Heterogeneously Integrated Microdisk Lasers for Optical Interconnects and Optical Logic

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ABSTRACT

Optical interconnect and optical packet switching systems could take advantage of small footprint, low power lasers and optical logic elements. Microdisk lasers, with a diameter below 10µm and fabricated in InP membranes with a high index contrast, offer this possibility at the telecom wavelengths. The lasers are fabricated using heterogeneous integration of InP membranes on silicon-on-insulator (SOI) passive waveguide circuits, which allows to combine the active elements with compact, high-index contrast passive elements. The lasing mode in such microdisk lasers is a whispering gallery mode, which can be either in the clockwise (CW) or counter clockwise direction (CCW) or in both. The coupling to the SOI wire waveguides is through evanescent coupling. Predefined, unidirectional operation can be achieved by terminating the SOI wires at one end with Bragg gratings. For all-optical flip-flops, the laser operation must be switchable between CW and CCW, using short optical pulses. Unidirectional operation in either direction is only possible if the coupling between CW and CCW direction is very small, requiring small sidewall surface roughness, and if the gain suppression is sufficiently large, requiring large internal power levels. All-optical flip-flops based on microdisk lasers with diameter of 7.5µm have been demonstrated. They operate with a CW power consumption of a few mW and switch in 60ps with switching energies as low as 1.8fJ. Operation as all-optical gate has also been demonstrated. The surface roughness is limited through optimized etching of the disks and the large internal power is obtained through good heat sink.

Keywords: microdisk lasers, all-optical flip-flops, gates, all-optical signal processing

1. INTRODUCTION

With the ever increasing data rates in telecom and datacom networks, as well as in different short distance interconnections, an alternative has to be found to overcome the bottlenecks imposed by the speed limitations of current microelectronic processors. All-optical packet switching implementations are good candidates to cope with the massive bandwidth requirements resulting from the huge growth of upcoming telecommunications services. Even though the optical transport of data has a clear proven advantage over the electrical transport, many previous solutions for all-optical signal processing of digital signals, such as switching, processing or buffering of signals, have one or more significant drawback as compared to their electronic counterparts. Indeed, the major issue of many all-optical signal processing techniques lies in their high power consumption[1], but several proposed solutions are also complex and bulky and their integration, let alone their fabrication as a small footprint integrated circuit or PIC, remains challenging.

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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 of data packets and/or provide control signals to optical switches[2].
Several concepts of AOFF's have been demonstrated 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 smallest on-chip AOFF's reported at telecom wavelength of 1.55µm consists of two coupled ring lasers, each ring having a diameter of 16µm, and the flip-flop, completely fabricated in InP and with a total area of 40x18µm^2 [5]. However, the ring lasers can only operate in the pulsed regime and they each have a threshold current of 30mA, which means a power consumption of over 30mW. 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. By injecting an optical pulse, one can switch between two directional states and obtain flip-flop operation. Single InP ring lasers have also been demonstrated as AOFF, but with diameters in excess of 50µm, switching times over 100ps and total power consumptions of tens of milliwatts[6-7].
Another small AOFF was achieved based on polarization switching in a vertical cavity surface-emitting laser (VCSEL). Switching energies of 0.3fJ and switching times of 7ps have been demonstrated at 980nm using such an AOFF[8]. They increased to several femtojoules at a wavelength of 1.55µm[9]. In terms of power consumption, the VCSEL at this wavelength required a bias current slightly above 14mA. Finally, VCSELs are also less suited for on-chip integration with other devices.

2. METHODOLOGY

The silicon-on-insulator material platform with its high refractive index contrast makes it possible to fabricate very compact passive optical waveguide circuits. However, since silicon has an indirect bandgap, it is not suitable for the implementation of active devices. Recently, III-V/SOI heterogeneous integration has been shown to give good lasing performance in silicon[10]. This technology is CMOS-compatible, allows the combination of III-V materials and SOI circuits without degrading their quality, and can also provide dense, large-scale integration of devices. It is then possible to implement high speed, low-power and compact active devices such as microdisk laser diodes and resonators[11].

Since several years, the Photonic Research Group of imec-Ghent University has been developing the heterogeneous integration of InP-based membranes with the aim of integrating laser diodes or optical amplifiers onto SOI circuits. We have demonstrated the continuous-wave operation of compact, electrically pumped microdisk lasers with diameters as small as 5µm[12]. Over the last 15 years, microdisk lasers have attracted considerable attention for their potential as compact and low-threshold coherent light sources for densely integrated photonic circuits[13]. These microdisk structures support whispering-gallery modes (WGMs) that enable ultracompact and low-threshold laser operation. The resonant modes propagate at the edge of the disk without the need of a guiding structure.

The entire process cycle for the fabrication of microdisk lasers is schematically depicted in Fig.1. The SOI circuit, with a 220nm top silicon layer and a 2µm buried oxide, is fabricated with 193nm DUV lithography through ePIXfab silicon photonic platform. First, the SOI and the InP dies are cleaned. An unpatterned III-V die is implemented on the SOI platform using the adhesive die-to-wafer bonding with the DVS-BCB (divinylsiloxane-benzocyclobutene) polymer. The BCB is spin-coated onto the SOI die (with the final thickness of the BCB depending on the dilution of the BCB solution), and then the die is attached to the BCB, after which the polymer is cured. It results in excellent bonding of III-V dies on silicon, with BCB bonding layer thicknesses as low as 100nm. The optical coupling between the III-V layer and the underlying waveguide is possible as the BCB is transparent. The III-V membrane has a total thickness of 583nm and includes 3 compressively strained quantum wells that provide the TE mode gain and a tunnel junction for a low loss p-contact. After removing the InP substrate, a pattern of 7.5µm diameter microdisk is defined with contact lithography in order to align the disk with respect to the underlying straight waveguide (500x220nm^2). The optical confinement is provided by the InP-membrane structure and couples evanescently to the underlying straight waveguide. The III-V layers are etched by inductively coupled plasma-reactive ion etching (ICP-RIE) until a thin bottom contact is achieved (n-doped InP layer). To isolate one disk from another, the InP contact layer is then removed on unwanted areas. The bottom contact is deposited on a slab around the disk without inducing optical losses and consists of titanium/platinum/gold layers. The whole structure is then covered with BCB in order to isolate the optical waveguides from the absorptive metal contacts. Via's are opened in the BCB to reach the bottom contact and to open the top of the disks. The top contact is then deposited using evaporation on the center of the microdisk laser and consists of another titanium/platinum/gold metal layer. The gold layer reaches here 600nm and acts as a heat sink as it improves heat-dissipation under continuous-wave bias. The heating is mainly due to the low thermal conductivity of the thick oxide layer in the SOI stack and of the BCB.

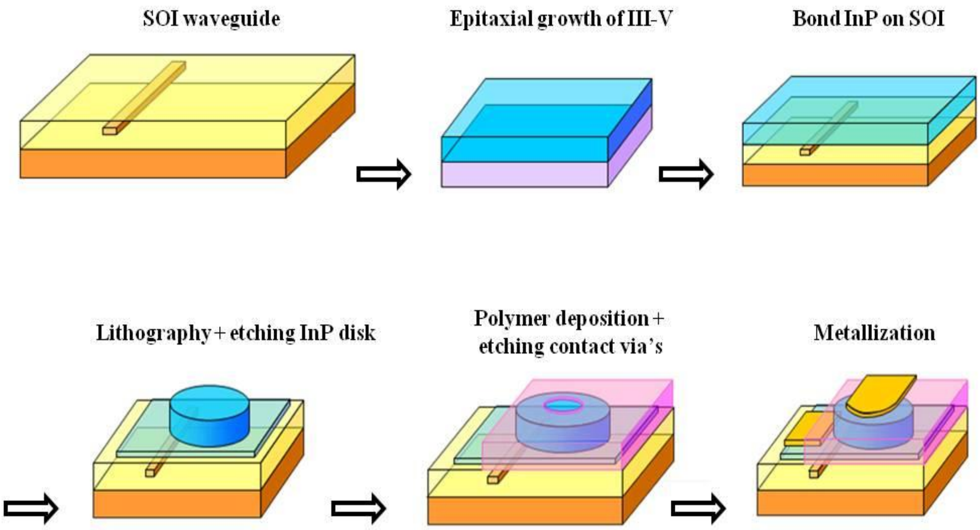

Figure 1. Schematic overview of the fabrication process of an SOI-integrated microdisk laser[11]

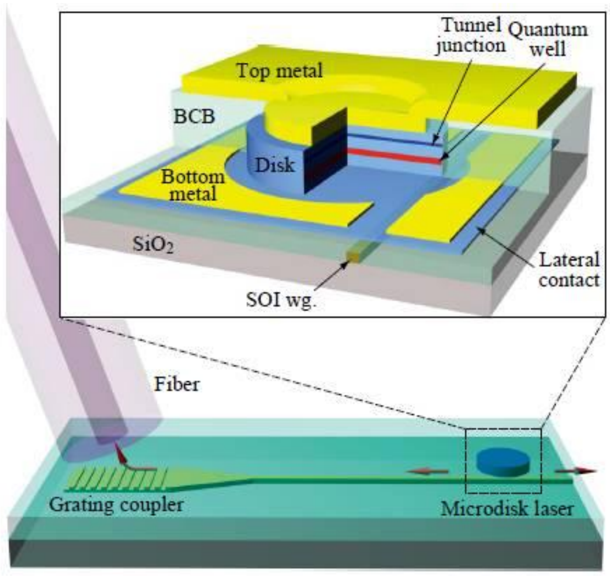

Figure 2. Schematic structure of the whole circuit (the grating coupler is depicted only on one end of the SOI waveguide) and the microdisk laser (inset)[14]

As the mode propagates at the edge, the presence of a metallic contact at the center of the disk will increase losses and then prevent higher modes to build up. Grating couplers on both sides of the waveguide allow an efficient output coupling to single-mode optical fibers. A schematic of the fabricated structure is depicted in Fig.2.

From theoretical considerations, the unidirectional regime only appears in structures with a low coupling between clockwise and counter clockwise modes with a high photon density in the WGMs of the disk laser[6]. Thanks to the high index contrast, the InP membrane ensures good mode confinement and hence large internal power. The thick top gold contact is used as a heat sink. The coupling between clockwise and counter clockwise modes is minimized by using optimized lithography and etching processes.

3. DATA

Microdisk lasers with reduced sidewall roughness exhibit bistable, unidirectional operation. The light-current (L-I) characteristic of the 7.5µm diameter microdisk, measured at the two ends of the SOI waveguide, is depicted in Fig.3. This measurement was undertaken under continuous wave operation at room temperature.

When the threshold current of 0.33mA is surpassed, a bidirectional regime is observed. The clockwise and the counter clockwise mode are equally present in this bidirectional regime. A different attenuation by the waveguides as well as small alignment mismatches are responsible for the difference in output power between the two sides. Between 1.4mA and 1.7mA, the reflection feedback from the grating coupler and/or the fiber facet causes a small periodic oscillating regime. The unidirectional, bistable operation starts at 1.7mA. After normalization with respect to the coupling loss of the gratings, the maximum measured optical output power in the waveguide is 20µW. Due to the improved thermal management, the thermal rollover only starts at 3.8mA. Fig. 4 shows the output power spectrum and illustrates the single mode behavior. In large ring lasers, the lasing direction switches while increasing the current in the unidirectional regime[7]. Theoretical calculations predict that the switching behavior occurs due to self-heating when the laser mode hops to a different azimuthal order that is several free spectral ranges away[16]. This means that such mode-hopping is unlikely to be present in such a small cavity because the free spectral range is larger than 30nm.

4. RESULTS

The low threshold currents and the high optical powers within the microdisk lasers make them suitable for all-optical signal processing. We have investigated the use of microdisk lasers for the realization of low-power, small footprint all-optical flip-flops. Key requirements for obtaining bistability are a weak coupling between clockwise and counter clockwise WGMs and a large non-linear gain. The large non-linear gain is present thanks to the high power density in our microdisk lasers. The weak coupling between clockwise and counter clowise WGMs however requires smooth disk sidewalls, as well as low reflection at the different interfaces.

The measurement setup for testing the dynamic response of the proposed AOFF is schematically depicted in Fig. 5. Light from a tunable laser source is sent through a modulator which is driven by a 10Gb/s pulse pattern generator. The width of the pulses is then 100ps (Fig. 6b). We use polarization controlling wheels after the laser source as the modulator only works in TE mode. The pulses are split by a 3dB coupler and variable delay line (ODL) is placed in one of the arms to adjust the relative between the set and the reset pulses. Variable optical attenuators allow adjusting the pulse height. Because the grating couplers are polarization dependent, we use gain polarization controlling wheel before the pulses are sent to the chip. With circulators on both sides, we can monitor the output power of the microdisk on a high-speed optical sampling scope. Because the grating couplers give a coupling efficiency of ~30% between the SOI waveguide and the access fibers, ~25dB amplification was needed from an erbium-doped fiber amplifier (EDFA) to increase the signal power. This was implemented in combination with an optical band-pass filter with $\Delta\lambda$=0.9nm to remove amplified spontaneous emission.

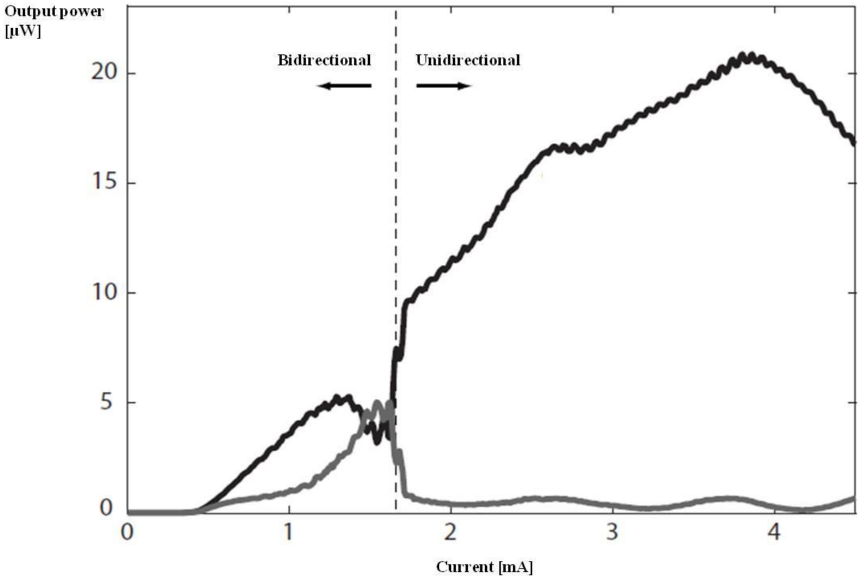

Figure 3. Measured L-I characteristic of the microdisk where unidirectional operation starts at 1.7mA[15]

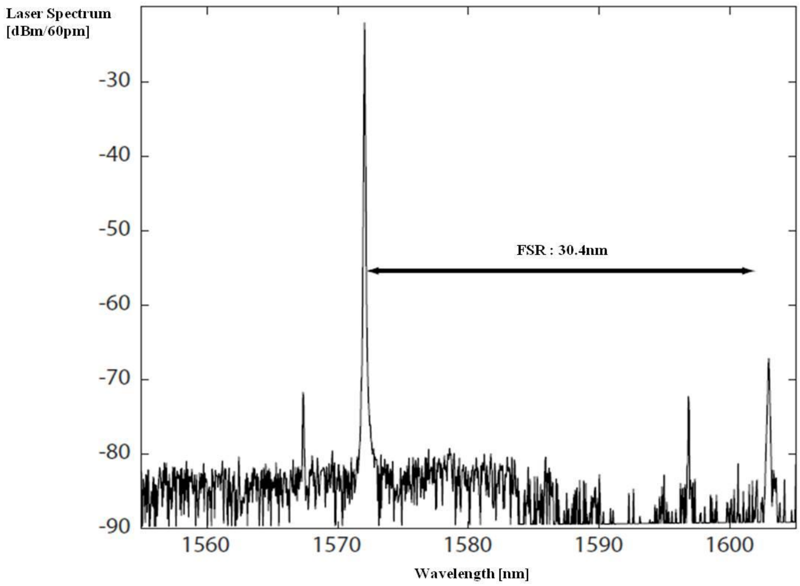

Figure 4. Spectrum of the clockwise mode of the microdisk at a bias of 3.8mA: unimodal operation with a free spectral range of 30.4nm[15]

The high-speed measurement result of the flip-flop operation is depicted in Fig. 6. The microdisk is biased at 3.5mA which is about twice the threshold current for unidirectional operation. At too low currents, self-switching due to noise can be observed. When we inject a pulse on the left side of the microdisk (Fig. 6b), the laser will start operating in counter clockwise dominant state. This state will remain, even after the pulse has passed through. Injection of a (reset) pulse at the other side will suppress the counter clockwise mode and induce the clockwise dominant state. The minimal pulse energies needed to switch the microdisk lasers are 1.8fJ (calculated inside the SOI waveguide by taking into account the efficiency of the grating coupler). Total power consumption is thus only a few mW, which for 10Gb/s signals corresponds to an average energy of 0.2fJ per bit, a figure which is competitive with that of electronic (CMOS) buffers or with recirculating delay lines. First experiment seem however to indicate that switching is only possible with microdisk lasers that have a very high side mode suppression. The injected pulses cover the transient of the microdisk output, making it difficult to determine the exact switching speeds of the flip-flop. The residual reset pulses mainly come from the interface reflection at the cleaved facet of the access fiber. They can to some extent be suppressed by using index-matching fluid between the access fibers and the SOI chip. The measured switch-off transient in this case is presented in Fig. 6c. A switching time of 60ps was obtained. From Fig. 6d, the switch-on time should be less than 100ps. However, the set pulses being at the same wavelength than the microdisk output, and propagating in the same direction, they cannot be removed in the current design. We can conclude that 10Gb/s operation can be supported in the proposed AOFF. To measure a fast transition, a smart design to efficiently separate the laser output from the injected pulses is being processed. One solution is to add another SOI waveguide coupled to the microdisk, so that the input and the output light signals can be physically isolated in different waveguides.

Gating operation can be achieved in microdisk resonators in pump-probe configuration with the probe beam tuned at one of the resonances and the pump at another. The gate output corresponding to the pulse train (Fig. 7a) is plotted in Fig. 7b. When the pump pulse has a high/low power level, the gate is in the closed/open state. The extinction ratio between the closed state and the open state is 4.5dB. To estimate the gating speed of the device under investigation, transient responses are measured and plotted in Fig. 8. The rise time (Fig. 8a) and fall time (Fig. 8b) are 8.5 and 41.5ps[17].

Using the microdisk based gates and set-rest AOFF, other sequential logic devices such as D flip-flops, shift registers, etc. can be readily conceived. Furthermore, combinatorial logic gates such as OR, NAND, NOR gates can be designed when combining microdisk lasers with Bragg reflectors in the SOI waveguides.

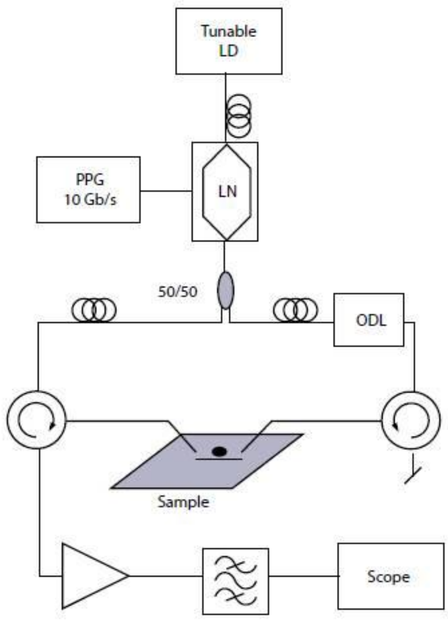

Figure 5. Schematic of the measurement setup

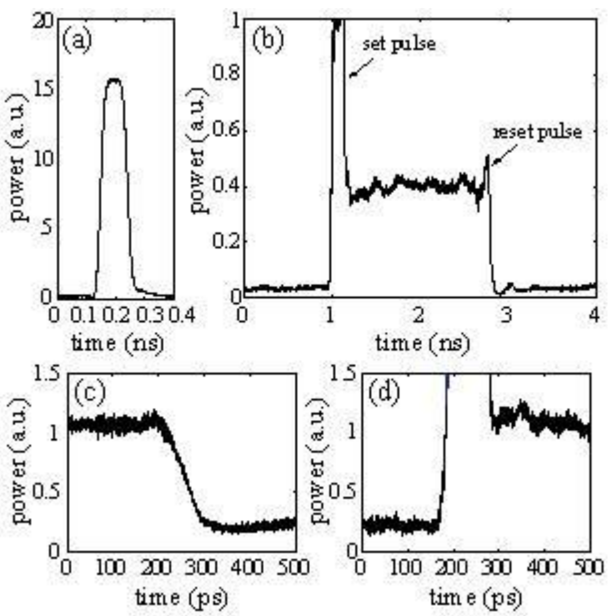

Figure 6. High-speed measurement setup of the switching characteristics[14]
a, Waveform of the injected optical pulse (central λ=1572,23nm)
b, Waveform of the measured optical signal at one side of the SOI waveguide
c, d, Details of the switch-off (c) and switch-on (d) transients, after applying the index-matching fluid

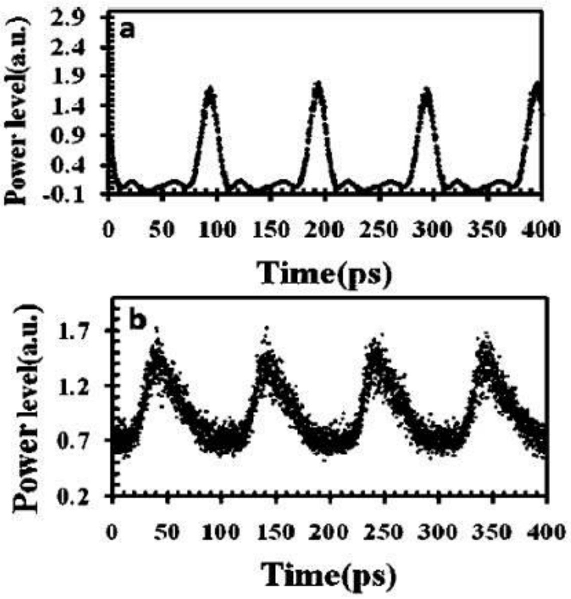

Figure 7. Pattern of the pulse train (a) and corresponding gate output (b)

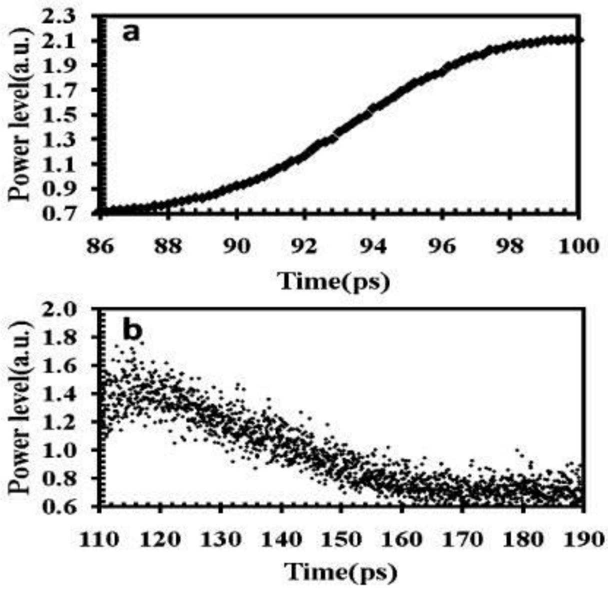

Figure 8. Transient response of the gate output : rise edge (a) and fall edge (b)

5. CONCLUSIONS

Heterogeneously integrated InP-membrane microdisk lasers can be used in a variety of photonic integrated circuits for applications in optical interconnect and all-optical signal processing. The high-index contrast in the InP membranes makes it possible to realize devices with small footprint, low power consumption and high speed. The combination of low-power active devices with high index contrast silicon-on-insulator passive waveguide structures opens perspectives for the fabrication of much more complex PICs with small footprint and low power consumption.

We have demonstrated compact, low power and high-speed optical logic devices such as set-reset flip-flops, gates and wavelength converters.

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 implemented by interconnecting different S-R flip-flops and gates. It is very important for this purpose that all microdisk lasers and gates have resonance wavelengths within small tolerances. Demonstration of other logic functions and new optimized designs are planned and will be reported on during the conference.

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