160 Gb/s All-Optical Packet Switching with Label Rewriting

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Abstract
We demonstrate for the first time 160Gbps error-free 1x4 all-optical packet switching including all-optical label rewriting. Power penalty 1.5dB enables application in multihop packet-switched networks.

Introduction
Several solutions have been proposed for all-optical packet switching (AOPS) [1-4 and the references therein], but despite the progress, an AOPS that includes both an all-optical label processor and an all-optical label rewriter has never been presented. Moreover, the solutions presented in the past show packet switching at the expense of large power penalties (> 5 dB), making multi-hop operation impossible. Here, we present a 160 Gb/s (single-wavelength) 1x4 all-optical packet switch that includes all-optical label processing and label-rewriting at the expense of a power penalty of 1.5 dB. The all-optical label processor and rewriter are based on ultra-fast “on-the-fly” optical signal processing, which guarantees narrow packet’s guard-times. The latter is essential for future photonic integration of the switch concept. Open eyes indicate that error-free operation for 320 Gb/s payload is possible.

System operation
The schematic of the 1x4 AOPS and the packet format are shown in Fig. 1. Packet payload is generated by time-quadrupling a 40 Gb/s data-stream consisting of 256 pre-defined return-to-zero bits (λ_p=1550.8 nm) into a 160 Gb/s data-stream using a fibre-based pulse interleaver. Each pulse has duration of 1.5 ps making the 20 dB bandwidth of the payload to be 5 nm. The resulting packet payload consists of a 6 ns data burst. The guard-time between the packets is 400 ps. We employ in-band labelling; the packet address information is encoded with cw-signals at wavelengths within the 5 nm payload bandwidth. Each label can have a binary value: ‘0’ means no signal at the label wavelength, ‘1’ means an optical signal at the label wavelength. The duration of the label equals the duration of the payload (see Fig. 1).

We encode 4 addresses by using two in-band labels at λ_L1=1551.9 nm and λ_L2=1552.5 nm. As advantage the labels can be asynchronously extracted by passive wavelength filtering.

The AOPS consists of a label extractor/eraser (LE), an optically controlled tunable laser (OCTL), and four optical gates for payload switching and label rewriting. The input packets are firstly processed by the LE, which consists of two fiber Bragg gratings (FBG) centred at λ_L1 and λ_L2, respectively. The data payload passes through the LE and is broadcasted into the 4 optical gates. The two labels are reflected by the FBGs and fed into the OCTL 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 in Fig. 1. Secondly, they rewrite the new labels.

The OCTL consists of four cw-lasers, two SOA-MZIIs and 2 AWGs [4]. The cw-signals are pair-wise fed into the two inputs of SOA MZI 1. 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-MZI 1 are separated by an AWG. Each of the separated cw-signals is fed into one of the two inputs of SOA-MZI 2. The control signal of SOA-MZI 2 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. Fig. 1 shows the routing table for the new addresses. For example if the old address was “10”, the OCTL selects a control signal with a wavelength of 1561.4 nm. It is also visible from the routing table the new address is “01”. This means that the new cw-label has a wavelength of 1552.5 nm (which is in band with the packet

Figure 1: Experimental set-up and packet format. The routing table is also reported.
payload). 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.

**Experiments and Results**

The experimental setup to demonstrate the 1x4 AOPS with label swapping functionalities is shown in Fig. 1. We processed four packets with addresses ‘0 0’, ‘0 1’, ‘1 0’, and ‘1 1’ to cover all possible combinations. The extracted labels are shown in Fig. 2 (a-b), while the payload is shown in Fig. 3a. The optical power of label 1 and label 2 at the input of MZI-SOAs of the OCTL were 1.8 dBm and 1.3 dBm, respectively. The optical power of each CW-signal was -2.5 dBm. The OCTL output traces are shown in Fig. 2 (c-f). The dynamic extinction ratio was 13 dB. The OCTL output was amplified by an SOA and distributed to the 4 optical gates by means of an AWG. The optical power of the control signal at the optical gate was -3.3 dBm. Figures 3 (b-e) report the traces of the switched payload and the inserted new labels at different output ports. We also report in the insets optical spectra showing the switched payload and the new labels.

![Fig. 2 a-b) Extracted labels. c-f) Output traces of the label processor. The vertical scale is in mV.](image)

To evaluate the performance, the switched packets are fed into a receiving node, consisting of a label extractor (only the payload is evaluated), a 160-to-40 Gb/s demux, and a 40 Gb/s detector. Fig. 4 shows the BER curves. As reference we report the BER curve of the back-to-back (b-t-b) 160 Gb/s payload. The BER curve of the switched packet at Output 2 (no new label inserted) shows error-free operation with 1 dB of power penalty. We also report the BER curve of the switched packet at Output 3, in which a new label (‘01’) is inserted. An additional power penalty < 0.5 dB was measured compared to the case without label insertion. This indicates that the switch with label rewriting introduces very small penalties. As a final result we report in Fig. 4 the eye diagrams of the b-to-b payload and the switched payload at 320 Gb/s. Although the eye diagram gives only qualitative information, the clear open eye suggests that error-free operation at 320 Gb/s is feasible.

![Fig. 3 a) 160 Gb/s payload; b-e) Output traces of the AOPS. The vertical scale is in mV.](image)

**Conclusions**

We have demonstrated error-free 1x4 AOPS with label rewriting. The label processor is based on ‘on the fly’ optical signal processing in SOA MZIs, and on a packet-by-packet basis. This makes extraction of a clock redundant and ensures that the AOPS is suitable for photonic integration and allows operation up to 40 Gb/s. This leads to a processing time of few tens of picoseconds, allowing short packet’s guard time. BER measurements on the 160 Gb/s switched packets show error-free operation with a power penalty of less than 1.5 dB, indicating potential application in multi-hop packet-switched network. Open eyes indicate that error-free operation for 320 Gb/s payload is possible.

**References**