Invited paper

All-Optical Techniques Enabling Packet Switching with Label Processing and Label Rewriting

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Abstract—Scalability of packet switched cross-connects that utilize all-optical signal processing is a crucial issue that eventually determines the future role of photonic signal processing in optical networks. After reviewing several labeling techniques, we discuss label stacking and label swapping techniques and their benefits for scalable optical packet switched nodes. All-optical devices for implementing the packet switch based on the labeling techniques will be described. Finally, we present a 1×4 all-optical packet switch based on label swapping technique that utilizes a scalable and asynchronous label processor and label rewriter. Error-free operation indicates a potential utilization of the swapping technique in a multi-hop packet-switched network.

Keywords*— *label processor, optical flip-flop memory, optical packet switching, optical signal processing, wavelength converter.

1. Introduction

The increase of the traffic in the access networks makes it likely that future all-optical metro and core networks should be capable to handle tens of Tbit/s data traffic. Current networks are based on electronic circuit switching technology that has fundamental limits due to the scalability of multi-racks electronic switching fabrics and power consumption required by the optoelectronic conversions [1]–[3]. All-optical packet switching has been proposed as a technology to solve the bottleneck between the fibre bandwidth and the electronic router capacity by exploiting ultra-high speed and parallel operation of all-optical signal processing. Moreover, photonic integration of the optical subsystems potentially allows a reduction of volume and power consumption.

To exploit the benefit of photonic technology to miniaturize and decrease the power consumptions of the system, photonic integration of the all-optical packet switch depends on the capability to integrate the label processor and the optical delay related to the latency of the label processing. This imposes stringent constraints on the latency time of the label processor. High speed operation of the label processor (< 100 ps) must to allow photonic integration of the packet switch system. Moreover, scalability of the label processor with the number of labels (or the number of label bits) is crucial too. Indeed, the number of active components that can be integrated in the label processor is limited by the thermal crosstalk and heat dissipation which can prevent photonic integration of the circuit. Therefore, the choice of the labeling technique determines the architecture and then the scalability of the node.

All-optical packet switch employing all-optical label processor were investigated in [1]–[10]. Mainly these works employed optical correlators, which recognize the labels, and set/reset optical flip-flops to store the information for the duration of the packet. However, as the number of addresses of the wavelength division multiplexing (WDM) channels carried by each fiber, and of the packet data rate increase, photonic integration, high speed operation, low latency, and scalability of the label processor remain key-issues to be solved.

Our research focuses on the realization of an all-optical packet switching system that is scalable and suitable for photonic integration. In this paper, first we give a comparison between several labeling techniques in terms of scalability and photonic integration of the node. Then, we discuss in detail the label stacking and label swapping techniques and their benefits for scalable optical packet switched nodes. Thus, we review the main subsystems blocks that enable the practical implementation of an optical packet switching (OPS) network based on the mentioned label techniques. Finally, we present a 1×4 all-optical packet switch based on label swapping technique that utilizes a scalable and asynchronous label processor and label rewriter.

The paper is organized as follows. In Section 2, the all-optical signal processing functionalities required to implement an all-optical node are described and a comparison of the labeling technique is reported. In Section 3, we review existing all-optical devices enabling all-packet switching, and in Section 4, we provide experimental results on a 1×4 packet switch in which all the functionalities were implemented in all-optical manner. Finally, we sum up and discuss the main results in the conclusion Section 5.

2. Labeling Techniques for All-Optical Packet Switch

A typical core network overlay is shown in Fig. 1(a). The edge router aggregates IP packets with common destination address to form the optical payload of the packet. An optical label is attached to the payload. Several labeling techniques can be used to generate the packet label. The choice of the labeling technique determines the scalability of the node. The generated optical packet is routed by the OPS nodes based on the assigned label, up to the destination. A typical $N \times N$ packet switched cross-connect node is schematically shown in Fig. 1(b). Each of the N inputs carries M the WDM channels are demultiplexed by an arrayed waveguide grating (AWG) before to be processed. The switching fabric performs the label processing and forwarding of the packets, while the synchronization and buffering stages are used to solve the contention resolution between packets leaving the same output port at the same wavelength.

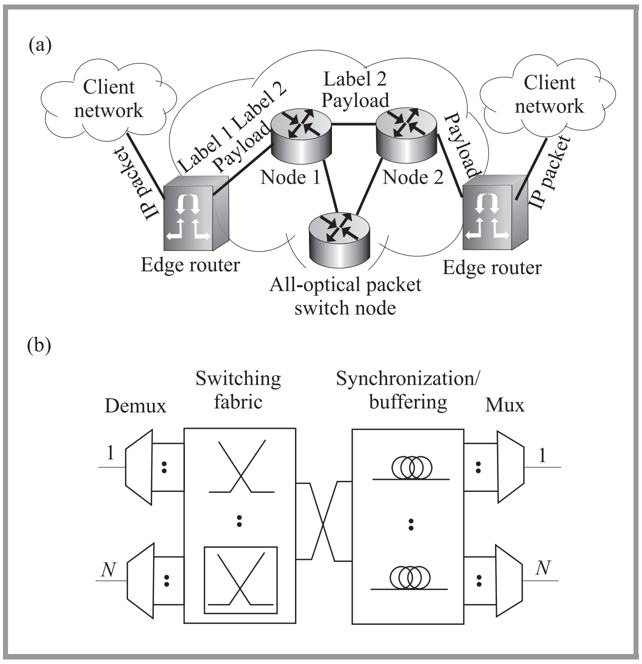


Fig. 1. (a) A general core network overlay. (b) Schematic of optical packet switch node.

The switching fabric consists of three main blocks as shown in Fig. 2: a label processor, a control signal generator and a routing switch. The optical label processor recognizes the optical label that, in combination with an optical control generator, provides the optical control signal to the routing switch to forward the packet. We use a wavelength routing switch as switching strategy, where the packet is routed to a proper output based on the wavelength's packet. Some crucial issues for practical realization of a scalable, all-optical and cost-effective switching fabric are low-power operation and limited amount of components. For practical applications we would also ask for photonic integration on a single chip. Furthermore, it is highly desirable that the label processing operation could be asynchronous, so that the label processor does not require any external synchronization of packets. Given the general cross-connect architecture, the scalability of the node, in terms of number of components and power, will depend on the label technique and the all-optical technology adopted.

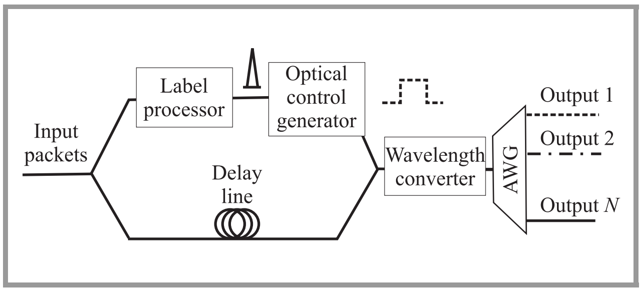


Fig. 2. Optical packet switching fabric.

In all-optical packet switching, the optical label provides information on the packet forwarding. Several techniques have been developed for labeling the optical packets which can be grouped in three main classes: end-to-end label, label swapping, and label stacking.

In the end-to-end label, a distinct label uniquely identifies a distinct node. Thus, the number of end-to-end labels increases linearly with the number of nodes. Moreover, the label does not change along the optical paths to the destination. In the label stacking technique, the label is composed by several sublabels. The number of sublabels is determined by the number of hops required to forward the packet from the source to the destination node. The size of each sublabel is determined by the number of optical output links of the node. As an example, we consider as case study the USA and European Union (EU) IP network backbones depicted in Fig. 3. In those two topologies, the maximum number of output ports that can occur in a node, which determines the size of the sublabel, is 7 in both topologies. The maximum number of hops, which determines the number of sublabels, required for a packet to reach the destination node is 8 and 5 for USA and EU, respectively. In the label swapping technique the labels have a local meaning, but instead to contain several sublabels for packet forwarding at each node, each node rewrites a new label containing the forwarding information for the next node. Thus, each node requires in addition an optical rewriting function.

In terms of scalability and power consumption of the OPS node, the label stacking technique seems to be the most efficient because it decreases the amount of active components required by the node, at the price of having a larger packet overhead. Indeed, in the end-to-end label, the OPS node requires $2 \times N \times M \times L$ active devices (the 2 accounts the label processors based on optical correlators and the optical control generators), N is the inputs port, M the WDM channels and L is the number of nodes of the considered network. Note that this number increases linearly with the network nodes because the label has a global meaning and therefore each node has to be capable to process all possible labels. On the contrary, the label stacking technique requires a number of active devices that is given by $2 \times N \times M \times H$, where H is the size of the sublabel, which is determined by maximum number of output ports of the node. As $H < L$, the label stacking technique requires a lower number of components than the end-to-end label one. The label swapping technique provides the same scalability as the label stacking, but at the price of an additional rewriting function that costs an increase of components. This makes label swapping more complicate of the simple forwarding processing as in the label stacking technique.

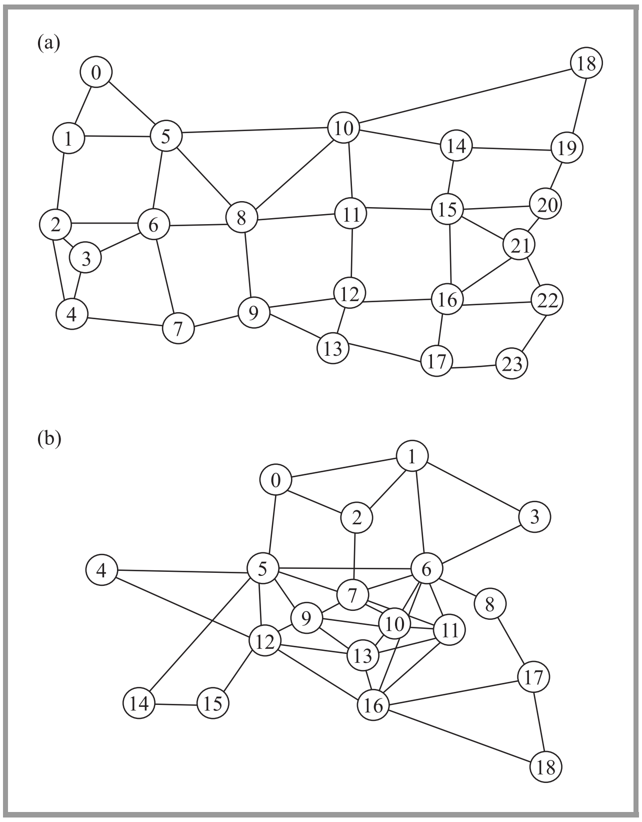


Fig. 3. (a) USA and (b) EU IP network backbones.

A possible disadvantage of the label stacking technique is the increasing of the packet overhead. However, if we consider the topologies depicted in Fig. 3, the number of nodes are 24 and 19 for the USA and EU networks, respectively, while the maximum number of output ports is 7 in both topologies and the maximum number of hops is 8 and 5 for USA and EU, respectively. As a result, considering a typical packet payload size of 1500 bits, the additional packet overhead introduced by the label stacking technique is less than 1%.

The label stacking and label swapping techniques present also other advantages. Those techniques can be applied either for an OPS network or optical burst switching (OBS) network. In the OBS case, implementation of the optical buffering, mandatory in the OPS node, can be done at edge-router stage, alleviating the node architecture. Moreover, some important function such as time-to-live processing are not required anymore but the expiring time of the packet is intrinsically calculated by decreasing one of the sublabels at the time after each hop.

Discussed the potential benefits of the label stacking and label swapping techniques, we will consider in the following section the required physical layer subsystems for the realization of the optical switching nodes.

3. All-Optical Devices Enabling Optical Packet Switching

A schematic example on the operation of the label stacking and label swapping techniques are represented Fig. 4(a) and Fig. 4(b), respectively. In the label stacking operation, the edge router, after consulting the network look-up table, generates the sublabels (label B and label C in the Fig. 4) necessary to route the packet to the destination. Each node processes only the front label, namely node A processes label B and node B processes label C. In the label swapping operation, the edge router, similar to the previous case, consults the network look-up table and generates the label necessary for routing the packet at the next node. Each node routes the packet to the next node based on the processed label, and inserts a new label.

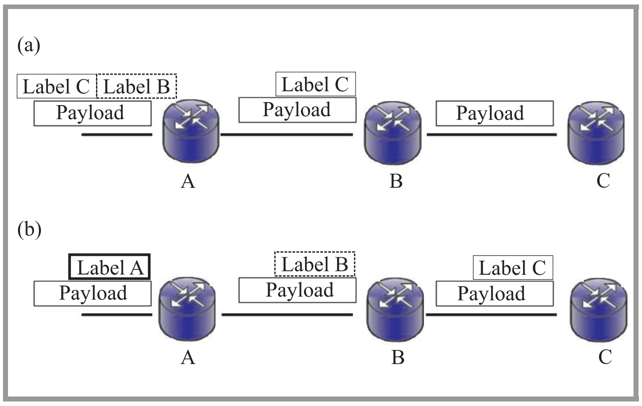


Fig. 4. Schematic of the operation of the (a) label stacking and (b) label swapping techniques.

Figure 5 shows schematically the optical packet switching and the subsystems blocks required to perform switching operation based on label stacking or label swapping technique. The switching fabric consists of three main blocks: a label processing subsystem, a control signal generator and a routing switch. The label processing subsystems may include the label extractor/eraser, the label recognizer and the label rewriter. The optical packets are first processed by the label processing subsystem. The label extractor/eraser separates the label from the payload packet. The payload is delayed for the time required to the label processor and optical control signal generator to provide the routing signal before to be fed into the wavelength routing switch. The extracted label is fed into the label recognizer, which provides the control signal for setting the optical signal generator. The optical control signal generator produces a routing signal for driving the wavelength routing switch. Simultaneously, the label rewriter produces the new label to be at-

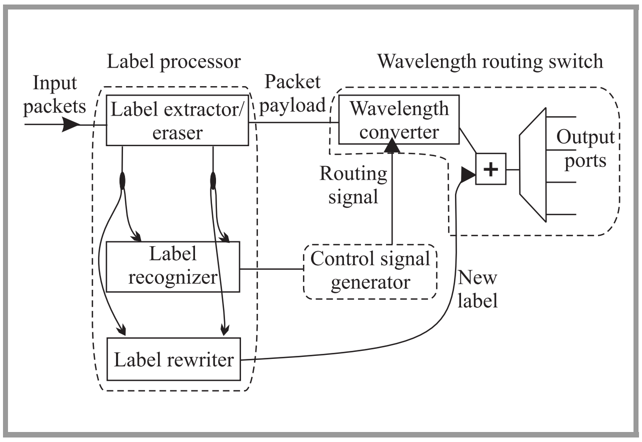


Fig. 5. The all-optical packet switch fabric including the three main blocks.

tached to the switched payload. We use a wavelength routing switch as switching strategy, where the packet is routed to a proper output based on the wavelength's packet. The wavelength routing switch can be implemented by a wavelength converter followed by an AWG. An alternative solution as routing switch can be a space routing switch. Here the packet is routed spatially to the output switch and can be implemented by using all-optical switches. In the following, we report some of the implementations of the single subsystem required to realize the all-optical packet switch. Although several solutions can be found in literature based on different technologies, our research focus is on the realization of an all-optical packet switching system suitable for photonic integration, and thus we have considered semiconductor based all-optical signal processing subsystems.

Label extractor/eraser. Demonstrations of several schemes capable to extract the label information are reported in [9]–[13]. The reported solutions are mainly based on the coding of the label. In [11]–[13] the in-band label bits separated in time from the payload were successfully extracted. The label extractor employed nonlinear gain and index dynamics in semiconductor optical amplifiers. In [9], [10], the label was also in-band with the payload but at different wavelength. The label extraction was achieved by using a passive filter.

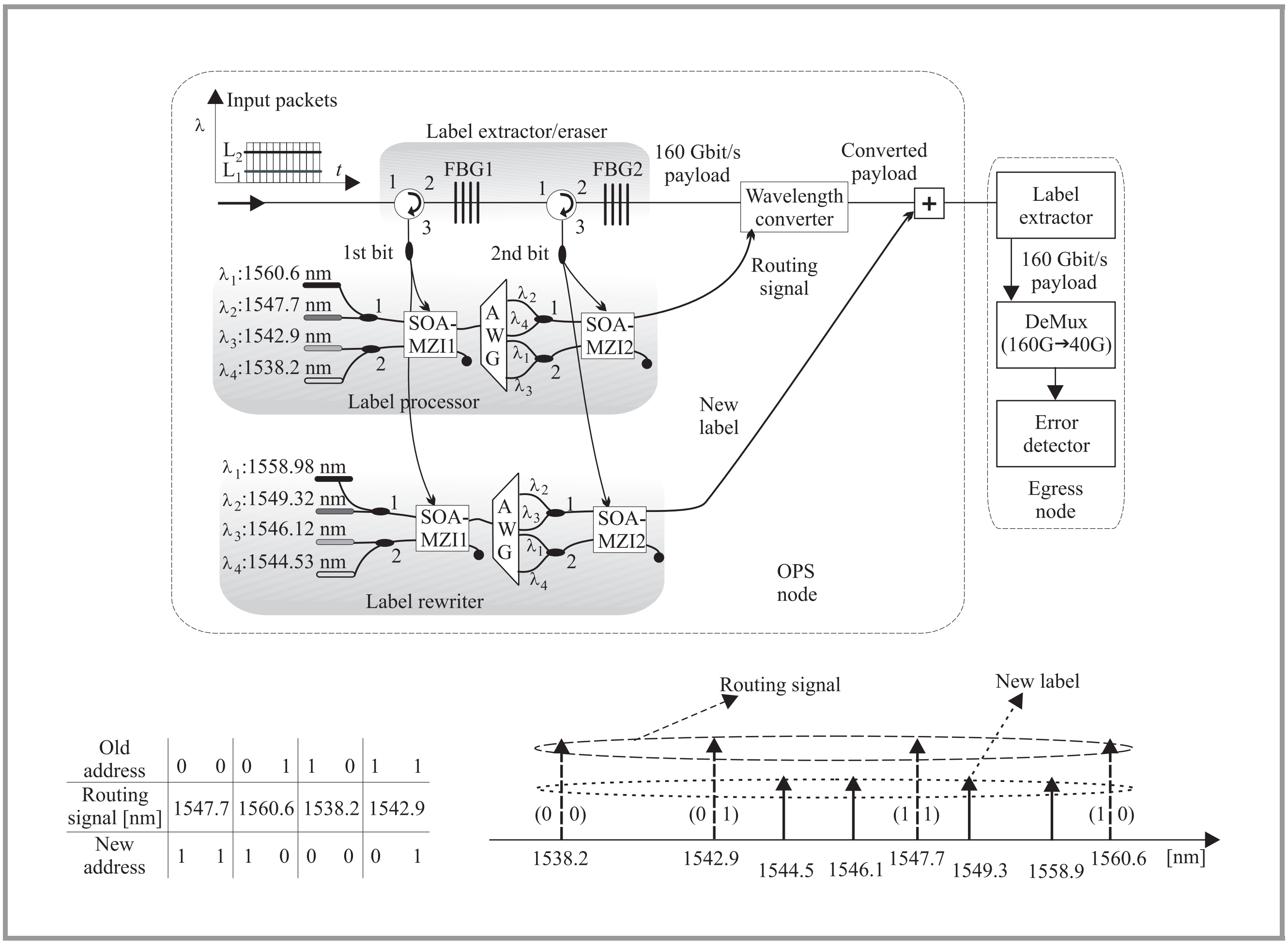
Label recognizer. The proposed solutions are based on three different paradigms. One is based on classical optical correlators; therefore an optical pulse is produced only at the correlator output that matches the label pattern [14]–[16]. The second paradigm is based on time-to-wavelength conversion, and in this case the address information is converted into a pulse at distinct wavelength univocally determined by the label [17]. In both cases, the address information employed in both strategies is encoded by using pulse position modulation (PPM) [2]. The main advantage to code the label information with PPM is the simplicity and feasibility of all-optically label matching that can be realized by using pulse position correlators, with very fast processing time. Furthermore there is no need to generate any local pattern for pattern-matching purposes. The disadvantage of those two techniques is that the number of optical correlators scales linear with the number of labels to be recognized. The third paradigm is based on binary processing of the label [10]. The advantage of the binary processing is that it scales logarithmic with the number of labels. Therefore it will require much less active components. Explanation on the operation of the binary processing will be discussed in the next section.

Optical control signal generator. Mainly the output of the label processor consists of a single pulse that identifies distinct routing information. The optical control generator, mainly acting as an optical flip-flop memory, converts the short pulse in a continuous wave (CW) control signal at a defined wavelength. The CW control signal is used in combination with the wavelength converter to route the packet to the proper output. Demonstrations of several optical flip-flop memory techniques can be found in [18], [19]. Generally speaking, the all-optical flip-flop memories are based on two coupled laser diodes (or two coupled switches biased by two distinct CW light-waves). The system can have two possible states. In state one, light from laser 1 suppresses lasing in laser 2. Conversely, in state 2, light from laser 2 suppresses lasing in laser 1. To change states, lasing in the dominant laser is stopped by injecting light (set and reset), not at the dominant laser's lasing wavelength, into the dominant laser. The output pulse of the label processor (and its delayed copy) is used as set (reset) pulse for setting (resetting) one of the optical flip-flop memories.

Wavelength routing switch. We employed as switching strategy for routing the packet the wavelength routing switch. The main device in this operation is a very fast, broadband operation non inverting wavelength converter. Non-inverted wavelength conversion based on a semiconductor optical amplifier (SOA) and an optical band pass filter (BPF) has been demonstrated in [20]. Typically the recovery time of the SOA employed is in the order of 100's of picoseconds, which means a maximum speed conversion up to 10 Gbit/s. The use of the optical BPF with a central wavelength that is blue shifted compared to the central wavelength of the converted signal shortens the recovery time of the wavelength converter. Wavelength conversion operation at bit rates up to 320 Gbit/s has been demonstrated [21]. Moreover, a monolithically integrated version has been also demonstrated showing the potential integration of this subsystem with the other ones [22].

4. All-Optical Label Swapping Implementation

In this section we present a 1×4 all-optical packet switch based on label swapping technique [23]. We demonstrate



Old address	0 0	0 1	1 0	1 1
Routing signal [nm]	1547.7	1560.6	1538.2	1542.9
New address	1 1	1 0	0 0	0 1

Fig. 6. Experimental set-up employed to demonstrate the all-optical packet switch based on the label processor and label rewriter. Self-routing table employed in the label swapping experiments.

a label processor for processing in-band labeling addresses and an all-optical label rewriting function that provides a new address according to the old one. The label processor and label rewriter processes "on the fly" the optical labels, operates in asynchronous fashion and can handle packets with variable length.

Figure 6 illustrates the all-optical packet switch based on label swapping technique and the label swapping table. The input packets consist of a 160 Gbit/s payload, with a pulsewidth of 1.6 ps making the 20 dB bandwidth of the payload to be 5 nm. The packet address information is encoded by in-band labels. With this we mean that the wavelengths of the labels are chosen within the bandwidth of the payload. We encode addresses by combining different labels. The label has a binary value: the label value is 1 if the label is attached to the payload, the label value is 0 if no label is attached to the payload. Thus, by using N in-band label wavelengths, 2^N possible addresses can be encoded, which makes this labelling technique highly scalable within a limited bandwidth.

To perform the label swapping and routing of the packet, we utilize four all-optical functions as shown in Fig. 6: label extraction/erasing, label processing, label rewriting, and wavelength conversion. The packet address encoded by the in-band labels is separated from the data payload by the label extractor/eraser which consists of (reflective) fiber Bragg gratings (FBG) centered at the labels wavelengths. While the labels are reflected by the FBGs, the packet payload can pass through the label extractor/eraser before to enter the wavelength converter. The data payload is optically delayed for the time required to the label process to provide a routing signal, before being fed into the wavelength converter.

The optical power of the extracted labels is used to drive the label processor and label rewriter. The label processor receives also as input 2^N CW bias signals at different wavelengths $\lambda_1 \ldots \lambda_2^N$. The wavelengths of the CW-signals are chosen according to the self-routing table and represent the wavelengths at which the payload will be converted. An example of self-routing table for addresses composed by two labels is reported in Fig. 6. For each input labels combination, a routing signal at distinct wavelength and a new combination of labels should be provided by the label processor and the label rewriter, respectively. Thus, the label processor provides a routing signal according to the input labels. The label processor consists of a cascaded of periodic filter and optical switch. The periodic filter has one input and two outputs. The optical switch has two inputs and one output. Each of the 1×2 periodic filter separates (in wavelength) half of the input CW-signal to output port 1 and the other half of the input CW-signals at the output port 2. The 2×1 optical switch selects the CW-signals of port 1 or port 2 based on the value of the label information. Therefore, the output of each pair of periodic filter and optical switch consists of half the number of CW-signals. Thus, after the first stage, the 2^N CW-signals becomes $2^N/2 = 2^{N-1}$. Therefore, after cascading N pairs in which each optical switch is driven by the corresponding label, a distinct CW-signal is selected. This CW-signal at distinct wavelength has a time duration equal to the packet time duration and represents the routing signal to which the payload will be converted. The wavelength of the routing signal represents the central wavelength at which the 160 Gbit/s data payload will be converted by means of wavelength conversion.

Simultaneously, the label rewriter provides the new labels, which have a time duration equal to the packet duration. The label rewriter has the same structure as the label processor discussed previously. The principle of operation of the label rewriter is similar to the label processor. In the case of label rewriter, the CW-signals and the periodic filters are set to provide the new label combinations according to the self-routing table shown in Fig. 6. The wavelengths of the CW-signals are set to be in-band with the switched payload (the central wavelength of the payload is set by the label processor). Thus, for a given old labels combination, the routing signal is provided by the label processor, and the new labels are provided by the label rewriter. Moreover, the wavelengths of the new labels are selected so that they are in-band with the bandwidth of the converted payload. The new labels are attached to the wavelength converted payload (see Fig. 6). The packet with the new labels is routed by means of an AWG to distinct output ports of the packet switch, according to the central wavelength of the converted payload.

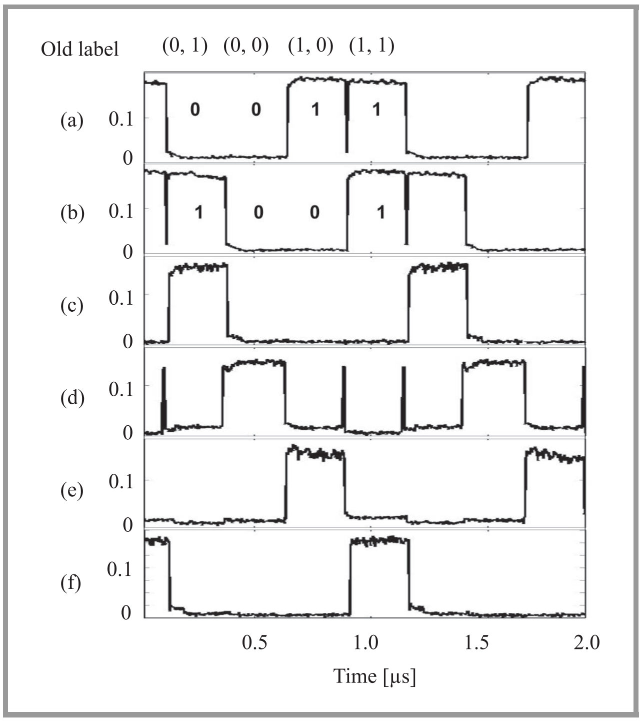


Fig. 7. Measured traces. Extracted labels: (a) label 1; (b) label 2. Output traces of the label processor: (c) 1560.6 nm; (d) 1547.7 nm; (e) 1538.2 nm; (f) 1542.9 nm.

The experimental results of the 1×4 packet switch based on label swapping technique by using two labels address. The extracted labels are shown in Fig. 7(a),(b). The measured optical signal to noise ratio (OSNR) at the SOA-MZI2 output was 32 dB, and the dynamic extinction ratio was 13 dB. The wavelength converter is based on ultrafast chirp dynamics in a single SOA [20]. We set the CW-signals according to the label swapping table. The label processor output traces are shown in Fig. 7(c)–(f), while in Fig. 8(c)–(f) it is shown the output traces of the label-rewriter. The new labels were then combined with the 160 Gbit/s wavelength converted payload. At the receiving node, the packet was processed by the label extractor /eraser, and the resulting 160 Gbit/s payload was evaluated.

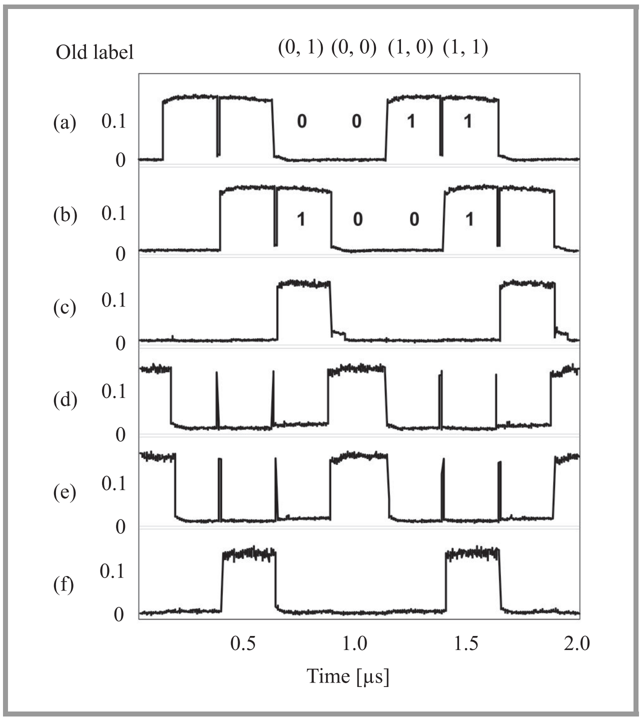


Fig. 8. Measured traces. Extracted labels: (a) label 1; (b) label 2. Output traces of the label rewriter: (c) 1558.9 nm; (d) 1549.3 nm; (e) 1546.1 nm; (f) 1544.5 nm.

Figure 9 shows the bit error rate (BER) performance at different position of the two nodes system. The BER measurements were performed in a static operation by using a 160 Gbit/s pseudorandom bit sequence (PRBS) $2^{31} - 1$ data payload and fixing one address (old label (0.1)). The label extractor in node 1 causes a penalty of less than

0.5 dB compared to the back-to-back payload. After the wavelength conversion, error-free operation was obtained with 5.5 dB of penalty. As reference we also reported the 160 Gbit/s back-to-back wavelength converted, which has 4 dB of penalty. The additional 1.5 dB penalty compared with 160 Gbit/s back-to-back wavelength conversion can be ascribed to the pulse broadening by the label extractor which affects the wavelength conversion performance. The switched packet was then fed into the receiving node 2.

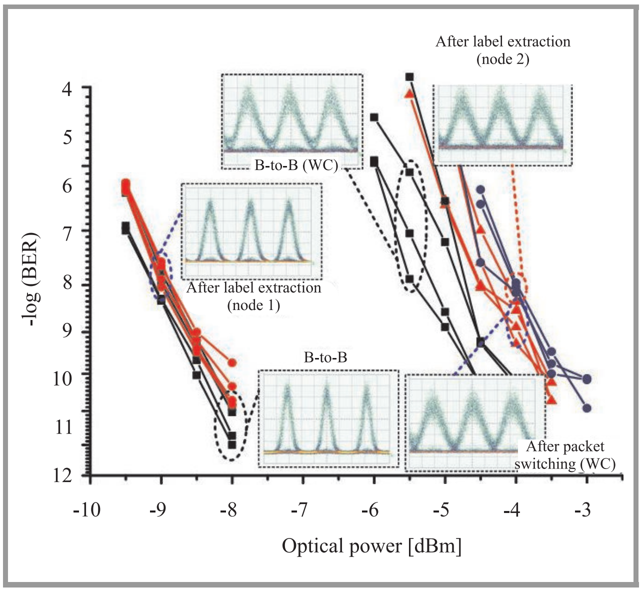


Fig. 9. BER measurements and eye diagrams at different points of the system (time scale: 2 ps/div).

The power penalty after the label extractor is 0.5 dB. This results in a limited power penalty caused by the extraction/insertion of the new labels.

5. Conclusions

We have discussed several all-optical building blocks that potentially can enable the realization of an all-optical packet switching node based on different labelling techniques. It has been discussed that label swapping and label stacking can improve the scalability of the cross-connect node by reducing significantly the number of active devices. The reviewed all-optical building blocks operate asynchronously, with low optical power and at high bit rate, and could be potentially monolithically integrated.

We demonstrated an all-optical 1×4 packet switch by using a scalable and asynchronous label processing and rewriting function. Experiments performed in two-cascaded nodes configuration show error-free packet switching operation at 160 Gbit/s, while the label erasing and new label insertion operation introduces only 0.5 dB of power penalty. Those results indicate a potential utilization of the presented technique in a multi-hops packet switched network.

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