Semiconductor ring lasers for all-optical flip-flop and signal processing

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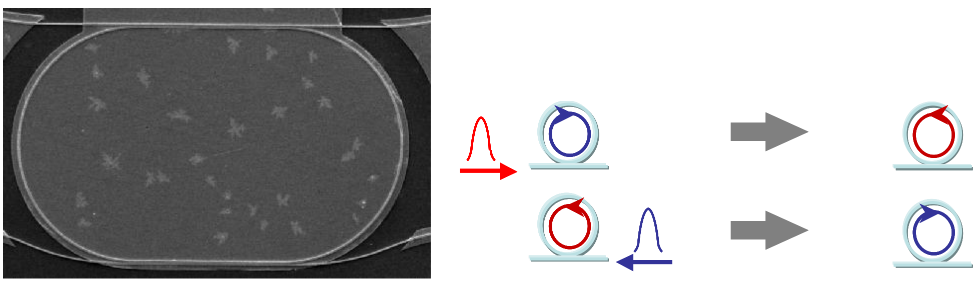
A monolithic semiconductor ring laser is operated as an all-optical Flip-Flop with a response time shorter than 100 ps. Device design, technology, experimental behavior, and thoretical modelling are reviewed. A conclusive experiment reports on error-free operation under Bit-Error-Rate measurements for arbitrary sequence of optical Set-Reset pulses.

Introduction

The realisation of digital functions is becoming a key issue for the development of future optical fiber communication systems, where the implementation of all-optical digital signal processing will allow for more flexibility and new capabilities increasing the system performance. Interesting applications can be foreseen in all-optical networks, and optical computation applications.

The EU-FP6 Project "IOLOS" proved that semiconductor ring lasers (SRLs) can be a viable solution for a monolithic implementation of such functions, thanks to tinherent directionally bistable behaviour and compact size [1,2]. In particular, the bistable SRL can be used as an all-optical Set-Reset Flip-Flop (SRFF) that can be triggered and switched by an externally injected optical signal, with a response time shorter than 100 ps. In the scientific literature there are few examples of all-optical SRFF devices that have been tested in system operation [3,4]. In this work we also report on experiments, aimed at the investigation of the SRL SRFF ability to operate in system conditions with an error-free performance assessed by Bit-Error-Rate measurements..

Device Description and Flip-Flop Function



(a) (b)

Figure 1. a) SEM picture of the SRL. b) Representation of Set-Reset Flip-Flop operation when the SRL is biased in the directionally bistable (uni-directional) regime

The SRL (shown in Fig. 1a) has a racetrack cavity, with 150 ?m radius connecting two straight sections of 200 ?m. Two straight output waveguides provide 4 input/output ports that can be used to inject/extract optical signals. The devices operate CW at room temperature, with threshold currents between 35 and 60 mA, emitting up to 3 mW at λ = 1550-1570 nm. Although the SRL can operate with the two counterpropagating modes being both active at the same time (bi-directional regime), for higher pump current non-linear effects intrinsic to the active semiconductor material induce a directional bistability, as lasing action can only occur unidirectionally either in the Clockwise (CW) or in the Counter-Clockwise (CCW) direction.

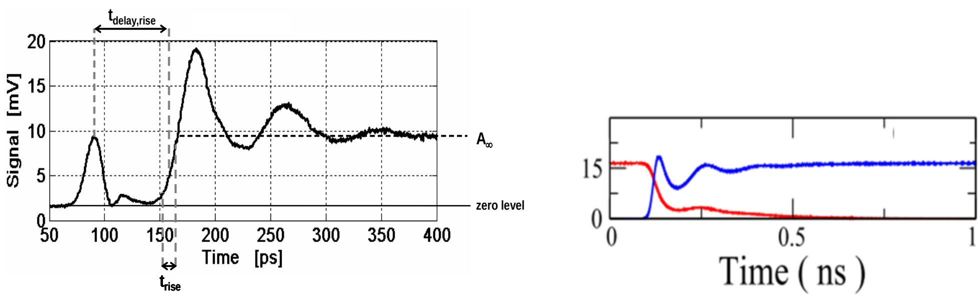
The lasing direction of this monolithic optical bistable can be switched by injecting an external optical signal in the direction to be activated, as shown in Fig. 1b, thus realizing the all-optical SRFF function. Static characteristics of the SRFF device are very good, with directional extinction ratio in excess of 15 dB [5]

Experimental results – Response time

The study of the temporal dynamics of the all-optical flip-flop is of primary importance, because it sets the maximum possible speed of operation in a telecommunication system. We have arranged an experimental set-up where 5 ps FWHM optical trigger pulses produced by an OPO were split in two paths, and injected alternatively into the SRL in opposite directions through opposite input/output waveguides. Two fast photodiodes connected to a 40 GHz sampling oscilloscope were used to measure the temporal response of the CW and CCW modes. The switching time decreases for increasing trigger peak power, reaching a minimum of 20 ps with a delay time of 65 ps (see Fig. 2a) .

Theoretical model

In order to evaluate the limits of switching speed that can be achieved, we have performed numerical simulations of the SRL using a recently developed Travelling-Wave Model [6]. The model includes coupling of the CW and CCW waves arising from both Spectral- and Spatial-Hole Burning in the carrier density. The numerical results are in excellent agreement with the experimental observations (Fig. 2b), and predict that rise-times as fast as 11 ps are achievable..



(a) (b)

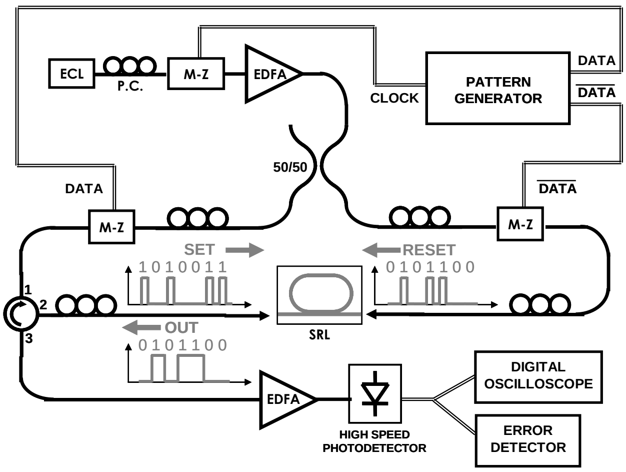
Figure 2. a) Experimental response (rising edge) of the SRL to 5 ps trigger pulses. b) Numerical simulation of the ON/OFF switching transients in a SRL triggered by a 5 ps pulse.

Bit-Error-Rate Measurements

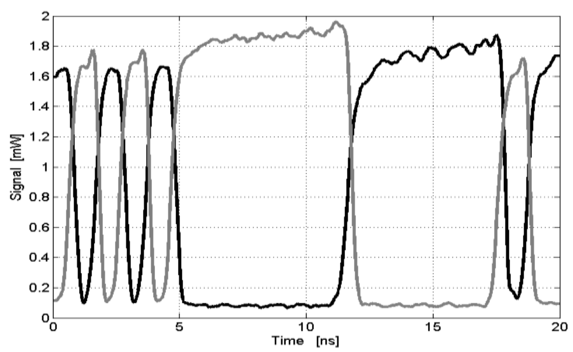
To test the all-optical SRFF under conditions similar to system operation, we measured the Bit-Error-Rate (BER) of the device when it was repeatedly and alternatively triggered by optical Set and Reset pulses in the form of a PRBS sequence. Fig. 3a shows the experimental set-up: we generated two RZ PRBS sequences: the Set signal (using *DATA* from the Pattern Generator) and the Reset signal (using $\overline{DATA}$). In this way, during each bit time-slot, the SRFF is injected by either a Set or a Reset signal. The response of the SRFF is a NRZ signal with the same data sequence of the Set or Reset bit-stream, depending on the side from which the output signal is extracted. The output signal is supplied to the Error Detector, that allows to investigate the BER of the device. A BER measurement is essential to test the proper and reliable operation of the SRFF. An error-free operation is a proof that the SRFF can indeed work with an arbitrary Set and Reset data sequence, without missing any externally triggered switching, nor exhibiting spontaneous switchings of its state.

The experimental results showed error-free operation at the Bit-Rate of 1 Gb/s with 2^{31}-1 PRBS for times longer than 5 minutes, corresponding to a BER better than $3{\cdot}10^{-12}$. The peak power injected into the SRL waveguide was -2 dBm.

Fig. 3b shows an example of the SRFF output signal for two cases: in black line for standard Set and Reset input data streams; in gray for complementary Set and Reset



(a)



(b)

Figure 3. a) Experimental set-up for BER measurements. b) Output of the SRL Set-Reset Flip-Flop device. Black trace: output for standard Set and Reset data. Gray trace: output for complementary (swapped) Set and Reset data

inputs (i.e., swapped). Correctly, the SRL exhibits complementary output, and a good eye opening can be inferred. Measurements using 10 GHz repetition rate pulses of ultrashort duration are under way.

Conclusions

We have reviewed the research and results of the EU FP6 Project "IOLOS" showing that a semiconductor ring laser can operate as monolithic all-optical Set-Reset Flip-Flop with response time well below 100 ps, and with error-free operation under system conditions. Other contributions in the framework of the IOLOS project can be found on p.145 and p.181 of this issue. A complete overview of IOLOS publications can be found on www.iolos.org.

References

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