Digital photonics using InP microdisk lasers heterogeneously integrated on Silicon-on-Insulator

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***Abstract*— We demonstrate the use of heterogeneously integrated microdisk lasers for application in low-power and high-speed all-optical flip-flops and gates. Flip-flop operation is experimentally demonstrated using pulse energies of 1.8 fJ in lasers with a diameter of 7.5 μm. Potential optimization of the performance and future photonic integrated circuits are also described.**

Keywords- microdisk laser, heterogeneous integration, digital photonics

I. INTRODUCTION

All-optical networks would benefit greatly from an increased use of all-optical signal processing, especially with the introduction of all-optical packet/burst switching [1-3]. In addition to wavelength conversion and signal regeneration, photonic devices implementing digital or logic functions are greatly desired, e.g. for header processing, routing or storing header information.

Solutions for the all-optical implementation of logic functions so far have suffered from a relatively large power consumption [4] and/or a slow operation. Sometimes they require complex photonic circuits that are difficult to integrate and comprise several power-hungry SOAs or laser diodes as well as optical filters or even isolators [5].

We have recently demonstrated the first low-power all-optical flip-flop on a silicon chip, making use of heterogeneously integrated microdisk lasers with diameter as small as 7.5 μm. The small footprint, the low power consumption and the use of the Silicon-on-Insulator (SOI) platform make this approach ideally suited for the realization of photonic integrated circuits comprising a number of gates, set-reset flip-flops and passive devices.

Below we will give more details on the fabrication technology and the operation principle, the first experimental results and the plans for the near future work.

II. FABRICATION TECHNOLOGY AND OPERATION PRINCIPLE

Figure 1 shows a schematic of the bonded microdisk lasers. The III-V/SOI heterogeneous integration is obtained through adhesive die-to-wafer bonding using DVS-BCB as a bonding agent [6]. The fabrication of the microdisks is discussed in more detail in [7]. 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. Unidirectional operation is only possible if the coupling between the CW and CCW modes is sufficiently small and if the gain suppression is sufficiently large. Therefore, extra care was taken to minimize the sidewall surface roughness of the disks and to obtain good power efficiency. A low sidewall surface roughness was obtained by using an optimized lithography and etch processes. A large internal power density results from the good mode confinement of the InP membrane, due to the high index contrast, and from the extra heat sinking we introduced by making the Au layer of the top contact thicker. This last measure avoided degradation at higher currents due to self-heating. The microdisk lasers are coupled to SOI wire waveguides and the light from these waveguides is coupled to fiber using grating couplers. The SOI wafers were fabricated through a MPW-approach by the Silicon Photonics platform ePIXfab [8].

The same microdisks that are used for all-optical set-reset flip-flops can in principle be used as all-optical gates for logic functions.

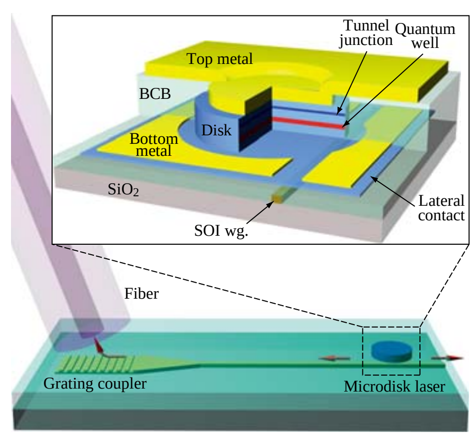

Figure 1. Structure of the whole circuit and the microdisk laser.

III. FIRST EXPERIMENTAL RESULTS

The L-I characteristic shows the typical behavior of disk lasers evolving from bidirectional towards unidirectional operation (Figure 2). The typical threshold current of the 7.5 µm microdisk lasers is below 0.5 mA. In Figure 2, the threshold current for lasing in the bidirectional regime is 0.33 mA. Bistable unidirectional behavior starts typically between 1 and 2 mA and at 1.7 mA in Figure 2. Due to the small dimensions, the lasers are single mode with a side mode suppression of over 40 dB.

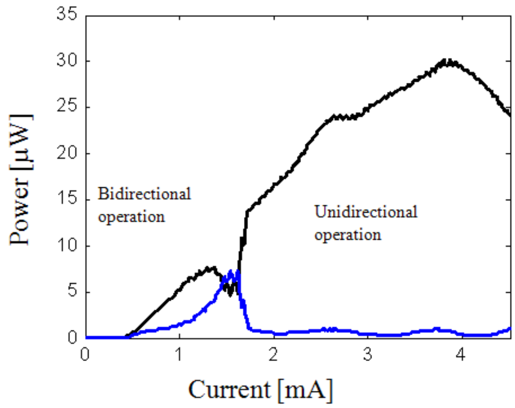

Figure 2. Typical L-I characteristic of a microdisk laser depicting the optical output power at both sides of the disk.

Switching between CW and CCW modes is achieved through injection locking. In our switching experiments we biased the laser at 3.5 mA to avoid self-switching due to noise and used 100 ps long switching pulses (generated using a 10 Gb/s pulse pattern generator). Figure 3 shows the typical time dependence of the on- and off-switching of a laser mode, measured on one side of the straight waveguide. Because the disk is only coupled to a single 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. However, we found switch off times as low as 60 ps. Required switching energy is as low as 1.8 fJ, which is a record low value at the 1.55 µm wavelength.

The total power consumption of this all-optical set-reset flip-flop is estimated to be about 6 mW, but could be reduced down to 1.5 mW. This corresponds with 0.15 pJ per bit at 10 Gb/s and is a number that is very competitive with current and even near future opto-electronic solutions, especially if the power consuming interconnections are taken into account for the opto-electronic approach.

All-optical gates have been demonstrated at 10 GHz so far using pump-probe experiments. The disks did not have to be biased for this purpose.

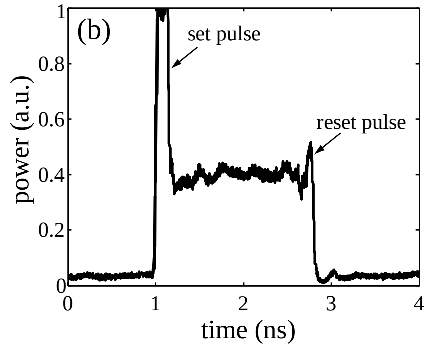

Figure 3. Waveform of the optical signal measured on one side.

IV. CONCLUSION AND FUTURE WORK

The demonstration of set-reset all-optical flip-flops and all-optical gates based on heterogeneously integrated microdisk lasers opens the way for the exploration of more complicated devices such as D-flip-flops and shift registers. These can be made by simply interconnecting different S-R flip-flops and gates. However, for this purpose it is very important that all microdisk lasers and gates have laser or resonance wavelengths within small tolerances.

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