10GHz All-Optical Gate Based on a III-V/SOI Microdisk

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Abstract—We demonstrate an ultra-fast and low power all-optical gate in pump-probe configuration based on free carrier induced refractive index modulation in a 5 μ m radius InP/InGaAsP microdisk heterogeneously integrated onto an SOI waveguide circuit. High speed gating is obtained by extracting the carriers from the microdisk active layer by applying a reverse bias. Measured transient responses show that this gate is capable of working up to 20GHz.

Index Terms—Microdisk, Optical gate, SOI.

I. INTRODUCTION

WITH the ever increasing demand of high speed communication and computing, electronics based devices and components are reaching their speed limit. All-optical signal processing seems to be the only way forward to meet these challenges. Various types of devices and components are needed for communication and computing. Many of these components have been realized in the optical domain using different approaches and technologies, e.g. [1], [2]. Power consumption is becoming a serious issue and hence there is a need for low power all-optical components and devices which are ever faster and smaller. Silicon photonics has emerged as a promising field of research, as monolithic integration of different optical components on a silicon chip offers the advantage of utilizing mature CMOS fabrication technology. Using heterogeneous integration [3], different types of components [4]–[6] have been reported in the recent past. Disk and ring resonators are attracting a lot of attention

for the realization of all-optical functionalities owing to their compact size, high quality factor and low power consumption. Availability of compact electrical injection schemes makes disks better suited as compared to the ring resonators. In this paper we report the fabrication and experimental results of a relatively low power 10 GHz all-optical gate operating at telecommunication wavelengths, based on a III-V/SOI microdisk. In this gate, the transmission of a low power probe beam is controlled by a high power pulse train which essentially behaves as a pump. The gating approach used here has the advantage of integration with other active devices such as all-optical flip-flops [7], resulting in the realization of more complex photonic integrated circuits. In section II, we give an overview of the fabrication. The gating concept is illustrated in section III, while measurements are described in section IV. In section V results are presented and the conclusions are drawn.

II. DEVICE FABRICATION

Before defining III-V microdisks, an unpatterned InP/InGaAsP epitaxial layer structure is bonded on top of an SOI waveguide circuit, containing 600nm wide and 220nm high silicon strip waveguides, using adhesive die-to-wafer bonding with the divinylsiloxane-benzocyclobutene (DVS-BCB) polymer [3]. After epitaxial layer transfer, microdisks of 10 μ m diameter are defined by photolithography and transferred to the InP based active material using RIE-ICP etching. The total thickness of the epitaxial layers is around 580nm, including three strained quantum wells, while the etch depth is around 500nm. After carving out the microdisks, metal electrodes are defined for contacting. The step by step fabrication process is similar to that reported in [4]. A schematic drawing of the device is shown in Fig. 1. Focused-ion-beam (FIB) scanning electron microscope (SEM) images of the fabricated device are shown in Fig. 2. It is clear from this figure that the offsets of the two waveguides are different with respect to the microdisk edge. This is due to a small registration error in the definition of the III-V microdisk. This offset is an important parameter which determines the coupling of light from the waveguide to the microdisk and vice-versa. Ultimately this determines the performance of the device. This will be discussed further in section IV.

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Fig. 1. Schematic view of the structure of the device.

Fig. 2. FIB-SEM micrograph showing (a) cross section of the fabricated device, zoom-in-view of cross-section part marked by rectangle and circle showing position of (b) drop port and (c) through port waveguide respectively.

III. CONCEPT OF THE ALL-OPTICAL GATE

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 intensity of the probe beam is kept low to avoid carrier generation in the III-V active region. The transmission characteristic of the microdisk is altered by having the pump intensity many times higher than that of the probe beam. Fig. 3 illustrates the gating concept in a pictorial way. The dotted blue curve shows the transmission dip of the microdisk around the probe wavelength. When pump light is injected into the microdisk, free carriers are generated which causes a blue shift in the transmission dip as shown by the solid red curve. Using a pulse train as a pump results in high or low output of the probe beam due to a periodic shifting of the resonance around the probe wavelength. If the probe

wavelength is slightly blue tuned off the transmission dip then in the absence of the pump pulse the output is high and the gate is said to be in the open state. In the presence of the pump pulse, due to blue shift of the resonance, the output will be low and the gate is said to be in the closed state. In this way, the power level varies between points A and B in the time domain as represented by the dotted black line. During this whole process, the variation in the power level of the output of the gate follows the pattern of the pump pulses.

Fig. 3. Illustration of concept for all-optical gate

Fig. 4. Transmission spectrum (green curve) of the microdisk, and a fit (black curve) for the light coupling efficiency of the grating couplers

IV. MEASUREMENTS

To find the microdisk resonances, the transmission spectra at the through and drop port were measured with TE polarized light from a CW tunable laser. Good transmission characteristic is observed only at the through port, which is shown in Fig. 4 with the green curve along with a fit (black curve) for the light coupling efficiency of the grating couplers. We attribute this to the better alignment of the through port SOI waveguide with respect to the disk edge, see Fig. 2(c). Since the whispering gallery modes propagate along the edge of the microdisk, the light which couples into the microdisk from the input port does not couple well to the drop port due to the position of the drop port SOI waveguide away from the microdisk edge and more to the centre of the disk as is clear from Fig. 2(b). Two resonances, one at 1563.9 nm and another at 1586.5 nm, are observed. We believe that ripples in the spectral response of the microdisk are due to a Fabry-Perot resonance formed between the two grating couplers used for coupling light from the tunable laser to the waveguide through single mode fiber, and reflections from fiber facets, connectors etc. We see large change in the resonance behavior (extinction ratio, Q-factor) at two wavelengths due to the fact that the

shorter wavelength(1563.9nm) has higher absorption as it lies far away from the band gap wavelength, which is ~ 1600 nm, while longer wavelength(1586.5nm) lies closer to the band gap wavelength of the microdisk. The wavelength of the pump light injected at the through port is set at the lower resonance(1563.9nm), while the wavelength of the probe light injected at the input port is set slightly below the longer resonance(1586.5nm). The probe light is TE polarized CW light from a tunable laser, while the pump light is a pulse train of 10GHz repetition rate with each pulse of 7.5ps duration, extinction ratio of more than 20dB and gaussian in shape as shown in Fig. 5(a). Probe and average pump power in the SOI waveguide is $170\mu\text{W}$ and 4mW respectively. While carrying out measurements, the microdisk was kept under a reverse bias of -1V to reduce the fall time by sweeping away the generated carriers from the active region[8].

V. RESULTS AND DISCUSSION

The gate output corresponding to the pulse train (fig. 5(a)) is plotted in Fig. 5(b). When the pump pulse has a high/low power level, the gate is in the closed/open state as discussed in section III. 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. 6. The rise time and fall time is 8.5ps and 41.5ps respectively which suggest that this device can operate up to 20GHz.

Fig. 5: Pattern of the pulse train (a) and corresponding gate output (b).

The low extinction ratio between the closed and the open state can be attributed to the spontaneous emission noise generated in the EDFA used to amplify the gate output before feeding it to the oscilloscope. We believe that the high speed of the gate is due to the surface-state recombination at the side walls of the microdisk, along with a contribution from the reverse bias. It seems that by increasing the pump power, the rise time can be reduced but it also requires increasing the reverse bias (e.g.

to -2 or -3V) to compensate the increased fall time. Under the same pump power and increasing the reverse bias to -2V , no improvement in the fall time was seen. The bandwidth of the pump pulse used is 1nm while the bandwidth of the transmission resonance at 1563.9nm is 0.4nm . This implies that the pump power can be further reduced by matching the bandwidth of the pump signal to that of the microdisk resonance.

In summary, we have demonstrated a fast all-optical gate based on a III-V microdisk heterogeneously integrated on the SOI waveguide platform, with a small foot-print and a low power consumption.

Fig. 6: Transient response of the gate output: rise (a) and fall edge (b).

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