All-Optical Directional Switching in Bistable Semiconductor-Ring Lasers

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***Abstract*— We investigate the operation of directionally bistable semiconductor-ring lasers as all-optical flip-flops. We demonstrate fast switching between the two lasing directions by injection of optical pulses acting as set and reset control signals with switching times as fast as 20 ps, delay times as short as 60 ps, and switching energy of 150 fJ.**

***Index Terms*— Optical bistability, optical signal processing, integrated optics, semiconductor lasers.**

I. Introduction

IN RECENT years optical network traffic has experienced a tremendous increase, mainly driven by the convergence of different applications and services (data and multimedia) within a unified Internet Protocol (IP) packet-oriented network infrastructure.

The growth in bandwidth demand has been addressed through a combination of coherent transmission technology, advanced modulation formats and digital signal processing, together with a flexible underlying optical layer that employs advanced amplification and ROADM technologies [1].

Although ROADM techniques greatly reduce the time required to establish a new wavelength service, they can only switch with the granularity of an entire wavelength. Thus electronic switching is still required for traffic grooming at the core nodes, causing unwanted latencies due to optical-electrical-optical (OEO) conversion.

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The ultimate solution to avoid latencies introduced by OEO conversion at the core nodes is to shift more functionalities towards the optical domain, in a true Optical Packet Switching (OPS) network architecture.

Main roadblocks to the achievement of this long envisioned solution are the lack of robust, low-power-consuming, low-cost and scalable all-optical buffers [2], [3]. All-optical buffers are key components in OPS networks as they allow storing and processing the header information for the duration of the packet [4].

The all-optical storage of one bit of information is achieved by exploiting optical bistable devices, so called all-optical flip-flops (AOFF), which operate in one of the two allowed stable states.

Note worthy examples of AOFFs, addressable by externally injected optical signals, reported so far are based on two mutually coupled micro-ring lasers fabricated in InP/InGaAsP platform [5] single microdisk laser coupled to a silicon-on-insulator wire waveguide [6] and Distributed Feedback Laser diodes [7].

An appealing solution for the implementation of an all-optical memory cell is represented by single Semiconductor Ring Lasers (SRLs), as these devices already showed robust bistable response [8], [9] and allow for large scale miniaturization thanks to the high index contrast of the InGaAs/InGaAlAs/InP platform. Directional switching in a SRL can be triggered by external electrical signals [9], by static external optical signals [10], and also by externally injected optical pulses [6], [13].

Besides being used as AOFFs , SRLs can be exploited for the implementation of several all-optical functions [10]–[12].

An example of practical exploitation of the SRL AOFF, on an all-optical network architecture for resolution of contentions between asynchronous optical packets is reported in [14].

In this paper we present a comprehensive and systematic experimental investigation of the switching dynamics in SRLs triggered by externally injected optical signals ranging from quasi static to ultrafast duration. The device is triggered by external optical pulses that are injected alternatively in opposite directions, realizing the Set-Reset Flip-Flop functionality. To investigate the switching dynamics, we used optical pulses with duration spanning over more than two decades (i.e., from 20 ns to 5 ps), with the purpose of supplying the SRL with an excitation having rise/fall times that are, respectively, much longer and much shorter than the intrinsic optical response time of the device.

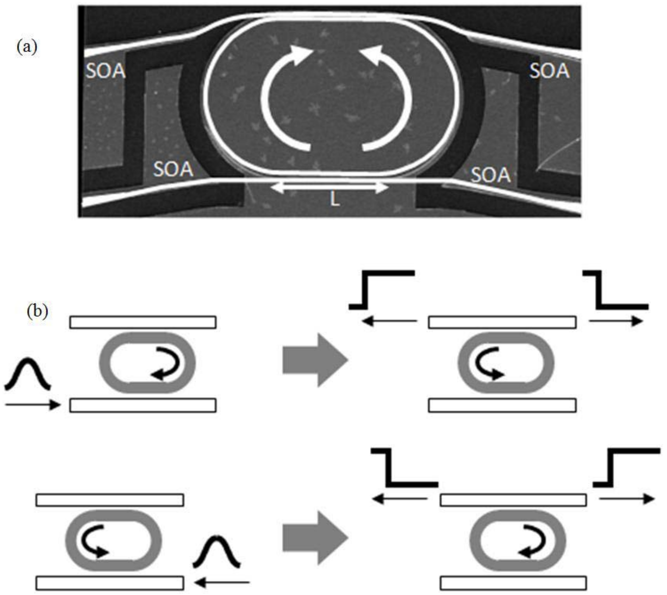

Fig. 1. (a) SRL structure. (b) Exploitation of the SRL directional bistability for the implementation of an all-optical latch. A clocked version of the device is attainable by adding AND gates before the SRL inputs that allow transmission of the input signals only when the clock signal is high.

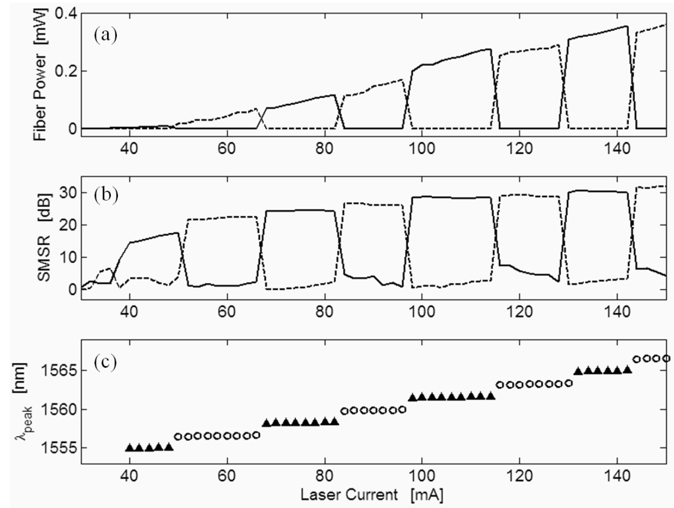

Fig. 2. (a) L–I curves measured on a racetrack shallow etched SRL with a total cavity length of 1.34 mm, using two lensed optical fibers that collect the power emitted in the opposite propagation directions. (b) Side-mode suppression ratio for the two lasing directions. (c) Peak emission wavelength. Open symbols: clockwise direction; full symbols: counter-clockwise direction.

The ultimate achievable switching speed and switching energies are assessed.

The paper is organized as follows. In Section II the SRL principle is reviewed and fabrication details are given, in section III the results of the thorough experimental analysis are reported, and in Section IV a phenomenological interpretation of the experimental results is given.

II. The Device

The basic structure of a SRL consists of a closed, single-transverse mode waveguide coupled to one or several bus waveguides by evanescent coupling (Fig. 1-a). The lack of localized reflections in the cavity implies that waves counter-propagating in the cavity interact mostly via their competition for the gain. This allows achieving bi-stable unidirectional operation [8], [9] which can be directly exploited as an all-optical latch where changes of state can be driven by externally injected optical signals (Fig. 1-b).

The SRLs are fabricated at the James Watt Nanofabrication Centre of Glasgow University on InGaAs/InGaAlAs/InP multiple quantum well platform. The racetrack/circular SRL cavity is formed by shallow/deep etching of the InGaAs/InGaAlAs/InP wafer. In the case of shallow etched racetrack devices, radii range from 150 to 250 μm and the two straight sections have 150–200 μm length; in the case of deep etched devices the cavity radius can be decreased down to $\sim$10 μm, the SRLs still showing robust directional bistability [16]. Two additional waveguides in close vicinity to SRL cavity allow for evanescent IN/OUT light coupling (with power coupling ratio between the ring and bus waveguide ranging from 0.1 to 0.3), and provide four input/output ports. Each waveguide end is tilted 10° from the normal to the facet in order to minimize back reflections. The waveguides are defined by electron beam lithography followed by Reactive Ion Etching using a chemistry of the CH_4 /H_2 /O_2 process, which is selective to the Al containing core layer and thus ensures a very good control over the etching depth, the sidewall smoothness and the power coupling ratio.

In addition to the metallic contact over the ring cavity, four additional, independent contacts are provided on each of the four output arms, allowing to operate each of them as either an optical amplifier or a saturable absorber.

The experimental characterization reported in the following sections focuses on shallow etched devices, nevertheless a similar behavior was observed on deep etched devices as discussed in section IV.

III. Experimental Results

A. Static Behavior

All tested devices operate CW at room temperature, have a threshold current around 30 mA, and emit up to 10 mW in air at wavelengths between 1550 nm and 1570 nm, for typical pump currents of 200 mA and with terminal SOAs pumped with 10–30 mA.

A typical L-I curve measured by taking the emitted light from the two directions using two lensed fibers is shown in Fig. 2-a. Fig. 2-b shows the side-mode suppression ratio (SMSR), while Fig. 2-c reports the peak emission wavelength. Just above threshold the SRL emits bi-directionally, and as the current is slightly increased the unidirectional regime occurs, where only one mode is active at a time, and the other one is largely suppressed. In the unidirectional bistable regime the SRL emits on a single longitudinal mode with a static SMSR larger than 20 dB, and the directional extinction ratio is larger than 15 dB. The latter parameter is defined as the ratio of the powers emitted in each of the two possible directions; it describes the degree of uni-directionality, and determines the extinction ratio of the device

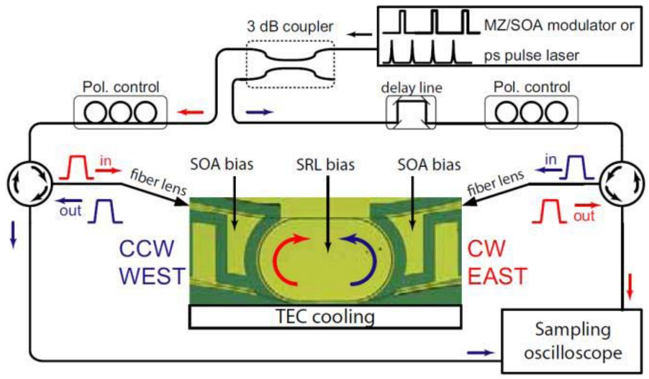

Fig. 3. Experimental set-up for all-optical switching experiments.

outputs under Flip-Flop operation. As outlined in [9], the bistable uni-directional regime occurs thanks to the effect of cross-gain saturation between the two counter propagating modes. As the SRL current is increased, longitudinal mode-hops occur simultaneously with directional switchings, and a wavelength jump is associated to each change of direction, typically corresponding to the spacing of three longitudinal modes of the ring cavity.

When the injected current and the device temperature are kept constant, the SRL remains for an indefinite time in its state, thus acting as an optical digital memory with an infinite persistence time of the stored information.

In the following, we study how the device reacts to the injection of an external optical signal in the direction opposite to the active one, as a basic step towards achieving an all-optical Set-Reset Flip-Flop.

B. Experimental Setup

The experimental set-up devised for studying all-optical switching is schematically shown in Fig. 3. Optical pulses generated by the light source are split by a 50:50 directional fiber coupler. Each arm of the coupler includes a polarization controller (PC) and a circulator which allows injecting the optical pulses and collecting the light output from the SRL via lensed fibers (with power coupling efficiency of 10–20%). The path-length difference between the two arms is controlled by an air-gap delay line to achieve precise relative timing of the pulses that are injected into the SRL in the two opposite directions. Main goals of the experiments are:

1) The demonstration of the operation of the SRL as an All-Optical Set-Reset Flip-Flop (SRFF).
2) A thorough investigation on the dynamics of the directional switching, including the effect of different durations of the optical pulses (from tens of ns to a few ps) and the influence of other operating parameters such as the SRL bias current, the power/energy of the externally injected signals, and their detuning with respect to SRL longitudinal modes.
3) An assessment of the practical functionality of the Flip-Flop operation, and an estimation of the maximum speed of operation.

In the following, the power and energy levels of the pulses acting as Set and Reset signals are reported with reference to their levels at the inside entrance of the input bus waveguides of the SRL device (net of the fiber coupling losses). The power/energy levels effectively injected into the ring cavity can be estimated by keeping into account that the pumped input/output waveguides have an optical gain of 3–8 dB, and that the power cross transmission factor of the coupler between the straight waveguides and the ring cavity is around $0.1 \div 0.3$.

C. Slow Optical Trigger Pulses

The first set of experiments was carried out using "slow" optical trigger pulses of quasi-Gaussian shape with 20 ns FWHM duration, i.e. having a rise time much longer than the response time of the SRL, which is typically much shorter than 1 ns. The pulses are obtained by amplitude modulating the CW light generated by a tunable laser using a SOA. The latter allows to achieve on-off extinction ratios larger than ~30 dB, hereby reducing to a minimum the residual "off" power level between two subsequent pulses. Fig. 4-a shows a typical experimental time-domain trace collected from one of the SRL outputs when the SRL is biased in the unidirectional regime at 130 mA, and the peak optical power of the Set and Reset pulses injected into the SRL waveguide is 10 μW. The SRL switches its operating direction upon the injection of each of the trigger pulses. The residue of the Set pulse that can be seen on top of the SRL response is due to the fact that a relevant fraction of the Set and Reset pulses travels directly from the input to the output of the device along the straight waveguide. This effect is greatly reduced when the output signal is taken from the opposite waveguide on the same side of the input fiber. This arrangement, which was not used during the experiments, is the standard one for practical applications, and it can be made feasible using a proper dual-fiber ribbon.

For this kind of slow quasi-static triggering of the SRL, the rise and fall times are around 700 ps, with negligible dependence upon SRL biasing condition and injected trigger pulse peak power. This time can be interpreted as the SRL "intrinsic spontaneous switching time", i.e. the time it takes for the SRL to change the direction of operation when triggered by the smallest externally injected power required to induce the switching. This is the switching time of the directional switchings that occur spontaneously when the SRL current is increased in quasi-static conditions (i.e., the switchings that are observed in P-I curves such as in Fig. 2-a).

The SRFF operation is very stable (as confirmed by acquiring traces on a digital oscilloscope with infinite persistence time), and it can be achieved at any pump current value within the unidirectional regime, provided the optical trigger has enough power and its wavelength matches one of the longitudinal modes of the SRL.

The "ON" output power level emitted by the SRL depends on the pump current level but not on the power and energy of the input trigger. Thus, the SRL acts as an optical analog thresholder, because it switches direction only when an external optical signal of sufficient power is injected in the direction

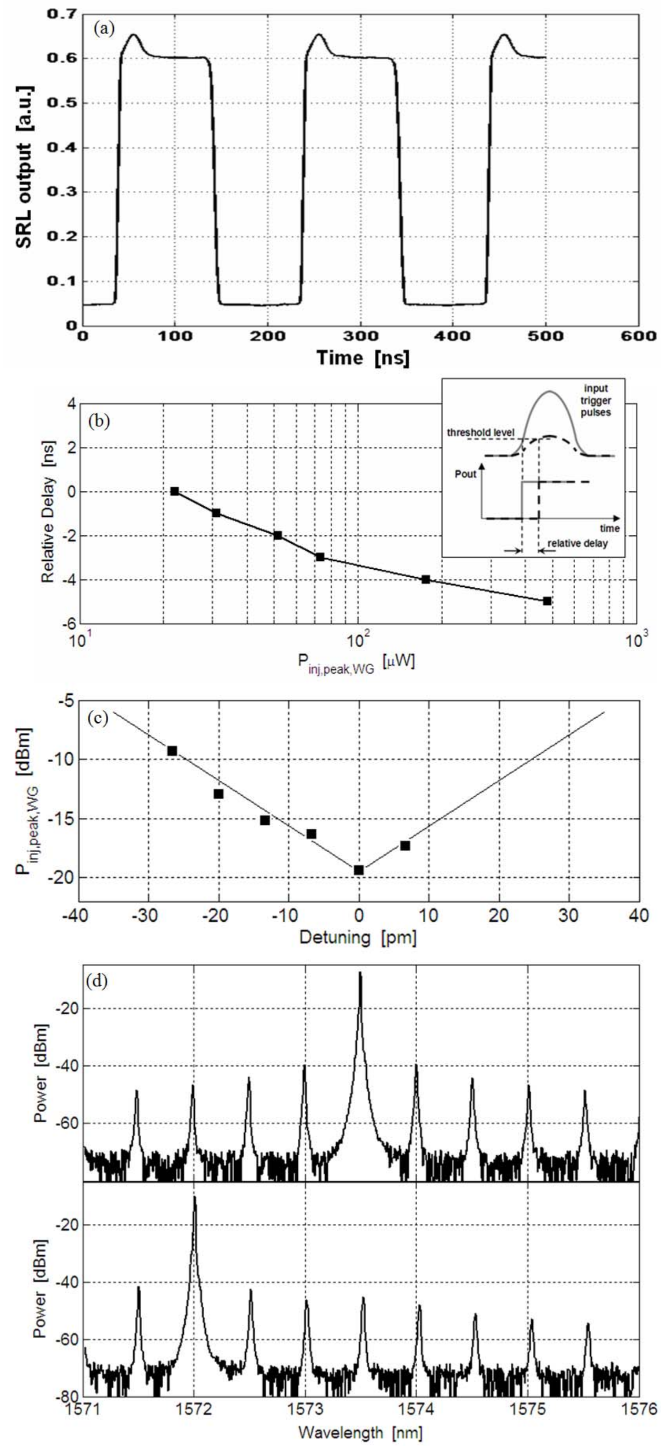

Fig. 4. (a) Time trace, measured on a racetrack shallow etched SRL with a total cavity length of 1.34 mm, of the East output waveguide in response to the repetitive application of Set-Reset pulses with 20 ns FWHM and 5 MHz repetition rate, with 100 ns delay between Set and Reset pulses. (b) Relative delay of the switching instant for varying input peak power (the inset shows schematically the effect of increasing power). (c) Dependence of the required peak power to achieve directional switching as a function of the detuning from the lasing mode. (d) Optical spectra of the SRL in the natural lasing mode (upper panel) and when the trigger optical pulse selects mode-3.

opposite to the lasing direction. The minimum power level that must be injected into the SRL straight waveguide in quasi-static condition to achieve a directional switching is 10 μW.

The thresholding behavior was confirmed by experiments in which slow pulses of different peak power were used as Set and Reset signals. When the peak power was increased, the instant at which the directional switching occurred was anticipated (while keeping a fixed temporal reference with respect to the Set and Reset pulses), as shown in Fig. 4-b.

The switching threshold value depends on the wavelength of the trigger pulses. In fact, as the wavelength of the Set and Reset pulses is detuned from the longitudinal mode resonance of the SRL, the power required to achieve the switching increases, as shown in Fig. 4-c.

From the experiments, it turns out that a detuning of 30 pm leads to a 10-fold increase in the power required to achieve the switching. As a consequence, for a fixed pulse energy there is a detuning value for which the SRL no longer switches direction. Noteworthy, if the wavelength of the trigger pulses is continuously scanned, the switching behavior is recovered as soon as the next longitudinal mode is approached.

Proper SRFF operation was achieved for injection on modes ranging from -3 to $+3$ (where modes are indexed with positive sign when they are at longer wavelength with respect to the natural lasing mode), as shown in Fig. 4-d. Within the above wavelength range, the Set and Reset pulses are capable to effectively select the operating wavelength of the SRFF, and the lasing state selected by the externally injected pulses is maintained for an indefinite amount of time, proving that the SRLs also exhibit wavelength multistability [15].

The intrinsic wavelength selectivity of the SRL does not prevent proper operation in a telecommunication system, provided the wavelength of the optical trigger is known. In fact, the longitudinal modes of the SRL can be finely tuned by changing the operating ring current, thanks to thermal effect. In addition, as shown in the in next sections, when using ultrashort optical trigger pulses whose optical spectrum overlaps with more than one cavity resonance, the directional switching occurs irrespective of the detuning, provided the pulse energy is sufficiently large.

As far as the polarization state of the injected pulses is concerned, we have verified that the injection of a trigger with polarization different from TE is equivalent to reducing the effectively injected power. Hence, the polarization dependence can be reduced by injection of a more powerful optical trigger.

It is also worth commenting on the effects of the extinction ratio (ER) of the optical trigger pulse. When the ER is not sufficiently large, FF operation is not guaranteed, especially for large input powers. The explanation is that an incomplete extinction of the trigger effectively acts as a CW holding beam that enforces the stability of the directional mode of the SRL that is already lasing.

D. Ultrafast Pulses

The "ultrafast" optical trigger pulses were generated by an optical parametric oscillator (OPO), having a FWHM time duration of 5 ps and a FWHM spectral width of 0.8 nm.

The response of the SRL was measured by a 100 GHz photodiode (u2t XPDV4120R) connected to a 40 GHz sampling oscilloscope (Agilent 83482 front-end). For the above chain

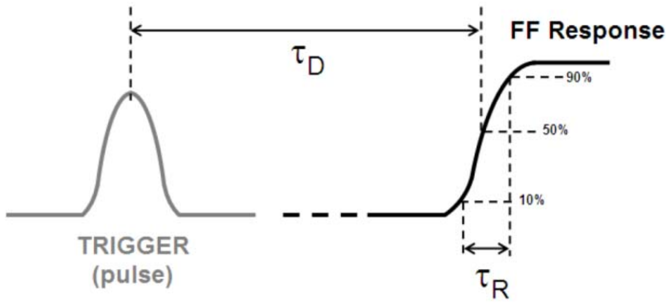

Fig. 5. Definition of parameters for the assessment of the temporal response of an all-optical FF for the case of a pulse like optical trigger.

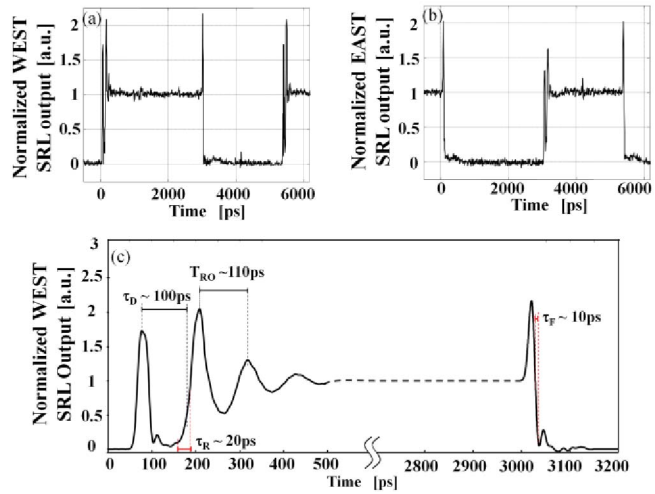

Fig. 6. Time trace of the response of the SRL to Set and Reset ultrashort pulses of 800 fJ energy. (a) Measured from the West output, (b) measured from the East output, (c) measured from the West output showing details for the rising and trailing edges. A similar response is observed from the East direction.

the measured FWHM duration on the sample scope of the 5 ps optical pulse was 15 ps.

Defining and quantifying the switching time (or response time) for an all-optical Flip-Flop poses some difficulties from both the conceptual and practical point of view. When working with electronic logical gates, it is customary to define the response of the gate in terms of the rise τ_R and fall τ_F times and the propagation delay, τ_D (see Fig. 5). τ_R is measured as the 10–90% time required for the FF output to pass from a logic "0" to a logic "1", and vice versa for τ_F. The propagation delay τ_D is defined as the time interval between the arrival of the Set or Reset signal and the time when the FF output reaches 50% of its final value. In this definition, the "arrival time of the trigger signal" shall be specified according to the type of trigger signal: for a pulse-like trigger, the arrival time coincides with the arrival time of the center of mass of the pulse, while for step-like optical trigger, the arrival time coincides with the instant in which the trigger reaches 50% of the amplitude representing its logic "1". From a practical point of view, when using pulse-like triggers it is convenient that their FWHM duration be shorter than the resulting FF propagation delay by at least a factor 2. Otherwise, the measurement of the propagation delay and rise time might be difficult. Also, the measurement of the FF propagation delay requires the knowledge of the precise arrival time of the trigger signal into the FF device input.

In the experimental traces recorded at the switch-on transition, the undiverted Set trigger pulse that traveled along the straight waveguide was clearly visible (first spike in Fig. 6). This pulse could be used as reference for the recorded time trace, thus allowing to measure the propagation delay according to the above definitions.

After adjustment of the experimental set-up, the SRL exhibited proper SRFF operation when triggered by 5 ps pulses used as Set and Reset optical signals. The operating conditions are summarized as follows:

1) Typical SRL operating currents ranged from 80 to 270 mA, i.e. from the onset of the bi-stable unidirectional region up to the maximum current values allowed by heat dissipation.
2) As the spectral width of the pulse train was larger than the free spectral range of the SRL, there was no need to tune the optical trigger to a specific longitudinal mode of the SRL. Proper SRFF operation was observed for detuning between the free-running lasing wavelength of the SRL and the peak wavelength of the OPO as large as 6 nm.
3) Although proper SRFF operation could be achieved also when the input/output waveguides of the device were left unbiased, for optimum high speed performance it was required that these waveguides were used as SOAs, i.e. forward biased by a current between 20 and 30 mA. Biasing is required to avoid distortion of the SRL output signal induced by the gain recovery dynamics of the bus waveguide caused by the undiverted trigger pulse, which saturates the bus waveguide.

The minimum recorded value for the peak pulse power injected into the bus waveguide, in order to achieve proper SRFF operation was 30 mW, corresponding to a minimum switching energy of 150 fJ. When the effect of amplification in the straight waveguide and coupler cross transmission were accounted for, it resulted that the value of 150 fJ is also the minimum energy that shall be injected into the SRL cavity in order to achieve directional switching. Not surprisingly, this value turns out to be of the same order of magnitude of the energy stored into the SRL cavity under the form of lasing photons. Typical values for the pulse energy used in the experiments that are reported in the present paper are around 500–1000 fJ.

Fig. 6 reports a typical time-domain trace of the SRL output for the case of 800 fJ pulse energy. After the injection of the Set pulse, the SRL switched the direction of lasing through a series of large-amplitude Relaxation Oscillations (RO) that smeared away after 500 ps. By identifying the first pulse in the trace as the Set signal, we can measure $\tau_D = 100$ ps at the rising edge, with $\tau_R = 20$ ps, and $\tau_D = 15$ ps at the falling edge, with $\tau_F = 10$ ps, while the period of the RO is $T_{RO} \sim 110$ ps. The amplitude of the peaks related to the RO

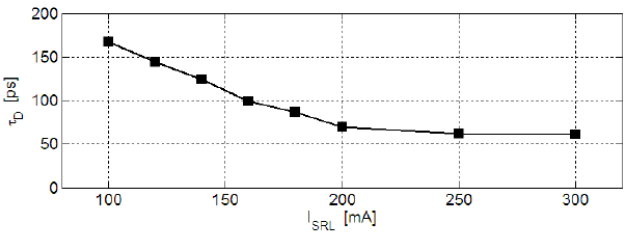

Fig. 7. Switch-on delay τ_D as a function of SRL current for constant energy of the Set pulse, corresponding to 800 fJ.

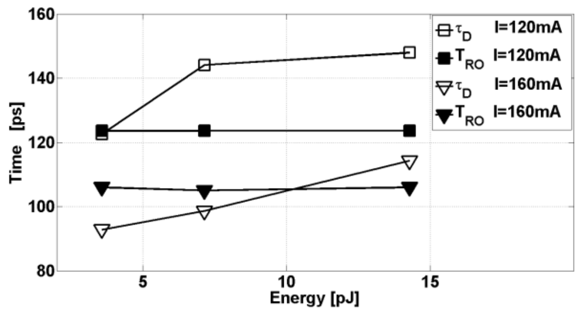

Fig. 8. Switch-on delay (open symbols) as a function of the energy of the injected pulse (coupled to the SRL input waveguide), for two SRL current values. Full symbols show the RO frequency as derived from a measurement of the RO period after the switching has occurred, from time traces similar to that of Fig. 6.

was proportional to the energy of the injected pulse. The pulse that can be seen in correspondence with the falling edge of the trace comes from a spurious reflection of the Reset pulse, occurring at the fiber tip. This reflection is useful to determine τ_D at the falling edge.

It is of great interest to investigate the dependence of the temporal parameters characterizing the SRL response (τ_D, τ_R, τ_F) for different operating conditions of the SRL.

As a first point, we shall notice that the rise and fall times are independent from the bias current and the pulse energy. The period of the relaxation oscillations decreased for increasing ring current, reaching a minimum value of 60 ps at 300 mA.

SRL size - We tested SRLs having a total cavity length ranging from 1.24 to 1.92 mm, and we did not observe any major or systematic dependence of the switch-on delay or rise-time vs. device size. It can thus be concluded that, for SRL cavities larger than 1 mm, the device size does not have an impact on the switching speed.

SRL ring current - While the switch-off delay, the rise-time and the fall-time are independent from the SRL current, the switch-on delay showed a strong dependence on the SRL current, as shown in Fig. 7. The switch-on delay takes on a broad range of values, i.e. from 160 ps at 100 mA current, down to 65 ps at 300 mA. The switch-on delay is a manifestation of non-linear Relaxation Oscillations, and it shows the same dependence on the injected current as the RO.

Energy of the injected pulse - While the switch-off transition was not affected by variations in the pulse energy, the switch-on delay exhibited a slight increase for increasing energy of the Set pulse, as shown by Fig. 8. This longer switch-on delay is related to the fact that when the injected pulse has a larger

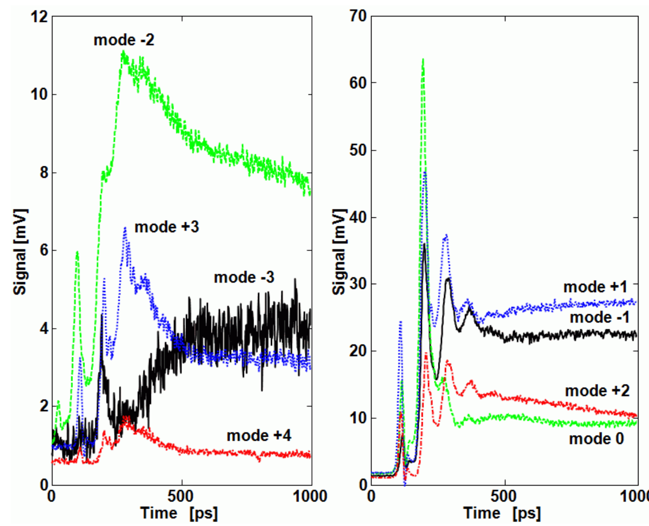

Fig. 9. Time trace of the response of the different longitudinal modes of the SRL to a switching pulse.

energy, it induces a larger departure from the steady-state of the SRL, in terms of overall carrier density depletion. As a consequence, the non-linear transient towards the final state has a longer duration, because the carrier density recovers at a constant rate, determined by the pump ring current.

It is worth remarking that the RO excited by the directional switching process have a strong multimode character, because the injected pulse excites several longitudinal modes of the SRL. Interestingly, the multimode character of the emission of the SRL lasts for much longer than the dynamics of the total intensity, as evidenced in Fig. 9 that shows traces obtained by placing a grating-based optical filter (JDS Uniphase TB9, 0.25 nm bandwidth) before the photodiode. The filter was tuned by varying the grating angle, and it allowed to record the response of the different SRL modes to the injected pulse.

It can be seen that the power in the different modes undergoes large-amplitude RO, eventually reaching a constant or slowly decaying level. This happens on time scales of the order of 1 ns or longer, i.e., multimode dynamics persists quite longer than the RO in the total power emitted by the laser.

E. Practical Operation and Maximum Speed

In order to show that SRLs are capable to perform the functionality of AO-SRFF in practical situations, the above experimental investigation must be complemented by measurements aimed at assessing the maximum speed of operation, and the correct operation when an arbitrary sequence of Set and Reset pulses be input into the device (and not just the basic alternate sequence Set-Reset-Set-Reset…). By modifying the set-up of Fig. 3, we were able to generate sequences of pulses of the kind Set-Set-Reset-Reset, with an adjustable delay between the pulses of either type. The application of two subsequent pulses of the same type (i.e. Set-Set and Reset-Reset) is crucial to determine whether the SRL really acts as a SRFF. In fact, upon injection of two pulses of the same type, the SRL must keep the state previously set, without being switched by the other pulse.

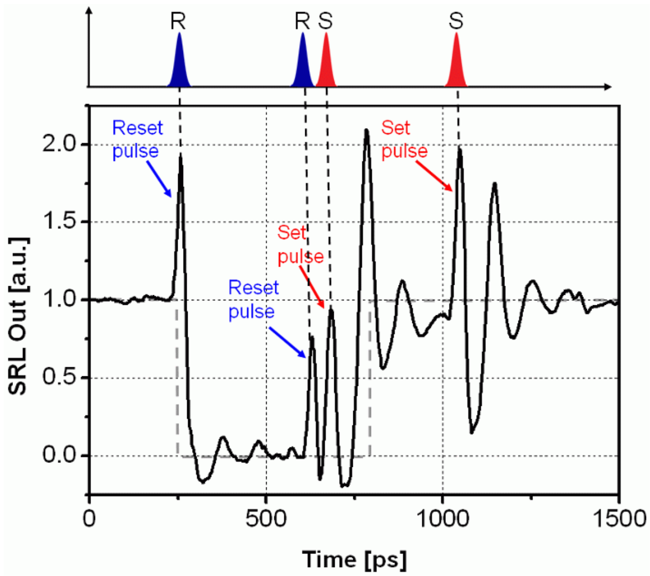

Fig. 10. Output trace of the SRL for injection of the following sequence of pulses: Reset-Reset-Set-Set (schematically illustrated in the upper panel).

The experimental trace of Fig. 10, shows that subsequent Set or Reset pulses does not change the state of the optical memory. After the injection of the second Set pulse the SRL underwent a transient, where RO were excited, that lasted for approximately two RO periods, the amplitude of the perturbation being proportional to the energy of the pulse. This effect did not prevent proper operation of the SRFF.

Given the above findings and the fact that the minimum switch-on time is around 60 ps, operation at 10 Gb/s is surely attainable, and a limit bit-rate for the present generation of SRL SRFFs appears to be 15 Gb/s.

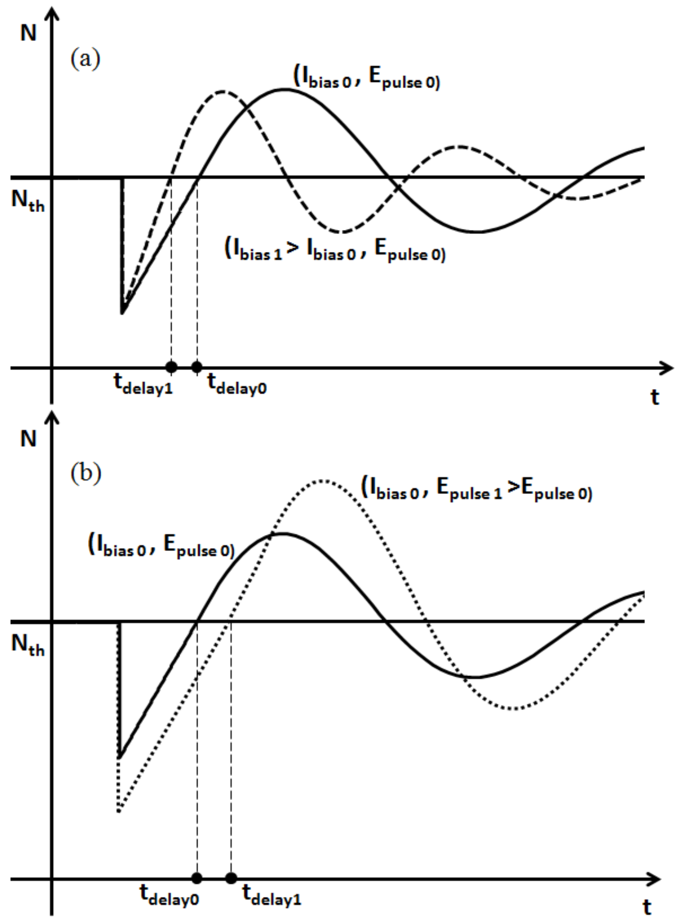

Fig. 11. Phenomenological description of the switching mechanism. (a) Effect of the bias current. (b) Effect of the pulse energy.

IV. Phenomenological Description of the Switching Mechanism

Based on the experimental characterization, a precise phenomenology for the switching dynamics triggered by ultrashort pulses can be inferred, keeping in mind that the injected pulse is shorter than the round-trip time of the ring cavity, and it has energy content comparable to that of the photons already stored within the cavity.

1) The photons of the injected counter-propagating pulse induce stimulated emission and significantly deplete the carrier density of the active region of the laser, thus reducing the optical gain below the threshold value, and quenching the originally lasing directional mode. The above phenomena occur within one cavity round-trip time (i.e., about 15 ps). This explains the ≈10 ps fall time of the SRFF.
2) The carrier density begins to increase linearly with time, at a rate that is set by the pump current of the ring section. As soon as the carrier density reaches the threshold value, the SRL starts lasing again. The new lasing direction is the direction in which there is a larger number of photons already present in the cavity. This is the direction of the newly externally injected photon pulse, as the original lasing photons have decayed. The new lasing action is accompanied by relaxation oscillations.
3) For a given pump rate, if the injected pulse energy is increased, the instantaneous carrier depletion is larger, and the recovery time is larger, thus yielding a larger switch-on delay for SRFF operation (Fig. 11-b), in agreement with results shown in Fig. 8. Obviously, if the injected pulse energy is not sufficient, the original lasing direction is not quenched, and the directional switching does not occur.
4) For a given energy of the injected pulse, an increase of the pump current causes a faster recovery of the carrier density, thus shortening the delay time (Fig. 11-a). This is in agreement with the results shown in Fig. 7.
5) A reduction of the SRL size implies a reduction of the rise- and fall-times, that are proportional to the cavity round-trip time. However, reducing the cavity size does not significantly affect the crucial delay time, as this only depends on the pump rate, i.e. ultimately on the injected current density. This consideration is consistent with the fact that smaller investigated SRL fabricated using the present technology (20 μm radius deep-etched racetrack cavity - overall cavity length of 165 μm) did

show delay times similar to that of larger devices. This is also consistent with results achieved in [5] using smaller SRLs.

The above considerations suggest that the ultimate speed limit of the SRL-based bistable Flip-Flop technology is limited by the carrier injection rate into the active region. In view of the above, large speed improvement can only be devised by using novel active materials capable of sustaining larger current densities before causing barrier carrier leakage.

The observed switching phenomenology of the SRL triggered by external optical pulses is also in good accordance with the accurate travelling wave model reported in literature [17].

V. Conclusion

We have reported on detailed experimental investigation carried out on monolithic semiconductor ring lasers that proved to be reliable devices for the implementation of all-optical digital signal processing. We have demonstrated that Set-Reset Flip-Flop operation can be obtained using externally injected Set-Reset optical pulses of duration ranging from 20 ns down to 5 ps. Ultimate directional speed results show a switch-on delay of 60 ps, and rise and fall times of 20 ps and 10 ps respectively.

Based on the physical analysis carried out and the technological expertise developed so far, future research efforts shall be devoted to increase the switching speed and to allow the operation of cascaded ring structures in order to achieve a cascadability similar to that offered by electronic logic families, with the goal of achieving more functionality at even higher speed.

References

[1] C. Glingener, "Optical networking trends and evolution," in *Proc. OFC/NFOEC*, Los Angeles, CA, USA, Mar. 2011, pp. 1–3.

[2] P. Monteiro, J. Pedro, S. Pato, J. Gomes, R. Morais, J. Santos, R. Meleiro, H. Rohde, and R. Winkelmann, "Challenges and trends in optical networking: A bottom-up approach," in *Proc. 5th Int. Conf. Broadband Commun., Netw. Syst.*, Sep. 2008, pp. 460–469.

[3] T. Cheng, "All-optical photonic packet switching revisited: What have changed and what have not changed after 20 years?" in *Proc. 9th ICOCN*, Nanjing, China, Oct. 2010, pp. 235–240.

[4] F. Ramos, E. Kehayas, J. M. Martinez, R. Clavero, J. Marti, L. Stampoulidis, D. Tsiokos, H. Avramopoulos, J. Zhang, P. V. Holm-Nielsen, N. Chi, P. Jeppesen, N. Yan, I. T. Monroy, A. M. J. Koonen, M. T. Hill, Y. Liu, H. J. S. Dorren, R. Van Caenegem, D. Colle, M. Pickavet, and B. Riposati, "IST-LASAGNE: Towards all-optical label swapping employing optical logic gates and optical flip-flops," *J. Lightw. Technol.*, vol. 23, no. 10, pp. 2993–3011, Oct. 2005.

[5] M. T. Hill, H. J. S. Dorren, T. De Vries, X. J. M. Leijtens, J. H. Den Besten, B. Smalbrugge, Y.-S. Oei, H. Binsma, G.-D. Khoe, and M. K. Smit, "A fast low-power optical memory based on coupled micro-ring lasers," *Nature*, vol. 432, pp. 206–209, Nov. 2004.

[6] L. Liu, R. Kumar, K. Huybrechts, T. Spuesens, G. Roelkens, E. J. Geluk, T. de Vries, P. Regreny, D. Van Thourhout, R. Baets, and G. Morthier, "An ultra-small, low-power, all-optical flip-flop memory on a silicon chip," *Nature Photon.*, vol. 4, no. 3, pp. 182–187, 2010.

[7] K. Huybrechts, R. Baets, and G. Morthier, "All-optical flip-flop operation in a standard tunable DBR laser diode," *IEEE Photon. Technol. Lett.*, vol. 21, no. 24, pp. 1041–1135, Dec. 15, 2009.

[8] M. Sorel, G. Giuliani, S. Donati, and P. J. R. Laybourn, "Unidirectional bistability in semiconductor waveguide ring lasers," *Appl. Phys. Lett.*, vol. 80, no. 17, pp. 3051–3053, 2002.

[9] M. Sorel, G. Giuliani, A. Scirè, R. Miglierina, S. Donati, and P. J. R. Laybourn, "Operating regimes of GaAs-AlGaAs semiconductor ring lasers: Experiment and model," *IEEE J. Quantum Electron.*, vol. 39, no. 10, pp. 1187–1195, Oct. 2003.

[10] B. Li, M. I. Memon, G. Mezosi, G. Yuan, Z. Wang, M. Sorel, and S. Yu, "All-optical response of semiconductor ring laser to dual-optical injections," *IEEE Photon. Technol. Lett.*, vol. 20, no. 10, pp. 770–772, May 15, 2008.

[11] B. Li, D. Lu, M. I. Memon, G. Mezosi, Z. Wang, M. Sorel, and S. Yu, "All-optical digital logic AND and XOR gates using four-wave-mixing in monolithically integrated semiconductor ring lasers," *Electron. Lett.*, vol. 45, no. 13, pp. 698–700, 2009.

[12] M. I. Memon, G. Mezosi, W. Zhuoran, M. Sorel, and S. Yu, "Characterization of all-optical regeneration potentials of a bistable semiconductor ring laser," *J. Lightw. Technol.*, vol. 27, no. 19, pp. 4233–4240, Oct. 1, 2009.

[13] A. Trita, G. Mezosi, F. Bragheri, J. Yu, S. Furst, W. Elsässer, I. Cristiani, M. Sorel, and G. Giuliani, "Dynamic operation of all-optical flip-flop based on a monolithic semiconductor ring laser," in *Proc. 34th ECOC*, Brussels, Belgium, Sep. 2008, pp. 1–2.

[14] C. Porzi, S. Chin, A. Trita, F. Fresi, G. Berrettini, G. Mezosi, P. Ghelfi, G. Giuliani, L. Poti, M. Sorel, L. Thevenaz, and A. Bogoni, "All-optical self-synchronizing scheme for contention resolution in asynchronous optical packet switched networks using continuously tunable optical delay line," in *Proc. OFC/NFOEC*, Los Angeles, CA, USA, Mar. 2011, pp. 1–3.

[15] Z. Wang, G. Yuan, G. Verschaffelt, J. Danckaert, and S. Yu, "Storing 2 bits of information in a novel single semiconductor microring laser memory cell," *IEEE Photon. Technol. Lett.*, vol. 20, no. 14, pp. 1228–1230, Jul. 15, 2008.

[16] G. Mezosi, M. J. Strain, S. Furst, and M. Sorel, "Bistable microring lasers with compact footprint and high output efficiency," *IEEE J. Quantum Electron.*, vol. 48, no. 8, pp. 1023–1030, Aug. 2012.

[17] J. Javaloyes and S. Balle, "All-optical directional switching of bistable semiconductor ring lasers," *IEEE J. Quantum Electron.*, vol. 47, no. 8, pp. 1078–1085, Aug. 2011.

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