An Ultra-small, Low-power All-Optical Flip-Flop Memory on a Silicon Chip

Rajesh Kumar[1], Koen Huybrechts[1], Liu Liu[1], Thijs Spuessens[1], Gunther Roelkens[1,2], Erik-Jan Geluk[2], Tjibbe de Vries[2], Philippe Regreny[3], Dries Van Thourhout[1], Roel Baets[1], Geert Morthier[1*]

1. Photonics Research Group, INTEC Department, Ghent University–IMEC, B-9000 Gent, Belgium
2. COBRA Research Institute, Technische Universiteit Eindhoven, Postbus 513, 5600 MB Eindhoven, The Netherlands
3. Université de Lyon; Institut des Nanotechnologies de Lyon INL-UMR5270, CNRS, EcoleCentrale de Lyon, Ecully, F-69134, France
[*]E-mail: Geert.Morthier@intec.ugent.be

Abstract: A 7.5µm-diameter InP microdisk laser, integrated on an SOI waveguide is demonstrated as all-optical flip-flop working in continuous-wave regime with an electrical power consumption of several mW, and allowing switching in 60ps with pulses of 1.8fJ.

OCIS-codes: (060.6719) Packet switching; (250.3750) Optical logic devices; (250.4745) Optical processing devices

1. Introduction

All-optical flip-flops (AOFF's) could be very useful building blocks of all-optical packet switching systems, as they can temporarily store the header information and/or provide control signals to the optical switches [1]. For practical implementation, it is important that not just one, but several bits can be stored at the same time and hence that a number of memory elements can be integrated on a single chip. Obviously, the footprint, the speed and the power consumption of single memory elements are of significant importance for these integration goals.

Compact AOFFs have been demonstrated with a number of InP-based devices, usually bistable laser diodes. One of the smallest AOFFs reported at 1.55 µm consisted of two coupled ring lasers with each ring having a diameter of 16µm, and with a total area of 40x18 µm^2 [2]. However, the ring lasers each have a threshold current of 30 mA and can only operate in pulsed regime. Single InP ring lasers have also been demonstrated as AOFF, but with diameters of 30 µm and total power consumption of several tens of mW [3]. Another small AOFF was based on the polarization switching in a VCSEL [4]. It required a bias current of slightly more than 14 mA and switching energies of several fJ at 1.55µm. VCSELs are however less suited for on-chip integration with other devices.

Electrically pumped AOFFs on the silicon-on-insulator (SOI) platform have not been reported yet, since laser emission in silicon is still difficult. Recently, we demonstrated the continuous-wave operation of compact, electrically pumped microdisk lasers with diameters as small as 5 µm using the III-V/SOI heterogeneous integration [5]. Here we present for the first time AOFFs built from such a single microdisk laser of diameter 7.5 µm. The AOFF works in continuous-wave regime with an electrical power consumption of only a few mW and allows switching in 60ps with pulses of just 1.8fJ. The power consumption, switching energy and device size are, to our knowledge, the smallest reported so far at the telecom wavelength. This is also the only electrically-pumped AOFF on silicon presented so far.

2. Concept and fabrication

The InP microdisk lasers are heterogeneously integrated onto SOI using adhesive die-to-wafer bonding with the divinylsiloxane-benzocyclobutene (DVS-BCB) polymer [5]. Figure 1 shows schematic drawings of the entire circuit and the bonded microdisk lasers. The flip-flop operation is based on the switching between the clockwise (CW) and the counter clockwise (CCW) whispering gallery modes (WGM) in the disk laser. The fabrication of the microdisks is as outlined in [6], but extra care was taken to minimize the sidewal surface roughness of the disks and to obtain good power efficiency.

It is known from theoretical work that the existence of bistable unidirectional behavior requires a large photon density in the WGMs of the disk laser as well as a small coupling between the CW and the CCW modes. In our microdisks, large internal power density results from the good mode confinement of the InP membrane due to the high index contrast. We also avoided degradation due to heating at higher currents, by making the Au layer of the top contact thick (600nm) and using it as heat sink. Since the WGM is confined to the edge of the disk, this top metal does not result in substantial optical absorption loss. The coupling between CW and CCW WGMs was minimized by using an optimized lithography and etching process. To reduce the influence of reflections at the grating couplers, we aimed for a small coupling between disk and straight waveguides and therefore a relative thick DVS-BCB bonding layer of about 250nm was used.

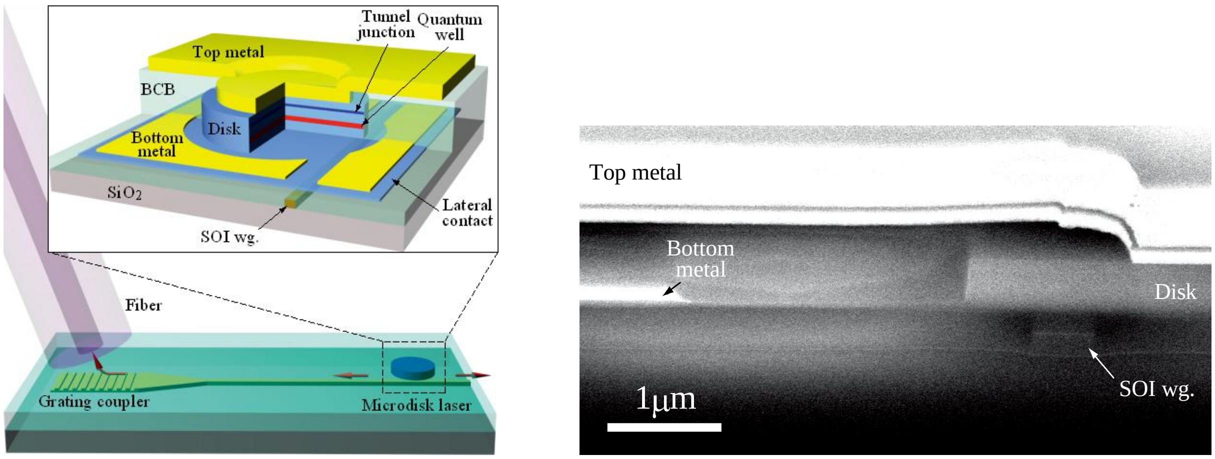

Fig. 1. Schematic structure of the whole circuit and the microdisk laser (inset) (lhs) and SEM picture of the cross section (rhs).

3. Static characteristics

Figure 2(a) gives a typical light-current (L-I) curve of the microdisk laser, measured from both ends of the SOI waveguide, and thus representing the CW and CCW mode power, respectively. The threshold current is as low as 0.33mA. The maximum power in the SOI waveguide is 21μW, limited by the thermal rollover around 3.8mA. Figure 2(b) presents the lasing spectrum at 3.8mA bias, showing a single mode operation with side mode suppression ratio higher than 40dB. Bistable, unidirectional operation starts at 1.7 mA. We did not observe any switching of the lasing direction in the unidirectional regime when increasing the bias current, which does occur in the large ring lasers. Theoretical calculations predicted that this switching behavior only happens when the laser mode hops to another azimuthal order, i.e., several free spectral ranges (FSRs) away, due to self heating. Such a mode-hopping is unlikely to happen in the present structure, since the microdisk cavity is so small that the FSR is larger than 30 nm as depicted in Fig. 2(b).

4. Switching Experiments

Switching between CW and CCW operation is achieved through short pulses that are injection locking the laser. For the switching experiments, we biased the laser at 3.5 mA, which is about twice the threshold for the unidirectional operation (1.7mA) and is chosen to avoid noise-induced switching. To test the switching speed and the switching energy, we used 100 ps long set and reset pulses as shown in Figure 3(a) and measured the laser output (shown in Figure 3(b)) with a high speed oscilloscope. Because the disk is only coupled to one straight waveguide, it is not possible to separate the switch pulses and the laser signal. Therefore the switch pulses always cover the transient of the microdisk signal, making it difficult to measure the exact switching times. The residual reset pulses also come from the reflection at the cleaved facet of the access fiber and have been suppressed to some extent by using index matching fluid. The measured switch-off transient in this case is shown in Figure 3(c); it is characterized by a switch-off time of 60ps. The peak power measured in the SOI waveguide was 18 μW, corresponding with a switching energy of 1.8 fJ.

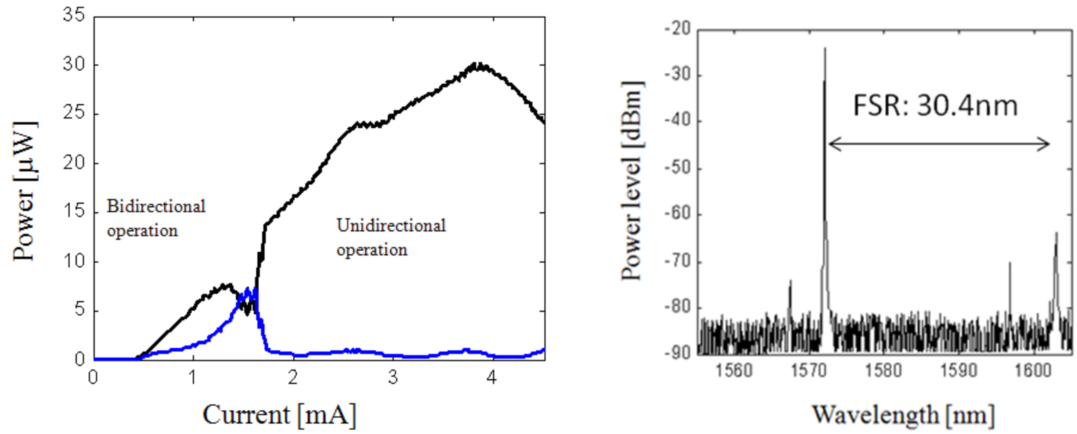

Fig. 2. L-I curve (left) and optical spectrum (right) of a 7.5 μm microdisk laser.

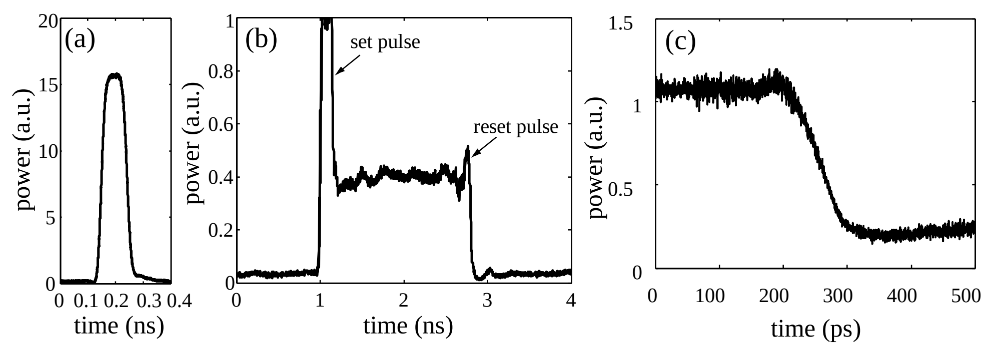

Fig. 3. (a) Waveform of the injected optical pulse, (b) Waveform of the measured optical signal at one side, (c) Details of the switch-off transient, after applying the index matching fluid to suppress the appearance of the reset pulses..

5. Conclusion

We demonstrated the smallest AOFF so far reported, with also the lowest power consumption. The device is also the only electrically-pumped AOFF built on SOI so far.

Acknowledgement

This work is supported by the European FP7 ICT-projects HISTORIC, WADIMOS and PhotonFab, the Fund for Scientific Research Flanders (FWO), and the IAP-project “Photonics@be”. The work of K. Huybrechts and T. Spuessens is supported by the Institute for the Promotion of Innovation through Science and Technology (IWT) under a specialization grant. We acknowledge the assistance from Steven Verstuyft during the device fabrication.

References

1. H. Dorren, *et al*, "Optical packet switching and buffering by using all-optical signal processing methods," JLT 21, 2-12 (2003).
2. G. Mezösi, *et al*, “Unidirectional Bistability in AlGaInAs Microring and Microdisk Semiconductor Lasers,” PTL21, 88-90 (2009).
3. Hill, M. T. *et al.* A fast low-power optical memory based on coupled micro-ring lasers. *Nature* **432,** 206-209 (2004).
4. T. Katayama, *et al*, “All-Optical Flip-Flop Operation using 1.55 μm Polarization Bistable VCSELs,” CLEO/QELS, paper CME5 (2008).
5. G. Roelkens, *et al*, “III-V/Si photonics by die-to-wafer bonding”, Materials Today, 10 (7-8), 36-43 (2007).
6. J. Van Campenhout, *et al.*, "Electrically pumped InP-based microdisk lasers integrated with a nanophotonic silicon-on-insulator waveguide circuit," Optics Express., vol. 15, 6744-6749 (2007).


OFCNFOEC 2010
THE FUTURE OF OPTICAL COMMUNICATIONS IS HERE
Technical Digest
ISBN 978-1-55752-884-1
MARCH 21–25, 2010
SAN DIEGO CONVENTION CENTER
SAN DIEGO, CALIFORNIA, USA
©2010