All-optical Switching of 80 Gb/s Data Packets using a Wavelength Converter and a Monolithically Integrated Optical Flip-flop

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We demonstrate that 80 Gb/s data-packets can be all-optically switched into two different ports employing an optical wavelength converter controlled by a monolithically integrated optical flip-flop memory. The optical wavelength converter consists of a semiconductor optical amplifier and an optical filter. The integrated optical flip-flop exhibits single-mode operation, has 35 dB contrast ratio between the states and switches state in about 2 ns. We show that the integrated flip-flop is capable to control an optical wavelength conversion up to 160 Gb/s. The system is capable of routing 80 Gb/s data packets with duration of 35 ns, separated by 15 ns of guard time.

Introduction

High-speed all-optical switches offer advantages in power consumption, foot-print and switching architectures compared to their electronic counterparts [1]. An essential building block of an all-optical packet switch is an optical flip-flop memory that is used to store the switch decision information. It has been demonstrated in [2] that an optical flip-flop based on two symmetrically coupled lasers can control an optical packet switch. In that particular configuration, the optical flip-flop state was set by an optical header recognizer, and the flip-flop controls a wavelength routing switch. The flip-flop presented in [2] had a switching time of about 2 μs, since it was implemented using fiber pig-tailed components, which made that the cavity length of each laser was in the order of 10 meters.

Recently, we realized a monolithically integrated version of the flip-flop used in [3]. This flip-flop exhibits single-mode operation, has 35 dB contrast ratio between the states and switches state in about 2 ns. In this paper, we show that a wavelength converter controlled by this flip-flop allows error-free wavelength conversion at 80 Gb/s. A clear open eye indicates that the system can also operate error-free at 160 Gb/s. Moreover, we demonstrate that this system is capable of switching data packets with duration of 35 ns and a guard time of 15 ns.

System

Our experimental setup is shown in Fig. 1a. The system under investigation consists of two parts: an integrated optical flip-flop (FF) and an all-optical wavelength converter (AOWC).

At the transmitter side, a 10-Gb/s 2^7-1 return-to-zero (RZ) pseudo random binary sequence (PRBS) data packet consisting of 1.9-ps optical pulses is multiplexed to 80-Gb/s by using a passive fiber-based pulse interleaver. The 80 Gb/s data packets have duration of 35 ns, separated by 15 ns of guard time. The data packets are combined with the continuous wave (CW) output from the FF, and are fed into the AOWC via a 3-dB coupler.

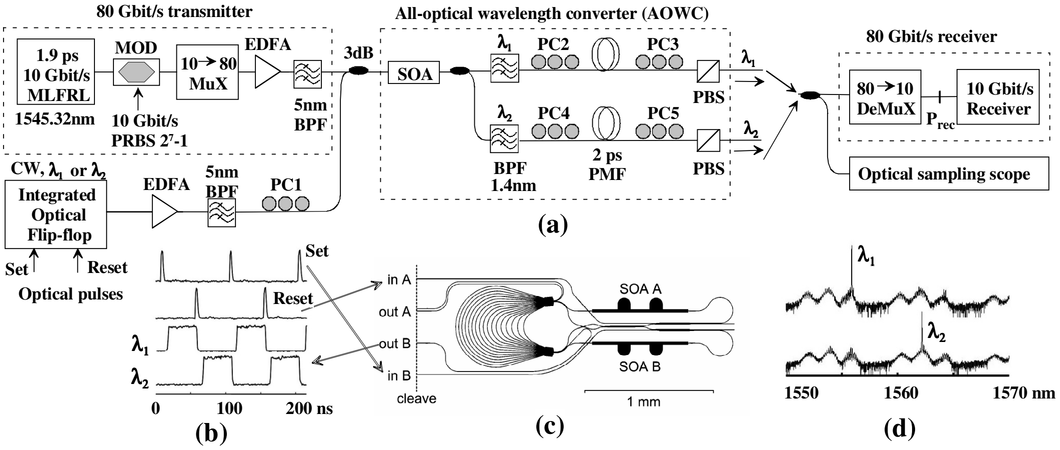

Fig. 1. (a) Experimental setup. (b) Optical pulses for setting and resetting, and output from flip-flop that shows the switching between the two states. (c) Mask layout of integrated flip-flop. (d) Spectra of the two states of flip-flop.

The optical flip-flop is an integrated InP/InGaAsP two state coupled laser device, fabricated on a InP/InGaAsP material wafer, which contains active areas with 1550 nm emission wavelength InGaAsP for semiconductor optical amplifiers (SOAs). A deep/shallow double etch process was employed to construct the waveguides. Deep etching permitted small radius waveguide bends and thus small device dimensions (2.4×0.8 mm^2). The wave-guide mask is shown in Fig. 1c. The use of an arrayed waveguide grating (AWG) and ring laser configuration permits monolithic integration without the need for cleaved facets. Details of the FF can be found in [2]. The FF is packaged by using a Peltier cooled micro-mechanical sub-assembly. The coupling efficiency is -5 dB, given the lens radii of 15 μm of the 4-fibre array and the geometrical dimensions of the waveguides (0.6×2 μm^2). The operation of the FF is described in [4]. In brief, the FF has two stable states. In State 1, Laser 1 is lasing, suppressing Laser 2. In this state the FF outputs CW light at wavelength λ_1. Conversely, in State 2, Laser 2 is lasing, suppressing Laser 1. In that state, the optical memory outputs CW light at wavelength λ_2. To change states, lasing of the dominant laser can be stopped by injecting external light into the dominant laser cavity to quench laser action. As a consequence, the suppressed laser could recover and become the dominant laser.

The second part of the set-up is an AOWC which converts the wavelength of the data packet in the wavelength that outputs the FF. The dashed box in Fig. 1a shows the AOWC that is constructed by using commercially available fiber-pigtailed components. It is shown in [5] that this configuration allows error-free non-inverted wavelength conversion at 160 Gb/s.

Both data packet and FF CW output are fed in the SOA to achieve inverted wavelength conversion based on cross gain modulation. The SOA output power is equally divided over two branches via a 3-dB coupler. Each branch contains a 1.4 nm (FWHM) optical bandpass filter (BPF) with a central wavelength that is 1 nm blue-shifted with respect to the center wavelength of the FF outputs, as shown in [5]. The central wavelengths of the BPFs are chosen such that in the upper branch, only light with wavelength λ_1 can pass and in the lower branch, light only with wavelength λ_2 can pass. In both branches, at the output of the BPF, inverted wavelength conversion at 80 Gb/s is realized. The inverted signal is injected into a delayed-interferometer to change the polarity of the converted signal (i.e., inverted signal is changed into non-inverted signal). Thus, during the time-slot that the FF outputs light at wavelength λ_1, the wavelength of the data packet is converted into λ_1 and the packet is routed to the upper port. Conversely, if the FF outputs light at wavelength λ_2, the packet is routed to the lower port.

Finally, the AOWC output signal is analyzed, either on a conventional oscilloscope, or on a 700 GHz optical sampling oscilloscope (Agilent 86119A). Bit-error-rate (BER) measurements are carried out after demultiplexing the 80 Gb/s signal to 10 Gb/s using a demultiplexer based on a gain transparent ultrafast nonlinear interferometer.

Experimental results

The center wavelength of the data packet is 1545.35 nm. The center wavelengths of the lasers in the FF are λ_1=1555.28 nm for Laser 1 and λ_2=1561.36 nm for Laser 2 respectively. The SOA injection currents are 146 mA for SOA A and 192 mA for SOA B to make the FF operate symmetrically. The inset of Fig. 1d shows the spectra of two states, the contrast ratio between the states is over 35 dB. Moreover, the lasers operate in single-mode. In Fig. 1b, FF dynamic operation is demonstrated by injecting external pulses with duration of 3 ns every 50 ns in the dominant laser. The switching signal is at a wavelength of 1550.23 nm and has an averaged power of 13 mW. It is clearly visible from the lower traces in Fig. 1b that the FF regularly switches its state, and remains in its new state, also after the set or reset pulse has vanished.

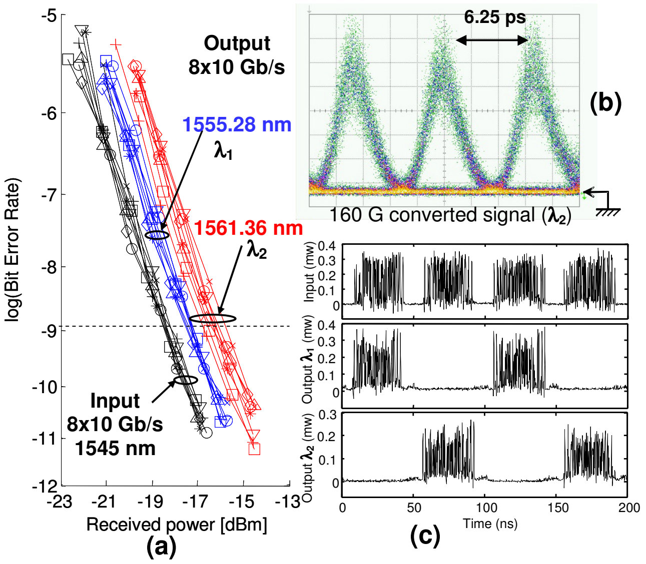

Fig. 2. The results: (a) BER values of 80 Gb/s wavelength conversion, (b) Eye-diagram of 160 Gb/s converted signal, (c) input and switched data packets.

The SOA in the AOWC is pumped with 250 mA of current. The averaged optical power, measured at the input pigtail of the SOA in the AOWC is 3.5 mW for the 80 Gb/s data stream and 2.2 mW for the FF output light.

Firstly, we operate the FF without switching between the flip-flop states. This means that the FF outputs light at either wavelength λ_1 or in wavelength λ_2. Fig. 2a shows the BER values if the 80 Gb/s RZ-PRBS data stream is fed into the wavelength converter. All the eight 10 Gb/s tributaries are presented. It is visible that the average sensitivity penalty of wavelength conversion at a BER=10^{-9} is less than 2 dB with respect to that of the original 80 Gb/s. Moreover, no error-floor is observed, indicating excellent performance of the system. The input dynamic range is about 6 dB to keep BER values under 10^{-9}. Fig. 2b shows eye-diagrams measured at 160 Gb/s at the AOWC output. The open eye indicates that the system also operates error free at 160 Gb/s.

Furthermore, we demonstrate routing of 80 Gb/s data-packets by operating the FF dynamically. It is clearly visible that the input packets were routed to different ports when the FF toggles between two states.

Conclusions

We have shown that a monolithically integrated optical flip-flop based on two coupled lasers is capable to control an optical wavelength converter up to 160 Gb/s. The system is capable of routing 80 Gb/s data packets with duration of 35 ns, separated by 15 ns of guard time. The guard time between the packets is limited by the switching speed of the FF, which is for this device approximately 2 ns.

This work was funded by STW EET6491, IST-LASAGNE (FP6-507509) and the NRC photonics grant.

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