent have collaborated with me. J. H. den Besten has helped me to understand the AWG lasers, M. Nikoufard has lent me some testing equipments. Dr. F. Karouta has kindly practiced Ping Pong with me. F. M. Soares has patiently explained the MMI coupler to me.

I sincerely thank all the Chinese friends in Eindhoven for their companionship over the past four years. There are so many Chinese friends who have supported me, especially when I served for the Chinese Student Association. I feel very guilty that I cannot list all their names here. I am greatly indebted to them.

I am greatly indebted to my parents, especially my father, Liu Zhongquan.

I am grateful to my sisters Liu Xia and Liu Xiaoming, my brother Liu Jie, Liu Bing and their families, my father-in-law, Yu Ping and mother-in-law Hu Lili for their love, care and support.

Lastly, I would like to thank my wife, Yu Li, who certainly has made the most sacrifices caused by my frequent absence from home and our years of separation. Her love and encouragement made this thesis possible. I am also grateful to my son, Liu Danji, who cheers me up with his unaffected child’s mind, and refreshes me to face every new day.
Curriculum Vitae

Yong Liu (Last name: Liu, First name: Yong) was born in Fushun County, Sichuan Province, P. R. China, in February 1970. He started his bachelor-degree program at the University of Electronic Science & Technology of China in September 1987 in the field of opto-electronic technology. After obtaining his bachelor’s degree in 1991, he enrolled in a master’s program in physics-electronics and opto-electronics at the same university. During his masters program he specialized in optical fiber communications. He received his master degree on 30th of March 1994. He stayed at the same university for teaching and research. He taught two courses: “Laser Devices” and “C Language”. In April 1996 he was promoted to lecturer. He has been involved in several research projects, including real-time digital signal processing in fiber optical gyroscopes, CATV optical fiber transmission and laser display systems.

In April 2000, he joined the COBRA Research Institute at Eindhoven University of Technology as a Ph.D. student. His research topic is all-optical signal processing with an emphasis on optical buffering. In 2003, he was awarded an IEEE Lasers & Electro-Optics Society Graduate Student Fellowship.