

All-optical packet switch at data-rate beyond 160 Gb/s

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All-Optical Packet Switch at Data-Rate Beyond 160 Gb/s

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ABSTRACT

Two different paradigms to realize a scalable all-optical packet switch with label swapping will be presented. All the functions required for switching the packets are based on all-optical signal processing without any electronic control. This allows very low latency and potential photonic integration of the systems. We report for both techniques experimental results showing the routing operation of the 160 Gb/s packets and beyond.

We will discuss and compare both techniques in term of devices and bit-rate scalability, latency, power consumption, power penalty performance and cascability as key parameters for the realization of an all-optical packet switch.

Keywords: optical packet switching, optical signal processing, label processor, label rewriter, label swapping, semiconductor optical amplifier.

1. INTRODUCTION

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 high speed and parallel operation of all-optical signal processing. Moreover, photonic integration of the optical packet switch potentially allows for a reduction of volume, power consumption and costs. In all-optical packet switches the optical packets are routed based on the address information that is encoded by the attached labels. The optical packet is stored (delayed) in the optical domain for the time required to the label processor to process the address and provide a routing signal for routing all-optically the stored packet. 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. Indeed, integrated delay lines using an InP photonic waveguides have around 2 dB/cm of optical losses. One centimeter of waveguide provides a delay of 100 ps. If the latency of the label processor is in the order of 1 nanosecond, integration of such delay exhibits a total waveguide loss of 20 dB, which is unpractical. Therefore, high speed operation of the label processor (< 100 ps) is a 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.

Several solutions of all-optical packet switch 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 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. Solutions employing 2^N optical correlators and 2^N optical flip-flop to process the addresses may prevent photonic integration.

Our research focuses on the realization of an all-optical packet switching system that is scalable and suitable for photonic integration. We present two all-optical packet switching techniques that utilize all-optical signal processing to implement the label processor and the label rewriter. The two techniques are based on two different paradigms. One is based on wavelength routing switching [1] and the other one on space routing switching [2]. Both techniques employ scalable and asynchronous label processor and label rewriter capable to process optical in-band labeling addresses. We demonstrate a 1×4 all-optical packet switch based on both techniques. We report for both technique experimental results showing the routing operation of the 160 Gb/s packets based on the processed in-band address information, and all-optical label erasing and new label insertion operation. Based on the experimental results, we discuss and compare both techniques in term of devices and bit-rate scalability, latency, power consumption, power penalty performance and cascability as key parameters for the realization of an all-optical packet switching node.

2. ALL-OPTICAL PACKET SWITCH ARCHITECTURE

Figure 1 illustrates the all-optical packet switch based on label swapping technique. The input packet format is also reported in figure 1. The input packets consist of a 160 Gb/s payload, with a pulse duration of 1.6ps 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. Each label is OOK encoded and 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. Note that by using filters with bandwidth narrower than 0.1 nm more than 10 labels can be allocated in the payload bandwidth, which means 2^{10} encoded addresses. Moreover, if the payload data rate increases above 160 Gb/s (i.e. 320 or 640 Gb/s), a larger number of labels can be allocated in the payload spectrum. Thus, the proposed labeling technique scales well with the packet data rate. Other advantages of the in-band labeling are that the labels can be extracted by passive wavelength filtering. Moreover, by using a label that has the same time-duration as the payload makes the use of optical flip-flops redundant, and allows to handle packets with variable lengths in an asynchronous fashion. In the experiment, we encode 4 addresses by using two in-band labels. Figure 1 shows packets carrying different addresses and the corresponding representation in the spectral domain.

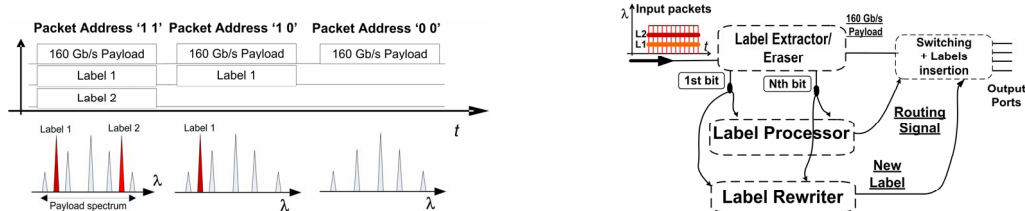


Figure 1. Packet format in the time and spectral domain, and all-optical packet switch configuration.

The all-optical packet switch is based on label swapping technique. In the label swapping technique, the input labels have only a local meaning. The input labels are used to provide the packet's routing information. New labels should be generated and attached to the packet payload before that the packet outputs the switch. To perform the label swapping and routing of the packet, we utilize four all-optical functions as shown in figure 1: label extraction/erasing, label processing, label rewriting, and switching and labels insertion. The packet address encoded by the in-band labels is extracted/separated from the data payload by the label extractor/eraser. The data payload is optically delayed for the time required to the label process to provide a routing signal, before being fed into the switching and labels insertion. The labels are all-optical processed by the label processor and label rewriter. The label processor provides a routing signal according to the input labels. The routing signal at unique wavelength has a time duration equal to the packet time. The wavelength of the routing signal is used to drive the switching and labels insertion. Simultaneously, the label rewriter provides the new labels, which have a time duration equal to the packet duration. 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 switched. It is worth to note that since the label processor and label rewriter operate 'on the fly', the time delay required to store the payload is very short. This may allow photonic integration of the whole packet switch system. Moreover, as the routing signal and the new labels produced by the label processor and label rewriter have a time duration equal to the packet time, the presented system can handle packets with variable length.

3. AOPS BASED ON WAVELENGTH ROUTING SWITCH

The first AOPS technique is based on wavelength routing switching [1]. To perform the label swapping and routing of the packet, we utilize four all-optical functions as shown in figure 2.

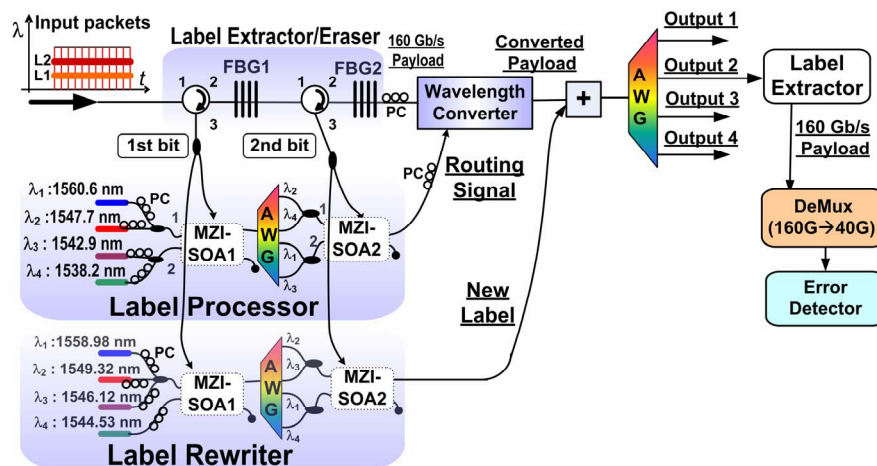


Figure 2. All-optical packet switch based on wavelength routing switch.

The input packet is firstly processed by the label extractor/eraser, which consists of 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 continuous wave (CW) routing signal that is needed for wavelength conversion is provided by the label processor. The optical power of the extracted labels is used to drive the label processor. The label processor receives also as input 2^N CW bias signals at different wavelengths $\lambda_1 \dots \lambda_{2^N}$. 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. The label processor consists of a cascaded of N pairs of periodic filter and optical switch. The periodic filter has one input and two outputs. The optical switch has two inputs and one output. The two outputs of the periodic filter have complementary wavelength transfer functions figure 3. Moreover, each of the N periodic filters has different period as also shown in figure 3. In particular the bandwidth (BW) of the i -th filter is equal to $BW_i = 2^{(i-1)} \times BW_{ch}$, with $i = 1, \dots, N$ and BW_{ch} , the bandwidth of the single CW-signal. 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 and represents the routing signal to which the payload will be converted. Note that the processing is performed entirely in the optical domain. By implementing the optical switches by means of very fast SOA-MZI devices, label processing with only tens of picoseconds of processing time can be possible. Moreover, as no synchronization is required in the scheme, and the routing signal at the output of the label processor has the same duration as the packet payload, the system can handle packets with variable lengths.

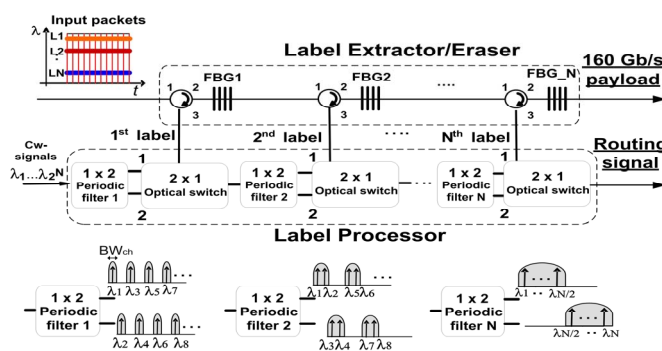


Figure 3. Label processor set-up.

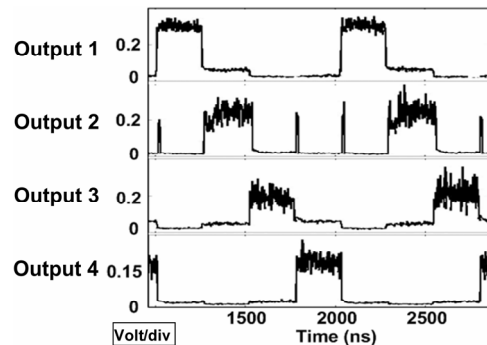


Figure 4. Switched packets at the four output ports

For each input labels combination, the label processor provides a routing signal according to the input labels. The routing signal at unique wavelength has a time duration equal to the packet time. The wavelength of the routing signal represents the central wavelength at which the 160 Gb/s data payload will be converted by means of wavelength conversion. Simultaneously, the label rewriter, which is based on the same operation principle of the label processor, provides the new labels, which have a time duration equal to the packet duration. 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. 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 as shown in Figure 4.

4. AOPS BASED ON SPACE ROUTING SWITCH

The schematic of the AOPS is shown in figure 5. The AOPS consists of a label extractor/eraser, an optically controlled tunable laser (OCTL), and optical gates for payload switching and label rewriting. The input packets are firstly processed by the label extractor/eraser, which consists of two fiber Bragg gratings (FBG) centred at λ_{L1} and λ_{L2} , respectively. The data payload passes through the label extractor/eraser and is broadcasted into the optical gates. The two labels are reflected by the FBGs and fed into the label processor via optical circulators. The labels optically control the output wavelength of the OCTL. The OCTL output acts as a control signal for one of the SOA-MZI based optical gates. These optical gates have two functions. Firstly, they route the packet payload according to the routing table. Secondly, they rewrite the new labels. The OCTL consists of two cw-lasers, two SOA-MZIs and 2 AWGs [2]. The cw-signals are pair-wise fed into the two inputs of SOA-MZI1. The control signal of SOA-MZI 1 is label 1. Thus the presence of label 1 selects two of the cw-signals. Conversely, if label 1 is not present, the other two cw-signals are selected. The two cw-signals that output SOA-MZI1 are separated by an AWG. Each of the separated cw-signals is fed into one of the two inputs of SOA-

MZI2. The control signal of SOA-MZI2 is label 2. Thus the presence of label 2 selects one of the two cw-signals that act as a control signal for the optical gates. Each of the four cw-signals can be selected by a combination of the two labels. Both the payload and the new cw-label are fed simultaneously in the SOA-MZI gate that is controlled by the OCTL output. If a control signal is present, the SOA-MZI gates both the packet payload together with the new label to the output. Conversely, the gate-output is blocked. The operation of the gate guarantees that the payload and the new label have the same duration at the gate output. Figure 5 shows the switched packets at the four outputs of the optical packet switch. It is worth to note that since the label processor and label rewriter operate 'on the fly', the time delay required to store the payload is very short. This may allow photonic integration of the whole packet switch system. Moreover, as the routing signal and the new labels produced by the label processor and label rewriter have a time duration equal to the packet time, the presented system can handle packets with variable length.

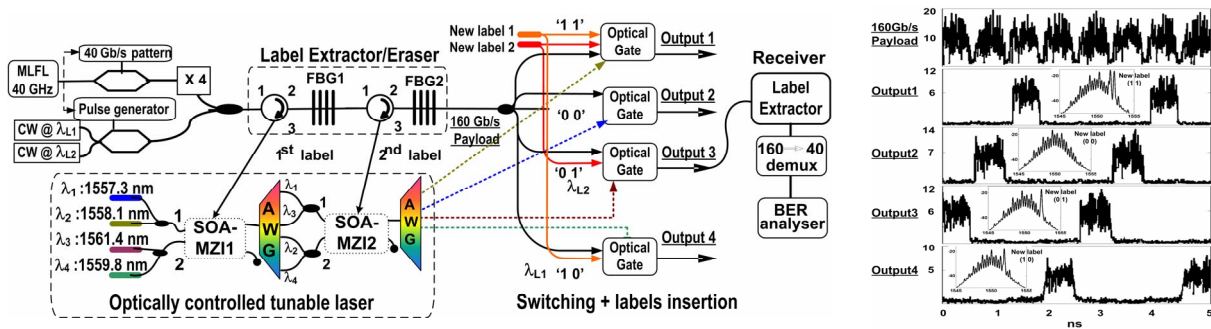


Figure 5. All-optical packet switch based on space routing switch and output switched packets.

5. COMPARISON BETWEEN THE TWO AOPS TECHNIQUES

Device scalability: The AOPS based on wavelength routing switch scales better than AOPS based on space switch. This is due to the fact that the label processor (and label rewriter) and the wavelength converter requires $1 + (\log_2 N)$ active components, while in the space switching N active components are required. The main limitation of the label rewriter is the OSNR degradation with the increase of the number of labels. On the contrary, in the space switch the OSNR degradation is much reduced since the label rewriter and the switching are implemented by a single active component.

Bit-rate scalability: For bit-rate beyond 160 Gb/s, the AOPS space switch outperforms the AOPS wavelength routing switch mainly because the capability to operate the wavelength converter with data rate beyond 160 Gb/s with acceptable power penalty.

Latency: The latency is due to the label processor in the wavelength routing switch case, and to the OCTL in the space switch. Both devices introduce the same amount of latency.

Node cascability: Cascadability of the AOPS is mainly limited by the power penalty introduced by the switching technique. In the AOPS based on wavelength routing switch the measured BER penalty was 6.5 dB [1], of which 5 dB is due to the wavelength converter operation. In the space switch we have recorded a penalty of 1.5 dB [2]. Thus, AOPS based on space switching is preferable for multi-hops operation.

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