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All-optical label swapping of in-band addresses and 160 Gbit/s data packets

N. Calabretta, H.-D. Jung, J. Herrera, E. Tangdiongga and H.J.S. Dorren

A 1 × 4 all-optical packet switch is presented, based on an optical label swapping technique that utilises a scalable label processor and a label rewriter with 'on the fly' operation. Experimental results show error-free packet switching with a data payload at 160 Gbit/s. The label erasing and new label insertion operation introduces 0.5 dB of power penalty. These results indicate a potential utilisation of the presented technique in a multi-hop packet switched network.

Introduction: All-optical packet switching (AOPS) is a promising candidate to route optical packets at higher bit rates and with lower power dissipation compared to electronics [1–3]. The key issue is to realise an AOPS node that is scalable and that allows photonic integration. Here we demonstrate a scalable 1 × 4 all-optical packet switch in which both the label processor and the label rewriter are implemented in the optical domain. Our approach allows for encoding of 2^N addresses within a limited bandwidth. Moreover, the system that we introduce is based on 'on the fly' label processing that reduces the latencies to values that can be handled by integrated delay lines.

System operation: The schematic of the 1 × 4 AOPS is shown in Fig. 1 and consists of a label extractor/eraser (LE), a label processor (LP) [4], a label rewriter (LR) and a wavelength converter (WC). The packets consist of 160 Gbit/s payload at $\lambda_p = 1550.8$ nm with a duration of 250 ns and a guard time of 10 ns. Each bit has duration of 1.6 ps making the 20 dB bandwidth of the payload to be approximately 5 nm. The packet address information is encoded with signals at wavelengths within the 5 nm bandwidth of the payload. We encode four addresses by using two in-band labels at $\lambda_{L1} = 1551.9$ nm and $\lambda_{L2} = 1552.5$ nm [4]. The advantage of the in-band labelling is that the labels can be asynchronously extracted by passive wavelength filtering.
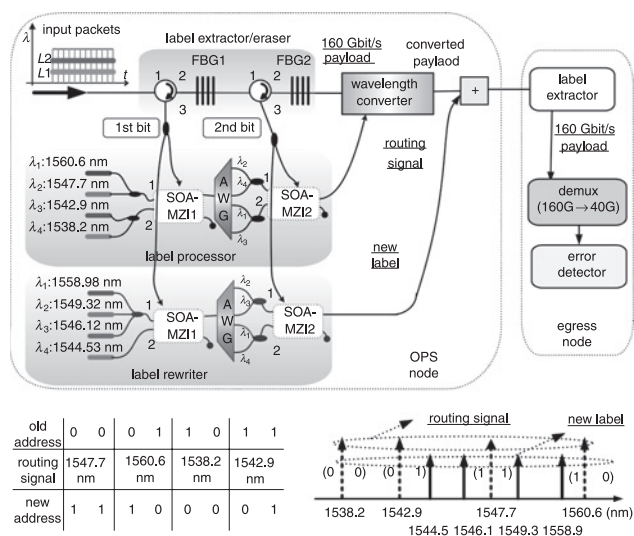

**Fig. 1** *Experimental setup with label swapping table and corresponding wavelengths*

The input packet is first processed by the LE, which consists of two fibre Bragg gratings (FBG) at λ_{L1} and λ_{L2}, respectively. While the data payload passes through the LE, the labels are reflected by the FBG. The packet-payload is fed into the WC [5]. The routing signal that is needed for wavelength conversion is provided by the LP (see Fig. 1). The optical power of the extracted labels is split and fed into the LP and the LR. The LP was demonstrated before [4]. In brief, the LP is made out of two SOA-MZIs, which act as wavelength selective switches that are optically controlled by the extracted labels. Each label can have a binary value: '0' means no optical signal at the label wavelength, '1' means an optical signal at the label wavelength. CW signals at wavelengths λ_1 and λ_2 and wavelengths λ_3 and λ_4 are fed into port 1 and port 2 of SOA-MZI1, respectively. If the value of label 1 is '0', SOA-MZI1 is in bar-state and the pair of signals (λ_1, λ_2) appear to the

SOA-MZI1 output. However, if the value of label 1 is '1', the SOA-MZI1 is set in its cross-state and the pair of signals (λ_3, λ_4) are switched to the SOA-MZI1 output. An array waveguide grating (AWG) and 2 × 1 couplers are used to separate the pair of CW signals (λ_1, λ_2) or (λ_3, λ_4) and to couple them into port 1 (λ_2 or λ_4) and port 2 (λ_1 or λ_3) of SOA-MZI2. Thus, according to the value of label 2, SOA-MZI2 is set in bar-state or cross-state, selecting only one signal at a distinct wavelength. This signal acts as the routing signal for the WC.

The label rewriter is based on the same principle of operation of the LP. In this case the CW signals represent the new labels. In AOLS techniques, the packet address determines both the packet's routing and the new address based on a pre-designed swapping table. According to the swapping table in Fig. 1, for a given old label combination, the routing signal is provided by the label processor, and the new labels at wavelengths in-band with the switched payload are provided by the label rewriter. As an example, if a packet with address '0 1' is processed, the payload is converted to 1560.6 nm and a signal at 1558.9 nm, in-band with the payload spectrum, that represents the new labels '1 0' is obtained at the label rewriter output. The new labels are coupled to the converted payload, so that at the 1 × 4 packet switch output, the switched packet contains the new in-band label information.
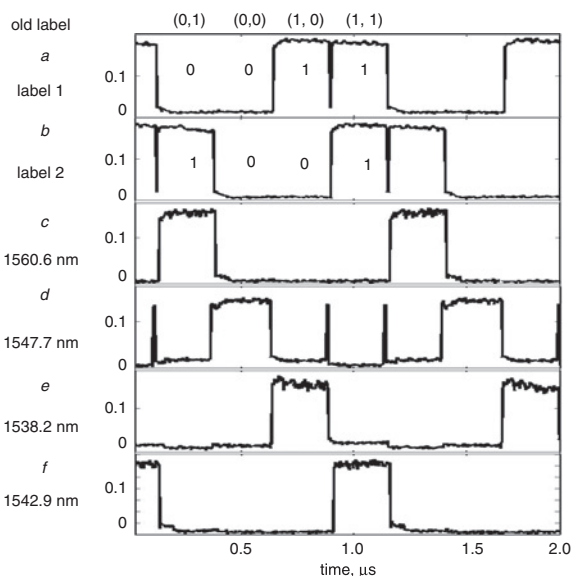

Fig. 2 *Measured traces*

a, b Extracted labels
c–f Output traces of label processor
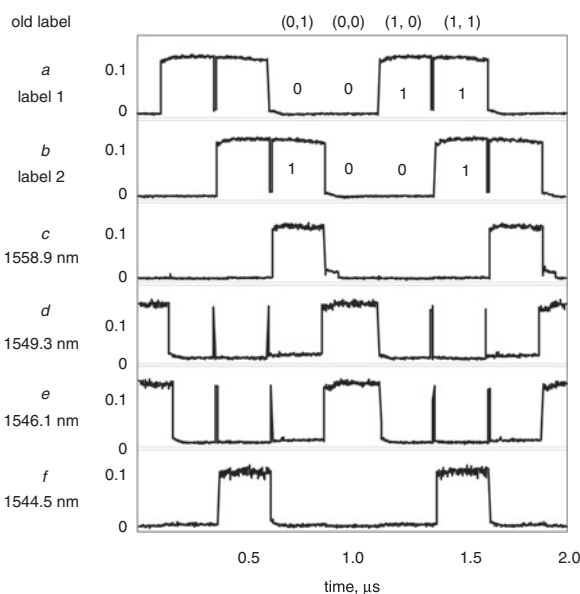
Fig. 3 *Measured traces*

a–b Extracted labels
c–f Output traces of label rewriter

Experiments: The experimental setup to demonstrate the 1×4 AOPS based on AOLS is shown in Fig. 1. We processed four packets with two labels. The extracted labels are shown in Figs. 2a and b. The optical power of label 1 and label 2 at the input of MZI-SOAs of the LP and LR were 1.5 and 0.3 dBm, respectively. The optical power per channel of the CW signals was -2.5 dBm. The measured OSNR at the MZI-SOA2 output was 32 dB, and the dynamic extinction ratio was 13 dB. The WC is based on ultra-fast chirp dynamics in a single SOA [5]. We set the CW signals according to the swapping table in Fig. 1. The LP output traces are shown in Figs. 2c–f, while Figs. 3c–f show the output traces of the LR. The new labels were then combined with the 160 Gbit/s wavelength converted payload.

To study the cascadability of the packet switch, the switched packet at the OPS output was fed into egress node, where the new address was extracted and the 160 Gbit/s payload was evaluated. Fig. 4 shows the BER curve at different points in the set-up. The BER measurements were performed in a static operation using a 160 Gbit/s PRBS $2^{31} - 1$ data payload and the address (0 1). As reference we report the BER curve of the back-to-back 160 Gbit/s payload and the BER curve after wavelength conversion by using a CW signal. Our wavelength converter introduces 4 dB of power penalty compared to the back-to-back curve. The label extractor in the OPS node causes a penalty of 0.5 dB compared to the back-to-back payload. After the wavelength conversion by using the routing signal, error-free operation was obtained with 5.5 dB of power penalty. The additional 1.5 dB penalty can be ascribed to the pulse broadening caused by the label extractor, which affects the wavelength conversion performance. However, by using a filter with a bandwidth of 0.1 nm as label extractor, pulse broadening can be prevented. The switched packet with the new address was then fed into the egress node. The additional power penalty after the label extractor is 0.5 dB. This indicates that only a limited penalty was caused by the extraction/insertion of the new labels.
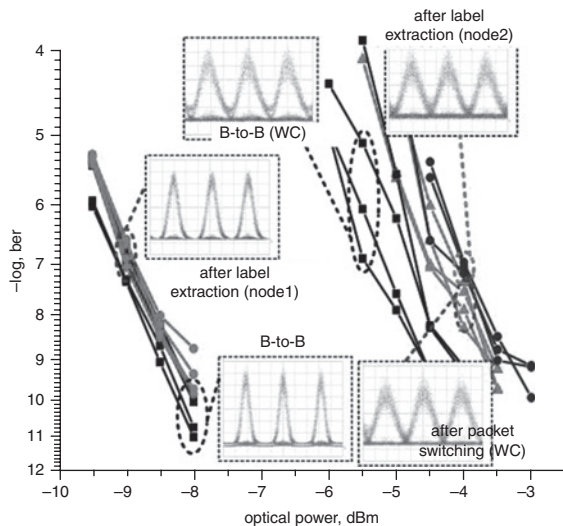
Conclusions: We demonstrate an all-optical 1×4 packet switch by using a scalable and asynchronous label processing and rewriting function. The proposed AOLS technique requires $2 \times N$ optical switches to process and rewrite 'on the fly' 2^N encoded addresses. The label swapping is demonstrated using SOA-MZIs as optical switches that are suitable for photonic integration and can operate at a data rate of up to 40 Gbit/s. This results in a label processing time of a few tens of picoseconds, and thus allows the photonic integration of the optical delay required to store the payload. Experimental results 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. These results indicate a potential utilisation of the presented technique in a multi-hops packet switched network.

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Fig. 4 *BER measurements and eye diagrams at different points of system*
Time scale is 2 ps/div