All-Optical Flip-Flops using Electrically Pumped Microdisk Lasers Integrated on Silicon

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***Abstract*— We demonstrate flip-flop operation using the directional bistability in ultra-small microdisks (7.5 µm diameter) heterogeneously bonded on a silicon chip. The pulse energies are only 1.8 fJ and the bias current is 3.5 mA.**

***Index Terms*— Microdisk lasers, All-optical flip-flops, Heterogeneous integration**

I. Introduction

All-optical flip-flops are considered potential elements in all-optical packet switching schemes in order to cope with the massive bandwidth requirements resulting from the huge growth of upcoming telecommunication services [1-2]. They are of great importance in realizing such transparent packet/burst switches because they can act as optical memory elements and temporarily store the header information of data packets.

Several concepts for all-optical flip-flops have been proposed so far, but most of them require multiple active sections which results in a difficult integration and large power consumption [3-4]. One of the most well-known flip-flop concepts in literature is composed of two coupled ring lasers that force each other to operate in a unidirectional operation either in a clockwise or a counterclockwise mode [5]. Using the non-linear gain suppression effect in such structures, it is possible to obtain this unidirectional regime also in a single ring or disk laser [6]. By injecting an optical pulse, one can switch between the two directional states and obtain flip-flop operation [7].

In this article we discuss recently obtained experimental results of all-optical flip-flop operation in a single microdisk laser heterogeneously bonded on a silicon chip. The ultra-small dimensions of the device (7.5 µm diameter) suggest a large potential for a dense integration. Moreover, the energy consumption is very low with a bias current of only 3.5 mA and pulse energies of 1.8 fJ.

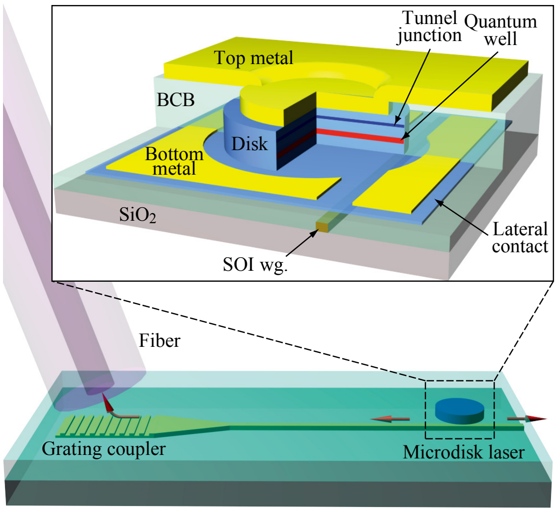

Fig. 1. Schematic of the fabricated structure: the microdisk laser is bonded on top of a silicon waveguide with grating couplers (from [10]).

II. Device Structure

A schematic of the fabricated structure is depicted in Fig. 1. The microdisk structure is heterogeneously bonded on a SOI chip through an adhesive die-to-wafer bonding [8]. The bonding agent is DVS-BCB (divinylsiloxane–benzocyclobutene). When current is injected through the top metal contact, the laser will start lasing in the whispering gallery mode. The laser light is evanescently coupled to a silicon waveguide underneath. Grating couplers on both sides of the waveguide allow an efficient output coupling to optical fibers. The SOI wafers were fabricated through a MPW-

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approach by the Silicon Photonics platform ePIXfab [9].

In order to obtain unidirectional operation, it is necessary to reduce the sidewall roughness and increase the photon density in the active layer. A low sidewall surface roughness was obtained by using an optimized etch process. To achieve a large internal power density, we introduced an additional heat sink which improved the thermal roll-over by a factor of two compared to previous designs. Using an improved wafer growth technique, the tunnel junction was placed on top of the microdisk to decrease absorption losses. A more detailed explanation of the device fabrication can be found in [10].

III. EXPERIMENTAL RESULTS

We measure the light-current (LI) characteristic simultaneously on both sides of the waveguide (see Fig. 2). We can see that the unidirectional regime starts at 1.7 mA. The lasing threshold is at 0.33 mA and at low currents we observe a bidirectional regime where the two lasing directions are equally present. To avoid self-switching due to noise, we work at a bias current of 3.5 mA for our experiments. After taking the losses from the grating coupler into account, we receive an output power of 20 μW in the silicon waveguide.

When the laser is in the unidirectional regime, the laser operates either in the clockwise or counterclockwise direction. We can switch between the two directions through injection-locking with optical pulses. Figure 3 shows the typical time dependence of the on- and off-switching of a laser mode measured at one side of the 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. The switch-off times were found to be as low as 60 ps. The pulse energies for switching are very low: all-optical flip-flop operation was observed using pulses of only 1.8 fJ (after normalizing with the losses from the grating coupler).

Besides flip-flop operation, we demonstrated also all-optical gates at 10 GHz using pump-probe experiments. The disks did not have to be biased for this purpose.

The microdisks offer also great potential to implement various other optical processing functions and can be especially interesting for advanced all-optical logic, shift registers and D-flip-flops by a combination of several disks.

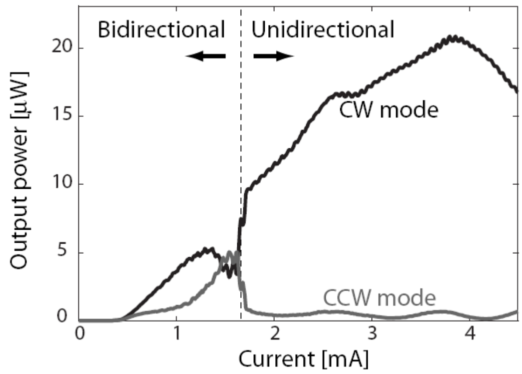

Fig. 2. Light-current (LI) characteristic (measured at the two ends of the waveguide) indicates that the unidirectional operation starts at 1.7 mA.

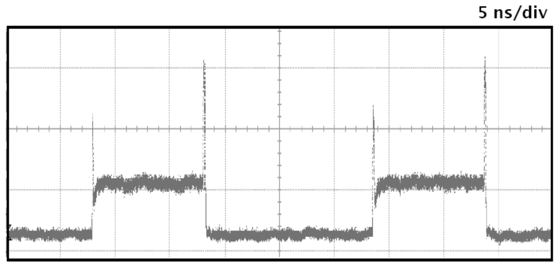

Fig. 3. Experimental demonstration of high-speed flip-flop operation in a single microdisk laser.

IV. CONCLUSION

All-optical flip-flop operation is demonstrated in ultra-small microdisk lasers with diameters of only 7.5 μm. The disks are bonded on a SOI chip and record-low pulse energies of 1.8 fJ can be used to switch between the clockwise and counterclockwise lasing mode. The device is promising for more advanced optical signal processing functions (eg. shift registers, all-optical logic). At the conference, results on new optimized devices will also be presented.

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