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# Novel Scheme for Simple Label-Swapping Employing XOR Logic in an Integrated Interferometric Wavelength Converter

T. Fjelde, A. Kloch, D. Wolfson, B. Dagens, A. Coquelin, I. Guillemot, F. Gaborit, F. Poingt, and M. Renaud

**Abstract**—We present a novel scheme for all-optical label swapping that relies on logic exclusive-OR (XOR) in an integrated SOA-based Michelson interferometer. The scheme allows simple, efficient and mechanically stable operation, while relaxing the requirements on packet format and simplifying switch management. Furthermore, the label-swapping scheme does not require a guard band between the header and payload to perform alterations in the header. The method, which incorporates simultaneous wavelength conversion, is demonstrated at 10 Gb/s with negligible penalty and a high output signal-to-ASE ratio of  $\sim 35$  dB.

**Index Terms**—Converters, optical communication, optical logic devices, optical signal processing, packet switching, semiconductor devices.

## I. INTRODUCTION

WITH the exponential growth in Internet traffic, scaling of Internet Protocol (IP) data networks far beyond their present performances is required. In order to meet this challenge, Multiprotocol Label Switching (MPLS) [1] is rapidly emerging as the technology that allows for enhanced speed and scalability as well as service provisioning capabilities in the Internet. All-optical packet switching exploiting wavelength-division-multiplexed (WDM) fits well into the MPLS concept, while offering flexibility, enabling scaling to very high bit rates and eliminating potential electronic bottlenecks.

In order to enable optical MPLS an efficient scheme for all-optical label swapping is required in packet switches [i.e., label-switching routers (LSR)]. This is because the label on an incoming packet is replaced with a new value in the LSR as it is forwarded to the appropriate outlet; thus, the forwarding mechanism is based on label swapping. Different methods for all-optical label swapping have been proposed within the last few years, including the employment of header erasure/rewriting to perform simultaneous label swapping and wavelength conversion as demonstrated in both [2] and [3]. Incorporating wavelength conversion is an advantage as it assures that header and payload maintain the exact same wavelength, which is important for dense WDM. Moreover,

wavelength conversion can be used for packet contention resolution [4]. In [2] header erasure/rewriting is performed using a two-stage method that employs semiconductor optical amplifier (SOA)-based cross-gain modulation followed by cross-phase modulation (XPM), while in [3] header replacement is done at 2.5 Gb/s in a single step using a loop mirror. Both schemes require very special packet formats; the scheme in [2] employs a subcarrier multiplexed header, while in [3] the peak power in the header is required to be  $\sim 10$  dB less than in the payload.

This letter presents an alternative method for all-optical label swapping that relaxes the requirements on packet format and, furthermore, does not require complete header erasure/rewriting; only a few header bits in the label are changed using a short “swapping sequence,” while the remaining header and payload are left unaltered. Thus, the complexity of switch management is reduced significantly, which, of course, is an important factor for the implementation of all-optical networks. Furthermore, since no header replacement is done a guard band between the header and payload is not necessary for this scheme. This means that a more efficient use of bandwidth is possible. The scheme relies on optical XOR in a monolithically integrated interferometric wavelength converter (IWC) to perform simultaneous label swapping and wavelength conversion in one stage. In this letter, the label swapping scheme is demonstrated at 10 Gb/s with a negligible penalty of 0.4 dB using a Michelson interferometer. Due to its simplicity, stability and power-efficiency the method is easy to implement in practice, clearly demonstrating the feasibility of all-optical label swapping in future networks.

## II. PRINCIPLE OF XOR LOGIC IN AN INTERFEROMETRIC WAVELENGTH CONVERTER

As mentioned previously, the label swapping scheme proposed in this letter relies on all-optical XOR logic in an IWC. In Fig. 1, the principle of XOR logic in a Michelson interferometer (MI) is shown schematically. As indicated in Fig. 1(a), two input data signals on which the logic operation is to be performed are coupled into the interferometer arms at port #1 and 2, while continuous-wave (CW)-light is coupled into the common arm at port #3. In the MI the data signals are launched into the two SOAs where they modulate the carrier density and thereby also the refractive index. This causes a phase modulation ( $\phi$ ) of the CW-light propagating in the SOAs according to the bit pattern of the input data signals. At the output of the interferometer, the CW-light from the two SOAs interferes either constructively

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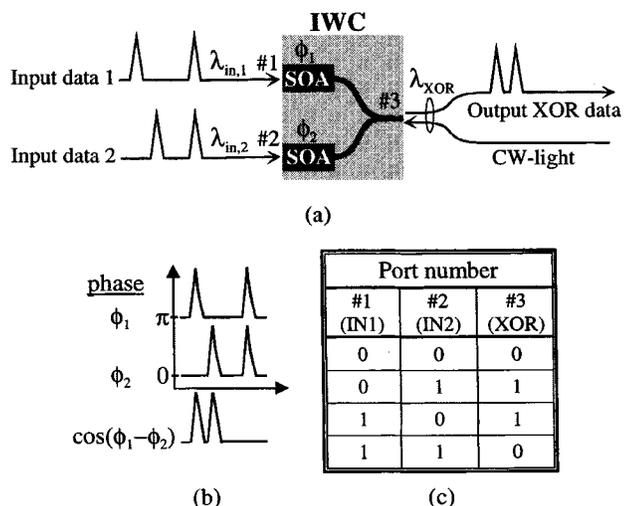


Fig. 1. (a) Schematic of integrated interferometric wavelength converter as an XOR gate. (b) Illustration detailing the principle of XOR operation. (c) XOR truth table.

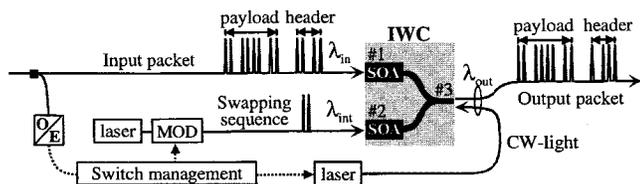


Fig. 2. Practical implementation of label swapping scheme (MOD: modulator).

or destructively depending on cosine to the phase difference between the light from the two SOAs ( $\cos(\phi_1 - \phi_2)$ ) and is, thus, controlled by the input data signals. This leads to a wavelength converted output signal at port #3 that corresponds to the XOR logical of the two input data signals, as indicated by the truth table shown in Fig. 1(c). Note that the CW-light is reflected from the end facets at ports #1 and 2, why it propagates twice through the SOAs before exiting the MI at port #3.

The capability of the interferometric wavelength converter as an XOR gate has previously been demonstrated at up to 20 Gb/s in [5], where a Mach-Zehnder interferometer (MZI) was employed. Furthermore, standard 40-Gb/s wavelength conversion has been performed in a Michelson interferometer [6], indicating the high-speed potential of the IWC.

### III. PRACTICAL IMPLEMENTATION OF LABEL-SWAPPING SCHEME

In Fig. 2 is shown a schematic of the label swapping scheme with the interferometric XOR gate as the central element to change selected bits from marks to spaces and vice versa. Label swapping is achieved in the following way: At the packet switch input, a fraction of the signal power in incoming packets is tapped off to the switch management to perform header clock recovery, packet delineation, label reading, etc.—all necessary for any header modifications. Using this information, the changes needed in the existing label to perform the label swapping are found and, at the appropriate time, modulated onto CW-light at a fixed internal wavelength  $\lambda_{int}$ . The optical

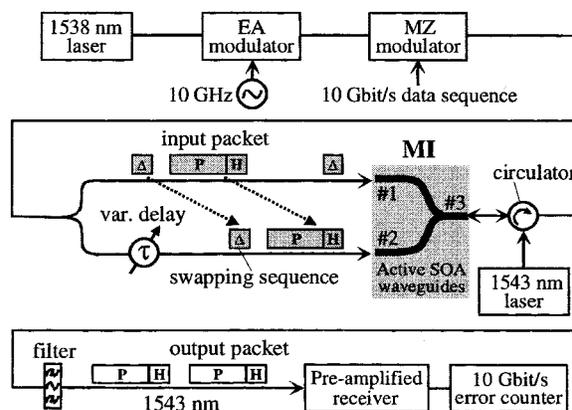


Fig. 3. Experimental setup for verification of label swapping scheme at 10 Gb/s.

swapping sequence is coupled into one of the interferometer arms (here, port #2), while the input packet at  $\lambda_{in}$  is coupled into the other. Furthermore, CW-light at the desired output wavelength,  $\lambda_{out}$ , is coupled into port #3. Through XPM as described above, the output packet at  $\lambda_{out}$  will correspond to the XOR logic of the input packet and the swapping sequence. So, a space in the swapping sequence will leave the input data bit unchanged at the output, while a mark will alter the bit in the output packet with respect to the input packet. Note that the scheme places no restrictions on the bit-rate of the payload data, which can be variable.

### IV. EXPERIMENTAL SETUP

Fig. 3 shows the experimental setup used to investigate the label swapping scheme at 10 Gb/s by bit-error-rate (BER) measurements on the output packet sequence. In order to avoid the use of two pattern generators for the input packet sequence and the label swapping sequence, the following scheme has been used: 10-GHz clock pulses having a pulse width of  $\sim 30$  ps are generated through modulation of CW-light at 1538 nm using an EA-modulator. A 10-Gb/s data sequence consisting of the input packet sequence followed by a label swapping sequence ( $\Delta$ ) is encoded onto the return-to-zero (RZ) pulses using a LiNbO<sub>3</sub> modulator. As shown in Fig. 3, the signal is passively split into two arms. By subsequently delaying one part appropriately with respect to the other, the swapping sequence will be injected into one arm of the all-active Michelson interferometer in synchronization with the packet header injected into the other arm. Both signals have input power levels below  $-3$  dBm, demonstrating the power efficiency of the scheme. In addition,  $+3$  dBm of CW-light at 1543 nm is coupled into the MI at port #3. Exiting port #3 is the wavelength converted output packet sequence with a power of  $-1.5$  dBm. This demonstrates conversion gain as the output signal level exceeds the input signal level. Finally, a filter selects the output packet sequence before detection and error counting.

### V. RESULTS AND DISCUSSION

Fig. 4 shows the measured pulse traces of input and output packet sequences. To enable illustration of all bits in the packet sequence clearly at the same time the packet has a limited length

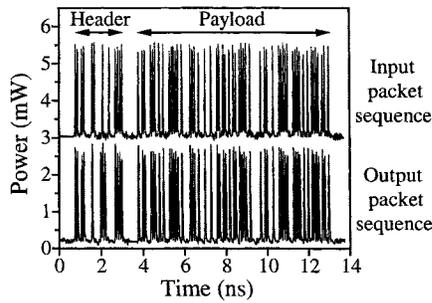


Fig. 4. Measured input and output packet sequences.

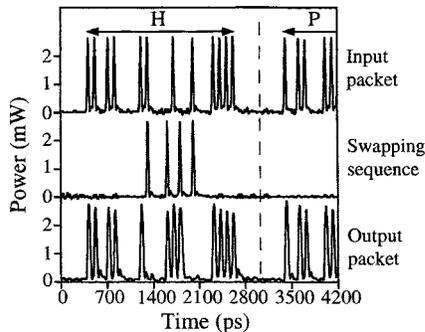


Fig. 5. Scheme verification-enlargement of header (H) and partial payload (P).

of 123 bits with a 23-bit header, a 7-bit guard band and a 93-bit payload. As indicated, the input and output packet sequences are identical except for the bits in the header that have been altered by the label swapping scheme. Note that the variation in the height of the marks is primarily due to the limited resolution of the oscilloscope used and not actual power fluctuations. This is verified in Fig. 5, which shows an enlarged version of the input header and partial payload along with the corresponding label swapping sequence and output header. Four marks in the label swapping sequence change the corresponding bits in the input packet sequence. As the output packet trace indicates, this has been performed successfully; an input mark is changed to an output space and vice versa. Note that, as mentioned previously, a guard band between the header and payload is not necessary for this scheme. Here, it is inserted only to visually separate header and payload.

To fully verify the performance of the label swapping scheme, bit error rate measurements have been performed on the input and output packet sequences shown in Fig. 4. In both cases, error counting was done on both the header and payload simultaneously. The results are shown in Fig. 6, indicating that the label swapping is performed with a negligible preamplified receiver penalty of 0.4 dB. The clear and open output packet eye diagram, shown as an insert, demonstrates that the header bits have been altered without signal quality degradation. Furthermore, the high output signal extinction ratio of  $\sim 13$  dB that is obtained indicates the good performance of the scheme. It should be mentioned that the IWC-based XOR gate has also been tested with a comparable performance on longer bit sequences. The good performance of the MI is also apparent from the high signal-to-ASE ratio of  $\sim 35$  dB (in 0.1 nm bandwidth) that was obtained for the output packet sequence. This high signal-to-ASE ratio is an essential factor for cascability. Finally, it should be mentioned that the scheme is not restricted to the RZ modulation format;

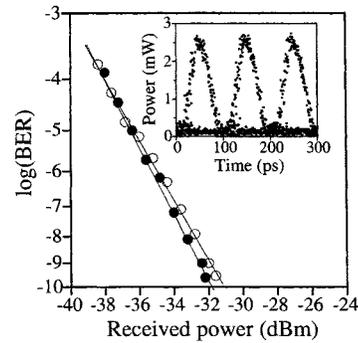


Fig. 6. Log(BER) versus received power for input and output packet sequences. • Input packet sequence (back-to-back) at 1538 nm. ◦ Output packet sequence at 1543 nm. Eye-diagram for the output packet is shown as an insert.

XOR logic has previously been demonstrated in [7] at 5 Gb/s in an integrated MZI using the nonreturn-to-zero modulation format.

## VI. CONCLUSION

In this letter, a novel scheme for all-optical label swapping has been presented. It relies on XOR logic in an integrated SOA-based interferometric wavelength converter and provides significant advantages including simplicity, low power consumption, relaxed requirements to packet format and reduced switch management complexity. Furthermore, the scheme does not require a guard band between header and payload. A negligible preamplified penalty of 0.4 dB and a signal extinction ratio of 13 dB demonstrate the excellent performance of the scheme at 10 Gb/s. This shows the feasibility of optical label swapping even at high bit rates.

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