Ultrafast asynchronous multioutput all-optical header processor

Citation for published version (APA):

DOI:
10.1109/LPT.2004.824993

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.
Ultrafast Asynchronous Multioutput All-Optical Header Processor

N. Calabretta, H. de Waardt, G. D. Khoe, Fellow, IEEE, and H. J. S. Dorren

Abstract—We present a novel all-optical header processing technique that can be utilized in all-optical packet switches. The header processor consists of a terahertz optical asymmetric demultiplexer in combination with a header preprocessor that separates the packet header from the packet payload. Experimental results show asynchronous operation of the header processor at a header bit rate of 10 Gb/s in the case of two output ports. This concept can, however, be extended to a larger number of output ports, operates at low power, and allows photonic integration.

Index Terms—Header recognition, optical packet switch, optical signal processing, polarization switching, semiconductor optical amplifier (SOA), terahertz optical asymmetric demultiplexer (TOAD).

All-optical header processing plays an important role in all-optical packet switching [1]–[3]. In [2], ultrafast all-optical header processing using a terahertz optical asymmetric demultiplexer (TOAD) is demonstrated at a bit rate of 250 Gb/s. This TOAD-based header recognizer operates at low energy and allows photonic integration, but a disadvantage is that the control pulse should be synchronous 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 [3], an asynchronous multioutput all-optical header processing technique based on the two-pulse correlation principle in a semiconductor laser amplifier in a loop optical mirror (SLALOM) configuration is presented. This concept was employed in an all-optical packet switch [4]. 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 semiconductor optical amplifier (SOA) recovery time $\tau_r (\sim 1 \text{ ns})$ [5]. Moreover, the SOA has to be placed offset to the center of the loop with a distance that is larger than $\tau_r/v_g (\sim 10 \text{ cm})$, where $v_g$ is the group velocity of light ($\sim 100 \text{ km/s}$). Thus, a disadvantage of the header processing method presented in [3] is that the SLALOM configuration is too large to allow photonic integration.

In this letter, we present a novel header processing technique that can distinguish a large number of header patterns and which allows asynchronous operation and photonic integration. The concept is based on combining the header preprocessor (HPP) that is presented in [6] 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 HPP output is fed into the TOAD for header recognition. Essential for TOAD operation is the employment of a control pulse for optical switching [7]. 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 optical header processing system is schematically presented in Fig. 1. It consists of an HPP 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 letter, is that the address information is encoded by the difference in time between the packets.
leading edges of two header pulses. The function of the HPP is to extract the header information from the data packet. It is shown in [6] that this can be done by employing self polarization rotation in a nonlinear polarization switch. The nonlinear polarization switch is shown in the dashed box of Fig. 1. In brief, in the nonlinear polarization switch, an optical bit with a polarization angle of approximately 45° is injected into the SOA. As the bit propagates through the SOA, the polarization angle rotates due to the polarization-dependent gain and index saturation [6]. 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 (PBS), only the leading edge of the header bit outputs the nonlinear polarization switch [6].

The space between the header pulses is filled with a sequence of alternating nonreturn-to-zero “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 [6]. 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 of the specific bit pattern [6].

The operation of the TOAD has been described in [7]. As shown in the dashed box of Fig. 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 \( \Delta r \) 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 clockwise (CW) propagating pulse and counterclockwise (CCW) propagating pulse. 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 [7]. The polarization of the control light that is orthogonal with respect to the polarization of the input pulses. Thus, the control light can be removed by using a PBS.

The TOAD can function as a header processor as follows. The HPP output pulses form the TOAD input signal and are split by an 80:20 coupler in 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 \( \tau_{ccw} = 2\Delta r/v_g \) 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 high power control signal is used to saturate the SOA. Header recognition can be implemented by accurately timing of the control pulses. There are three interesting cases that are shown in Fig. 2. In the first case [see Fig. 2(a)], 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 Fig. 2(b)], 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, so a pulse is created at the TOAD output. In the third case [see Fig. 2(c)], the control light arrives at the SOA after 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.

We conclude that a pulse outputs 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 switching, as described in [4]. 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.

The concepts described above were demonstrated by using the experimental setup shown in Fig. 1. The laser source had a wavelength of 1550.91 nm and was modulated by a 10-Gb/s Mach–Zehnder modulator, which was driven by a pattern generator. The packet format is also shown in Fig. 1. The duration of the sequence of “0s” that were placed in front of the second header pulse was 0.9 ns. The payload section consisted of Manchester-encoded pseudorandom binary sequence data at a bit rate of 10 Gb/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 Fig. 3(a)]. This means that the time between the header pulses are 5 and 5.1 ns for Header 1 and
is
was
was 50 ps, but optical switching of a 250-Gb/s
fore being distributed over the TOADs. For both TOADs,
The input and control signal are split by 50 : 50 couplers be-
pulses have a duration of 50 ps each. The average payload sup-
represented in Fig. 3(b). It is clearly visible in Fig. 3(b) that the HPP
The oscilloscope trace of the signal that outputs the HPP is pre-
123.5 mA of current. The PBS has an extinction ratio of 30 dB.
HPP. The average optical power of the packets at the input of
Header 2, respectively. The packets are first preprocessed by the
HPP. The average optical power of the packets at the input of
the HPP was 2.3 dBm. The extinction ratio of the input optical
HPP. The average payload suppression is 18.4 dB. The HPP output is then 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, τsw is
50 ps. The control signals were delayed by 4.95 and 5.05 ns before
being fed in TOAD 1 and TOAD 2, respectively. The SOAs
in TOAD 1 and TOAD 2 were pumped with 116 and 121 mA of
current, respectively. The energy of the control pulses was 0.8 pJ.
According to the design of the TOADs and the header patterns, we expect
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 the output Port 1 and output Port 2
are shown in Fig. 3(c) and (d), 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. We can observe 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 sup-
pressed payload is higher than 14.4 dB.

These experiments indicate that the setup presented in Fig. 1
is indeed capable of recognizing two different headers but the
concept is scalable so that a larger number of packet headers
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 pro-
cessor can be decreased to 4 ps [7]. This means that the length
of header patterns can be reduced with more than a factor 25.

We have shown that the header processing system can distin-
guish between two different packet headers and the output
is sent to two distinct output ports. We believe that this prin-
ciple can be extended to recognize more header patterns by con-
structing packet headers that are made out of a sequence of two
header bits as shown in this letter.

The design of the header processing system provides several
advantages over alternative techniques. The HPP operates asyn-
chronously which means that the header processing system as a
whole can be operated in an asynchronous fashion. Also, the
system operates at low power. In this letter, the bit rate was
10 Gb/s and τsw was 50 ps, but optical switching of a 250-Gb/s
signal has been demonstrated using a TOAD for which τsw was
4 ps [2], [7]. Thus, we believe that the header processor can op-
erate at higher bit rates than 10 Gb/s. Moreover, a shorter offset
time in the order of 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.

ACKNOWLEDGMENT

The authors would like to thank R. J. W. Jonker for the helpful
discussions and M. T. Hill and Y. Liu and two anonymous re-
viewers for commenting on the manuscript.

REFERENCES

Hauer, “All-optical address recognition for optically-assisted routing in
J. S. Dorren, “Multiple-output all-optical header processing technique
and H. J. S. Dorren, “1 × 2 optical packet switch using all-optical header
Dorren, “Optical signal processing based on self-induced polarization
rotation in a semiconductor optical amplifier,” J. Lightwave Technol.,