All-optical header processing based on nonlinear gain and index dynamics in semiconductor optical amplifiers

Citation for published version (APA):

DOI:
10.6100/IR573184

Document status and date:
Published: 01/01/2004

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 19. Dec. 2019
ALL-OPTICAL HEADER PROCESSING
BASED ON NONLINEAR GAIN AND
INDEX DYNAMICS IN 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 dinsdag 13 april 2004 om 16.00 uur

door

Nicola Calabretta

geboren te Catanzaro, Italië
Dit proefschrift is goedgekeurd door de promotoren:

prof.ir. G.D. Khoe
en
prof.dr. D. Lenstra

Copromotor:
dr. H.J.S. Dorren

The work described in this thesis was performed in the Faculty of Electrical Engineering of the Eindhoven University of Technology and was financially supported by Netherlands Organization for Scientific Research (NWO) through the “NRC Photonics” grant.

CIP-DATA LIBRARY TECHNISCHE UNIVERSITEIT EINDHOVEN

Calabretta, Nicola

Proefschrift. – ISBN 90-386-1543-4
NUR 959
Trefw.: optische patroonherkenning / optische signaalverwerking / nietlineaire optica / halfgeleiderversterkers / optische telecommunicatiesystemen / computernetwerken ; packet switching.
Subject headings: optical information processing / optical logic / nonlinear optics / semiconductor optical amplifiers / packet switching.

Copyright © 2004 by Nicola Calabretta
All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means without the prior written consent of the author.

Typeset using Microsoft Word, printed in The Netherlands.
This thesis is devoted to all optical header recognition. All-optical header recognizers play an important role in futuristic all-optical packet switches. In the literature several approaches for all-optical header recognition have been discussed, but in this thesis, we focus on all-optical header recognition based on nonlinear gain and index dynamics in semiconductor optical amplifiers.

After a general introduction on the topic, in Chapter 2 an all-optical packet switch concept is discussed. This packet switch contains an optical header processor that is operated by employing two-pulse correlation principles in a semiconductor optical (laser) amplifier that is placed in an optical loop mirror (SLALOM). The header processor used in the packet switch presented in Chapter 2 can only recognize 1 specific header pattern. In Chapter 3 of this thesis, it is shown how header recognition concepts that are based on two-pulse correlation principles can be extended to recognize a larger amount of packet headers.

Also the packet switch presented in Chapter 2 contains an optical threshold function. This function was necessary since the header recognizer in the packet switch could only suppress the packet payload. Therefore in Chapter 4 and all-optical header pre-processor is discussed that solves this issue.
In Chapter 5 of this thesis all-optical header processing is discussed employing self-induced nonlinear polarisation rotation in a semiconductor optical amplifier. The advantage of employing header processing and header pre-processing employing nonlinear polarisation rotation is that the optical powers to be injected in the header processing system could be drastically reduced.

Finally, in Chapter 6, we show concepts for all-optical header recognition employing terahertz optical asymmetric demultiplexers (TOADs). The advantage of employing TOADs instead of SLALOMs is that header recognizers employing TOADs can be made so compact so that the system allows photonic integration. In Chapter 6, a concept is presented in which TOADs are employed for optical header recognition. In contrast to other optical header recognition concepts employing TOADs, the one presented in Chapter 6 of this thesis does not require optical clock recovery.
To Suzanne
Contents

1   Introduction ................................................................. 1
   1.1  Why all-optical packet switching? .............................. 1
   1.2  All-optical packet switch: state-of-the-art ................. 4
   1.3  1x2 All-optical packet switch................................... 9
   1.4  Scope of the thesis .................................................. 12
   1.5  Structure of the thesis ............................................. 14

2   All-optical packet switch ............................................. 17
   2.1  Introduction .......................................................... 17
   2.2  All-optical header processing ................................... 19
   2.3  All-optical flip-flop memory ..................................... 22
   2.4  All-optical packet switch: experiments ...................... 25
   2.5  Conclusions .......................................................... 29

3   Multi-output all-optical header processor ....................... 33
   3.1  Introduction .......................................................... 33
   3.2  Multi-output all-optical header processor ................. 34
   3.3  Experiments .......................................................... 37
   3.4  Conclusions .......................................................... 40

4   All-optical header processor assisted by an all-optical header pre-processor 43
   4.1  Introduction .......................................................... 43
   4.2  All-optical header pre-processor ......................... 45
   4.3  Experiments .......................................................... 47
   4.4  All-optical header processing system ...................... 50
4.5 All-optical header processing system: experiments ........................................53
4.6 Conclusions......................................................................................................55

5 Optical signal processing based on self-induced nonlinear polarization rotation in a semiconductor optical amplifier 59
5.1 Introduction......................................................................................................59
5.2 Self-polarization rotation.................................................................................61
5.3 Self-induced nonlinear polarization switch: experiments ..............................63
5.4 All-optical header processor............................................................................69
5.4.1 All-optical header processor: experiments ...........................................73
5.5 All-optical header pre-processor ......................................................................76
5.6 All-optical seed pulse generator ......................................................................79
5.6.1 All-optical self-synchronizer: experiments .............................................80
5.7 All-optical arbiter ............................................................................................83
5.7.1 All-optical arbiter: experiments .................................................................84
5.8 Conclusions......................................................................................................87

6 Ultrafast asynchronous multi-output all-optical header processor 91
6.1 Introduction......................................................................................................91
6.2 Ultrafast all-optical header processor .............................................................93
6.3 Experiments.....................................................................................................98
6.4 Conclusions....................................................................................................100

7 Conclusions.....................................................................................................103

A Model for nonlinear polarization rotation in a semiconductor optical Amplifier 109

B Characterization of the semiconductor optical amplifier 117

C Description of the hexadecimal notation and Manchester code 125
<table>
<thead>
<tr>
<th>CONTENTS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>References</td>
<td>129</td>
</tr>
<tr>
<td>List of abbreviations</td>
<td>135</td>
</tr>
<tr>
<td>List of publications</td>
<td>137</td>
</tr>
<tr>
<td>Summary in Italian</td>
<td>141</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>143</td>
</tr>
<tr>
<td>Curriculum vitae</td>
<td>145</td>
</tr>
</tbody>
</table>
Chapter 1
Introduction

1.1 Why all-optical packet switching?

In the last ten years, we have been witness of one of the most powerful telecommunication revolutions that has radically changed our habits, the Internet. A multitude of telecommunication services based on the Internet has captured many users and has pushed the telecom industry to invest in higher capacity systems. Internet demand together with WDM technology has driven a tremendous growth to the optical fiber infrastructure. Today’s optical networks are built on transponder based point-to-point WDM transmission systems with a speed of 10–40 Gbit/s. In Internet, data are transmitted in blocks called data packets; each data packet includes a header that specifies its destination. Optical circuit switches, mostly based on SDH/SONET technology [Garnot, O’Mahony, Sonet], interconnect the point-to-point WDM transmission system as well as route the data packets and monitor the optical networks. Optical packet switches, read the header, interpret the address, and route the data out a suitable port. A packet generally passes through a large number of packet switches on its way to its destination.
A number of studies show that the Internet traffic on the networks is still doubling every 8-12 months [Bourouha, Rau]. Moreover, new services such as video-based on IP networks in education, medical, entertainment and shopping will increase the demand for more bandwidth [Akiba]. Thus, optical networks operating at higher bit rate than the today’s networks will be required. However, while ultrafast point-to-point WDM transmission systems have been demonstrated in laboratory with a speed of tens of Tbit/s [Bakhshi, Charlet], high-speed optical packet switches operating at the same line-rate of the transmission system should be realized to effectively distribute high bit rate data packets to the users through optical networks.

The current generation of optical packet switches is based on electronic circuit switching technology that makes connections between networks terminals. Historically, circuit switching evolved from the voice telephone network, which original purpose was to form an electrical circuit connecting two telephones. In the telephone networks, wires carry electrical analog voice signals between individual phones and a point in the network where the calls are digitized and time-division multiplexed (TDM) into data streams. Today’s optical packet switches should handle digital packets assembled by multiplexing many digitalized voice circuits and IP data, but the principle is similar; the switches form an optical connection between two devices or points. In these opaque networks, the optical path between the end-users is interrupted at intermediate nodes by optical-electrical-optical (OEO) conversions. As well as being expensive, these OEO conversions introduce line-rate dependencies, which make it difficult for carriers to scale the infrastructure with bandwidth demand. Thus, the speed of the today’s optical packet switches is fundamentally mismatched with the line-rate of the optical transmission system.
A possible scenario for futuristic optical networks is one that implements all-optical packet switching technology. In such a case, the data packets are kept in the optical domain. The switching is based on routing information contained in the header section of the packets. In today's electrical packet switched networks, the common way of sending the routing information is in the header bits that are located near the front of the data packet. One can envision that futuristic all-optically packet switched networks will maintain this convention and require optical recognition of header bits in order to route a packet. Thus, transparent optical networks based on all-optical packet switching can take advantage of photonic parallel processing to route bands of optical channels at speeds that are not achievable through electronic processing.

An all-optical packet switch that acts as an optical router should perform several functions. Firstly, optical packet switches should be able to all-optically read the header of each packet (header processing). Secondly, the processed header information should be stored in an optical memory (optical flip-flop memory). Finally, the processed header information should drive the optical switches that routes the packet to the proper destination perhaps with a revised header (optical switching). This thesis will deal with realizing an all-optical header processing system.

In the next section, an overview of the state-of the art of the all-optical packet switching and the techniques to recognize the header patterns are presented. From this overview, it turns out that two fundamental functions should be developed to all-optically route optical packets: All-optical header processing and all-optical flip-flop memories. These two functions will be discussed in this thesis. In Section 1.3, a novel 1x2 all-optical packet switch that employs all-optical header processor to route the optical packets is briefly introduced. A crucial function to extend the 1x2 all-optical
packet switch to 1xN all-optical packet switch is a header processor that distinguishes a large number of header patterns. Moreover, low power asynchronous, and high speed operation as well as photonic integration are important features of the header processor to make a 1xN all-optical packet switch feasible. In Section 1.4, such an all-optical header processing is stated as the scope of the thesis. Finally, the structure of the thesis is presented and the major results developed in this thesis are summarized.

1.2 All-optical packet switch: state-of-the-art

Several research groups have used the architecture of the all-optical packet switch cross-connect as shown in Figure 1.1 [Keops, Murata]. It follows from Figure 1.1 that in the switching fabric three important steps take place: synchronization of the packets (including pre-amplification and regeneration of the incoming data packet), buffering that solves the contention resolution between packets at the given moment, and the third step is the switching block that routes the packets to the defined output ports based on the header information.

![Figure 1.1: Generic node structure for all-optically packet switched cross-connects.](image)
Approaches to realize a switching fabric depend on the format of the header address and data payload of the packets. The header and the data need not be necessarily transmitted at the same rates since they are processed separately. Different signaling configurations are possible for the optical header as shown in Figure 1.2. Mainly, two ways of signaling can be distinguished: in-band signaling and out-of-band signaling.

**Figure 1.2:** Resume of signaling configuration employed in the reviewed all-optical packet switch.

In the in-band signaling, the label bits are serially transmitted as an initial block data preceding the encapsulated data packet. In the mixed rate, the header and the
payload are transmitted at different data rates (see Figure 1.2); the header data has a lower data rate than the payload. An interval called the guard time separates the header address from the data payload, giving time for the system to start processing the header information before dealing with the encapsulated data. Moreover, a tail section could be attached at the end of the packets. The tail section can be used in systems that employ packets with variable length.

In the Optical Code Division Multiplexer (OCDM), see Figure 1.2, the in-band signaling is a time-space pre-processed CDMA information transmitted in the same optical channel.

In the out-of-band signaling the header information is transmitted in parallel with the encapsulated packet, either via Sub-Carrier Multiplexing (SCM) on the same optical channel as the data, or on a separate optical channel using wavelength-division multiplexing (WDM), as shown in Figure 1.2. Each of the reported possibilities depends on the technique employed to recognize the header information.

During the past few years a number of switching fabric strategies towards optically packet switching has been conducted. Glesk et al. firstly demonstrated all-optical address recognition and self-routing of photonic packets in a 250 Gbit/s packet-switched network [Glesk2]. They employed a Terahertz Optical Asymmetric Demultiplexers (TOADs) as header recognizer. Cotter et al. presented experimental results from a 100 Gbit/s self-routing packet demonstration and from a synchronous TDMA test bed [Cotter1]. Both of the reported experiments employed in-band signaling and a specially designed address code is needed to retrieve the header address from the data payload. Although both header recognizing methods operate at low power and allow photonic integration, they require a form of optical synchronization that
introduces additional complexity in the switching system. Afterwards, Carena et al. [Carena] presented an Optical Packet Experimental Routing Architecture (OPERA) network based on optical network interface router design that is optically regenerative and supports optical IP related functions including packet routing and forwarding operations and wavelength re-use. Switching of the packets is based on SCM header addressing, that was recognized by an electro-optics device, while the data payload is routed all-optically. A similar approach has been presented by Hunter et al. in WAvelength Switched Packet NETwork (WASPNET) [Hunter]. In this project, several schemes for packet header implementation are described, using sub-carrier multiplexing, separate wavelengths and in-band signaling. Experimental and computed results are analyzed to determine which of the implementations presents better performances. Wonglumsom et al. have demonstrated a Hybrid Optoelectronic Ring NETwork (HORNET) as a packet-switched WDM network for Metropolitan Area Network (MAN) [Wonglumsom]. HORNET uses a combination of optical and electrical packet switching and an optical Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) media access to provide large bandwidth to many users. The optical packets employed in HORNET consist of 2.5 Gb/s payload data, an embedded 2.5 GHz clock tone, and a SCM header at lower bit rate (80 Mbit/s) than the payload data. In ACTS KEOPS (Keys to Optical Packet Switching) project [keops], the definition, development and assessment of optical packet switching and routing networks that are capable of providing transparency to the payload bit rate were investigated. In this approach the optical packets consist of 2.5 Gb/s payload data, while the header bits at the bit rate of 622 Mbit/s were chosen to allow the use of electronics. Rau et al. reported all-optical label swapping to switch variable length 80 Gbit/s packets
with 10 Gbit/s headers over two hops [Rau]. Although the recognition of the header information has been carried out partly in electronics, this demonstrates that optical packet switching technology can operate at much higher bit rate than the electronic circuit switching technology. Moreover, Murata et al. developed an all-optical header processor without the conventional opto-to-electronic conversion [Murata]. The address information was expressed in a code used in OCDMA technology. Passive optical correlators were employed for recognizing the address information. When the optical correlator recognizes the address, a correlation pulse is formed at the optical correlator output. This correlation pulse can be used to control the switching block. Although the header processor allows photonic integration, the number of addresses that this header processor can recognize could be limited by the phase noise built up along the transmission between two nodes. Moreover, the optical switching block is still controlled by using OEO conversion.

All these approaches have shown that developments of ultrafast all-optical switches for ultra high speed routing based on wavelength routing switching of payload up 160 Gbit/s and beyond [Patel, Sokoloff, Schreieck] give to all-optical packet switch effectively advantages over electronics. However, the leak of an all-optical header processor that all-optically controls a wavelength routing switch based all-optical packet switch has limited the processing speed of the header information to a few Gbit/s.

In the following section, a proof-of-principle of a 1 x 2 all-optical packet switch concept that employs all-optical header processor to route all-optically the packet is presented [Hill1, Dorren1]. The all-optical header processor is a low power device, asynchronous and bit-rate transparent.
1.3 1x2 All-optical packet switch

An optical packet switch that operates in an optical packet switched cross-connect with a node structure as schematically presented in Figure 1.1 was demonstrated in [Hill1, Dorren1]. The function of the packet switch is to route the packet to the proper output port. The 1x2 all-optical packet switch is schematically shown in Figure 1.3 [Hill1, Dorren1]. The packet switch is based on wavelength routing principles. All the processing of the header information is carried out in the optical domain. The all-optical packet switch is made out of three functional blocks: an all-optical header processing block, an all-optical flip-flop memory block, and a wavelength conversion block.

The packets employed have a fixed duration and consist of an optical header and optical payload (shown in Figure 1.3). Between the header and the payload, there is some guard time. 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. While the header data is Non-Return to Zero (NRZ) encoded, the payload data is Manchester encoded. Moreover, the header data has a lower bit rate than...
the payload. 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 functions.

The principle that is used for wavelength conversion is cross-gain modulation [Durhuus]. Wavelength conversion by using cross-gain modulation can be obtained in a SOA by simultaneously injecting a continuous wave signal and a modulated data signal into the SOA. By using a demultiplexer, the desired wavelength channels can be separated spatially. Wavelength conversion by using cross-gain modulation leads to an inverted data signal. By using a combination of cross-gain modulation and cross-phase modulation through interferometric wavelength converters a non-inverted signal can be obtained [Durhuus]. In order to use wavelength conversion principles to route optical packets all-optically, the binary optical header pattern must be translated into a continuous wave signal of the desired wavelength. Therefore, firstly the header block has to recognize the header bits. If a packet header is recognized, the header processor creates a correlation pulse that is converted into the continuous wave by an optical flip-flop memory. The optical flip-flop memory’s output is fed into the wavelength converter to convert the packet into the desired wavelength.

The header processor employed in the packet switch is based on the two-pulse correlation principles in a Semiconductor Laser Amplifier in Loop Optical Mirror (SLALOM) configuration [Srivatsa, Eiselt]. The advantage of this method is that it does not require optical clock recovery, which reduces the complexity of the header recognition system. Moreover, the method can be used to recognize low power optical headers. On the other hand, header recognition by using two-pulse correlation in a
SLALOM structure only works for well-chosen header patterns, and Manchester encoding of the payload is necessary to guarantee that the header pattern is not repeated in the packet’s payload. In [Calabretta1] it is discussed how a multiple output low power optical header processor could be realized. Finally, the header processor is bit rate transparent.

The second function that is needed in order to realize all-optical switching of data packets is an all-optical flip-flop memory function. In [Kawaguchi] a review is presented on available technology with respect to optical flip-flop memories. We use in our optical packet switch an all-optical flip-flop concept that is based on the bi-stable operation of two coupled laser diodes. The operation principle of the optical flip-flop is described in [Hill2, Hill3]. The optical flip-flop that we use in this paper has a number of advantages. Firstly, it can provide high contrast ratios between the states. Moreover, there is no different mechanism for the set and reset operation. Furthermore, the wavelength range of the input light and the output wavelength can be large and the flip-flop has controllable and predictable switching thresholds. Finally, the flip-flop operation does not rely on second order laser effects and is not tied to a specific structure or technology.

In [Hill1, Dorren1] a 1×2 all-optical packet switch was realized that uses a SLALOM structure as a header processor and an optical flip-flop memory based on coupled laser diodes to store the processed header information. The packet switch concept is bit-rate transparent for both the header and the payload. Moreover, the packet switch requires only a limited amount of active components, and it does not require optical clock recovery or external control. The header processor employed in the 1x2 all-optical packet switch can recognize between well-designed packets. In principle, the
concept of the 1x2 all-optical packet switch can be generalized to a 1xN all-optical packet. Crucial is then to extend the header processing technique of [Hill1] to form a header processor that has a large number of output ports.

### 1.4 Scope of the thesis

The purpose of this thesis is to realize an all-optical header processing that can be used in all-optical packet switches. The header processing system must be able to distinguish between a large number of header patterns, operate at low power and allow photonic integration. These features of the header processor are essential in developing a scalable and packet-level switching all-optical packet switch. These issues associated with the header processor will be addressed in the following chapters of the thesis.

First, an all-optical header processor based on two-pulse correlation technique in a SLALOM configuration is discussed as an optical header processor unit that can recognize a distinct well-designed header pattern. The header processing unit is a low power device. Thus, the scalability of the header processor is not limited by the power consumption. Moreover, the asynchronous operation of the header processor avoids any additional synchronization stage. Experimental results that demonstrate the operation of the header processor for two header patterns are presented. Moreover, the design conditions to realize a header processor that can distinguish between a large number of header patterns are discussed.

Secondly, a simple header pre-processor based on Self-Phase Modulation (SPM) in a SOA that separates the header pattern from the data payload is presented.
Experimental results show that the performance of the header processor in combination with the header pre-processor improves, while the packet overhead is reduced. Also a pre-processing stage that discriminates the header pulses from the data payload can allow to employ an ultrafast switch to realize a multi-output all-optical header processor.

Thirdly, all-optical signal processing functions based on a nonlinear polarization switch driven by self-induced polarization rotation in a SOA are presented. An all-optical header pre-processor, an all-optical header processor, an all-optical self-synchronizer, and an all-optical arbiter function for buffering based on self-induced polarization rotation are demonstrated. The advantages of these functions with respect to the ones based on SLALOM and header pre-processor based on self-phase modulation are the low power operation and higher performances.

Finally, a novel header processing method based on ultrafast switches in combination with the header pre-processor is demonstrated. This novel method allows ultrafast operation and photonic integration, two fundamental features needed to scale the header processor for an all-optical packet switch and to save costs as well.
1.5 Structure of the thesis

The thesis is organized in seven chapters. Each of the chapters is based on published papers.

Chapter 2: A 1x2 all-optical packet switch that employs an all-optical header processor and all-optical flip-flop memory is presented. This chapter is based on results published in [Hill1, Dorren1].

Chapter 3: A multi-output all-optical header processor is presented. This chapter is based on results published in [Calabretta1].

Chapter 4: An all-optical header pre-processor that separates the header from the payload is demonstrated. The header pre-processor is useful to improve the performance of the header processing of Chapter 3. This chapter is based on results published in [Calabretta2, Calabretta3].

Chapter 5: A new technique for optical header (pre) processing based on self-induced polarization rotation in a SOA is presented. The header processor and header pre-processor operate at lower power than the header processor based on SLALOM and header pre-processor based on self phase modulation, respectively. This chapter is based on results published in [Calabretta4].
Chapter 6: An ultrafast asynchronous all-optical header processor is presented. The header processing method is a low power device that allows photonic integration. This chapter is based on results published in [Calabretta5].

Chapter 7: Conclusions are presented.
Chapter 2
All-optical packet switch

2.1 Introduction

The concept of the optical switch based on all-optical signal processing is presented schematically in Figure 2.1. The all-optical packet switch consists of three functional blocks: the all-optical header processing block, the all-optical flip-flop memory block, and the wavelength conversion block. The packet format is also shown in Figure 2.1.

The packets that are used have a fixed duration and consist of an optical header and optical payload. Between the header and the payload, there is some guard time. 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.

Figure 2.1: System concept for 1×2 all-optical packet switch.

<table>
<thead>
<tr>
<th>Packet format:</th>
<th>Header (2.5 Gb/s)</th>
<th>Manchester Encoded Payload (10 Gb/s)</th>
<th>Tail (2.5 Gb/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[FFFF0100]</td>
<td>[FFFFFFFF010]</td>
<td>[FFFF010]</td>
</tr>
</tbody>
</table>

This chapter is based on results published in:

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 functions.

The principle that is used for wavelength conversion is cross-gain modulation [Durhuus]. Wavelength conversion by using cross-gain modulation can be obtained in a SOA by simultaneously injecting a continuous wave signal and a modulated data signal into the SOA. The continuous wave signal must have a different wavelength than the data signal. The modulation of the carriers ensures that the data signal is copied onto the continuous wave signal. By using a demultiplexer, the desired wavelength channels can be separated spatially. Wavelength conversion by using cross-gain modulation leads to an inverted data signal. By using a combination of cross-gain modulation and cross-phase modulation through interferometric wavelength converters a non-inverted signal can be obtained [Durhuus]. At the output of the packet switch, the wavelengths of the routed packets could be set back to the original wavelength by using integrated wavelength converters (not shown in Figure 2.1).

In order to use wavelength conversion principles to route optical packets all-optically, the binary optical header pattern must be translated into a continuous wave signal of the desired wavelength. To obtain this goal, an optical correlator is used as an optical header processor that recognizes the header pattern. The header processor produces an optical correlation pulse at the output port only for a well-defined header pattern. The correlation pulse at the output of the header processor is converted into the continuous wave that is necessary to obtain the wavelength conversion by an optical flip-flop memory. The optical flip-flop memory's output is fed into the wavelength
converter to convert the packet into the desired wavelength.

In the next sub-sections, the operation principle of the header processor and optical flip-flop memory is presented.

### 2.2 All-optical header processing

The header-processing unit (HPU) is implemented using the structure shown in Figure 2.2. The packet structure is shown in Figure 2.1. The optical header consists of a hexadecimal FF0FF pattern followed by a guard band consisting of a hexadecimal 000 pattern. The optical payload consists of 80 bytes of a pseudorandomly generated Manchester encoded data-stream. Finally, the packet has a tail section consisting of a hexadecimal FFFFFFF pattern. The header and tail sections are effectively at a lower bit-rate than the payload. A description of hexadecimal notation and Manchester encoding is given in Appendix C.

![Figure 2.2: Experimental Setup to demonstrate SLALOM based serial all-optical header processor. MZ – Mach-Zehnder Modulator; PG – Pattern Generator; PC – Polarization Controller; τ – SLALOM Delay Line.](image)

If a packet as described above enters the HPU at port 1, the two-pulse correlation principle in a SLALOM configuration can be employed for processing the optical header. To obtain two-pulse correlation in a SLALOM configuration, three
time-scales play an important role. Firstly, there is the time $T$ between the two pulses. Moreover, there is the time $\tau$ that represents the displacement of the SOA with respect to the center of the loop. The third time scale is the recovery time $\tau_r$ of the SOA. If we chose $2\tau$ and $T$ large compared to $\tau_r$, three important cases can be distinguished as shown in Figure 2.3. The first case is when $T - 2\tau > \tau_r$ (see Figure 2.3a). This implies that the first pulse of the counter clockwise propagating pulse arrives at the SOA between the two pulses of the clockwise propagating signal. As a result of this, all the pulses in the packet header receive unsaturated gain and no correlation pulse is formed at the output port. The second case is when $|T - 2\tau| < \tau_r$ (see Figure 2.3b). This is the case in which a correlation pulse is formed, since the first pulse of the counter clockwise propagating pulse experiences a saturated SOA due to the second pulse of the clockwise propagating signal [Calabretta1]. The third case is when $2\tau - T > \tau_r$ (see Figure 2.3c). This implies that the first pulse of the counter clockwise propagating signal arrives at the SOA after the second pulse of the clockwise propagating signal has left the SOA. Hence, all the involved pulses receive unsaturated gain and no correlation pulse is formed at the output port.

Figure 2.3. The three relevant cases for the operation of the two-pulse correlation technique in a SLALOM configuration.
Suppose that a packet with a hexadecimal FF0FF header enters the HPU. Here we assume that the time $T$ corresponds to the time represented by the hexadecimal symbol 0 between the header pulses. The header pulses are both represented by the hexadecimal symbol FF. The delay time $\tau$ is chosen so that $T - 2\tau < \tau_e$ and thus a correlation pulse is formed at the output of the header processor. However if a packet with a F000F enters the HPU, no correlation pulse is formed since the time between the two pulses is so large that the first pulse of the counter clockwise propagating signal arrives at the SOA after the second pulse of the clockwise signal. Hence both pulses receive unsaturated gain and no correlation pulse is formed. The high bit-rate optical payload is suppressed because it drives the SOA in saturation. In order to obtain efficient suppression of the payload, a tail section is necessary to guarantee that the SOA remains in saturation when the payload passes through. A tail section could be useful in applications where the packet size is variable, and packet length information is needed.

Manchester encoding of the packet payload is used to achieve a crucial criterion of the header processor, the need to differentiate between header and payload. By Manchester encoding the payload, it is ensured that the header sequence will never be duplicated in the payload. Therefore the payload will never be able to produce the correlation pulses made by header data streams. In addition the Manchester encoding increases the suppression of the payload by keeping the SOA in saturation when the payload passes through. The saturated SOA can only provide a limited gain to the payload. The tail section is included to ensure that the SOA stays saturated for the entire payload. The disadvantage of Manchester encoding is the loss of effective bit rate in the payload; however, this is offset by benefits such as easier clock recovery in packet switched applications.
2.3 All-optical flip-flop memory

The all-optical flip-flop memory employed in the packet switch of Figure 2.1 is based on two coupled lasers with separate laser cavities [Hill3]. The device is schematically depicted in Figure 2.4. The system can have two states. In State 1 light from Laser 1 suppresses lasing in Laser 2. In this state the optical flip-flop memory emits continuous wave light at wavelength $\lambda_1$. Conversely, in State 2, light from Laser 2, suppresses lasing in Laser 1. In state 2, the optical flip-flop memory emits continuous wave light at wavelength $\lambda_2$.

To change states, lasing in the dominant laser can be stopped by injecting external light different from the dominant laser’s lasing wavelength. The output pulse of the optical header processor is used, to set the optical flip-flop memory into the desired wavelength.

![Figure 2.4](image)

**Figure 2.4:** Arrangement of two coupled identical lasing cavities, showing the possible states. In State 1, light from Laser 1 suppresses lasing in Laser 2. In State 2, light from Laser 2 suppresses lasing in Laser 1. To change states lasing in the master is stopped by injecting light not at the lasing wavelength.

Details about the all-optical flip-flop memory can be found in [Hill3]. In brief, it is shown that the optical flip-flop memory can be described by four coupled differential
(rate) equations, representing the carrier densities and photon densities of each laser respectively. From the rate equations two important results with respect to the operation of the all-optical packet switch are presented in [Hill3].

The first result concerns the switching power of a symmetric system of two coupled lasers. It was demonstrated in [Hill3] that changing the laser current $I$ and the facet reflectivity $R$ changes the laser output power and also the flip-flop switching power. However, the optical switching power can be varied independently from the laser output power by changing the coupling parameter between the lasers, $\eta$, [Hill3]. In Figure 2.5, the output power of the two coupled lasers versus increasing external light (switching power) is shown. On the horizontal axis the increasing optical power of external light that is injected into Laser 1 is plotted. The vertical axis represents the output power of Laser 1 and Laser 2. It is clearly visible that if the amount of external light that is injected into Laser 1 exceeds a critical threshold level (here about 0 dBm), Laser 1 switches “off” and Laser 2 switches “on”.

![Figure 2.5: Output power of the two coupled lasers versus increasing external light injected into Laser 1.](image)

The solid curve represents the output power of laser 1 (1549.32 nm). The dotted curve represents the output of laser 2 (1552.52 nm). It is clearly visible that laser 1 switches “off” and laser 2 switches “on”. The external injected light is at the wavelength $\lambda_s$ (1560.61 nm).
The property that the optical flip-flop memory can change states with low switching power is important for the design of the optical packet switch. It makes it possible to bias the optical flip-flop in such a way that it can be set or reset by the optical header processor output. The flip-flop can distinguish between the difference in optical power of the correlation pulse and the suppressed payload, by biasing the laser currents in such a way, that the optical switching power is exceeded by the correlation pulse but not by the suppressed payload.

The second result discussed in [Hill3] is the stability for coupled laser systems. The underlying concept for the operation of the optical flip-flop memory is suppression of the lasing modes by injection of external light. In principle, there are two different cases of stability. In the first case, the coupling parameter between the two lasing cavities is weak. With this it means that the maximum amount of light that is coupled from Laser 1 into Laser 2 and from Laser 2 into Laser 1 is insufficient to suppress lasing. Hence, for a sufficient injection current \(I\) both the lasers are above threshold and lasing with the identical power.

In the second case, the coupling parameter between the two lasing cavities is so strong that the amount of light that is coupled from Laser 2 into Laser 1 or from Laser 1 into Laser 2 is sufficient to suppress lasing. In this case lasing in one of the lasers is suppressed and only one of the coupled lasers is lasing. The system is now either in State 1 if Laser 1 is lasing or in State 2 when Laser 2 is lasing.

If the system of two coupled laser diodes is biased asymmetrically the system can form an all-optical threshold function [Hill3]. The system of two coupled lasers can be made asymmetric by setting the bias current \(I\) differently for Laser 1 as for Laser 2. The system of two coupled lasers is now an optical threshold function (OTF) instead of an optical flip-flop memory.
2.4 All-optical packet switch: experiments

The experimental setup to demonstrate an all-optical packet switch is presented schematically in Figure 2.6. The set-up that is presented in Figure 2.6 employs all the functionality that is described in Figure 2.1. It contains an optical header processor based on the two-pulse correlation principle in a SLALOM configuration, an optical flip-flop memory based on two coupled lasers and a wavelength routing switch based on cross-gain modulation.

In the particular experiment, the data rate of the packet payload was 2.5 Gbit/s. The header pattern was repeated for a duration of 7.5 µs. The payload consists of a data stream of 35 µs of Manchester encoded pseudo-randomly generated bits. Header and payload were separated by 5 µs of guard time. The time between to packets was 17.5 µs. Packets with two kinds of headers were employed in the experiments. The first packet header (Header 1) consists of a repeated hexadecimal FF0FF00 pattern. The second packet header (Header 2) consists of a repeated hexadecimal 0000000 pattern. Packets with alternating headers were used throughout the experiments. The optical power of an optical packet arriving at the packet switch is split in two equal parts. Half of the optical power of the packet is delayed by 2.8 km fiber and injected into a wavelength converter. The other half of the optical power is fed into the header processor.

Suppose a packet with Header 1 enters the SLALOM that is employed for header processing. In Section 2.2.2, it is discussed that the two-pulse correlation principle of SLALOM causes a correlation pulse to appear at the SLALOM’s output. The high bit-rate payload is suppressed because the SOA is driven into saturation [Srivatsa, Calabretta1].
Figure 2.6: Experimental set-up to demonstrate the 1x2 all-optical packet switch. Traffic from the network is coupled in the packet switch at the input. The packet format is given. SOA is Semiconductor Optical Amplifier, FBG is Fiber Bragg Grating, EDFA is Erbium Doped Fiber Amplifier, ISO is Isolator and PHASAR is Phased array demultiplexer.

The SOA current in the SLALOM was 136 mA and the averaged input power of the data packets was –3 dBm. The SLALOM’s output is then passed through an OTF to differentiate more strongly between the correlation pulse and the suppressed payload. The SOAs in the OTF were pumped with 135.6 mA and 198 mA respectively. The threshold function increases the contrast between the correlation pulse and the suppressed payload from 3 dB at the output of the SLALOM to over 25 dB. The operation of the OTF is explained in detail in [Hill3]. The output of the threshold function is then amplified by an EDFA and filtered. If a packet with Header 2 enters
the SLALOM structure, then no correlation pulse is formed and consequently, no pulse is generated by the optical header processor [Srivatsa, Calabretta1].

The output of the header processor produces an optical pulse when there is a packet containing Header 1, indicating that the packet should be routed to wavelength $\lambda_1$. The optical power of the pulse is split into two parts. One half of the pulse is sent directly to the set input of the optical flip-flop. This pulse sets the output wavelength of the flip-flop to wavelength $\lambda_1$. The other half is delayed by 12.5 km fiber and resets the flip-flop output back to wavelength $\lambda_2$, after a delay equal to the packet length. The SOAs in the flip-flop were pumped with 250 mA and 220.9 mA of current respectively. The optical flip-flop memory implemented here employed coupled ring lasers using Fabry-Perot filters with a bandwidth of 0.18 nm as wavelength selective elements, corresponding to the wavelength $\lambda_2$ and $\lambda_1$ respectively. This implementation provided a low noise light source suitable for wavelength conversion. It is clearly visible in Figure 2.5 that the difference in output power between the two states is over 45 dB. The threshold function was implemented using two coupled lasers made from SOAs and fiber Bragg gratings as wavelength selective elements.

Finally, the flip-flop output was then fed into a SOA where the packets were converted to the flip-flop output wavelength via cross-gain modulation [Hill1]. The SOA that was used for wavelength conversion was pumped with 386 mA of current. The output of the wavelength converter SOA was then passed through a phased array demultiplexer to spatially separate the two output wavelengths.

All the couplers used in the experiment were 50/50 couplers except those couplers used in the flip-flop. Their coupling ratios are given in Figure 2.6. The wavelength outputs 1 and 2 were converted to electrical signals via photodiodes and observed on an oscilloscope. Packets with Header 1 and Header 2 were alternatively sent through the
packet switch. The resulting waveforms are shown in Figure 2.7. The switching of packets between the two wavelengths can be clearly observed.

Figure 2.7: Oscilloscope traces of the optical power at the two switch outputs. Packets with alternating header patterns are fed into the packet switch input. The two different packets are directed to outputs at wavelength $\lambda_1$ and $\lambda_2$. If a packet with a specific header arrives at the packet switch, the designated output wavelength is switched-on, and the packet information is modulated on that specific wavelength.

Also shown in Figure 2.8 is an eye diagram of the converted output data when the flip-flop was set to wavelength 2.

Figure 2.8: Eye-diagram of the converted output data when the flip-flop was set to $\lambda_2$. The timescale is 100 psec/div and the voltage scale is 50 mv/div.
2.5 Conclusions

An advantage of all-optical switching technology over hybrid electro-optical packet switch technology is that the all-optical approach allows a much higher processing speed than the hybrid electro-optical approach. In the reported experiment the packet payload data rate was 2.5 Gbit/s. This was limited by the wavelength converter, and could potentially reach 100 Gbit/s [Ellis]. The header data rate however was much slower. This was due to the particular implementation of the optical threshold function and flip-flop used in the experiment. The lasers used to form these functions were constructed from standard commercially available fiber pigtailed components having cavity lengths of many meters. Thus the component lasers had low intrinsic modulation bandwidths, which limited the speed of the threshold function and the flip-flop. However integrated versions of these functions using lasers with cavity lengths of less than a millimeter could attain speeds in the GHz range, allowing high header data rates and shorter packet lengths. Moreover, by using optical flip-flops that are not based on coupled laser operation, but on for instance coupled Mach-Zehnder interferometers ultrafast operation of all-optical flip-flops is possible [Hill2, Hill4]. The laser based optical flip-flop however provides a high on-off contrast ratio. This makes a laser based all-optical flip-flop ideal to control a wavelength routing switch with low cross-talk.

The optical header-recognizing concept that is explained in this Chapter is bit-rate transparent, since the header recognizer based on the SLALOM structure is capable of recognizing optical packets at different bit-rates. This is true because only the time between the two pulses plays a role in the header recognition, while the data rate is bit-rate transparent. The minimum time between the two pulses is limited by the recovery time of the SOA in the SLALOM. Thus, the set-up as presented in Figure 2.4 can be
used to recognize an optical header at a data rate of 622 Mbit/s, but two-pulse correlation can also be successfully demonstrated at 10 Gbit/s header data rates [Srivatsa, Calabretta1]. Moreover, the contrast between the correlation pulse and the suppressed payload increases if the payload bit-rate increases. This is due to the gain saturation of the SOA. If a data-bit passes through, the SOA gain rapidly saturates. Afterwards the SOA gain slowly recovers. The recovery time of the SOA gain is in the order of a nanosecond. For a low data-rate (2.5 Gbit/s), the bit-time is about 0.4 nanoseconds. In this time the SOA gain typically recovers by about 50 %. If the data-rate is higher, the time between two bits is shorter, and thus there is less recovery of the SOA gain. In the case of high-bit-rate optical data, the clockwise and counter clockwise signals makes the SOA remain in deep saturation and the entire optical payload is suppressed. Theoretical analysis predicts about 18 dB suppression for packet payload at a data rate of 40 Gbit/s. As a result, the threshold function could become redundant.

Thus, since the operation of the optical flip-flop only depends on the presence of a correlation pulse, the optical header-processing concept is bit-rate transparent for the header bit-rate, and the routing of the optical payload is based on wavelength conversion principle that is also bit-rate transparent, it can be concluded that the proposed all-optical packet switch is bit rate transparent.

Finally, the 1x2 all-optical packet switch concept can be generalized to a 1xN all-optical packet switch. Crucial is to extend the two-output header recognizer to a multi-output header processor that can distinguish between a large numbers of header patterns. In the next Chapter, a multi-output all-optical header processor that can recognize a large number of header patterns is presented in order to realize a 1xN all-optical packet switch.
Chapter 3
Multi-output all-optical header processor

3.1 Introduction

In the previous Chapter, an all-optical header processing method based on a two-pulse correlation principle in a SLALOM configuration has been demonstrated [Srivatsa]. It was shown that if the packet header is chosen well, a correlation pulse can be generated at the SLALOMs output (state 1). Alternatively, suppressed payload with much smaller amplitude arrives at the SLALOMs output (state 2). This header processing method was successfully employed in a 1x2 all-optical packet switch [Hill1, Dorren1]. The two states of the packet switch correspond to the two output states of the header processor.

In principle, the concept of the 1x2 all-optical packet switch can be generalized to a 1xN all-optical packet switch. Crucial is then to generalize the header processing technique presented in Section 2.2.2, which has only one output gate that could have two different states.
In this Chapter, an all-optical header processing technique that could have N different output gates is presented. The header processor presents several advantages: the serial processing nature avoids complicated serial-to-parallel conversion, low power operation, and this method does not impose a fixed packet length and an external clock.

### 3.2 Multi-output all-optical header processor

The optical header processor and the data format are presented schematically in Figure 3.1. The optical packet has a header section of 20 bits and a payload section of 74 bytes. Header and payload are separated by a guard band of 15 bits. The payload is followed by a tail section of 5 bytes. The optical packet header consists of NRZ data at effectively lower bit-rate than the payload. The payload is Manchester encoded. Manchester coding of the payload is necessary to avoid repeated header patterns in the payload.

Two-pulse correlation technique in a SLALOM configuration has been discussed in Section 2.2 [Eiselt]. It results that if $2\tau$ and $T$ are chosen large compared to the recovery time of the SOA, $\tau_e$, three important cases can occur[Eiselt, Calabretta1]. In the first case (condition A) $T - 2\tau > \tau_e$, no correlation pulse is formed at the output gate, since all the pulses in the packet header receive unsaturated gain. In the second case (condition B) $|T - 2\tau| < \tau_e$, a correlation pulse is formed, since the first pulse of the counter clockwise propagating pulse experiences a saturated SOA due to the second pulse of the clockwise propagating signal. In the third case (condition C) $2\tau - T > \tau_e$,
no correlation pulse is formed at the output gate, since all the involved pulses receive unsaturated gain.

Figure 3.1: Experimental set-up to demonstrate SLALOM based serial all-optical header processor. The optical packets are also shown. HPU1 – Header Processor Unit 1; HPU2 – Header Processor Unit 2; \( \tau_1 \) – Delay Line for HPU1; \( \tau_2 \) – Delay Line for HPU2.

The header processor is implemented as shown in Figure 3.1. The optical power of a packet arriving at the header processor is split into two equal parts by the optical splitter. Half of the optical power is fed into the SLALOM structure of HPU1. The other half of the optical power is fed into the SLALOM structure of HPU2. The SLALOM structure in HPU1 differs from SLALOM structure in HPU2 by the displacement of the SOAs with respect to the center of the loop, hence \( \tau_1 \) differs from \( \tau_2 \).
Assume packets with two different header patterns. The first packet has a header section consisting of a hexadecimal ‘F00F0’ pattern corresponding to the time $T_1$ (see Figure 3.1). The second packet has a header section consisting of a hexadecimal ‘F000F’ pattern corresponding to the time $T$. We choose the displacement times $\tau_1$ and $\tau_2$ of the two HPUs in such a way that $T_1 - 2\tau_1 < \tau_e$ and $T_2 - 2\tau_2 < \tau_e$.

Suppose that a packet with a header F00F0 enters HPU$_1$. Since $T_1 - 2\tau_1 < \tau_e$ (condition B) a correlation pulse is formed at the output of the header processor. However if the same packet enters HPU$_2$, no correlation pulse is formed since $2\tau_2 - T_1 > \tau_e$ (condition C). Conversely, if a packet with a header F000F arrives at HPU$_2$ a correlation pulse is formed at output port 2, since the condition B is satisfied. However, no correlation pulse is formed at output port 1 since $T_2 - 2\tau_1 > \tau_e$ (condition A).

The high bit-rate optical payload is suppressed because it drives the SOA in saturation. In order to obtain efficient suppression of the payload, a tail section is necessary to guarantee that the SOA remains in saturation when the payload passes through [Srivatsa].

The conditions described above can be used to design the header processor and the header patterns. It is clear that by matching, the displacement time $2\tau_i$ and $T_i$ between the two header pulses, a large number of payload headers can be recognized. Moreover, the conditions highlight the fact that the speed of the header processor is limited by the recovery time of the SOA.

In the next Sub-section, experimental results that employ HPUs and the header patterns designed by using the discussed conditions are presented in order to validate the concept discussed.
3.3 Experiments

The concepts described above are demonstrated experimentally by using the set-up in Figure 3.1. The WDM source at $\lambda = 1550.9\,nm$ was modulated by a 10 Gbit/s Mach-Zehnder modulator, which is driven by an electronic packet generator. The packet consists of a header and tail section at a 2.5 Gbit/s NRZ data format, and the electrical payload format consists of a 10 Gbit/s Manchester encoded PRBS data stream. The average optical power was $-1.73\,dBm$ at the input of the optical header processing system. The SOAs were manufactured by JDS Uniphase and employs a $800\,\mu m$ strained bulk active region. SOA$_1$ was pumped by 126.9 $mA$ of current, and SOA$_2$ was pumped by 131.2 $mA$ of current. The displacements of the SOAs in the SLALOM configuration are set to $2\tau_1 = 4.8$ ns for the HPU$_1$ and $2\tau_2 = 6.4$ ns for HPU$_2$. The frequency of the signal generator was 9.5132 GHz.

Firstly, data packets with a hexadecimal ‘F00F0’ header pattern enter the header processor. The photocurrents at output 1 of HPU$_1$ and output 2 of HPU$_2$ are presented in Figure 3.2. It can be observed from Figure 3.2 that a correlation pulse is formed only at output 1. The header processor produces a 1.8 ns wide header correlation pulse and 4 ns correlation pulse for the tail. The suppression between the average power of the payload and the header correlation pulse was 14.39 dB.
Figure 3.2: Packet structure and output of the header processor. The average packet payload is suppressed by 14.39 dB. The timescale is 10 ns/div and the voltage scale is 50 mV/div.

In Figure 3.3, the photocurrents at output 1 and output 2 are presented if a packet with a hexadecimal “F000F” pattern enters the header processor. It follows from Figure 3.3 that a header correlation pulse is formed only at output 2. The header processor produces a 1.8 ns wide header correlation pulse and 4 ns correlation pulse for the tail. The suppression between the average power of the payload and the header correlation pulse was 14.44 dB.
Figure 3.3: Packet structure and output of the header processor. The average packet payload is suppressed by 14.44 dB. The timescale is 10 ns/div and the voltage scale is 50 mV/div.

It has been demonstrated that the set-up presented in Figure 3.1 is indeed capable of processing two different headers. Moreover, since the HPUs and the header patterns employed in the experiments have been designed by using the conditions above discussed, this principle can be extended to process a larger number of optical header patterns by (cascading) including more HPUs (with a different displacement time) in the set-up of Figure 3.1. The header processor can benefit from the fact that the HPU is a low power device, so that cascading a large number of HPUs implies affordable power consumption. Finally, the predicted increase of the suppression between the average power of the payload and the header correlation pulse as the payload data rate
increases was experimentally confirmed. This could result in a decreasing number of active components necessary to build the packet switch, since the threshold function becomes redundant.

3.4 Conclusions

The header processing method employed to demonstrate the 1x2 all-optical packet switch concept can be extended to recognize a large number of header patterns. As a result of this the optical packet switch can also be generalized to a 1xN all-optical packet switch. In order to generalize the all-optical packet switch, a multi-output all-optical header processor that can distinguish a large number of header patterns has been demonstrated. The multi-output all-optical header processor is realized by combining two-pulse correlation technique in a SLALOM configuration and proper designed header patterns. In particular, each header processing unit is designed to distinguish one pre-designed header pattern. Conditions to design the header processor units and the header patterns are also reported. The header processor unit is a low power device. This makes the header processing unit able to distinguish a large number of header patterns with an affordable power consumption.

The concept of the multi-output header processor and the design condition have been demonstrated experimentally. Two header patterns are distinguished at two distinct output ports by two distinct HPUs. The data rate of the Manchester encoded payload that was employed in the experiment was 10 Gbit/s (5 Gbit/s effectively). The measured contrast ratio at one output port between the header correlation pulse and the suppressed payload was higher than 14.4 dB. This result is in agreement with the
predicted increase of the payload suppression as the payload data rate increases. As a consequence, the threshold function could become redundant. Moreover, the contrast ratio between the header correlation pulse at one output port with respect to the suppressed payload at the other output port was also higher than 14.4 dB. In the context of a 1xN packet switch, these parameters indicate that only one flip-flop memory can be set by the optical power of the header correlation pulse, while the optical power of the suppressed payload is not sufficient to change the original state of the other flip-flops. This makes the multi-output all-optical header processor suitable for 1xN all-optical packet switch.
Chapter 4

All-optical header processor assisted by an all-optical header pre-processor

4.1 Introduction

To generalize a 1x2 all-optical packet switch into a 1xN all-optical packet switch, a multi-output all-optical header processor based on two-pulse correlation principle in a SLALOM configuration was successfully demonstrated in the previous Chapter. The packet format employed in the experiments to demonstrate the header processor [Srivatsa, Calabretta1] is shown in Figure 4.1a. The header of the data packets that were used in the experiments was at a lower bit-rate (2.5 Gbit/s) than the packet payload (10 Gbit/s). Moreover, the payload was Manchester encoded to avoid that the header pattern is repeated in the packet payload. The packets had a guard-time between the header and the payload and a tail section. The length of the guard-time was equal to the length of the header section. The guard-time section and the tail section were necessary to adequately suppress the packet payload.
Figure 4.1: Packet structure of the packets employed in the demonstration of the header processor: a) packet format employed in the demonstration of the all-optical header processor in the Chapter 3; b) the simplified packet format employed in the demonstration of the all-optical header processor assisted by an all-optical header pre-processor is illustrated.

In order to minimize the packet overhead, a Bragg grating assisted all-optical header pre-processor [Calabretta2, Calabretta3] is presented in this chapter. In the optical packet switch that is presented in Chapter 2, an optical threshold function is used to compensate for an insufficient contrast between the correlated header pulses and the suppressed packet payload. A pre-processing step that discriminates the header and payload is useful for two reasons. Firstly, it improves the performance of the header processor so that the optical threshold function becomes redundant. Secondly, the packet structure could be simplified. We will show that by using the Bragg-grating assisted all-optical header pre-processor, the guard-time and the tail section become redundant so that the packet overhead is reduced.

This chapter is organized as follows. In Section 4.2, the concepts of the header pre-processor are discussed. Experimental evidences are presented as well in order to confirm the operation of the header pre-processor. In Section 4.3, experimental results
are presented to show that the header pre-processor improves the performance of the SLALOM based header processor (enlarge the contrast between the correlation pulse and the suppressed packet payload) and that the packet structure can be simplified. Finally, the chapter is concluded with a discussion.

4.2 All-optical header pre-processor

The optical header pre-processor based on Self-Phase Modulation (SPM) in an SOA is given in Figure 4.2. The system is made out of an SOA in combination with a narrow bandwidth Fiber Bragg Grating (FBG). The packet format is presented in Figure 4.1b. The simplified packet format is similar as the packet format employed in the demonstration of the header processor in the Chapter 3 (also shown in Figure 4.1a), with the exception that the guard time and tail sections are taken out. The header section consists of NRZ data-bits that are at a lower bit-rate than the packet payload but in this case the data packets have no guard-time section an no tail section.

Figure 4.2: Experimental set-up of the Bragg-grating assisted all-optical header pre-processor. EDFA – Erbium doped fiber Amplifier; OC – Optical circulator; PC – Polarization Controller; FBG- Fiber Bragg Grating; SOA – Semiconductor Optical Amplifier.
The packet payload is Manchester encoded. In a Manchester encoded data stream a binary “1” and a binary “0” is represented by the rising or falling transitions respectively. Therefore, the average signal power of the payload is constant, regardless of the specific bit pattern. In the header pre-processing concept, using Manchester encoded payload is essential to guarantee that the SOA remains in saturation when the packet payload passes by.

When an optical bit at wavelength $\lambda$ with sufficient optical power arrives at the SOA, an overshoot in the amplification at the leading edge of the bit is generated due to the gain saturation of the SOA, while the rest of the bit experiences a constant saturated gain. The SOA gain variations also cause SPM and consequently a frequency shift of the bit that is described by [Agrawal 1]:

$$\omega = -\frac{1}{2\pi} \frac{d\phi}{dt}; \quad \frac{d\phi}{dz} = -\frac{1}{2} \alpha g$$

In the equation, $\omega$ is the chirp, and $g$ is the SOA gain. Furthermore, $\alpha$ is the linewidth enhancement factor, and $\phi$ is the phase of the bit. Furthermore, $z$ and $t$ are distance and time respectively. A characterization of these parameters as a function of the SOA drive current and of the optical input power is reported in Appendix B. The equation describes the frequency shift as a function of the SOA gain. As a result, the wavelength at the leading edge of the bit is red chirped ($\lambda \rightarrow \lambda + \Delta \lambda$), while the rest of the bit experiences no chirp. By using a FBG centred around $\lambda + \Delta \lambda$, the red chirped leading edge of the pulse can be filtered out. The amplitude of the filtered leading edge of the bit depends on the gain of the amplifier.

When an optical data packet is fed into the Bragg grating assisted optical header pre-processor, a red shift is generated at the leading edge of all the data bits. The time
between the pulses in the header has been chosen larger than the recovery time of the SOA. This results in a strong red shift at the leading edges of the header bits. The constant averaged optical power of the Manchester encoded payload ensures that the SOA remains in deep saturation when the payload passes by. Hence, the red shift that is introduced at the leading edge of the payload bits is small compared to the red shift introduced at the leading edge of the header bits.

In the next sub-section, two experiments will be performed to show the operation of the header pre-processor. In the first experiment, the SPM effect in a SOA as a function of the data rate of the input data signal is investigated. In the second experiment the operation of the header pre-processor is demonstrated.

### 4.3 Experiments

The experimental set-up used to demonstrate the concept of the Bragg grating assisted optical header pre-processor is shown in Figure 4.2. The laser source had a wavelength of 1558.34 nm and was modulated by a 10 Gbit/s Mach-Zehnder modulator, which was driven by a pulse-pattern generator. The SOA in the header pre-processor was pumped with 204 mA of current. The FBG employed had a reflectivity of 99.9 % at $\lambda=1558.93$ nm with a bandwidth equal to 0.43 nm. The measured red shift at the leading edge of the data bit was 0.42 nm.

First, a NRZ encoded PRBS $2^7-1$ data at a bit-rate of 10 Gbit/s is employed in the experiment. The input data signal is shown in Figure 4.3a, where the PRBS generates a casual sequences of ‘0s’ between the ‘1’ pulses. Longer sequences of ‘0s’ can be interpreted as low data bit rate, while short sequences of ‘0s’ can be interpreted as high data bit rate. The average optical power of the optical packets at the input of the header
pre-processor is 4 dBm. The output of the header pre-processor is shown in Figure 4.3b. It consists of pulses with different amplitude corresponding to the leading edges of the input data signal. The effect of the SPM in a SOA as a function of the data bit rate can be clearly seen. If the sequences of ‘0s’ between two pulses is longer than the recovery time of the SOA, the SPM effect is very high, and the amplitude of the leading edges is high. While if the sequences of ‘0s’ between two pulses is shorter than the recovery time of the SOA, the SPM effect is low and then the amplitude of the leading edges is low. The measured contrast ratio between the amplitude of the highest and the lowest leading edge pulse is higher than 11 dB.

![Figure 4.3: Measured oscilloscope traces. The timescale is 500 ps/div and voltage scale 100 mV/div. In Trace a, the NRZ encoded PRBS data optical signal is shown. In Trace b, the output of the optical header pre-processor is shown.](image)

In the second experiment, the operation of the header pre-processor is demonstrated. The packet format is shown in Figure 4.1b. The packets have a header
section consisting of NRZ data at a bit-rate of 2.5 Gbit/s, and a payload section consisting of Manchester encoded PRBS data at a bit-rate of 10 Gbit/s. Note that in contrast to the results presented in [Srivatsa, Calabretta1], the packets used in this experiment have no guard-time in between the header and the payload and no tail sections. Sequential optical packets with two different header patterns are used in the experiments. The first header (Header 1) has a ‘1100 0000 1100’ bit pattern. The ‘11’ symbol represents the header pulse. The sequence of ‘0s’ represents the time in between the header pulses. The second header (Header 2) has a ‘1100 0000 0011’ bit pattern. In Figure 4.4a packets with Header 1 and Header 2 are shown. The average optical power of the optical packets at the input of the header pre-processor is 4 dBm. The oscilloscope trace of the signal at the output of the Bragg grating assisted header pre-processor is presented in Figure 4.4b. It is clearly visible in Figure 4.4b that the header pre-processor generates a pulse at the leading edges of the header bits. The averaged suppression of the packet payload is 11.4 dB.

These experimental results conclude that a Bragg grating assisted all-optical header pre-processor can discriminate the header at lower data rate than the payload. The payload suppression increases as the data rate increases. Operation at a header bit-rate of 2.5 Gbit/s and a payload data rate of 10 Gbit/s has been demonstrated. However, operation at higher bit-rate may be possible by decreasing the gain recovery time of the SOA [Girardin]. Moreover, the design of the optical header pre-processor involves only a single SOA and an optical filter, thus the system could be integrated in a photonic integrated circuit.

In the next Section experimental results will be presented to demonstrate that the header pre-processor improves the performance of the optical header processor based
on SLALOM configuration and simplifies the packet structure so that the packet overhead is reduced.

**Figure 4.4:** Measured oscilloscope traces. The timescale is 2 ns/div and voltage scale 100 mV/div. In Trace a, the optical packets are shown. In Trace b, the output of the optical header pre-processor is shown.

### 4.4 All-optical header processing system

In this section it will be shown that the performance of the SLALOM based header processor assisted by the header pre-processor improves, while the packet structure can be simplified. The experimental set-up that is used to demonstrate the improvements of the header processor in combination with the header pre-processor is shown in Figure
4.5. It consists of two main parts enclosed in the dash box; the header pre-processor discussed in the previous section, and the header processor based on SLALOM configuration.

![Experimental set-up of the Bragg-grating assisted all-optical header pre-processor in combination with an optical header processor based on two-pulse correlation in a SLALOM configuration.](image)

**Figure 4.5:** Experimental set-up of the Bragg-grating assisted all-optical header pre-processor in combination with an optical header processor based on two-pulse correlation in a SLALOM configuration. EDFA – Erbium doped fiber Amplifier; OC – Optical circulator; PC – Polarization Controller; \( \tau \) – Delay of the SOA in the SLALOM; SOA – Semiconductor Optical Amplifier; FBG- Fiber Bragg Grating.

The concept of an optical header processor unit based on two pulse correlation in a SLALOM configuration was explained in the Section 2.2 and the design conditions to realize a multi-output header processor by cascading several header processing units was discussed in Section 3.2. Such a header processing unit can be implemented as shown in the dashed box in Figure 4.5. The data format is shown in Figure 4.1b. The optical packet consists of a header section and a payload section. The optical packet header consists of NRZ data at effectively lower bit-rate than the packet payload.
Manchester coding of the payload is necessary to avoid repeated header patterns in the payload [Srivatsa, Calabretta1].

Assume that two packets with two different header patterns are used in the demonstration. The first header (Header 1) has a header section consisting of a ‘1100 0000 1100’ bit pattern corresponding to the time $T_1$ (see Figure 4.6). The second header (Header 2) has a header section consisting of a ‘1100 0000 0011’ bit pattern corresponding to the time $T_2$. Assume that the header pre-processor is the same of that demonstrated in the previous Section. Moreover, assume that the SLALOM based header processing unit illustrated in Figure 4.5 has a displacement of the SOA with respect to the center of the loop equal to $\tau_1$ in such a way the relationship $T_1 - 2\tau_1 < \tau_e$ ($\tau_e$ is the electron-hole recombination time) is satisfied.

Following the set-up shown in Figure 4.5, the two sequential packets are first pre-processed by the header pre-processor. As a result, the output of the header pre-processor consists of two pulses corresponding to the leading edges of the header pulses while the data payload is suppressed. The output of the header pre-processor is fed into the header processing unit. In the Section 3.2 it has been shown that if the displacement times $\tau_1$ of the header processing unit satisfy both the relationships $T_1 - 2\tau_1 < \tau_e$ and $T_2 - 2\tau_1 < \tau_e$, only for packet with Header 1 a correlation pulse is formed at the output of HPU, while no correlation pulse is formed at the output of HPU when a packet with Header 2 is processed. Although the operating principle of the header processing unit does not change, no tail or guard time sections have been employed to suppress the data payload, since the payload has been previously suppressed by the header pre-processor. This results in a reduction of the packet overhead (guard-time and tail sections are redundant). In the following sub-section, experimental results are presented that
demonstrate the advantages of the header processor assisted by the header pre-processor.

4.5 All-optical header processing system: experiments

The experimental set-up used to demonstrate the concept of the header processor assisted by the optical header pre-processor is shown in Figure 4.5. The laser source had a wavelength of 1558.34 nm and was modulated by a 10 Gbit/s Mach-Zehnder modulator, which was driven by a pulse-pattern generator. The packets have a header section consisting of NRZ data at a bit-rate of 2.5 Gbit/s, and a payload section consisting of Manchester encoded PRBS data at a bit-rate of 10 Gbit/s. Note that in contrast to the results presented in [Srivatsa, Calabretta1], the packets used in this experiment have no guard-time in between the header and the payload and no tail sections. The SOA in the header pre-processor was pumped with 204 mA of current, corresponding to a saturation gain of 10 dB with CW light. The FBG employed had a reflectivity of 99.9 % at $\lambda=1558.93$ nm with a bandwidth equal to 0.43 nm. The measured red shift at the leading edge of the data bit was 0.42 nm.

Sequential optical packets with two different header patterns are used in the experiments. The first header (Header 1) has a ‘1100 0000 1100’ bit pattern. The ‘11’ symbol represents the header pulse. The sequence of ‘0s’ represents the time in between the header pulses. The time between the leading edges of the two header pulses is equal to $T_1=3.2$ ns. The second header (Header 2) has a ‘1100 0000 0011’ bit pattern. In this case the time between the leading edges of the two header pulses is equal to $T_2=4$ ns. In
Figure 4.6a packets with Header 1 and Header 2 are shown. The average optical power of the optical packets at the input of the header pre-processor is 4 dBm.

In order to demonstrate that the use of the Bragg grating assisted header pre-processor improves the performance of a SLALOM based header processor [Srivatsa, Calabretta1], the packets are first pre-processed by the header pre-processor. Then, the output of the header pre-processor is fed into the SLALOM based optical header processor (see Figure 4.5). The oscilloscope trace of the signal at the output of the Bragg grating assisted header pre-processor is presented in Figure 4.6b (measured at point A in Figure 4.5). It is clearly visible in Figure 4.6b that the header pre-processor generates a pulse at the leading edges of the header bits. Moreover, the time between the header pulses of the first and second header pattern remains equal to $T_1$ and $T_2$, respectively.

The output of the header pre-processor is fed into the header processing unit. The SOA in the SLALOM configuration was pumped with 119 mA of current. The displacement of the SOA with respect to the centre of the loop is $\tau = 1.6$ ns. The displacement of the SOA matches with the time $T_1$ between the leading edges of pulses in Header 1. Thus, a correlation pulse is expected to be formed at the output of the header processor only for optical packets with Header 1.

This is confirmed in Figure 4.6c where it is clearly visible that only for the packet with Header 1 a correlation pulse is formed. The contrast ratio between the average optical power of the header correlation pulse and the suppressed payload is equal to 17.8 dB, resulting in an improvement of 3.3 dB compared to the results presented in the previous Chapter.
Figure 4.6: Measured oscilloscope traces. The timescale is 2 ns/div and voltage scale 100 mV/div. In Trace a, the optical packets are shown. In Trace b, the output of the optical header pre-processor (measured at point A in Figure 4.5) is shown. In Trace c, the output of the SLALOM is presented.

4.6 Conclusions

A simple Bragg grating assisted all-optical header pre-processor that can be used to enlarge the suppression of the packet payload has been demonstrated. Increasing the packet payload suppression is important since it makes the optical threshold function in the packet switch that is presented in [Hill1] redundant, and thus allows us to simplify the optical packet switch architecture. In order to integrate the packet switch as a photonic integrated device, a simpler switching architecture is desirable. Also extension of the 1 x 2 packet switch to a packet switch with more output gates, makes it attractive to use a header pre-processor [Calabretta2, Calabretta3]. In
this case a single header pre-processor could replace all the optical threshold functions that are required at the SLALOM outputs. Thus, leading to a reduction of the number of active components in the optical packet switch.

Operation of the header pre-processor has been demonstrated for data packets with a payload data rate of 10 Gbit/s, and an optical header at 2.5 Gbit/s. Operation at higher bit-rates is possible by decreasing the gain recovery time of the SOA [Girardin]. Moreover, the design of the optical header pre-processor involves only a single SOA and an optical filter, thus the system could be integrated in a photonic integrated circuit. It should be remarked that in the header pre-processor only a small portion of the bit experiences a red-shift and in this specific configuration there is a large loss in the FBG. Nevertheless, the output of the header pre-processor contains sufficient energy to utilize the two-pulse correlation principle in the SLALOM configuration.

It has been shown that using an optical header pre-processor makes the guard-time and the tail section of the optical packets redundant so that the packet overhead is reduced by more than 50%. A reduced packet overhead improves the efficiency of the packet switch. The contrast ratio of the header pre-processor is equal to 11.4 dB. If the SLALOM based header processor operates in combination with the header pre-processor, it has been shown that the contrast ratio between the header correlation pulse and the suppressed payload is equal to 17.8 dB, which is an increase of 3.3 dB compared to the result obtained in the previous Chapter [Srivatsa, Calabretta1].

Finally, a header pre-processor that discriminates between the header pulses and the data payload can allow the use of an ultrafast optical switch [Sokoloff]-[Schreieck]-[Patel] as header processor to recognize the position of the second pulse with respect to the first header pulse. As a result, ultrafast implementation of the header processor is
feasible. Moreover, as an important advantage of increasing the switching speed, the
optical delay lines involved in the correlation can be shortened and photonic integrated.
In Chapter 6, an ultrafast switch in combination with the header pre-processor will be
investigated in order to design an ultrafast optical header processor.
Chapter 5
Optical signal processing based on self-induced nonlinear polarization rotation in a semiconductor optical amplifier

5.1 Introduction
In the previous Chapters an all-optical header processing system assisted by an all-optical header pre-processor was demonstrated. The optical signal processing functions implemented to realize the header processor and header pre-processor are based on a nonlinear device such as an SOA. In particular, the header processor and header pre-processor have been realized by employing self-induced effects in a nonlinear SOA such as SPM or XGM/XPM in a loop mirror (such as SLALOM). These effects occur when an optical signal introduces a change in a nonlinear medium through which the signal propagates while the medium reacts back on the signal itself. Other examples of self-induced effects in a SOA employed to realize all-optical signal processing functions are all-optical threshold functions [Zhao,Hill3], optical self-synchronization [Cardakli, Xia, Cotter, Deng] and optical clock recovery [Lee]. Most of these optical signal-processing functions have been realized by employing self-induced optical
effects in combination with an interferometer. The evident advantages of realizing an all-optical signal processing functions based on the self-induced effects in a SOA are the absence of external controls involved in the processing, and then the asynchronous operation of the device. As a consequence of these advantages, the total system is simplified (no synchronization issues or additional active components are required). Recently, considerable attention has been paid to optical signal processing based on nonlinear polarization switches [Soto, Manning]. Examples include wavelength conversion [Liu1] and all-optical flip-flop memories [Liu2]. A model for a nonlinear polarization rotation switch has been presented in [Dorren2]. The examples mentioned above are based on nonlinear polarization rotation in an SOA in which the polarization state of a probe pulse is controlled by external (saturating) pump light. In this Chapter, experimental results are presented in which the nonlinear polarization switch is driven by self-induced effects [Calabretta4]. First, Self-induced Polarization Rotation (SPR) in an SOA is investigated in the context of all-optical signal processing. It will be shown that the polarization dependent gain saturation model presented in [Dorren2] can be applied to describe SPR in an SOA. In the case of SPR the role of the saturating control beam is taken over by the data bits themselves. Furthermore, it will also be shown that SPR in an SOA in combination with a nonlinear polarization switch can be employed for all-optical signal processing. In order to illustrate the potential of this concept for telecommunication technology, an all-optical header processor, an all-optical seed pulse generator, and an optical arbiter based on SPR are presented. Finally, experimental results indicate that optical signal processing functions based on self-polarization rotation have a higher extinction ratio and a lower power operation compared to similar functions based on self-phase modulation.
The Chapter is organized as follows: In Section 5.2, SPR in an SOA and a nonlinear polarization switch based on SPR is demonstrated. In Section 5.3, applications of all-optical signal processing based on SPR are presented. An all-optical header processing system, an optical seed pulse generator for packet synchronization and an all-optical arbiter that could be employed in a packet buffer are demonstrated at a data rate of 10 Gbit/s. The Chapter is concluded with a discussion.

5.2 Self-polarization rotation

The general configuration of a nonlinear polarization switch is depicted in the dashed box in Figure 5.1. In [Dorren2] a model for nonlinear polarization rotation driven by polarization dependent gain saturation in a SOA is presented. Details are provided in Appendix A. In brief, the polarization switch operates in a similar fashion to a Mach Zehnder Interferometer switch, but the role of the different arms is taken over by the TE and TM modes of the incoming light. The modes propagate independently through the SOA but they have indirect interaction via the carriers. In the model presented in [Dorren2] the TE and TM modes couple to two different reservoirs of holes. Thus, if the SOA is saturated by an optical control signal, the gain saturation of the TE mode differs from the gain saturation of the TM mode [Dorren2]. Hence, also the refractive index change of the TE mode differs from the refractive index change of the TM mode. If a small probe signal with well-defined polarization is simultaneously injected into the SOA with a saturating pump signal, a phase difference between the modes builds up as the light propagates through the SOA. When the two modes recombine at the polarization beam splitter (PBS), the phase difference determines which of the output ports of the PBS the signal is switched to [Dorren2].
In the experiments a commercially available strained bulk SOA (produced by JDS-Uniphase) was employed. This device is similar to the one that is used in [Dorren2] and thus the modeling results presented in that reference can be used to describe the system applications that follow. In [Dorren2] the presence of tensile strain in the SOA was modeled by using a population imbalance factor $f$ that has to be determined from characterization measurements. The model presented in [Dorren2] can also be used to model nonlinear polarization rotation in unstrained SOAs by setting $f=1$. In the latter case the nonlinear polarization rotation is described by the different confinement factors of the TE and TM modes and thus for $f=1$, the model in [Dorren2] is equivalent to that presented in [Stephens].

In the case of SPR, the phase difference between the TE and TM modes is created by the signal itself. When an optical bit with sufficient optical power arrives at the SOA, the leading edge of the bit introduces gain saturation in the SOA. Since the SOA gain saturation is polarization dependent, the TE component of the data bit
experiences a different gain saturation than the TM component. Thus, the leading edge of a data bit can introduce a rotation of the polarization state.

5.3 Self-induced nonlinear polarization switch: experiments

In this sub-section, it will be demonstrated that an optical switch can be driven by SPR. The experimental set-up that is used to demonstrate the SPR concepts is given in Figure 5.1. The laser source emits Continuous Wave (CW) light at a wavelength of 1550.91 nm that is injected into the polarization switch via an optical attenuator. The polarization switch consists of a SOA, two polarization controllers (PC’s) and a PBS. At the PBS the two modes recombine. PC1 is used to adjust the polarization of the input signal with respect to the SOA layers (the angle between the TE and TM modes is approximately 45 degrees [Manning]). PC2 is used to adjust the polarization of the SOA output with respect to the orientation of the PBS. As an initial experiment, to characterize the population imbalance factor \( f \), we measure the output power at output port 2 as a function of the pump current. The attenuator was set in such a way that the power of the CW-light that enters the SOA via the PC1 was equal to \(-20\) dBm. This guarantees that the CW-light does not saturate the SOA. PC2 was set in such a way that no light outputs at port 2. The solid line in Figure 5.2 shows the power at output port 2 as a function of the SOA pump current. It can be observed that the power of output port 2 increases as the pump current increases. The population imbalance factor \( f \) can be determined as a function of the SOA injection current from the curve presented in Figure 5.2 by following a similar approach as used in [Dorren2]. We find that \( f \) varies in a range of 0.5 and 0.6 if the SOA injection current varies between 70 mA and 390 mA.
All the other parameters that are used in modeling results throughout this Section are listed in Table 5.1 [Dorren2].

### Table 5.1: Parameters used in the simulations of self-polarization rotation in a semiconductor optical amplifier.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>500 ps</td>
</tr>
<tr>
<td>$f$</td>
<td>0.52</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>$1 \times 10^{-3}$ mA$^{-1}$</td>
</tr>
<tr>
<td>$N_0$</td>
<td>$10^8$</td>
</tr>
<tr>
<td>$v_g^{TE}$ = $v_g^{TM}$</td>
<td>100 μm/ps</td>
</tr>
<tr>
<td>$J^{TE}$</td>
<td>0.2</td>
</tr>
<tr>
<td>$J^{TM}$</td>
<td>0.14</td>
</tr>
<tr>
<td>$\xi^{TE}$</td>
<td>$7 \times 10^{-9}$ ps$^{-1}$</td>
</tr>
<tr>
<td>$\xi^{TM}$</td>
<td>$6.5 \times 10^{-9}$ ps$^{-1}$</td>
</tr>
<tr>
<td>$e$</td>
<td>$1.6 \times 10^{-19}$ C</td>
</tr>
<tr>
<td>$\alpha_{int}^{TE}$ = $\alpha_{int}^{TM}$</td>
<td>0.27 ps$^{-1}$</td>
</tr>
<tr>
<td>$\alpha_{TE}$ = $\alpha_{TM}$</td>
<td>5</td>
</tr>
<tr>
<td>$L$</td>
<td>800 μm</td>
</tr>
<tr>
<td>$h$</td>
<td>$6.626 \times 10^{-34}$ J s</td>
</tr>
</tbody>
</table>

The dashed curve in Figure 5.2 shows the computed output power as a function of the injection current. This curve is computed by using the model of [Dorren2]. It can be observed that the simulations are in excellent agreement with the measurements.
In the second experiment, measurement of the static behavior of the polarization switch as a function of the power of the input light is presented. In this case the SOA current is set to 170 mA and PC$_2$ was set in such a way that the light is suppressed at output port 2 for low optical input power. The optical power at output port 2 has been measured as a function of the power of the input light. The result is shown by the solid line in Figure 5.3, from which it can be observed that the output power at port 2 increases as a function of the input power. The shape of the curve in Figure 5.3 matches with the theoretical model of [Dorren2] which predicts that the relationship between the output power at port 2 and the polarization angle ($\Delta \theta$) is proportional to 1-cos($\Delta \theta$).

The dashed line in Figure 5.3 represents a simulation result for the output power of the nonlinear polarization switch using the model of [Dorren2]. In the simulations, $f$ is set to 0.52, and moreover, the optical input power used in the computations has been
increased by 4.6 dB to compensate for the insertion losses (1.3 dB for each PC, and 3.3 dB for the facet losses, including the connector losses).

**Figure 5.3:** Curves showing the measured optical power (solid line) and computed optical power (dashed line) at output port 2 as a function of the intensity of the CW input optical power. The inset shows a zoomed-out view of the switching region.

It is clearly visible in Figure 5.3 that the modeling results are in excellent agreement with the measured data. In Figure 5.4, the computed gain for the TE and TM modes is presented. It can be observed that the difference between the TE gain (solid line) and the TM gain (dashed line) decreases when the input power increases. The gain difference introduces a phase difference between the modes that results in a rotation of the polarization angle [Dorren2]. Since the output power at port 2 changes as a function of the polarization angle ($\Delta \theta$) according to $1 - \cos(\Delta \theta)$, for small $\Delta \theta$, the transfer function can be approximated by $\Delta \theta^2$. This indicates that a linear change in the input power leads to a quadratic change in the polarization rotation, and thus a large variation in the output power.
Figure 5.4: Computed SOA gain for the TE (solid line) and the TM (dashed line) modes as a function of the intensity of the input signal.

Measurements show a static contrast ratio larger than 18 dB between the output light in the case that $\Delta \theta = 0$ (the intensity of the input light was 0.63 mW) and the output light in the case that $\Delta \theta$ has been changed by increasing the intensity of the input light with 3 dB with respect to the case where $\Delta \theta = 0$ (see also the inset of Figure 5.3). Also the dynamic contrast ratio has been measured for a NRZ data signal at a bit rate of 2.5 Gbit/s. The experimental set-up is shown in Figure 5.5.

Figure 5.5: Experimental set-up of the nonlinear polarization switch. PC: Polarization Controller, SOA: Semiconductor Optical Amplifier, BPF: Band Pass Filter, PBS: Polarization Beam Splitter.
In Figure 5.6a and Figure 5.6b, the input signals with average powers of 0.63 mW (corresponding to $\Delta \theta = 0$) and 1.35 mW are presented. In Figure 5.6c and Figure 5.6d, the traces measured at port 2 are presented. It follows that a signal with an average power of 0.63 mW cannot pass through the PBS (see Figure 5.6c), while the signal with higher input power (1.35 mW) can pass through the PBS (see Figure 5.6d). The dynamic contrast ratio was measured larger than 10 dB.

These results provide evidence that a nonlinear polarization switch (NPS) can be driven by SPR in an SOA and also that the model presented in [Dorren2] can explain SPR in an SOA.

![Figure 5.6: Experimental switching results for the nonlinear polarization switch. a) Optical input signal (average power 0.63); b) Optical input signal (average power 1.35); c) Trace of output port 2 for an input signal with average optical power of 0.63 mW; d) Trace of output port 2 for an input signal with average optical power of 1.35 mW.](image)
In the next Section, applications of all-optical signal processing functionalities based on NPS, that can be applied in all-optical packet switched cross-connects, will be demonstrated.

5.4 All-optical header processor

An all-optical correlator is a fundamental building block to realize all-optical header recognition [Hill1, Calabretta1, Calabretta2, Dorren1]. In Chapter 3 and 4, an all-optical correlator for all-optical header processor was demonstrated by employing a SLALOM configuration.

In Chapter 4, an all-optical header pre-processor that can separate the header pulses from the data payload was shown. In this sub-section, it will be shown that the NPS discussed in the previous section can act as an optical correlator. Thus, an alternative header processing method based on the combination of the NPS and the header pre-processor is presented. Experimental results are provided to demonstrate this header processing method.

The optical correlator is presented schematically in the dashed box of Figure 5.7. The optical power of the data signal is split by a coupler into one data signal that enters the SOA on the right side (henceforth called the left propagating data signal) and one data signal that enters the SOA (via the optical circulator) on the left side (henceforth called the right propagating data signal). The right propagating data signal is first delayed by a time \( \tau_L \) and then fed into the SOA of the optical correlator via an optical circulator. PC2 is set to switch the light to output port 1, only if the left propagating data signal passes through the SOA.
When the right propagating data signal also enters the SOA, one can distinguish two cases. In the first case, the optical power of the right propagating data signal is not sufficient to saturate the SOA. As a result, the left propagating data signal experiences
no polarization rotation. Thus, the left propagating data signal is switched to output port 1. In the second case, the optical power of the right propagating data signal is sufficient to saturate the SOA. In this case a correlation between the left propagating and the delayed right propagating data signal is formed since the left propagating data signal experiences a saturated SOA and thus polarization rotation. As a result, the left propagating data signal is switched to output port 2. Moreover, the time window in which pulse correlation can take place is $\tau_e$, where $\tau_e$ is the time that the SOA needs to recover from the saturation state.

The optical correlator can function as an all-optical header processor as follows. Output port 2 represents the output of the header processor. Suppose that the header addresses consist of two header pulses and that the displacement (in time) between two header pulses is $\tau$ (see packet format in Figure 5.7). A header correlation pulse is formed at output port 2 if $\tau_L - \tau < \tau_e$, since the second left propagating header pulse experiences a saturated SOA introduced by the first right propagating header pulse, while no header correlation pulse is formed at output port 2 if $\tau - \tau_L > \tau_e$ or $\tau_L - \tau > \tau_e$ since in this case, all pulses propagate through an unsaturated SOA [Calabretta1].

The header processing system is schematically presented in Figure 5.7. It consists of a header pre-processor (HPP) [Calabretta2] followed by the header processor discussed above. The optical packet format is also presented in Figure 5.7. The header section consists of two header pulses that are separated by a sequence of alternating NRZ ‘0’ and ‘1’ bits at the same bit rate as the data payload, with the exception of a sequence of ‘0s’ with duration longer than the recovery time of the SOA which is placed in front of the second header pulse. The position of the second header pulse within the header section is used to define a unique header pattern. Moreover, the
space between the second header pulse and the payload is also filled with the sequence of alternating NRZ ‘0’ and ‘1’ bits. The sequence of alternating NRZ ‘0’ and ‘1’ bits is used to keep the SOA in saturation when the packet passes through the SOA, while the sequence of ‘0s’ gives the SOA time to recover before the second header pulse passes through the SOA. The payload was Manchester encoded to avoid repetition of the header pattern in the packet payload. Manchester encoding also guarantees that the average signal power of the payload is constant, regardless the specific bit pattern.

As an example, let’s assume packets with only two different header patterns. The first packet has a header section consisting of a hexadecimal ‘FAAAAAA00FA’ pattern (Header 1). For this header pattern, the time between the header pulses is $\tau_1$ (see Figure 5.8a). The second packet has a header section consisting of a hexadecimal ‘FAAAAAAA00F’ pattern (Header 2) corresponding to a time $\tau_2$. First, the packets are pre-processed by an HPP that separates the two header pulses from the packet payload. The operation of the HPP based on Self-Phase Modulation (SPM) in an SOA is described in [Calabretta2]. The output signal of the HPP consists of the leading edges of the two NRZ header pulses while the rest of the packet is suppressed (see Figure 5.8b).

The output of the HPP is fed into the optical correlator based header processor. The delay $\tau_L$ was chosen in such a way that $\tau_L - \tau_1 < \tau_c$ and $\tau_2 - \tau_L > \tau_c$. Thus, only a correlation pulse is formed at output port 2 for packets with Header 1 (since $\tau_L - \tau_1 < \tau_c$). No correlation pulse is formed at the output port 2 for packets with Header 2 since $\tau_2 - \tau_L > \tau_c$. 


5.4.1 All-optical header processor: experiments

The concepts described above were demonstrated by using the experimental set-up shown in Figure 5.7. The laser source had a wavelength of 1558.34 nm and was modulated by a 10 Gbit/s Mach-Zehnder modulator, which was driven by a pulse-pattern generator. The packet format is shown in Figure 5.7. The packets had a header section that consisted of two NRZ header pulses at a bit-rate of effectively 2.5 Gbit/s. The header pulses were separated by a sequence of alternating NRZ ‘0’ and ‘1’ bits at the same bit rate of the packet payload. The duration of the sequence of ‘0s’ that were placed in front of the second header pulse was 0.8 ns. The payload section consisted of Manchester encoded PRBS data at a bit-rate of 10 Gbit/s. The SOA in the HPP was pumped with 204 mA of current. The FBG employed had a reflectivity of 99.9 % at λ=1558.93 nm with a bandwidth equal to 0.43 nm.

The optical packets used in the experiment consisted of sequential optical packets with Header 1 and Header 2 as shown in Figure 5.8a. The time between the leading edges of the two header pulses was equal to \( \tau_1 = 3.8 \) ns and \( \tau_2 = 4.8 \) ns for the Header 1 and Header 2 respectively. The average optical power of the packets at the input of the HPP was 4 dBm. The oscilloscope trace of the signal at the output of the HPP is presented in Figure 4.8b. It is clearly visible in Figure 5.8b that the HPP generates a pulse at the leading edges of the header bits. The average payload suppression is 11.4 dB. The output of the HPP is then amplified by an EDFA, filtered by a 2 nm band pass filter and fed into the header processor (see Figure 5.7). The average optical power of the left and right propagating signals was –8 dBm and 2.35 dBm respectively (before the optical circulator). The SOA in the header processor was pumped with 178 mA of current. The PBS has an extinction ratio of 30 dB. The delay
was $\tau_L = 3.8$ ns that matches the time $\tau_1$ between the leading edges of pulses in Header 1. Thus, a correlation pulse only for optical packets with Header 1 is expected. This is confirmed in Figure 5.8c, where a correlation pulse is only formed for packets with Header 1. The contrast ratio between the average optical power of the header correlation pulse and the suppressed payload is equal to 18.6 dB. This is an improvement of 4.4 dB compared to the results presented in [Hill1, Calabretta1, Dorren1].

The experimental results indicate that the header processing system can distinguish between two different header patterns. A limitation of this approach is that a packet header only contains two bits of information. The length of the packet header can be extended by creating larger packet headers that are built up out of combinations of two bits (in a similar fashion as in [Calabretta1]). The minimum interval between different header bits is determined by the SOA recovery time (~ 1 ns). This means that the duration of the packet is proportional to the number of header bits times the SOA recovery time. It should be noted however that the SOA recovery time can be decreased to 60 ps [Girardin]. This means that the length of header patterns can be reduced with more than a factor 10.
Figure 5.8: Experimental results demonstrating the operation of the header processor. a) Optical input signal; b) Output of a header pre-processor based on SPM; c) Output of header processor (measured at output port 2).
5.5 All-optical header pre-processor

In this Section, it will be shown that the NPS of Figure 5.5 can also be used as a header pre-processor. In this case PC₂ is set in such a way that the unsaturated input data packets are switched to port 2. The header pre-processor can be employed in an all-optical header processor to discriminate between signals at different data rates as demonstrated in the previous Sub-section.

When a data pulse enters the NPS, the leading edge will saturate the SOA. In Section 5.2, it was explained that the SOA gain saturation is polarization dependent, and hence, rotation of the polarization angle takes place. This ensures that only the leading edge of a data pulse is switched to output port 2 (at the leading edge the SOA is not yet saturated), while the rest of the bit leaves the NPS at port 1 (since the SOA is saturated and the polarization angle of the light is changed).

When a packet with a header as described in the previous subsection enters the header pre-processor, the leading edges of both header pulses are routed to port 2. The packet payload and the remainder of the header pulse are switched to port 1.

Assume that the optical packets have a packet format as shown in Figure 5.7. The sequence of NRZ ‘0s’ placed in front of the NRZ header pulse is longer than the gain recovery time of the SOA. The transitions of the Manchester encoded data payload and the alternating ‘1’ and ‘0’ bits in the header section are faster than the gain recovery time of the SOA. This packet format guarantees that when the optical packet enters the header pre-processor, only the leading edges of the two NRZ header pulses experience full gain, while the rest of the packet experiences the SOA in saturation. Thus, the leading edges of the two header pulses are switched to output port 2 and the rest of the packet is switched to output port 1.
The experimental set-up used to demonstrate the header pre-processor is shown in Figure 5.5. The laser source had a wavelength of 1550.91 nm and was modulated by a 10 Gbit/s Mach-Zehnder modulator, which was driven by a pulse-pattern generator. The packets employed in the experiments are shown in Figure 5.9a. The SOA was pumped with 141.5 mA of current. The average optical power of the packets measured before the SOA was –0.2 dBm. The measured output signals at output port 1 and output port 2 are shown in Figure 5.9b and Figure 5.9c. Output port 2 represents the output of the header pre-processor. The extinction ratio between the header pulses and the suppressed payload is larger than 15 dBm, which is an improvement of circa 4 dB with respect to the HPP presented in [Calabretta2]. In addition, output port 1 provides an amplified copy of the input packets. Moreover, the header pre-processor operates at much lower power compared to the HPP presented in [Calabretta2].

In conclusion, an alternative header pre-processor based on an NPS that can operate at a bit rate of 10 Gbit/s has been demonstrated. Higher operation speed is possible by decreasing the recovery time of the SOA [Girardin]. This header pre-processor presents several advantages over HPP: lower power operation, higher extinction ratio, and an extra output port that provides an amplified copy of the packet.
Figure 5.9: Experimental results of the header pre-processor based on nonlinear polarization switch. a) Optical input signal; b) Header pre-processor output (measured at the output port 2); c) Amplified copy of the input signal (measured at the output port 1).
5.6 All-optical seed pulse generator

An optical packet switched cross-connect requires bit-level synchronization and phase alignment for each packet in order to perform signal processing and routing [Xia]. Self-synchronization is one of the methods employed to achieve bit-level synchronization [Xia, Cotter1, Deng]. In general, a self-synchronization method requires a seed pulse synchronized at the beginning of the packet. The pulse can be used to generate a local clock for packet synchronization [Cardakli, Xia, Cotter1, Deng, Sakamoto]. An advantage of the self-synchronization approach is that it is insensitive to timing jitter between packets or network architectures [Cotter2]. In this Section, an all-optical seed pulse generator based on the NPS described in the previous section is presented.

The optical seed pulse generator is schematically shown in Figure 5.10. It consists of an asymmetric passive Mach-Zehnder Interferometer (MZI) followed by the NPS. The format of the packets that are used is shown in Figure 5.7.

![Experimental set-up of the optical seed pulse generator. MZI: asymmetric Mach-Zehnder Interferometer, \( \tau_d \): time delay between the two arms of the MZI.](image)

The role of the MZI is to merge the packet with a delayed copy of itself. It is essential that the delay is shorter than the interval between the header bits. As a result at the MZI
output the specific packet structure is lost. When the output of the MZI enters the NPS, only the leading edge of the first NRZ header pulse experiences the unsaturated gain of the SOA, while the remainder of the data packet experiences a saturated gain. Thus, only the leading edge of the first NRZ header pulse is switched to output port 2, while the remainder of the data packet is switched to output port 1. The pulse switched to output port 2 is synchronized with the beginning of the packet and this represents the seed pulse.

5.6.1 All-optical self-synchronizer: experiments

The experimental set-up used to demonstrate the optical seed pulse generator is shown in Figure 5.10. The laser source had a wavelength of 1550.91 nm and was modulated by a 10 Gbit/s Mach-Zehnder modulator, which was driven by a pulse-pattern generator. The input packets employed in the experiments are shown in Figure 5.11a. The asymmetry $\tau_d$ between the two arms of the MZI was measured to be ~ 1 ns. The SOA was pumped with 142.5 mA of current. The average optical power of the packets measured before the MZI was 1.5 dBm.

In the first experiment, it will be demonstrated that the optical seed pulse generator forms a seed pulse synchronized with the beginning of the packet. The output of the optical seed pulse generator is shown in Figure 5.11b. The seed pulses, synchronized with the beginning of the packets, are clearly visible. The extinction ratio between the seed pulse and the suppressed packet is larger than 15 dB.
Figure 5.11: Experimental results demonstrating the operation of the optical seed pulse generator. a) Optical input signal; b) Output of the self-synchronizer (measured at the output port 2).

In the second experiment, it will be shown that the optical seed pulse generator can still extract timing information, even when the input data packet has an extinction ratio of 5 dB. This confirms that the optical seed pulse generator can be employed as a first stage to generate a local clock for synchronization purposes. The optical input packet is shown in Figure 5.12a. The output of the optical seed pulse generator is presented in Figure 5.12b.
Figure 5.12: Experimental results demonstrating the operation of the optical seed pulse generator. The extinction ratio of the input data packet employed in this experiment is 5 dB. a) Optical input signal; b) Output of the self-synchronizer (measured at the output port 2).

The seed pulses synchronized with the beginning of the packets are clearly visible in Figure 5.12b. The measured extinction ratio between the average power of the seed pulse and the suppressed payload is over 10 dB. However, since PC2 is set in such a way that the input data are switched to port 2, the power of the guard time between the packets also leaves port 2. This leads to a reduction of the extinction ratio with 5 dB. The extinction ratio can be increased by cascading another NPS or an optical threshold function similar to that presented in [Hill2, Hill3] after the optical seed pulse generator.
5.7 All-optical arbiter

The header processing system demonstrated in Section 5.3.1 can only handle one packet at any given moment. Therefore, optical buffers are necessary to avoid packet contention. In [Dorren1, Liu3] an all-optical buffering concept is demonstrated based on a wavelength routing approach. The arbiter function was obtained by using an optical threshold function. 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. The wavelength routing switch consists of a wavelength converter followed by a demultiplexer. In this Section, a novel all-optical arbiter function (OAF) based on an NPS that can indicate whether packet contention takes place is presented.

The OAF consists of a MZI and a NPS as schematically shown in Figure 5.13. The packet format is shown in Figure 5.7.

Figure 5.13: Experimental set-up for the all-optical arbiter. $T_p$: time delay equal to one packet slot. $\tau_d$: time delay between the two arms of the MZI.
It can be distinguished between a packet with low priority (packet 1) and a packet with high priority (packet 2). Packet 1 enters the NPS via the MZI, while packet 2 enters the NPS via the optical circulator (OC). Let’s assume that the packets arrive synchronously at the NPS. If no contention takes place, only packet 1 enters the NPS. In that case the NPS acts as the self-synchronizer discussed before. Thus, a single output pulse corresponding to the leading edge of the NRZ header pulses is formed at output port 2.

When packet contention takes place, packet 1 and packet 2 arrive simultaneously at the NPS. In this case packet 1 experiences a saturated SOA introduced by packet 2, and thus the polarization angle of packet 1 is rotated. Hence, no output pulse is formed at output port 2. The OAF can be employed in a buffering system as follows [Dorren1, Liu3]. The pulse at the output of the OAF (output port 2) can be used to set/reset a flip-flop memory [Hill1, Hill3, Dorren1]. The output of the flip-flop controls an optical wavelength routing switch.

5.7.1 All-optical arbiter: experiments

The experimental set-up used to demonstrate the concept of the OAF is shown in Figure 5.13. The laser source had a wavelength of 1550.91 nm and was modulated by a 10 Gbit/s Mach-Zehnder modulator, which was driven by a pulse-pattern generator. The packets employed in the experiment are shown in Figure 5.14a. Two sequential optical packets were used in the experiments. Packet 1 contains a header pattern consisting of a hexadecimal ‘FAAAAAA00FA’ bit pattern. Packet 2 contains a header pattern consisting of a hexadecimal ‘FAAAAAAA00F’ bit pattern. Also visible in
Figure 5.14a is a third dummy packet that consists of a sequence of ‘0s’ with a length equal to the other packets.

Since a single modulated source is employed in the experiment, an optical coupler has been used to create two sequences of packets to be used as different inputs of the OAF. One sequence of packets that enters the SOA (via the MZI) on the right side (left propagating sequence of packets) is shown in Figure 5.14a. The other sequence of packets that enters the SOA (via the optical circulator) on the left side (right propagating sequence of packets) is first delayed by $T_p$ as shown in Figure 5.14b. The time delay $T_p$ was set equal to one packet duration. This ensures that alternating conditions of packet contention between Packet 1 and Packet 2 take place. The coupler ratio was chosen to compensate for the different propagation losses experienced by the left and right propagating sequences of packets. The average optical power of the left propagating sequence of packets that entered the NPS via the MZI was 1.5 dBm (measured before the MZI), while the average optical power of the right propagating sequence of packets that entered the NPS via the OC was 2.2 dBm (measured before the OC). The SOA was pumped with 126 mA of current.

The output of port 2 of the OAF is shown in Figure 5.14c. It is clearly visible that when contention takes place, no optical pulse is formed at the output of the OAF. However, an optical pulse is formed at output port 2 when no contention takes place. The extinction ratio between the average optical power of the optical pulse and the suppressed packet is 14.3 dB, enough to drive the optical flip-flop memory [Hill1, Hill3, Dorren1].
**Figure 5.14:** Experimental results demonstrating the operation of the all-optical arbiter. a) Optical input signal via the asymmetric Mach-Zehnder Interferometer (MZI); b) Optical input signal via the Optical Circulator (OC); c) Output of the all-optical arbiter (measured at output port 2).
5.8 Conclusions

In this Chapter, all-optical signal processing based on self-induced nonlinear polarization rotation in an SOA has been demonstrated. Experimental and numerical results confirm that the mechanism behind the self-polarization rotation is the polarization dependent gain saturation as described in [Dorren2]. It has also been demonstrated that an NPS based on SPR in a polarization switch interferometer can be used to achieve optical signal processing functions that are useful for all-optical packet switching. It should be remarked that an NPS can only be utilized if the polarization of the input signal is well-defined. In system applications, this could be realized by employing a polarization independent regenerator in front of the NPS.

An all-optical header processing function at a bit rate of 10 Gbit/s has been realized, which can distinguish between two different header patterns by employing nonlinear polarization rotation in an SOA. These results show that by properly designing the header processor and the header patterns, a large number of different header patterns can be recognized. The header processor based on SPR has an extinction ratio between the header correlation pulse and the suppressed payload of 18.6 dB, which is an improvement of 4.4 dB compared with results published in [Hill1, Calabretta1, Dorren1]. Moreover, it should be noted that the recognition of the header pattern means the recognition of the position of the second header pulse with respect to the first header pulse. An advantage of employing a header pre-processor that separates the header pulses from the data payload, is that an all-optical logic AND can be used as optical correlator that distinguishes the header pattern. In Section 5.3.1, the all-optical logic AND has been realized by an NPS. However, the NPS can be replaced by ultrafast switches such as TOAD, MZI, or UNI. As a result, the header processing method
discussed in this Chapter can potentially operate at ultrafast speed. Ultrafast processing will be investigated in Chapter 6.

An all-optical arbiter function at a bit rate of 10 Gbit/s has also been demonstrated. The arbiter can be used in a buffering system in a similar way as that presented in [Dorren1, Liu3]. The main difference between our arbiter and the one presented in [Dorren1, Liu3] is that the output of the arbiter presented in [Dorren1, Liu3] was a CW signal. In this approach, the output of the arbiter is an optical pulse that drives the wavelength routing switch via an optical flip-flop [Hill1, Hill3, Dorren1].

A novel optical seed pulse generator at a bit rate of 10 Gbit/s that produces a seed pulse synchronized with the beginning of the data packet has also been demonstrated. The seed pulse can be used to generate a local clock for packet synchronization. Moreover, the operation of the optical seed pulse generator does not require any particular marker [Cardakli, Xia, Cotter1, Deng] in the packet format that identifies the beginning of the packet, rather it uses the packet format itself. The extinction ratio between the seed pulse and the suppressed packet was 15 dB. In addition, experimental results have shown that a seed pulse can be extracted even with an input signal extinction ratio of 5 dB, confirming that the optical seed pulse generator could be used as the first stage in an optical cross-connect node.

Finally, experimental results show that the signal processing functions based on self-polarization rotation have a lower power operation and a higher extinction ratio than the same functions based on self-phase modulation.
Chapter 6
Ultrafast asynchronous multi-output all-optical header processor

6.1 Introduction

For a practical implementation of an all-optical header processing system utilized in
devise an all-optical packet switch, the header processor should be scalable, high-
speed, have low power consumption and be photonic integrated on a chip. In particular,
scalability defines the capacity of the header processor to recognize a large amount of
header information and eventually to update the system easily to recognize more
headers. High-speed operation is required to match the line-rate of the optical
transmission system so that no bottleneck is generated. Low power consumption and
photonic integration guarantee large scale production, low cost and integration with
other functionalities on the same chip.

Several header processing systems have been proposed that can be used to implement
an all-optical packet switch [Glesk1, Willner]. In [Glesk1], ultrafast all-optical header
processing using a Terahertz Optical Asymmetric Demultiplexer (TOAD) is
demonstrated at a bit rate of 250 Gbit/s. This TOAD based header recognition operates

This chapter is based on results submitted as:
at low energy and allows photonic integration, but a disadvantage is that the control pulse should be synchronized with the header bits. Also, since this header recognition concept is based on the binary value of a single bit, the header recognizer can only distinguish between two header patterns. In [Calabretta1], an asynchronous multi-output all-optical header processing technique based on the two-pulse correlation principle in a Semiconductor Laser Amplifier in a Loop Optical Mirror configuration (SLALOM) is presented. This concept was employed in an all-optical packet switch [Hill1]. This header processing technique does not require a synchronous control pulse, but the processing speed of the SLALOM based header processor is determined by the SOA recovery time $\tau_r (~1\,\text{ns})$ [Eiselt]. Moreover, the SOA has to be placed offset to the center of the loop with a distance that is larger than $\tau_r v_g (~10\,\text{cm})$ where $v_g$ is the group velocity of light ($~100\,\mu\text{m}/\text{ps}$). Thus, a disadvantage of the header processing method presented in [Calabretta1] is that the SLALOM configuration is too large to allow photonic integration.

In this Chapter, a different header processing technique that can distinguish a large number of header patterns and which allows asynchronous operation and photonic integration, is presented. The concept is based on combining the header pre-processor that is presented in [Calabretta2, Calabretta4] with a TOAD that acts as a header recognizer. The function of the HPP is twofold: it separates the packet header from the packet payload, but it also creates the control signal that is required for TOAD operation. The header pre-processor output is fed into the TOAD for header recognition. Essential for TOAD operation is the employment of a control pulse for optical switching [Sokoloff]. Whereas for header recognition based on two-pulse correlation in a SLALOM configuration, the SOA recovery time plays a critical role,
for header recognition based on TOAD operation, the timing of a control pulse is essential. As a direct consequence of this a header recognizing system based on TOAD operation allows photonic integration. Moreover, TOAD operation guarantees ultrafast header processing at low power. Finally, the header processing system as a whole operates asynchronously and the system can be extended to have multiple output ports.

The Chapter is organized as follows. In Section 6.2, the operation principle of the header processing technique is presented. In Section 6.3, the experimental results are shown to validate the header processing operation. Finally, the Chapter is concluded with a discussion.

### 6.2 Ultrafast all-optical header processor

The optical header processing system is schematically presented in Figure 6.1. It consists of a header pre-processor and two TOADs that are placed in parallel. Each of the TOADs is designed to recognize a specific header pattern.

An essential point of the header processing concept as proposed in this paper, is that the address information is encoded by the difference in time between the leading edges of two header pulses. The function of the HPP is to extract the header information form the data packet. It is shown in [Calabretta4] that this can done by employing self polarization rotation in a nonlinear polarization switch. The nonlinear polarization switch is shown in the dashed box of Figure 6.1. In brief, in the nonlinear polarization switch an optical bit with a polarization angle of approximately 45 degrees in injected into the SOA. As the bit propagates through the SOA, the polarization angle rotates due to the polarization dependent gain and index saturation [Calabretta4].
Figure 6.1 The experimental setup that demonstrates the header processing system and packet structure are presented. PC: Polarization Controller, EDFA: Erbium Doped Fiber Amplifier, BPF: Band Pass Filter, PBS: Polarizing Beam Splitter A - Header pulses; B - Alternates ‘1’ and ‘0’ bits; C - Sequence of ‘0’ bits.

Essential however is that the rotation of the polarization angle of the leading edge of the header bit differs from the rotation of the polarization angle of the trailing edge due to
self gain saturation. By aligning the polarization of the SOA output carefully with the polarizing beam splitter, only the leading edge of the header bit outputs the nonlinear polarization switch [Calabretta4]. The space between the header pulses is filled with a sequence of alternating NRZ ‘0’ and ‘1’ bits at the same bit rate as the data payload, which ensures that the SOA remains saturated while the packet header passes through [Calabretta4]. Also, a series of ‘0’ with a duration that is longer than the SOA recovery time \( \tau_r \) is placed before the second header bit, to allow the amplifier to recover before the second header pulse arrives at the SOA. Similarly, the guard time in between the header section and the payload section is filled with a sequence of alternating ‘0’ and ‘1’ bits to keep the amplifier saturated when the packet passes by. Finally, the packet payload is Manchester encoded to avoid repetition of the header pattern in the packet payload. Manchester encoding also guarantees that the average signal power of the payload is constant, regardless the specific bit pattern [Calabretta4].

The operation of the TOAD is described in [Sokoloff]. As shown in the dashed box of Figure 6.1, a TOAD consists of an optical loop that contains an SOA, which acts as a nonlinear element. The SOA is placed with an offset \( \Delta x \) with respect to the center of the loop. When an optical input pulse enters the TOAD, the pulse power is split by a 50:50 coupler into a clock-wise propagating pulse (CW) and counter-clockwise propagating pulse (CCW). The optical power of the CW- and CCW propagating pulses should be lower than the SOA saturation power, thus both pulses experience the same gain and phase shift when passing through the SOA. Hence, if no control pulse is present, the recombined CW- and CCW propagating pulses reflect back at the TOAD input port. The role of the control pulse that is coupled into the loop via a 90:10 coupler is to create a refractive index change in the SOA. If the control pulse arrives at the SOA after the
CW propagating pulse has passed through but before the CCW propagating pulse arrives at the SOA, the CW- and CCW propagating pulses no longer experience the same gain and refractive index. This leads to the creation of a pulse at the TOAD output [Sokoloff]. The polarization of the control light is orthogonal with respect to the polarization of the input pulses. Thus the control light can be removed by using a Polarizing Beam Splitter (PBS).

The TOAD can function as a header processor as follows. The header pre-processor output pulses form the TOAD input signal and are split by an 80:20 coupler into a low power CW- and CCW propagating data signal and a high power control signal. The CCW propagating pulses arrive at the SOA a time \( \tau_{sw} = 2 \Delta x / v_g \) later with respect to the CW propagating pulses. If no control is present the data signal is reflected back to the TOAD input. The first pulse of the high power control signal is used to saturate the SOA. Header recognition can be implemented by accurately timing the control pulses.

There are three interesting cases that are shown in Figure 6.2. In the first case (see Figure 6.2a), the first control pulse arrives at the SOA after the second CCW propagating data pulse. Thus, the control pulse arrives too late at the SOA to create a pulse at the TOAD output. In the second case (see Figure 6.2b), the control light arrives at the SOA after the second CW propagating data pulse has passed through the SOA, but before the second CCW propagating data pulse arrives at the SOA. Hence, the control light creates a refractive index change in the SOA that is only experienced by the second CCW propagating pulse. Hence, a pulse is created at the TOAD output. In the third case (see Figure 6.2c), the control light arrives at the SOA before the second CW- and CCW pulses. In this case the SOA refractive index change is experienced by both the second CW- and CCW pulses. Thus no pulse is formed at the TOAD output.
The separation of the two pulses should be large enough to ensure that the control light cannot switch the first header pulse.

Figure 6.2. Timing of the control pulses for the three relevant cases for the operation of the header processor; a) The control arrives at the SOA after that all the pulses have passed the SOA; b) The control arrives at the SOA after that the second CW pulse has passed the SOA but before that the second CCW arrives at the SOA; c) The control arrives at the SOA before that both the CW and CCW second pulses arrive at the SOA.

It can be concluded that a pulse is only output from the TOAD if the time between the two header pulses matches with the timing of the control pulse. The TOAD output pulse can be used to set/reset an optical flip-flop that controls the optical wavelength routing switch, similarly as described in Chapter 2. It is important to notice that in contrast to header recognition based on two-pulse correlation in a SLALOM configuration, this header recognition concept does not critically depend on the SOA recovery time. Hence, the offset of the SOA with respect to the center of the loop and the delays for the control pulses can be made sufficiently small in order for this header processing concept to allow photonic integration.
## 6.3 Experiments

The concepts described above were demonstrated by using the experimental set-up shown in Figure 6.1. The laser source had a wavelength of 1550.91 nm and was modulated by a 10 Gbit/s Mach-Zehnder modulator, which was driven by a pattern generator. The packet format is also shown in Figure 6.1. The duration of the sequence of ‘0’ bits that were placed in front of the second header pulse was 0.9 ns. The payload section consisted of Manchester encoded PRBS data at a bit-rate of 10 Gbit/s.

Sequential optical packets with header sections consisting of a hexadecimal ‘D555 5555 5500 3555’ pattern (Header 1) and a hexadecimal ‘D555 5555 5540 1C55’ pattern (Header 2) were used in the experiments (see Figure 6.3a). This means that the time between the header pulses are 5 ns and 5.1 ns for Header 1 and Header 2 respectively. The packets are first pre-processed by the header pre-processor. The average optical power of the packets at the input of the header pre-processor was 2.3 dBm. The extinction ratio of the input optical data packet was 12 dB. The SOA in the header pre-processor was pumped with 123.5 mA of current. The PBS has an extinction ratio of 30 dB. The oscilloscope trace of the signal that outputs the header pre-processor is presented in Figure 6.3b. It is clearly visible in Figure 6.3b that the header pre-processor generates a pulse at the leading edges of the header bits. The pulses have a duration of 50 ps each. The average payload suppression is 18.4 dB. The header pre-processor output is than split by an 80:20 coupler to create the input- and control signals of the TOADs. The input and control signal are split by 50:50 couplers before being distributed over the TOADs. For both TOADs $\tau_{sw}$ is 50 ps. The control signals were delayed by 4.95 ns and 5.05 ns before being fed in TOAD 1 and TOAD 2, respectively.
Figure 6.3. Measured oscilloscope traces. a) The optical data packets that input the header processor. Packets with two different headers are shown. The inset shows details of the packet header; b) The output of the header pre-processor. It is clearly visible that only pulses synchronized with the leading edge of the header bits output the header pre-processor; c) Output at port 1. It is visible that only packet 1 is recognized; d) Similarly as in c, but now for packet 2.
The SOAs in TOAD 1 and TOAD 2 were pumped with 116 mA and 121 mA of current, respectively. The energy of the input pulses was 50 fJ while the energy of the control pulses was 0.8 pJ. According to the design of the TOADs and the header patterns, it is expected that a pulse is formed at output port 1 only for packets with Header 1 and a pulse is formed at output port 2 only for packets with Header 2. The traces of output port 1 and output port 2 are shown in Figure 6.3c and 6.3d, respectively. It is clearly visible that indeed a pulse is formed at output port 1 only for packets with Header 1 while no pulse is formed for packets with Header 2. It can be observed that a pulse is formed at output port 2 only for packets with Header 2 while no pulse is formed for packet with Header 1. The contrast ratio between the pulse and the suppressed payload is higher than 14.4 dB.

These experiments indicate that the set-up presented in Figure 6.1 is indeed capable of recognizing two different headers but the concept is scalable so that a larger number of packet headers can be processed. A limitation of this approach is that a packet header only contains two bits of information. The length of the packet header grows linearly with the number of packet header times the header processor’s speed (~100 ps). It should be noted however that the processing speed of the header processor can be decreased to 4 ps [Sokoloff]. This means that the length of header patterns can be reduced with more than a factor 25.

6.4 Conclusions

An all-optical header processing system based on combining a single header preprocessor and two TOADs that act as header recognizers was demonstrated. The header processing system can distinguish between two different packet headers and the output
is sent to two distinct output ports. We believe that this principle can be extended to recognize more header patterns by constructing packet headers that are made out of a sequence of two header bits as shown in this paper.

The design of the header processing system provides several key advantages over alternative techniques. The header pre-processor operates asynchronously so that the header processing system as a whole can be operated in an asynchronous fashion. The system also operates as a low power device. In the presented experiments the bit rate was 10 Gbit/s and $\tau_{sw}$ was 50 ps, but optical switching of a 250 Gbit/s signal has been demonstrated using a TOAD for which $\tau_{sw}$ was 4 ps [Glesk1, Sokoloff]. Thus, we believe that the header processor can operate at higher bit rates than 10 Gbit/s. Moreover, a shorter offset time in the order of a few picoseconds allows photonic integration of the header processor. Finally, a header processing system that can recognize a large number of header patterns can be utilized in devising an all-optical packet switch.
Chapter 7
Conclusions

In this section the most important conclusions with respect to the original results that can be found in Chapter 3 to Chapter 6 of this thesis are given.

In Chapter 3, an all-optical serial header processor is discussed that is capable of recognizing 2 different packet headers and that forms correlation pulses at two distinct output ports. This header recognizing principle can be extended to recognize more header patterns. Our demonstration showed the header processor working with payload data rates of 10 Gbit/s, however we believe that it is possible to process payloads at higher bit rates.

The design of the header processor shown in Chapter 2 provides several key advantages over alternate techniques. Firstly, the serial nature of the header processor removes the additional complexity of the separation of payload and header sections of the packet and does not impose a fixed packet length. In addition, the header processor is a low power device; the amount of input power required can be adjusted by changing the current into the SOA.

In Chapter 4, a Bragg grating assisted all-optical header pre-processor is demonstrated. The contrast ratio of the header pre-processor is 11.4 dB. It was demonstrated the operation for data packets with a packet header at a bit-rate of 2.5 Gbit/s and payload at
a data rate of 10 Gbit/s. Operation at higher bit-rate may be possible by increasing the gain recovery time of the SOA. Moreover, the design of the optical header pre-processor involves only a single SOA and an optical filter, thus the system could be integrated in a photonic integrated circuit.

It was also demonstrated that the header pre-processor improves the performance of the optical header processor that is used in the packet switch of Chapter 2. The guard-time and the tail section of the optical packets become redundant so that the packet overhead is reduced. Moreover, the contrast ratio between the header correlation pulse and the suppressed payload is equal to 17.8 dB, which is an increase of 3.3 dB compared to the result obtained in Chapter 2.

Chapter 5 is devoted to all-optical signal processing based on self-induced nonlinear polarization rotation in an SOA. Experimental and numerical results confirm that the mechanism behind the self-polarization rotation is the polarization dependent gain saturation as described in Appendix A. It was also demonstrated that a nonlinear polarization switch based on self-polarization rotation can be used to achieve optical signal processing functions that are useful for all-optical packet switching. It should be remarked that a nonlinear polarization switches can only be utilized if the polarization of the input signal is well-defined. In system applications, this could be realized by employing a polarization independent regenerator in front of the nonlinear polarization switch.

It was realized an all-optical header processing function at a bit rate of 10 Gbit/s, which can distinguish between two different header patterns by employing nonlinear polarization rotation in a SOA. We believe that by properly designing the header processor and the header patterns, a large number of different header patterns
can be recognized. The header processor based on SPR has an extinction ratio between
the header correlation pulse and the suppressed payload of 18.6 dB, which is an
improvement of 4.4 dB compared with the header processor of the packet switch in
Chapter 2.

It was also demonstrated an all-optical arbiter at a bit rate of 10 Gbit/s. The
arbiter can be used in a buffering system in a similar way as that presented in [Liu1].
The main difference between our arbiter and the one presented in [Liu1] is that the
output of the latter arbiter was a CW signal. In this approach, the output of the arbiter is
an optical pulse that drives the wavelength routing switch via an optical flip-flop
[Hill2].

Also presented in Chapter 5 is a novel optical seed pulse generator that operates
at a bit rate of 10 Gbit/s and produces a seed pulse synchronized with the beginning of
the data packet. The seed pulse can be used to generate a local clock for packet
synchronization. Moreover, the operation of the optical seed pulse generator does not
require any particular marker in the packet format that identifies the beginning of the
packet, rather it uses the packet format itself. The extinction ratio between the seed
pulse and the suppressed packet was 15 dB. In addition, experimental results have
shown that a seed pulse can be extracted even with an input signal extinction ratio of 5
dB, confirming that the optical seed pulse generator could be used as the first stage in
an optical cross-connect node.

Finally, experimental results in Chapter 5 show that the signal processing functions
based on self-polarization rotation have a lower power operation and a higher extinction
ratio than the same functions based on self-phase modulation.
In Chapter 6, an all-optical header processing system based on combining a single header pre-processor and two TOADs that act as header recognizers is introduced. The header processing system can distinguish between two different packet headers and the output is sent to two distinct output ports. We believe that this principle can be extended to recognize more header patterns.

The design of the header processing system provides several key advantages over alternative techniques. The header pre-processor operates asynchronously so that the header processing system as a whole can be operated in an asynchronous fashion. The system also operates as a low power device. In this chapter, the bit rate was 10 Gbit/s and $\tau_{sw}$ was 50 ps but optical switching of a 250 Gbit/s signal has been demonstrated using a TOAD for which $\tau_{sw}$ was 4 ps [Solokoff]. Thus, we believe that the header processor can operate at higher bit rates than 10 Gbit/s. Moreover, a shorter offset time in the order of a few picoseconds allows photonic integration of the header processor. Finally, a header processing system that can recognize a large number of header patterns can be utilized in devising an all-optical packet switch.
Appendix A
Model for nonlinear polarization rotation in a semiconductor optical amplifier

In this appendix, a model of nonlinear polarization rotation in a semiconductor optical amplifier is presented. This model can be found in [Dorren2]. An introduction and the schematic of the nonlinear polarization switch are presented in Section 5.2. The incoming arbitrarily polarized electric field was decomposed 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.

The propagation equation for the TE polarized electric field component $A_{TE}(z,t)$ is given by:

$$\left( \frac{\partial}{\partial t} + v_g^{TE} \frac{\partial}{\partial z} \right) A_{TE}^{TE}(z,t) = \frac{1}{2} \Gamma_{TE} (1 + i\alpha_{TE}) g^{TE}(z,t) A_{TE}^{TE}(z,t) - \frac{1}{2} \alpha_{int}^{TE} A_{TE}^{TE}(z,t) \quad (A.1)$$
Here, $A^{TE}(z,t)$ is the weakly time and space dependent complex envelope of the optical field, $v^{TE}_g$ the corresponding group velocity taken at the central frequency of the wave, $\Gamma^{TE}$ the confinement factor, $g^{TE}(z,t)$ the (real) gain function, $\alpha^{TE}$ the phase-modulation parameter and $\alpha^{TE}_{int}$ the modal loss. A similar rate-equation holds for the complex field envelope $A^{TM}(z,t)$ corresponding to the TM mode:

$$\left( \frac{\partial}{\partial t} + v^{TM}_g \frac{\partial}{\partial z} \right) A^{TM}(z,t) = \frac{1}{2} \Gamma^{TM} (1 + i \alpha^{TM}) g^{TM}(z,t) A^{TM}(z,t) - \frac{1}{2} \alpha^{TM}_{int} A^{TM}(z,t) \quad (A.2)$$

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

$$A^{TE}(z,t) = \sqrt{S^{TE}(z,t)} e^{i\phi^{TE}(z,t)} \quad A^{TM}(z,t) = \sqrt{S^{TM}(z,t)} e^{i\phi^{TM}(z,t)} \quad (A.3)$$

where $S^{TE}(z,t)$ and $S^{TM}(z,t)$ are the photon numbers and $\phi^{TE}(z,t)$ and $\phi^{TM}(z,t)$ are the phases for the TE and TM components.

The two optical modes have indirect interaction via the carriers. It is assumed 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 the 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 [Dorren2]. 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 (A.8), (A.9) and (A.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{A.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{A.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:

$$\xi^{TE/TM} = \frac{\xi^{TE/TM}}{1 + \varepsilon S^{TE/TM}}$$

where $\varepsilon$ is typically $10^{-7}$ per photon present in the SOA [Agrawal2]. 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 (A.4) and (A.5) it was tacitly assumed that the semiconductor medium in the active layer gives rise to anisotropic gain, such as can be realized in a bulk layer with tensile strain [Kakitsuka]. If it is assumed that the total number of holes is equal to the number of electrons:
and substitute this into (A.5) and (A.6), \( g^{TE}(z,t) \) and \( g^{TM}(z,t) \) can be expressed as:

\[
g^{TE}(z,t) = \gamma [2n_x(z,t) + n_y(z,t) - N_0] \quad g^{TM}(z,t) = \gamma [2n_y(z,t) + n_x(z,t) - N_0]
\] (A.7)

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

\[
\frac{\partial n_x(z,t)}{\partial t} = -\frac{n_x(z,t) - \bar{n}_x}{T_1} - \frac{n_x(z,t) - fn_x(z,t)}{T_2} - g^{TE}(z,t)S^{TE}(z,t)
\] (A.8)

and similarly for \( n_y(z,t) \)

\[
\frac{\partial n_y(z,t)}{\partial t} = -\frac{n_y(z,t) - \bar{n}_y}{T_1} - \frac{fn_y(z,t) - n_x(z,t)}{T_2} - g^{TM}(z,t)S^{TM}(z,t)
\] (A.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 \( T_2 \) the inter-hole relaxation time. The last terms in the right hand sides of (A.8) and (A.9) account for the stimulated recombinations. It should be noted that the inter-hole relaxation time \( T_2 (~100 \text{ fs}) \) is much shorter than the electron hole recombination time \( T_1 (~500 \text{ ps}) \). Since it is not considered here applications that involve ultrafast dynamics, the two populations \( n_x \) and \( n_y \) will be clamped tightly together i.e.

\[
n_x(z,t) = fn_y(z,t)
\] (A.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 it can be written, consistent with (A.10):

\[
\bar{n}_x = \frac{\bar{n}f}{1 + f} \quad \bar{n}_y = \frac{\bar{n}}{1 + f}
\] (A.11)
where:
\[
\bar{n} = \frac{I}{e} T_1
\]

(A.12)

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

The equations (A.1)-(A.12) form a closed set of equations. First it will be calculated the small-signal gain. To this end, the equilibrium values (A.11) is substituted in the gain expressions (7) and obtain the small signal gain \(g_{TE/TM}^0\):

\[
\begin{align*}
\begin{bmatrix}
\frac{1}{1+f} & \frac{1+f}{1+f} & 0 \\
\frac{1+f}{1+f} & \frac{1}{1+f} & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
N_f \\
N_g \\
\bar{n}
\end{bmatrix}
&= 
\begin{bmatrix}
\frac{1}{1+f} & \frac{1+f}{1+f} & 0 \\
\frac{1+f}{1+f} & \frac{1}{1+f} & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
N_f \\
N_g \\
\bar{n} - N_0
\end{bmatrix}
\end{align*}
\]

(A.13)

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

According to (A.1) and (A.2) the net amplifications by the SOA (in dB), in absence of spatial inhomogeneity, are given by:

\[
4.343 \times (\Gamma^{TE} g^{TE} - \alpha_{int}^{TE}) \frac{L}{v_g^{TE}} \quad \text{For TE}
\]

(A.14)

and

\[
4.343 \times (\Gamma^{TM} g^{TM} - \alpha_{int}^{TM}) \frac{L}{v_g^{TM}} \quad \text{For TM}
\]

(A.15)

where \(L\) is the length of the SOA. The small-signal amplification can be obtained by replacing \(g^{TE}\) by \(g_{0}^{TE}\) and \(g^{TM}\) by \(g_{0}^{TM}\) in (A.14) and (A.15).
It should be noted that the SOA parameters $N_0, I, P^{TE/TM}, a_m^{TE/TM}, v_g^{TE/TM}$ cannot be estimated accurately. This problem is solved by compensating the combined uncertainties in these parameter values by assigning values to $f$ and $\xi^{TE/TM}$ in such a way that the (measured) fiber-to-fiber gain is reproduced. In the most simple approach, one would choose $\xi^{TE} = \xi^{TM}$, 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 (A.14) and (A.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. It was therefore chosen to allow for a small difference in the values for $\xi^{TE}$ and $\xi^{TM}$ (as 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 difficulties in estimating $f$ and $\xi^{TE/TM}$ may be inherent to our modelling 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.
Nonlinear effects in a semiconductor optical amplifier (SOA), i.e. self-phase modulation (SPM) or cross-gain modulation (XGM), have been used in this thesis to achieve the presented optical signal processing functions. These nonlinear effects are the results of nonlinear gain and index dynamics in the SOA. In this appendix, data are presented about the SOAs used in the experiments. Firstly the SOA gain is shown as a function of the wavelength. Afterwards, the SOA gain saturation is presented as a function of the driving current, and as a function of the optical CW input power.

The strained bulk SOA (CQF872/0 # 459) was manufactured by JDS-Uniphase. The characterizations of the fiber-to-fiber gain, saturation output power and gain ripple versus wavelength have been done under the conditions reported in Table B.1 For this specific SOA the operating temperature is between -15 and + 60 °C. The SOA reverse voltage should be less than 2 V, while the SOA forward current should not exceed 600 mA. The length of the active region of the SOA was around 800 µm.
CHARACTERIZATION OF THE SEMICONDUCTOR OPTICAL AMPLIFIER

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifier forward drive current</td>
<td>$I_f = 400 \text{ mA}$</td>
</tr>
<tr>
<td>Amplifier forward voltage</td>
<td>$V_f = 1.72 \text{ V}$</td>
</tr>
<tr>
<td>Thermistor resistance</td>
<td>$R_{NTC} = 9.8 \text{ k}\Omega$</td>
</tr>
<tr>
<td>Temperature of the amplifier chip</td>
<td>$T_{\text{chip}} = 25 \text{ °C}$</td>
</tr>
<tr>
<td>Amplifier module case temperature</td>
<td>$T_{\text{case}} = 25 \text{ °C}$</td>
</tr>
<tr>
<td>Thermoelectric cooler current</td>
<td>$I_{\text{TEC}} = 257 \text{ mA}$</td>
</tr>
<tr>
<td>Thermoelectric cooler voltage</td>
<td>$V_{\text{TEC}} = 0.55 \text{ V}$</td>
</tr>
</tbody>
</table>

Table B. 1. Parameter values employed in the characterizations of the SOA.

Figure B.1 shows the fiber-to-fiber gain in decibel versus wavelength measured under small signal conditions. The curves represent a fit of the measured data. The gain peak varies between 21.2 dB (maximum polarization) and 19.5 dB (minimum polarization) at the wavelength of 1503 nm (maximum polarization) and 1501 nm (minimum polarization). The resulting 3 dB gain bandwidth (BW) is equal to 81 nm. The amplified spontaneous emission (ASE) from the output fiber when no input optical signal is applied to the SOA was 3.8 dBm, while the ASE from the input fiber was 5.2 dBm. The average signal spontaneous beat noise factor (NF), estimated from ASE power was 11.5 dB. In Figure B.2 the measurements of 3 dB gain saturation output powers (fiber-to-fiber) is shown as a function of the wavelength. In Figure B.3 the gain ripple is reported as a function of the wavelength. The averaged gain ripple was 0.31 dB.
Figure B.1 Fiber-to-Fiber gain versus wavelength.

Figure B.2 Saturation output power versus wavelength.

Figure B.3 Gain ripple versus wavelength.
The experimental set-up employed to characterize the SOA gain as a function of the driving current as well as a function of the optical input power is shown in Figure B.4.

![Experimental set-up employed to characterize the SOA gain versus current and optical power.](image)

**Figure B.4** Experimental set-up employed to characterize the SOA gain versus current and optical power.

The scheme consists of a laser source emitting CW light at a wavelength of 1550.91 nm. The CW light is injected into the SOA via an optical isolator (ISO) placed at the input of the SOA. Another isolator is employed at the output of the SOA to isolate the device from possible reflection. A band pass filter (BPF) is centred at the probe wavelength to eliminate the broad ASE of the SOA.

Firstly the fiber-to-fiber SOA gain is measured as a function of the driving current. In this case, the optical power of the input light at the SOA was -20 dBm. The coupling losses are estimated to be 3 dB at each side of the SOA. The measured SOA gain versus drive current is shown in Figure B.5. The measured current threshold was 32 mA. In Figure B.6 the fiber-to-fiber SOA gain is shown as a function of the optical input power. The drive current is 300 mA. The saturation power of the SOA was measured to be equal to –2.6 dBm.
Figure B.5 Measured SOA gain as a function of the drive current.

Figure B.6 Measured SOA gain as a function of the optical power of the probe light.
Figure B.5 and B.6 give an estimation of the gain change as a function of the drive current and of the input optical power. To estimate also the phase changes associated with the gain changes, the SOA parameters should also be characterized. Although some parameters are wavelength and current dependent [Summers, Morthier, Manning1], the typical values of a strained bulk SOA parameter are reported in Table B.2 [Visser1, Visser2].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron hole recombination time</td>
<td>500 ps</td>
</tr>
<tr>
<td>Total number of electronic states</td>
<td>( N_0 = 10^9 )</td>
</tr>
<tr>
<td>Group velocity for TE and TM modes</td>
<td>( v_{g}^{TE} = v_{g}^{TM} = 100 \mu m/ps )</td>
</tr>
<tr>
<td>Confinement factor for TE and TM</td>
<td>( \Gamma^{TE} = 0.2 ); ( \Gamma^{TM} = 0.14 )</td>
</tr>
<tr>
<td>Gain coefficient for the TE and the TM modes</td>
<td>( \xi^{TE} = 7 \times 10^{-9} \text{ ps}^{-1} ); ( \xi^{TM} = 6.5 \times 10^{-9} \text{ ps}^{-1} )</td>
</tr>
<tr>
<td>Modal losses</td>
<td>( \alpha_{int}^{TE} = \alpha_{int}^{TM} = 0.27 \text{ ps}^{-1} )</td>
</tr>
<tr>
<td>Linewidth enhancement factor for TE and TM modes</td>
<td>( \alpha_{TE} = \alpha_{TM} = 5 )</td>
</tr>
</tbody>
</table>

Table B.2 Typical parameters of a strained bulk semiconductor optical amplifier.
Appendix C
Description of the hexadecimal notation and Manchester code

In this appendix, a brief description of the hexadecimal notation and Manchester encoding is given.

C.1 Hexadecimal notation

The most commonly used numbering system is the binary system. Binary digits (also known as bits) are made entirely out of ‘0’s and ‘1’s. Each digit represents a power of 2 (also known as Base 2). If the number of digits (bits) required to represent a value (i.e. a memory address) is large, hexadecimal notation can be used as a more compact way to represent the same binary information. Each hexadecimal digit represents four binary digits (a group of four binary is also known a nibble). Hexadecimal digits are 0 to 9 and A to F. To convert between hexadecimal and binary digits, the following lookup table can be used:
HEXADECIMAL NOTATION AND MANCHESTER CODE

<table>
<thead>
<tr>
<th>Hex</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>0</td>
</tr>
<tr>
<td>0001</td>
<td>1</td>
</tr>
<tr>
<td>0010</td>
<td>2</td>
</tr>
<tr>
<td>0011</td>
<td>3</td>
</tr>
<tr>
<td>0100</td>
<td>4</td>
</tr>
<tr>
<td>0101</td>
<td>5</td>
</tr>
<tr>
<td>0110</td>
<td>6</td>
</tr>
<tr>
<td>0111</td>
<td>7</td>
</tr>
<tr>
<td>1000</td>
<td>8</td>
</tr>
<tr>
<td>1001</td>
<td>9</td>
</tr>
<tr>
<td>1010</td>
<td>A</td>
</tr>
<tr>
<td>1011</td>
<td>B</td>
</tr>
<tr>
<td>1100</td>
<td>C</td>
</tr>
<tr>
<td>1101</td>
<td>D</td>
</tr>
<tr>
<td>1110</td>
<td>E</td>
</tr>
<tr>
<td>1111</td>
<td>F</td>
</tr>
</tbody>
</table>

*Table C.1* Lookup table to convert hexadecimal to binary and binary to hexadecimal.

C.2 Manchester code

In telecommunications, Manchester encoding is a form of data communication in which each bit of data is signified by at least one transition. Manchester encoding is therefore considered to be self-clocking, which means that accurate synchronisation of a data stream is possible. Each bit is transmitted over a predefined time period. Each encoded bit contains a transition at the midpoint of a bit period (see Figure C.1).
For a ‘0’ bit the signal levels will be Low-High (assuming an amplitude physical encoding of the data) - with a low level in the first half of the bit period, and a high level in the second half. For a 1 bit the signal levels will be High-Low.

![Figure C.1 Representation of a Manchester encoded data bits.](image)

A consequence of the transitions for each bit is that the bandwidth requirements for Manchester encoded signals is doubled compared with asynchronous communications. However, the advantage of the Manchester coding with respect to the NRZ coding is that the optical power of the Manchester encoded data is constant regardless the specific bit pattern. In optical transmission systems that include SOAs, this will result in a lower waveform distortion of the Manchester encoded bits compared to NRZ encoded bits [Inoue]. As a result, the eye-opening penalty is nearly 0 dB for Manchester encoded bits while it increases with the input power or with the bit rate for NRZ encoded bits. Moreover, the extinction ratio degradation between the ‘1’ level and the ‘0’ of the Manchester encoded data signal at the SOA output is smaller than that for NRZ.
References


REFERENCES


REFERENCES


REFERENCES


## List of abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPF</td>
<td>Band Pass Filter</td>
</tr>
<tr>
<td>CSMA/CA</td>
<td>Carrier Sense Multiple Access with Collision Avoidance</td>
</tr>
<tr>
<td>dB</td>
<td>decibel</td>
</tr>
<tr>
<td>dBm</td>
<td>decibel milliwatt</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium-doped Fiber Amplifier</td>
</tr>
<tr>
<td>FBG</td>
<td>Fiber Bragg Grating</td>
</tr>
<tr>
<td>GaAs</td>
<td>Gallium Arsene</td>
</tr>
<tr>
<td>HPP</td>
<td>Header Pre-Processor</td>
</tr>
<tr>
<td>HPU</td>
<td>Header Processing Unit</td>
</tr>
<tr>
<td>InP</td>
<td>Indium Phoshide</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>MAN</td>
<td>Metropolitan Area Network</td>
</tr>
<tr>
<td>MZI</td>
<td>Mach-Zehnder Interferometer</td>
</tr>
<tr>
<td>NPS</td>
<td>Nonlinear Polarization Switch</td>
</tr>
<tr>
<td>NRZ</td>
<td>Nonreturn-to-Zero</td>
</tr>
<tr>
<td>OAF</td>
<td>Optical Arbiter Function</td>
</tr>
<tr>
<td>OC</td>
<td>Optical Circulator</td>
</tr>
<tr>
<td>OCDM</td>
<td>Optical Code Division Multiplexer</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>OEO</td>
<td>Optical-Electro-Optical</td>
</tr>
<tr>
<td>PBS</td>
<td>Polarization Beam Splitter</td>
</tr>
<tr>
<td>PC</td>
<td>Polarization Controller</td>
</tr>
<tr>
<td>PRBS</td>
<td>Pseudo-Random Binary Sequence</td>
</tr>
<tr>
<td>RZ</td>
<td>Return-to-Zero</td>
</tr>
<tr>
<td>SCM</td>
<td>Sub-Carrier Multiplexer</td>
</tr>
<tr>
<td>SDH</td>
<td>Synchronous Digital Hierarchy</td>
</tr>
<tr>
<td>SLALOM</td>
<td>Semiconductor Laser Amplifier in a Loop Optical Mirror</td>
</tr>
<tr>
<td>SPM</td>
<td>Self-Phase Modulation</td>
</tr>
<tr>
<td>SPR</td>
<td>Self-induced Polarization Rotation</td>
</tr>
<tr>
<td>SOA</td>
<td>Semiconductor Optical Amplifier</td>
</tr>
<tr>
<td>SONET</td>
<td>Synchronous Optical Network</td>
</tr>
<tr>
<td>TDM</td>
<td>Time-Division Multiplexing</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse Electric</td>
</tr>
<tr>
<td>TM</td>
<td>Transverse Magnetic</td>
</tr>
<tr>
<td>TOAD</td>
<td>Terahertz Optical Asynchronous Demultiplexer</td>
</tr>
<tr>
<td>UNI</td>
<td>Ultrafast Nonlinear Interferometer</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
</tr>
<tr>
<td>XGM</td>
<td>Cross-Gain Modulation</td>
</tr>
<tr>
<td>XPM</td>
<td>Cross-Phase Modulation</td>
</tr>
</tbody>
</table>
List of publications

Journal papers


LIST OF PUBLICATIONS


International conferences


Regional conferences


Sommario

Questa tesi tratta un riconoscitore (tutto) ottico di indirizzi. Il riconoscitore di indirizzi è una delle funzioni fondamentali per lo sviluppo e l’implementazione di un commutatore (tutto) ottico di pacchetti. Diversi approcci per l’implementazione di un riconoscitore ottico di indirizzi sono riportati in letteratura, tuttavia in questa tesi si è considerato un approccio del riconoscitore ottico di indirizzi basato sulle nonlinearità del guadagno e le dinamiche dell’indice di rifrazione negli amplificatori ottici a semiconduttore.

Dopo un’introduzione generale sull’argomento, il principio di operazione di un commutatore ottico di pacchetti è discusso nel Capitolo 2. Il commutatore di pacchetti consiste di un riconoscitore di indirizzi basato sul principio di two-pulse correlation in un amplificatore ottico a semiconduttori posizionato in un loop ottico (SLALOM). Il riconoscitore di indirizzi usato nel commutatore di pacchetti come presentato nel Capitolo 2 può riconoscere un solo specifico indirizzo. Nel Capitolo 3 si è dimostrato che il principio di operazione del riconoscitore di indirizzi basato sul two-pulse correlation può essere generalizzato per riconoscere un maggior numero di indirizzi di pacchetto.
Inoltre il commutatore di pacchetti presentato nel Capitolo 2 contiene una funzione (tutto) ottica di soglia. Questa funzione di soglia è stata necessaria per aumentare il contrasto tra l’impulso derivante dalla correlazione dell’indirizzo e il payload del pacchetto. Per ovviare l’impiego delle funzioni di soglia (uno per ogni uscita del riconoscitore di indirizzi) nel Capitolo 4 un pre-processore tutto ottico dell’indirizzo è stato dimostrato.

Nel Capitolo 5 un sistema di riconoscimento ottico dell’indirizzo basato su un pre-processore (tutto) ottico dell’indirizzo e un riconoscitore di indirizzi e’ stato dimostrato utilizzando effetti auto-indotti della rotazione nonlineare di polarizzazione nell’amplificatore ottico a semiconduttore. Il vantaggio di utilizzare un processore di indirizzi e un pre-processore di indirizzi basati sulla rotazione nonlineare di polarizzazione e’ che la potenza ottica di operazione utilizzata nel sistema di processamento dell’indirizzo puo’ essere notevolmente ridotta rispetto al sistema discusso nel Capitolo 4.

Infine, nel Capitolo 6 e’ stato dimostrato il principio di operazione di un riconoscitore ottico di indirizzi basato sul terahertz optical asymmetric demultiplexer (TOAD). Il vantaggio di utilizzare dei TOAD invece di SLALOMs consiste nel fatto che il riconoscitore di indirizzi basato su TOADs puo’ essere integrato su chip. La dimostrazione del riconoscitore di indirizzi basato su TOADs e’ presentata nel Capitolo 6. In contrasto con le altre tecniche di riconoscimento degli indirizzi basati sui TOADs, il riconoscitore di indirizzi discusso in questa tesi opera in modo asincrono e quindi ha il vantaggio di non richiedere il recupero del clock del segnale.
Acknowledgments

I would like to thank everybody who supported me in writing this thesis. In the first place the ones those are dearest to me, my girlfriend Suzanne and my families. Furthermore my promoter Djan Khoe who gave me the possibility to work and carry out research at the COBRA Institute. He encouraged me in conference and public talks by giving me the nickname of “Pavarotti”. Sure the comparison is too big! A lot of thanks to my supervisor Harm Dorren who believed in my work and led me towards the Ph.D. I am also grateful to my second promoter Daan Lenstra for supporting this work. I would like to thank my roommates for the nice time we spent together. Idelfonso Tafur for the interesting discussion and the very useful advises. Yong Liu with whom I discussed a lot about research objectives, laboratory experiences, courses and conferences. Thank you for all and ‘Nihao”. To Arvind Mishra, I wish “Shuprabhatam” for your ongoing Ph.D.

Many thanks to Huug de Waardt and Martin Hill who were always willing to discuss results and to help in the laboratory. René Jonker especially for his useful discussions concerning my last paper. I am also grateful to Frans Huijskens who manufactured several components employed in my experiments, Peter van Bennekom for his support in the laboratory, and Ronelle Geldenhuys for commenting the English in the thesis. A kind thanks to Susan and Els both for their sympathy and for helping me out in the official matters. Hans Moerman for his patience in arranging a computer to write this thesis. Moreover, there are people who I wish to thank not only for the professional discussion but also for sharing their fun, Eduard Tangdiongga, Jarek Turkiewicz, Johan The Dubbliner van Zantvoort (unfortunately for him also my Beugelen mate), Daniel “Mucho trabajo” Baez Puche, J.J. Vegas Olmos, Erwin “hou doe” Verdurmen and Oscar “The Dancer” Diaz.

I wish to thank also all the other members of the ECO and also OED group for their kindness, and I wish good luck to all the Ph.D. students. Moreover, SAS to Cosimo for the “lekker koffie” time, thanks to Ronald Broeke for his collaboration to arrange a joint experiment. Many thanks to all my friends in Italy and Netherlands who always support me. I would like to say to Djan Khoe, Daan Lenstra, Harm Dorren, Prof. Geert Morthier, Prof. Jørn Hvam, Prof. Meint Smit en Prof. Alfred Driessen that I am very grateful for all the time they invested in improving the quality of this thesis. Finally, I wish to thank Carola van Oudheusden for providing me her two beautiful works represented in the cover.
Nicola Calabretta was born the 25th of September 1974 in Catanzaro, Italy. After his graduating at the Liceo Scientifico Statale in Soverato, he started his studies in Telecommunications Engineering at the Politecnico di Torino, Italy. He received his Bachelor degree in 1995, and his Master of Science degree in 1999. In 1999 he started his PhD at the faculty of Electrical Engineering, COBRA Research Institute, located at the Eindhoven University of Technology in Eindhoven.

In 1995 he visited the RAI Research Center (Italian broadcasting television) in Turin. He designed an automatic procedure for designing and optimizing a 3 dB coupler at 2.5 GHz in microstrip technology for an antenna system. This work was included as a part of the Bachelor thesis. In 1999 he won a scholarship for the European exchanging program Erasmus that enabled him to carry out his master thesis at the faculty of Electrical Engineering at the Eindhoven University of Technology. There he investigated a novel cost-effective system for monitoring of WDM channels. He is currently acting as a referee for the IEEE Photonic Technology Letters.