Dynamic Operation of All-Optical Flip-Flop based on a Monolithic Semiconductor Ring Laser

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Abstract *A monolithic semiconductor ring laser (SRL) is demonstrated as a fully all-optical Flip-Flop that can be triggered by optical pulses of 400 ps duration, showing 130 ps response time.*

Introduction

In the recent years there has been a growing interest in the realisation of digital functions directly implemented in the optical domain, with application to all-optical digital signal processing for telecommunications and optical computing. The semiconductor ring laser (SRL) proved to be a viable solution for a monolithic implementation of such functions, thanks to its inherent directionally bistable behaviour and compact size [1,2].

In this work we report on the first demonstration of the dynamic operation of the all-optical Flip-Flop, that is triggered by two trains of alternate optical pulses with duration of 400 ps, to which the device responds with 130 ps rise time.

Device

Racetrack shaped SRL devices were fabricated at Glasgow University in a InGaAs/InGaAlAs/InP MQW material. The device (inset of Fig. 1) has two semi-circular sections with 150 μm radius connecting two straight sections of 200 μm length that are coupled to two straight output waveguides. The device has four input/output ports.

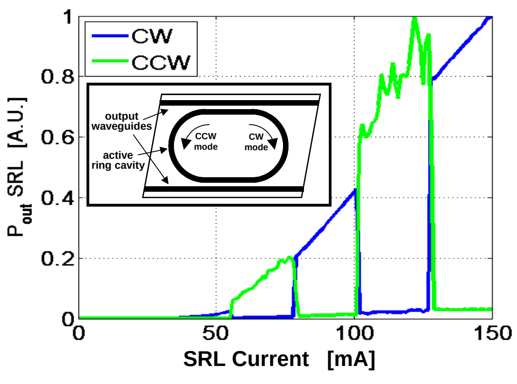

Figure 1. CW P-I curve of SRL at 15 °C. Inset: Sketch of SRL device

The SRLs operate CW at room temperature, with threshold currents between 35 and 60 mA, emitting up to 3 mW at λ = 1550-1570 nm. Fig. 1 shows a typical P-I curve measured for the two counterpropagating modes (CW = clockwise; CCW = counter-clockwise) using a lensed optical fibre. A bidirectional regime (i.e., CW and CCW modes both active) appears just above threshold, and as the current is increased a neat unidirectional regime takes place, where only one mode is active and the other is highly suppressed. This is a consequence of the optical directional bistability intrinsic to all-active SRLs, that occurs thanks to the non-linear cross-gain saturation in the active medium. This bistability is observed in all fabricated devices and it is extremely robust, showing a directional extinction ratio in excess of 20 dB. The SRLs operate in a single-longitudinal mode, with SMSR between 20 and 35 dB.

When the SRL is operated in the unidirectional bistable regime, the device acts as an optical digital memory cell, capable of storing one bit of information. The status of the meory depends on the particular lasing direction. The direction of operation (and thus the status of the memory cell) can be changed by injecting an external optical signal into one of the input/output ports, so that the injected signal propagates within the ring cavity in the opposite direction with respect to the lasing mode [2]. If the injected power exceeds a certain threshold level, photons travelling in the new direction induce a regenerative directional switching that reverts the state of the memory. The new lasing direction is maintained after the triggering external light is switched off. Hence, the SRL operates as an all-optical Set-Reset Flip-Flop (SR-FF).

Experimental Results

In the experiment described below, two input/output ports of the SRL are used to inject external optical pulses from the two alternate directions, with the goal of demonstrating the dynamic operation of the all-optical SR-FF. The experimental set-up is depicted in Figure 2. Optical pulses of 400 ps duration are generated by a Mach-Zehnder modulator cascaded to a tunable laser. The puses are amplified and splitted by a 50/50 coupler, and in one arm a suitable fiber delay is inserted so that pulses from either sides reach the SRL at alternate time instants, as schematically shown in Figure 3. At each injected pulse, the SRL changes its direction of operation, and so does the value of the stored bit, realizing the

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above mentioned all-optical SR-FF function.

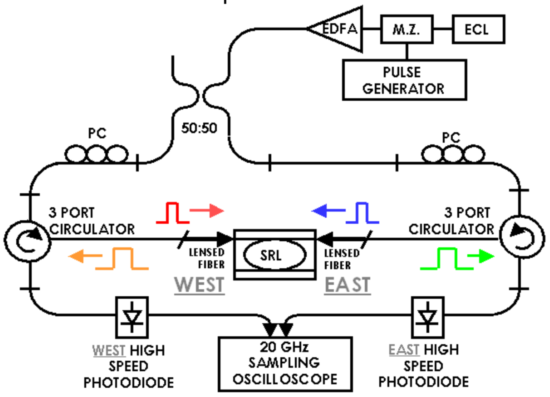

Figure 2. Experimental set-up.

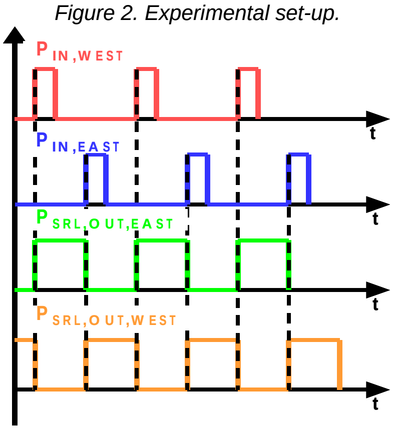

Figure 3. Diagram of temporal signals sequence.

Figure 4 shows the experimental time trace of the SRL output power collected by the fiber from the East side of the device. The operating current is 140 mA. This trace confirms the Flip-Flop operation, as the status of the memory is toggled by each incoming pulse. The peak power coupled into the SRL waveguide that is required to toggle the direction of operation is between 1 and 10 mW. As the power coupling ratio from the straight waveguide to the ring cavity is around 10%, the power effectively coupled into the ring cavity is between 0.1 and 1 mW, that is a value 100 to 10 times smaller than the lasing power travelling in the ring cavity. In Figure 4, the triggering optical pulses cannot be observed, because their residual amplitude is much smaller than the output power from the SRL.

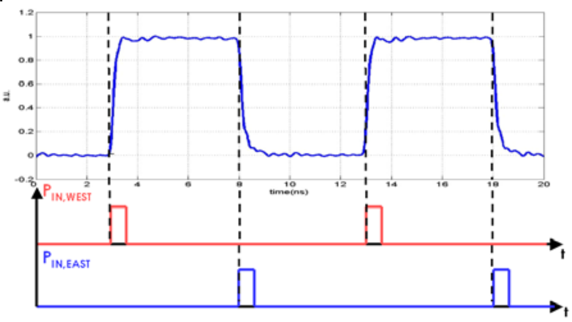

Figure 4. Experimental time trace from EAST output (upper). Diagram of input signals sequence (lower).

It is of interest to analyze the response time of the SRL Flip-Flop. This is done by zooming the switch-on and switch-off trasitions on the digital sampling oscilloscope. The results are shown in Figure 5a and 5b. The 10%-90% switch-on time equals 130 ps, while the The 90%-10% switch-off time amounts to 190 ps.

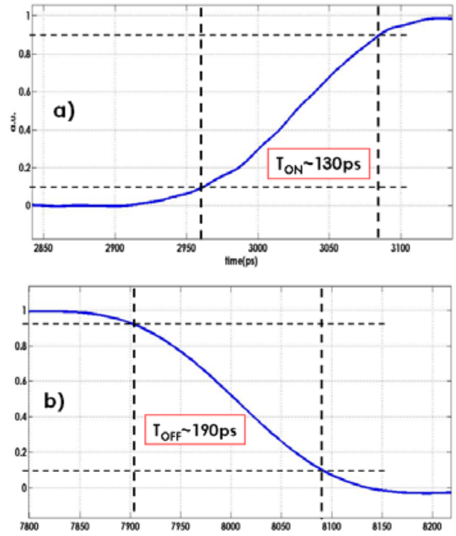

Figure 5. Switch-on (a) and switch-off (b) transitions for the SRL output.

The switch-on time is limited by the SRL temporal dynamics, according to which some time is required to build-up the steady-state photon population in the new lasing direction. The shortest switch-on time is achieved when the injected peak power into the SRL waveguide is 10 mW. For smaller powers the switch-on time is longer, because the switching dynamics is limited by the effective carrier lifetime of the ring laser which, in turn, depends on the instantaneous photon density travelling in the new direction. Hence, for smaller injected powers the transition to the new direction is slightly slower, and the switch-on time can increase to 300 ps. The switch-off time of one lasing direction is slightly longer than the switch-on time of the opposite lasing direction.

Conclusion

It has been demonstrated that a semiconductor ring laser acts as a monolithic all-optical Set-Reset Flip-Flop, that can be triggered by a low power external optical signal. The measured response time for the switch-on of the SR-FF is 130 ps, and it is expected to be faster for smaller devices. As an example, SRLs with equivalent radius of 27 μm have been fabricated, and showed CW lasing at room temperature [3]. These devices are promising to demonstrate switch-on times of the order of 10 ps.

Acknowledgement

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References

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