

Exploiting micro-ring resonators for all-optical label extractor/eraser of inband labels and 160 Gb/s payload

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Photonic integration of an all-optical packet switch (AOPS) allows a great reduction of volume, power consumption and costs. Recently a 1x4 AOPS was successfully demonstrated by using an all-optical label extractor/eraser. Nonetheless, photonic integration of the AOPS was prevented by the label extractor/eraser integration.

Here, we demonstrate a photonic integrated label extractor/eraser for in-band labeling addresses and 160 Gb/s payload by using a silicon micro-ring resonator with pass-through and drop ports. By exploiting the narrow bandwidth of the drop port and pass-through port simultaneous error-free label extraction/erasing has been performed without noticeable pulse distortion.

Introduction

All-optical packet switching based on all-optical signal processing is a promising technology to solve the mismatch between the fibre bandwidth and the router forwarding capacity [1-2]. Moreover, it has been argued that all-optical technology can profit from the capability to integrate all the required switching functionalities in a photonic integrated chip to allow a great reduction of volume, power consumption and costs. It is then an essential issue to provide all-optical signal processing functionalities that are suitable for photonic integration.

Recently an all-optical label extractor/eraser for in-band labeling addresses and 160 Gb/s data payload was employed to demonstrate a 1x4 all-optical packet switch (AOPS) [3]. The AOPS schematic and the packet format are shown in fig. 1. The optical address is encoded by combining the in-band labels (the wavelengths of the labels are located within the 20 dB bandwidth of the payload). In-band labelling technique has the advantage that label extraction can be implemented by using passive optical band-pass filters centered at the labels wavelength and label erasing by using notch filters. In [3], the label extractor/eraser was implemented by exploiting the reflection and pass-through ports of two pigtailed fiber Bragg gratings (FBG) centered at the labels wavelength and two optical circulator (see fig. 1). Thus, the labels, reflected by the FBGs, are extracted via the optical circulators, while the data payload passes through the FBGs and is fed into the switching fabric. The extracted labels are optically processed by the label processor, which produces an optical routing signal driving the switching fabric.

Despite the demonstration of the AOPS and the potential integration of the label processor and switching fabric [3], photonic integration of the entire AOPS is prevented by the label extractor/eraser integration. Moreover, the broad bandwidth of the FBGs caused a splicing and distortion of the spectrum of the payload which resulted in a pulse broadening of the 160 Gb/s payload. This leads to a closed eye and thus to extra power penalty. The pulse distortion can be avoided by using optical band-pass filters with narrow bandwidth and optical notch filters with narrow stop-band and flat all-pass-band.

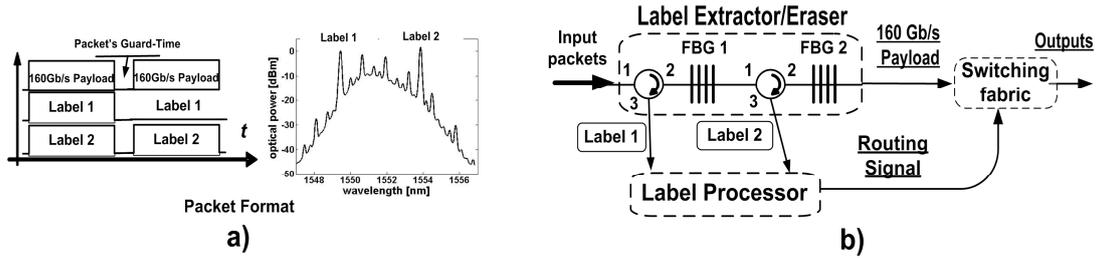


Figure 1. a) Packet format with the in-band labelling technique. b) All-optical packet switch configuration.

In this work, we demonstrate a label extractor/eraser for in-band labeling addresses and 160 Gb/s payload by using an integrated micro-ring resonator with pass-through and drop ports. By exploiting the narrow bandwidth of the drop port and the narrow bandwidth and flat all-pass band of the pass-through port simultaneous error-free label extraction and label erasing has been performed without noticeable pulse distortion.

Experiments and Results

The experimental set-up employed to demonstrate the micro-ring based label extractor/eraser is shown in Fig. 2. The packet format is the same as the one 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 ($\lambda_p=1551.6$ nm) into a 160 Gb/s data-stream using a passive 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 5.6 ns data burst. The guard-time between the packets is 800 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 has a binary value: ‘0’ means no signal at the label wavelength, and ‘1’ an optical signal at the label wavelength. The label duration equals the duration of the payload. We encode the addresses by using two in-band labels at $\lambda_{L1}=1549.45$ nm and $\lambda_{L2}=1553.85$ nm. Note that the two CW-signals are modulated by one single amplitude modulator driven by a low speed pattern generator.

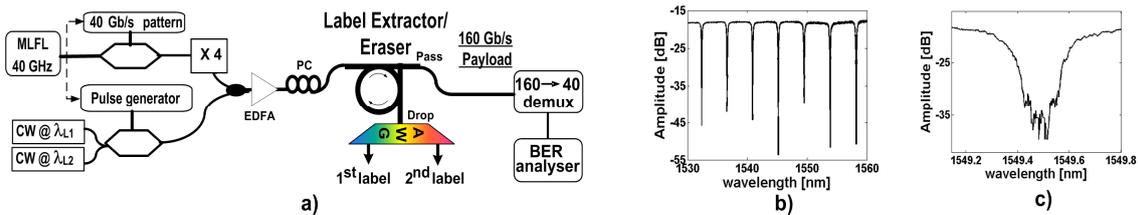


Figure 2. a) Experimental set-up; b) transfer function of the pass-through; c) Zoom-in of the stop band.

The label extractor/eraser consists of a pigtailed vertically coupled micro-ring resonators fabricated in the Si₃N₄/SiO₂ materials system [4] (high contrast materials system, $\Delta n \approx 0.55$), with a pass-through port and a drop port as shown in Fig. 2a. The transfer function of the pass-through port is reported in Fig. 2b. The FSR of the periodic stop-bands is 4.4 nm. A zoom-in of the stop band is shown in Fig. 2c. The measured -3 dB bandwidth was 0.16 nm and the flatness of the pass-band was ± 0.4 dB. The total loss of the device is 20 dB, of which 16 dB are coupling losses and 4 dB are waveguide loss. The optical packets are amplified and processed by the label extractor/eraser. A polarization controller controls the input polarization to the micro-ring. The stop-bands at multiple FSR are designed to be at the wavelengths matching the labels wavelengths.

Therefore, the labels wavelengths are filter out at the drop-port, while the wavelength payload is output to the pass-through port. The two labels at wavelength λ_{L1} and λ_{L2} are output from the drop port and then separated by an AWG filter ready to be fed into the label processor. This is confirmed by spectral and time domain measurements. In Fig. 3 the optical spectra measurements with resolution bandwidth of 0.06 nm at the drop and pass-through ports are reported. The optical spectrum of the input packet before the label extractor is shown in Fig. 3a. The optical spectrum at the output of the drop port and the pass-through output port are reported in Fig. 3b-c. More than 25 dB separation/erasing between the labels and the optical payload was measured.

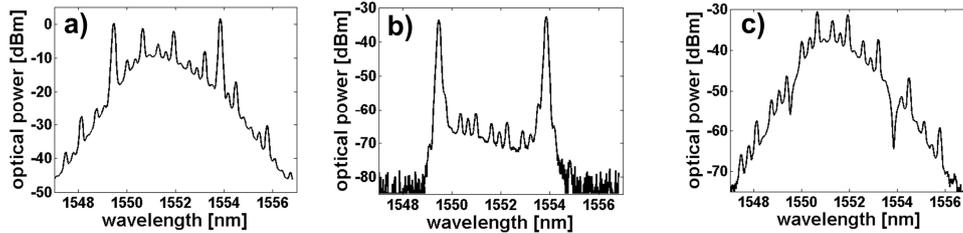


Figure 3. Measured optical spectra. a) Optical packets at the input of the label extractor; b) Output of the drop port; c) Output of the pass-through port showing the optical spectrum of the 160 Gb/s payload.

We also report in Fig. 4a-c the time-domain traces of the 160 Gb/s payload and the extracted labels traces (after the AWG) recorded at the pass-through port and drop port, respectively. Note that the two labels have the same pattern, because we employed a single amplitude modulator driven by a pattern generator to modulate the two CW-signals at λ_{L1} and λ_{L2} . The labels present no shape distortion and no visible cross-talk due to the payload.

The eye diagrams of the original input 160 Gb/s data payload and of the 160 Gb/s payload after the label extractor/eraser are reported in Fig. 4d-e. An optical sample oscilloscope with a 700 GHz of bandwidth was employed to record the eye diagrams of the 160 Gb/s pulses. Very small degradation and broadening of the pulses is observed after the label extraction. The measured pulse-width broadening was 0.4 ps. The measured RMS time jitter was 212 fs for the pulses after the label extractor/eraser, which results in an increase of 40 fs compared to the 173 fs of the input 160 Gb/s payload pulses. For comparison, we also reported in Fig. 4f the eye diagram of the 160 Gb/s payload after the label extraction implemented by using the FBGs as in [3]. A much larger pulse broadening can be observed caused by the broad bandwidth of the FBGs (-3 dB bandwidth of 0.42 nm and 0.1 nm for FBG1 and FBG 2, respectively) compared to the bandwidth of the micro-ring add/drop resonator.

To quantify the performance of the label extractor/eraser, BER measurements are reported in Fig. 4. The BER measurements were performed in a static operation by time-quadrupling 40 Gb/s PRBS $2^{31}-1$ data payload. The resulting 160 Gb/s data payload after the label extractor/eraser is amplified and time-demultiplexed from 160 Gb/s to 40 Gb/s by using an electrically clocked EAM that creates a 5 ps switching window with a periodicity of 25 ps. The resulting 40 Gb/s data is then detected by a 40 Gb/s detector and analyzed by using a BER tester. As reference we report the BER curve of the back-to-back (b-t-b) 160 Gb/s payload. The BER curve of the 160 Gb/s payload after the label extraction/eraser shows error-free operation with limited power penalty of around 0.5 dB. The power penalty can be ascribed to the additional ASE noise introduced by the amplification stage required to compensate the total loss of the label extractor/eraser.

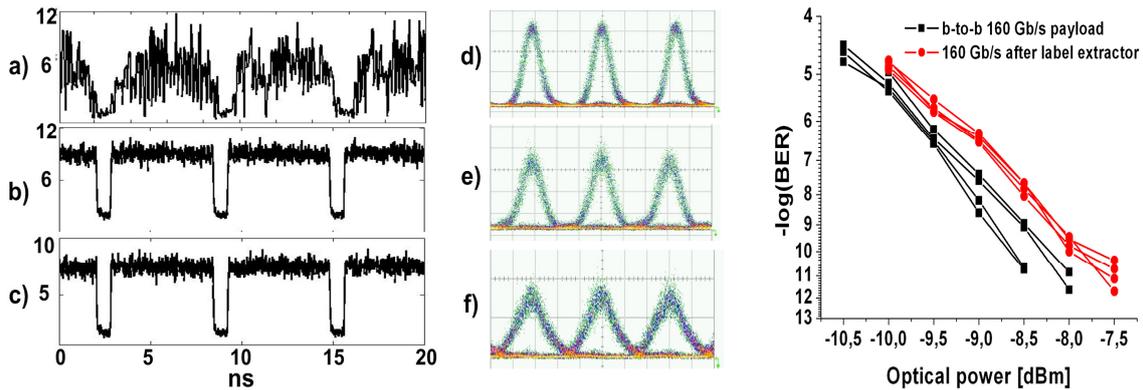


Fig. 4 a) 160 Gb/s payload after the label extractor; b-c) Extracted Label 1 and Label 2. The vertical scale is mV/div. Eye diagrams: d) input 160 Gb/s payload; e) 160 Gb/s payload after the label extractor; f) 160 Gb/s payload after the label extractor employed in Ref.[3]. The time scale is 2 ps/div. g) BER measurements before and after the label extractor/eraser.

Conclusions

We have demonstrated error-free operation of a photonic integrated all-optical label extractor/eraser for in-band labelling addresses by using a passive silicon-nitride micro-ring add/drop resonator. The in-band labels and the 160 Gb/s payload of the optical packets were successfully separated to the drop port and pass-through port, respectively. Due to the narrow stop-band and flatness of the pass-band of the pass-through port of the micro-ring, almost no distortion is experienced by 160 Gb/s payload spectrum. As a result, the 160 Gb/s payload pulses exhibit very limited broadening, in contrast with the visible broadening experienced by the payload pulses by using FBGs with broader stop-band [3]. This resulted in a low power penalty of 0.5 dB. The negligible spectral distortion of the payload due to the utilization of micro-ring with a narrow stop-band is also very important in the perspective to operate the label extractor/eraser with a larger number of labels. We are currently designing for the realization of a micro-ring resonator capable of extracting/erasing a larger number of in-band labels. Moreover, novel design will benefit from the achievement in technology to realize polarization independent and low insertion loss micro-ring add/drop resonator as demonstrated in [5-6]. Finally, this work demonstrates the feasibility for photonic integration of the label extractor/eraser, which may allow for photonic integration of the entire all-optical packet switch configuration.

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