Optical Flip-Flops and Their Applications in Optical Communications Networks

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Abstract

It provides a review of all-optical flip-flops technologies, and their possible experimental implementation solutions, for a variety of applications in optical communication networks. A description of the state-of-the-art experimental implementations and validation testing of the technologies used in different all-optical flip-flops schemes is made, presenting to the interested reader an overview of the up to date all-optical flip-flops design schemes.

Keywords: Flip-Flops, optical communications

1. Introduction

The exponential growth of internet traffic has been the major driving force for the increasing demand for transmission bandwidth. To increase the efficiency of the network and to allow high data bit rates is desirable that switching and routing can be carried out in the physical layer, avoiding optical-to-electrical and electrical-to-optical converters [1].All-optical devices provide data format transparency, and may provide lower power consumption and higher-speed processing, compared to their electronic counterparts [2].

Recent developments in optical signal processing and in photonic switching have made it possible toreach bit rates in the order of gigabits per second per wavelength and terabits per second per fibre [3]. In this context, all-optical flip-flops (AOFF) can be used to perform many optical signal processing functions in future optical packet switching networks.

Examples of such applications are: as storage of the header information of a packet, as basic building blocks of optical shift registers and optical counters, in threshold functions and self-routing, in optical contention resolution schemes, as regenerative memory elements, among others.

Optical Flip-Flops

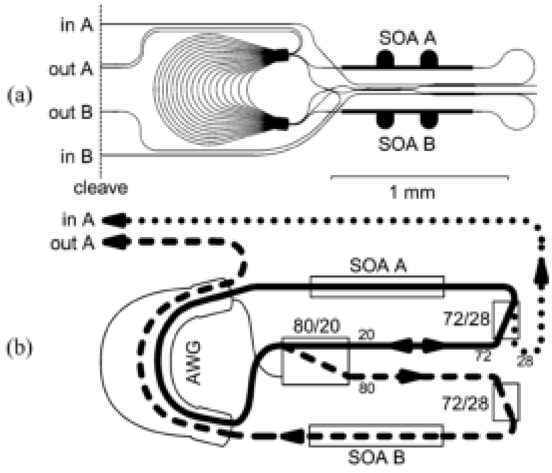
All-optical flip-flops present, at least, two stable states and since they are sequential circuits, their outputs not only depend on the information at the inputs, in a considered instant, but also depend on the information presented in the previous state.

To implement an AOFF, an element that presents a bistable behaviour is required. This can be achieved by a combination of a nonlinear effect with a feedback mechanism [4].

In a conventional S-R AOFF, the bistability operation is performed in the 'S-shaped' hysteretic region, and the output state is distinguished by the different output pow er. In the optical memory, the state can be distinguished by different outputwavelengths [5].

In the last few years, several research efforts have been carried out in order to implement all-optical flip-flops memories. In [6], an AOFF is implemented using two coupled ring lasers and an arrayed waveguide grating (AWG), acting as the frequency selective element of each cavity. Each ring laser has its own gain element (SOA) and the light propagates bidirectional in the ring. Its operation principle is shown and based on the gain quenching concept. In state 1, light from laser A flows in counter clockwise direction and saturates the gain element of laser B, suppressing laser B from lasing. In this situation, the light from the dominant laser (laser A) is sent to an output by the AWG.

Thus, the AWG ensure isolation between the device input and output. In the same way, in state 2, only laser B is lasing, suppressing laser Afrom lasing. Thus, only one of the lasers can be lasing at a time, due of the fact that the dominant laser suppresses the other laser through gain saturation. Lasing in the master can be turned off by injecting external optical pulses, changing in this way the state of the system. The cavity length of this AOFF scheme is about 4.5 mm, which cause speed limitation.



a) Mask layout for two-state multi-wave length laser.

b) Operation of device showing laser A suppressing lasing in laserB. SOA: semiconductor optical amplifier; AWG: arrayed waveguide grating [6].

The general concept proposed in [5] can be extended to other AOFF schemes, where the coupled nonlinear optical elements can be Mach-Zehnder interferometers (MZIs) [7] and nonlinear polarization switches [8]. In [7] and [9], all-optical flip-flops are demonstrated using two coupled Mach-Zehnderinterferometers with semiconductor optical amplifier (SOA-MZI) and two SOA fibre ring lasers respectively. Both technologies are based on the gain quenching effect, in which the signal output from the dominant laser suppresses the other laser, through gain saturation of the SOA.

2. Literature review

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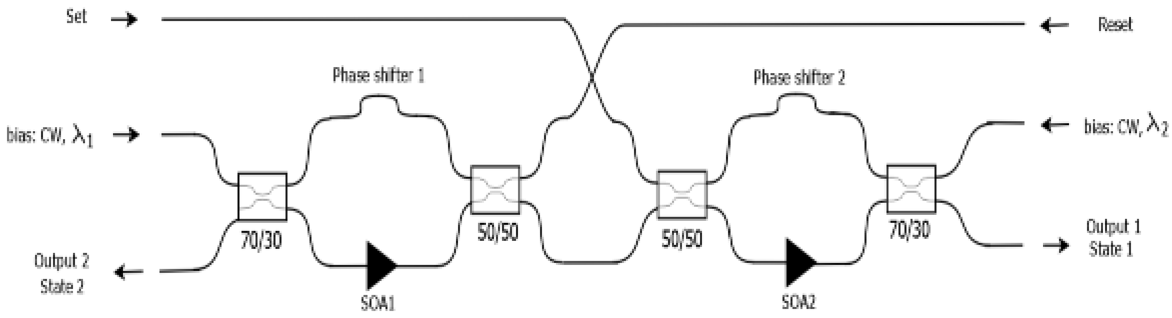

Figure 3 Schematic diagram of optical flip-flop based on coupled SOA-MZI [7]

Expertise among EURO-FOS partners gave origin to the first efforts, to the best of the author’s knowledge, in the experimental investigation of all-optical clocked flip-flops. In particular in [10], clocked all-optical S-R, D, T, and J-K type flip-flops, whose state switching is triggered by a pulsed clock, are demonstrated. The core components of all the clocked flip-flops, proposed in [10], are a bi-stable S-R latch based on coupled SOA fibre ring lasers [9] and all-optical logic gates [11]. The Boolean functions, between the input pulsed clock and control signals, are carried out by exploiting four wave mixing (FWM) and cross gain modulation (XGM) nonlinear effects in SOA.

The clocked S-R flip-flop setup is shown in Fig. 4. It consists of two AND gates and one coupled SOA fibre ring lasers latch. The “AND 1” and “AND 2” outputs are connected to the “Set” and “Reset” latch ports, respectively, in order to achieve clocked functionality.

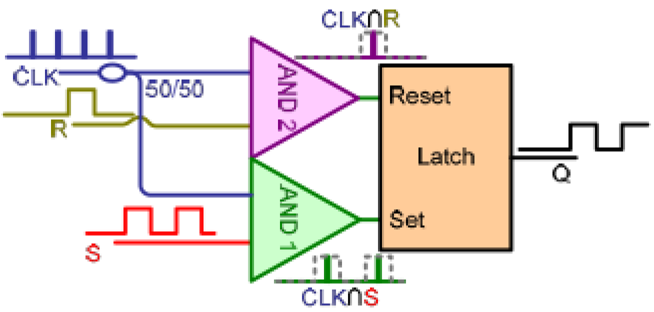

Figure 4 Logic circuits for clocked S-R flip-flop.

The experimental setup of the optical clocked T flip-flop is shown in Fig. 6 and consists of three logic gates and one S-R latch, based on two fibre ring lasers. Unlike the previously described S-R and D flipflops, in the T flip-flop a feedback of the output Q is launched into its inputs. The “AND 1” logic gate carried out the AND function between the clock and T signal, whereas "AND 2" performs AND function between the "AND 1" output (CLKIT) and the feedback Q. The other logic gate, "AND 3", performs the AND function between CLKIT and inverted Q.

3. Optical Quaternary Logic Based Information Processing

The proposed scheme in [18] is based on a single SOA-MZI, with an external feedback loop, which needs to be as short as possible to obtain fast switching times, with low set/reset pulse energies. The flipflop state is determined as a function of the phase shift between the two arms of the interferometer. So, when a Reset signal is injected, the SOA-MZI is unbalanced and AOFF output is at a low logical level; on the other hand, when the SOA-MZI is balanced, the AOFF output is in the high logical level.

In [19], a slightly different AOFF architecture, using a single SOA-MZI, is experimentally assessed and it is based on the theoretical analysis demonstrated in [20]. The operation principle of this scheme relies on adding a feedback loop to an optical exclusive-OR gate, in order to maintain bistability. Initially, with no input pulse, the device delivers no signal. When a pulse is launch into the Set input, the output switches from the OFF to the ON state (Set (1) XOR Reset (0) = 1).

A Reset pulse allows to go back to the OFF state since the result of Set (1) XOR Reset (1) = 0. This configuration is wavelength independent but power sensitive. The required width of Set and Reset pulses to switch between states, depends on the length of the loop, therefore as the feedback loop increases, a higher energy of Set and Reset is needed.

The AOFF proposed in [21], consists of two coupled injection locked single-mode Fabry-Perot laser diode (FP-LD). The slave FP-LD is a commercially available laser and the master FP-LD is designed with a built-in external cavity, operating in single longitudinal mode, with a high side mode suppression ratio. When a control light has a power higher than the locking threshold, the slave FP-LD is injection locked and holds its state even if the input power decrease to a value lowered than the initial threshold

In [22], an AOFF is demonstrated using a single distributed feedback (DFB) laser diode, operating with a CW signal to obtain optical bistability. If the CW signal is injected in the laser diode, it is possible to observe two states, for the same power, due to the spatial hole burning effect.

In one of the states, when the laser is lasing, an external light will suffer a small amplification, due to the gain clamping, and its influence will be almost negligible on the laser light. In the other state, when the DFB laser is turn off, the external signal will experience a high amplification, which results in a strong non-uniform distribution of the carriers. Thus, if a Reset signal is injected into the DFB laser, at the same side of the CW signal, it will turn off the laser, causing a non-uniform carrier distribution. By injecting a Set pulse in the other side of the DFB laser, the uniformity of the carrier distribution is restored, and the laser starts lasing. To prevent interaction with the DFB grating, the wavelength of the external set/reset pulses should not be close to the lasing wavelength.

In [23] and [24], AOFFs are demonstrated based on single and coupled micro-ring lasers, respectively. In a micro-ring laser typically exists two lasing modes, based on the direction that laser light propagates - clockwise (CLKW) or counterclockwise (CCLKW) and depending on the bias current, different operating regimes can occur. Also, ideally, the CLKW mode is not coupled to the CCLKW mode and vice-versa. The AOFF configuration proposed in [23] is depicted in Fig. 9. It has racetrack cavity geometry and it is produced in a InGaAs/InGaA1As/InP MQW material. The AOFF exhibits bistability between the counterpropagation cavity modes that can be switched by external optical pulses. It has four inputs/outputs ports that are all-active, and can be use to inject or extract optical signals

4. Conclusion

In two micro-ring lasers coupled by a waveguide are presented and this AOFF configuration has two stable states. In state 1, CLKW light from a ring laser 1 is injected into a ring laser 2 and will suffer a significant amplification if the resonant frequencies of both lasers are close. If sufficient light is injected into laser 2, its gain will decrease below threshold, which suppresses its oscillations, forcing the light to propagate only in the CLKW direction, injecting an optical pulse, close to the lasing wavelength, in the waveguide that connects the ring-lasers, set both lasers in the CLKW or CCLKW direction.

An electrically pumped AOFF based on a single micro disk laser is demonstrated and its schematic diagram is shown in Fig. 10. The production of bistable AOFF is based on a heterogeneous integration of In P-based devices onto silicon-on-insulator, and the high refractive index contrast in the In P membranes allows reducing the device size. The bistability of this configuration is caused by a weak coupling between the CLKW and CCLKW whispering gallery modes (WGMs) and by the presence of a high non-linear gain. Switching occurs between predominant clockwise and counter clockwise lasers modes, through injection of short optical pulses.

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