All-optical label processing in optical packet switched networks

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Abstract: We present a data-format transparent all-optical label processing system suitable for photonic integration that requires N active device to process 2^N addresses. We demonstrate error-free all-optical packet switch with label swapping operation at 160 Gb/s.

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Boosted by the traffic increase in the access networks future optical networks should handle hundreds of Tb/s data traffic [1]. High capacity optical links might carry ultrafast OTDM data packets or multi-wavelength data packets with highly spectral efficient modulation formats, such as D(Q)PSK, OFDM, M-QAM. The increase of power consumption and dissipation as the required capacity increases will limit the scalability of current electronic circuit switching. 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 and photonic integration to reduce volume, power consumption and costs.

In an all-optical packet switch (AOPS), 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 packet. To realize an AOPS for practical applications, several issues should be addressed. Scalable AOPS sub-systems that can address a large number of inputs/outputs are required. This will demand for a scalable label processor technique that is capable to process large number of addresses with a limited number of active components. A way to minimize the amount of labels that should be processed (and thus the number of active components) is the implementation of all-optical label swapping technique (AOLS) [2]. In AOLS only few labels for routing the optical packet has to be processed at each node, thus leading to a considerable simplification of the label processor architecture. However, this means that the AOPS should also include a practical label rewriting functionality. It is important that the label processor is suitable for photonic integration. Compact device minimizes the latency and thus maximizes the node throughput. The integration of the AOPS 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 processing time of the label processor. Indeed, integrated delay lines using photonic waveguides have few dB/cm of optical losses. Large delay, in the order tens of nanoseconds, clearly limits the photonic integration of the AOPS. Therefore, high speed operation of the label processor is essential to allow for integration of the packet switch system. Moreover, the AOPS should be able to handle optical packets with multiple data format. This implies that both the label processor and the optical switching fabric should operate independently of the data-format and data rate of the packets.

In this talk we present the realization of a label processing technique that is scalable, suitable for photonic integration, has a latency < 400 ps, low power, asynchronous and "on-the-fly" processing operation, and it is capable to operate with multiple data formats and data rate packets. We will present experimental results to validate the operation of the label processor and we employ the label processor to demonstrate a 1x4 all-optical packet switch for packet at data rate of 160 Gb/s and beyond.

Figure 1 shows the schematic of the AOPS and the packet format. The packet address information is encoded by in-band labels, which means that the wavelengths of the labels are chosen within the bandwidth of the payload. The packet address information is encoded by in-band labels. Generally, optical packets with payload at high data rate *B* can be generated in serial by using OTDM technique or in parallel by using *N* colored channels so that each channel has bit-rate *B/N*. Both the OTDM packets and N-channels can be encoded by many modulation formats. The labels are located within the spectrum of the OTDM signal [3] (see fig. 1b). For the DPSK multi-wavelength packets, we use the same label wavelengths, but they are spectrally located in the notches of the spectra of the DPSK multi-wavelength payload [4] (see fig. 1c). Each label is OOK encoded and has a binary value and the same duration as the payload. Thus, 2^N addresses can be encoded by only using *N* in-band labels. This makes the in-band labelling

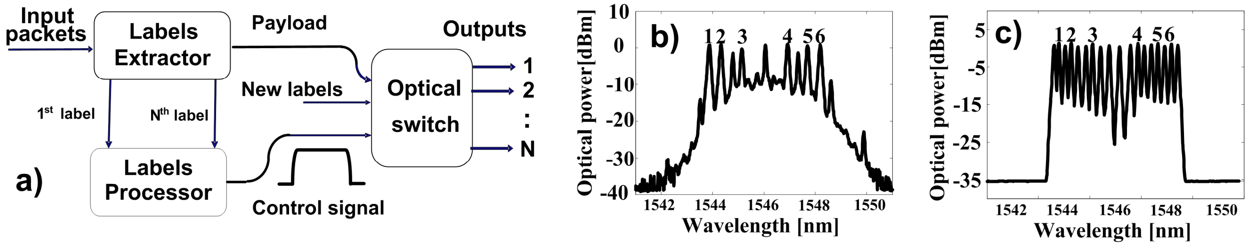

Figure 1. a) All-optical packet switch configuration. b-c) Optical spectra of OTDM and multi-wavelength packets, respectively.

technique scalable within the limited payload bandwidth. Moreover, the labels can be extracted by passive wavelength filtering. The asynchronous labels extraction avoids precise synchronization to separate the label from the payload. No reconfiguration of the label processor is needed when changing data format, and no optical flip-flops are required.

The AOPS consists of a label extractor/eraser, a label processor, and optical gates for payload switching and label rewriting. The label extractor/eraser, which consists of narrow filters centered at the labels wavelength [3, 5], separates the packet address from the data payload. In figure 2 the optical spectra and BER curves of the packets before and after the label extractor for 160 Gb/s OOK and 120 Gb/s DPSK are shown. Note that the label extractor operates transparently for different data rates and data formats and the measured power penalty is lower than 0.7 dB. The data payload is optically delayed for the time required to process the labels and fed simultaneously with new cw-label into the SOA-MZIs based optical switch. The labels are processed by the all-optical label processor. For each input labels combination, a control signal at distinct wavelength should be provided by the label processor. The output of the label processor acts as a control signal for one of the SOA-MZI based optical gates (see details of the experimental set-up in figure 4). 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.

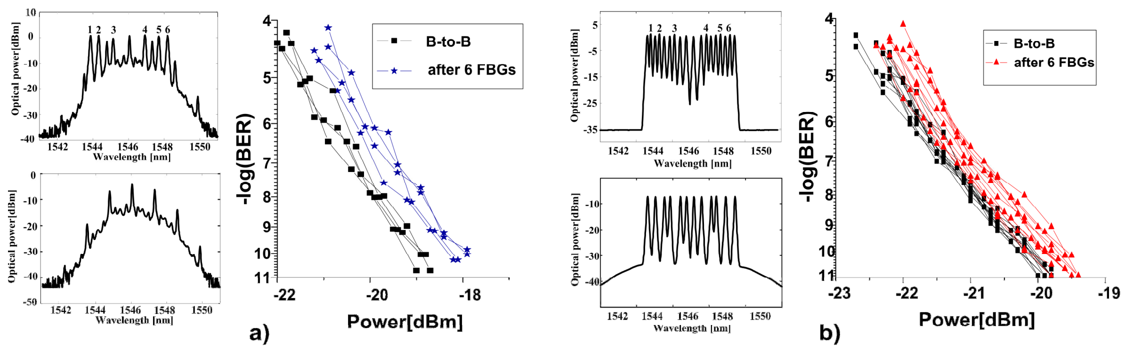

Fig 2: Optical spectra of the packets before and after the label extractor and BER curves for a)160 Gb/s OOK; b) 120 Gb/s DPSK.

The schematic of the all-optical label processing system is shown in fig. 3. The optical power of the extracted labels controls the label processor. The label processor consists of a cascaded of N pairs of periodic filter and optical switch. The label processor receives as input 2^N CW bias signals at different wavelengths $\lambda_1 \ldots \lambda_{2^N}$. The 1x2 periodic filter separates (in wavelength) half of the input CW-signals to port 1 and the other half of the CW-signals to port 2. The two outputs of the periodic filter have complementary wavelength transfer functions as shown in 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,…, N and BW_{ch}, the bandwidth of the single CW-signal. The 2x1 optical switch selects the CW-signals of port 1 or port 2 based on the binary value of the labels. 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 duration and acts as control signal of the gate. Note that the processing is performed entirely in the optical domain and on the fly. Moreover, the label processor requires only N active components to process 2^N addresses. Figure 3 reports the SEM photo of the integrated InP label processor capable to process 3 labels (8 addresses). The device is currently under characterization.

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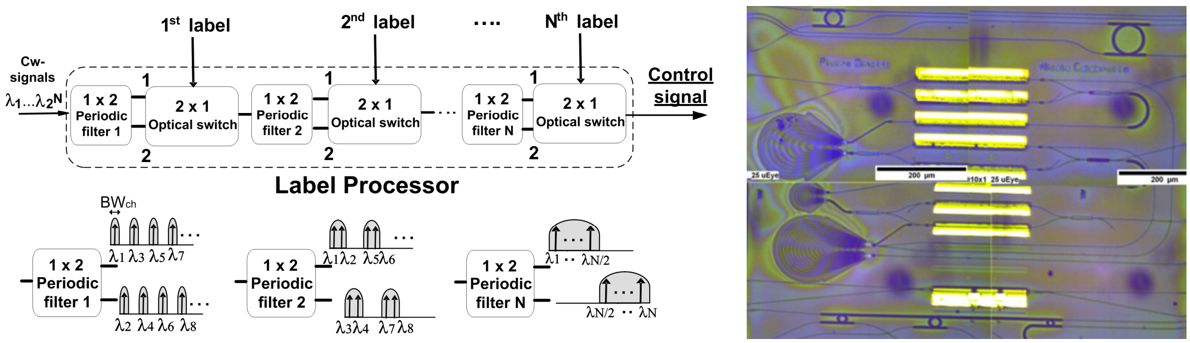

Figure 3. Schematic of the all-optical label processing system, and SEM photo of the photonic integrated chip.

As an application of the label processor, we have demonstrated a 1x4 AOPS with label rewriting for 160 Gb/s data packets. The schematic of the 1x4 AOPS is shown in Fig. 4a. Data burst of 6 ns long and 400 ps of guard-time were employed in the experiments. The data rate of the payload was 160 Gb/s and 4 different addresses (2 labels) were employed to control the 4 outputs of the AOPS. More details of the experiment are reported in [6]. The separated payload is fed into the optical gates. The labels drive the label processor, which provides the control signal of the optical gates. Figure 4b shows the scope traces and optical spectra of the signals recorded at the four output of the switch. The switched packets are received and BER was measured. Figure 4c shows the BER curves of the back-to-back (b-t-b) 160 Gb/s payload and the BER of the switched packet at Output 2 (no new label inserted) and at Output 3, in which a new label ('01') is inserted. The BER curves show error-free operation with 1.6 dB of power penalty.

In conclusion, we have presented a data-format and bit-rate transparent all-optical label processing system for in-band labels with on the fly operation and suitable for photonic integration. The label processor is scalable in terms of number of addresses since it requires only N active device to process 2^N addresses. By using this label processing technique, we have demonstrated error-free operation of 1×4 AOPS with label swapping at 160 Gb/s data rate at the expense of only 1.6 dB of penalty, which indicates that use of the AOPS in large systems is possible.

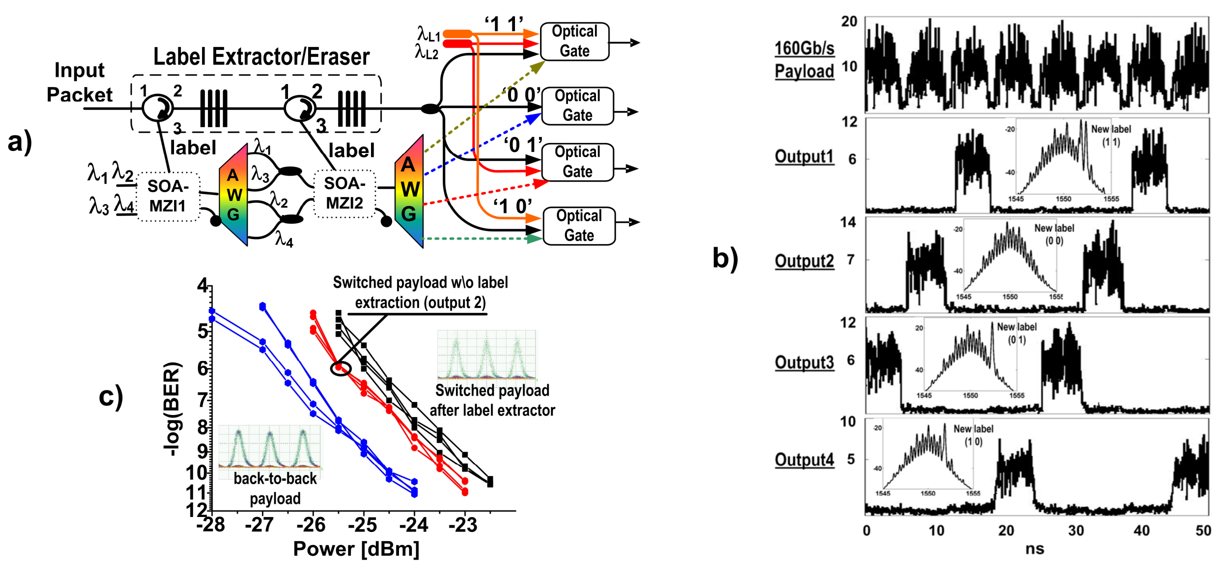

Figure 4 a) Experimental set-up of the 1x4 AOPS. b) the scope traces and optical spectra of the signals recorded at the four output of the switch. c) BER curves. Time scale eye diagrams 1ps/div.

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