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Citation for published version (APA):

Reis, C., Maziotis, A., Kouloumentas, C., Stamatiadis, C., Bougioukos, M., Calabretta, N., Andr, P., Dionisio, R., Neto, B., Dorren, H. J. S., Avramopoulos, H., & Teixeira, A. (2010). All-optical synchronous S-R flip-flop based on active interferometric devices. *Electronics Letters*, 46(10), 709-710.
<https://doi.org/10.1049/el.2010.1017>

DOI:

[10.1049/el.2010.1017](https://doi.org/10.1049/el.2010.1017)

Document status and date:

Published: 01/01/2010

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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All-optical synchronous S-R flip-flop based on active interferometric devices

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An all-optical clocked set-reset flip-flop is experimentally demonstrated. It is based on a hybrid-integrated S-R latch and two additional Mach-Zehnder interferometer structures with semiconductor optical amplifiers acting as AND logic gates. The switching behaviour of the synchronous S-R flip-flop was investigated and 18 dB extinction ratio performance was achieved.

Introduction: All-optical flip-flops are key elements to perform optical signal processing operations in next generation photonic transmission systems, in particular as buffering memories for temporary storage of decisions in optical packet routers [1]. In the last few years, several approaches have been proposed to realise optical bistable devices. In [2] the proposed scheme uses a single SOA based Mach-Zehnder interferometer (MZI) with a feedback loop, which consists of an interferometer containing semiconductor optical amplifiers (SOAs) in both arms, and the energy of set/reset pulses, that change the state of the flip-flop, are highly dependent of the loop delay. In [3] and [4] two coupled laser diodes and SOA fibre ring lasers are used, respectively, in which one of the two lasers is lasing and suppressing the other laser.

Most of the optical bistable devices known in the literature do not work with a synchronisation signal, and any change of information in the set/reset inputs is transmitted, immediately, to the output, according to its truth table. In some cases input S and R can suffer unwanted variations and if we are using asynchronous devices, we can be storing unwanted information. Therefore, a clock input signal can be very important to control the enabling of the latch, making it sensitive or not to the values present in the inputs S and R. In [5] an optical synchronous S-R flip-flop based on coupled fibre ring lasers was implemented. However, this technology has a serious speed limitation. In this Letter, we experimentally demonstrate the operation of a synchronous S-R flip-flop, with fast switching speeds, high extinction ratio and photonic integration since all building blocks are based on hybrid MZI-SOAs.

Experiment: An S-R flip-flop with a clock signal input is shown in Fig. 1. It consists of a latch S-R and two AND gates to enable the flip-flop by the logical level of the clock signal. In this type of optical bistable device, it is necessary that the clock signal is in the high level so that the information present in the inputs produces effects on the output.

Fig. 1 Scheme of optical clocked S-R flip-flop

Fig. 2 shows the setup used for the experimental tests. To generate the set and reset optical pulses, an external cavity laser peaking at 1558.17 nm was used, followed by a polarisation controller and an external Mach-Zehnder modulator (MZM). The NRZ data signal is amplified and split into two equal parts using a 3 dB coupler. Different set and reset patterns are obtained by delaying the signals.

The Boolean logic operations were implemented using integrated SOA-based Mach-Zehnder interferometers and the principle operation relies on nonlinear effects in the SOAs. MZI-SOA1 performs the AND logic function between the reset control signal and the clock signal; MZI-SOA2 performs the AND function between the set signal and the clock signal. Since both AND gates were implemented in a co-propagation configuration, the wavelength of the control signals (set/reset signal) and the incoming signal (clock signal) must be separated wide enough to avoid undesired crosstalk and nonlinear effects such as four-wave mixing (FWM). The powers of the continuous-wave signals (CW) used in MZI-SOA1 and MZI-SOA2 were set to adjust the gain of the SOAs. As can be seen in Fig. 2, the outputs of AND1

and AND2 are obtained at the switching ports of the MZI-SOA and they will be coupled into reset and set ports of the asynchronous latch, respectively. The latch S-R consists of two coupled MZI-SOAs, powered by two CW signals at different wavelength and switches between two states (0 or 1) by injecting set and reset optical pulses into the MZI-SOA that is currently dominant. Its principle of operation as well as some experimental results were published in [6].

Fig. 2 Experimental setup

The truth table of the clocked S-R flip-flop is the same as the S-R latch but only when the clock signal remains at high level (CLK = 1). If CLK = 0, the flip-flop maintains its previous state (last Q).

The output signal from the clocked S-R flip-flop was filtered, amplified by an EDFA and analysed by an oscilloscope (Agilent 86100C), connected through a pin photodiode.

Results: The experimental results of the clocked S-R flip-flop are presented in Fig. 3. The input set and reset signals have a repetition rate of 40 MHz with a pulse width of 2 ns and are delayed by 11.6 ns. The pulses energies are set to be 100 pJ. The clock signal has a repetition rate of 300 MHz with a pulse width of 1.67 ns.

Fig. 3 Experimental results

Vertical scale is arbitrary and horizontal scale is 5ns/div. for Figs. 3a and b and 10 ns/div. for Figs. 3c–e

- a Clock signal
- b Reset signal
- c AND2 optical gate (set $\cap$ clock)
- d AND1 optical gate (reset $\cap$ clock)
- e Optical clocked S-R flip-flop output

Fig. 3c demonstrates the logic AND function between the set and clock signals and an optical pulse will be obtained at the output only in the case that both data signals are equal to 1. Fig. 3d shows the AND operation between the reset signal and the clock signal. The clock signal and the control set/reset pulses were launched only in one of the two arms of the MZI-SOA and after balancing we achieved an extinction ratio (ER) of 36 and 25 dB in MZI-SOA1 and MZI-SOA2, respectively.

In Fig. 3e it is possible to distinguish the two different stable states of the flip-flop and it is very noticeable that the inputs of the S-R flip-flop are transferred to the Q output only when the clock signal is enabled.

We achieved switching speeds of 430 ps and 420 ps for rise time and fall time, respectively. We also analysed the performance of the synchronous S-R flip-flop and 18 dB of extinction ratio was obtained.

Conclusion: A novel scheme for an all-optical synchronous S-R flip-flop, based on MZI-SOAs, has been presented. We have demonstrated that the clocked S-R flip-flop dynamically changes its state only when the clock signal is enabled, which allows the flip-flop to work as a finite state machine. We achieved 18 dB of extinction ratio and switching times less than 450 ps.

Acknowledgments: This work was supported by the EURO-FOS project and by the Portuguese Scientific Project PANORAMA (ADI 2009/003144).

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15 April 2010

doi: 10.1049/el.2010.1017

One or more of the Figures in this Letter are available in colour online.

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