High-speed silicon-based microring modulators and electro-optical switches integrated with grating couplers

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Abstract. We demonstrate high-speed silicon-based microring modulators and electro-optical switches which are integrated with grating couplers. Wafer-level measurements are set up for the devices characterizations without wafer cleaving and facet polishing. 10 Gbit/s NRZ modulation is realized under pre-emphasis driving signals. Switch on / off time of 300 / 380ps are demonstrated in the asymmetrical 1×2 microring switch with an add-drop crosstalk of -23dB.

1. Introduction

With the help of advanced silicon processing techniques, silicon photonics is developing rapidly aiming at high operation speed, high integration density and CMOS-compatibility. Recently, great success has been made on the basic components of silicon photonics, especially for the silicon-based modulators and switches [1-5]. Compact, high speed silicon modulators and switches will play indispensable roles in the on-chip optical interconnects and the next generation communication networks.

However, electro-optical switching and modulation in silicon are not as easy as what in III-V materials. Pure silicon is a kind of centro-symmetric crystal which exhibits no linear (Pockels) effect and extremely weak Kerr and Franz-Keldysh effect. The mostly used fast modulation and switching method in silicon is the plasma dispersion effect, in which the concentration of free carriers in silicon changes the refractive index and the optical absorption [6]. So the modulation and switching speed is normally limited by the carrier injection, accumulation and depletion. Although the carrier mobility of single crystal silicon is much lower than that in III-V and Ge, the electro-optical response can still be greatly enhanced by adopting resonating optical structures which are very sensitive to the index change. Due to the high-index-contrast (HIC) offered by silicon-on-insulator (SOI) wafers, SOI microring resonators are able to provide very high quality factors (Q factors) while the footprint are small enough for dense photonic integrations. High bandwidth SOI microring switches have already realized nanosecond-scale switch time [7-9]. Ultra-high modulation bandwidth density of 100 Tbit/s· mm² has also been demonstrated based on the microring modulators [10]. Active microring devices are becoming the ideal building blocks of the optical networks-on-chip.
In this talk, we review our recent work on the silicon-based 10 Gbit/s modulator and the sub-ns electro-optical switch based on the SOI microring resonators which are embedded with forward p-i-n diodes to fast manipulate the carrier concentrations [11, 12]. For the microring switch, an asymmetrical add-drop configuration is employed to reduce the add-drop in-band crosstalk. While for the modulator, we adopt the notch type microring structure to ensure the high Q factor and thus high modulation speed. Grating couplers have also been fabricated at all the input and output ports for wafer-scale online measurements without wafer cleaving and facet polishing. During the measurements, pre-emphasis signals were used to speedup the active microring devices, under which < 400 ps electro-optical switching and 10 Gbit/s NRZ modulation are respectively demonstrated.

2. Device fabrication and description
All the waveguide devices were fabricated on a SOI wafer with a 340 nm top silicon layer and a 2 μm buried oxide layer by electron-beam lithography (EBL) and inductively-coupled-plasma (ICP) processes. The waveguides are single mode rib waveguides designed for TE-mode transmission. The SEM images of the fabricated passive microrings are shown in figure 1(a) and (b). Both of the modulator and the switch consist of a 20 μm-radii microring with 600 nm wide bent waveguide. For the modulator, a notch-type microring was employed for the high Q factor. While for the switch, we chose the add-drop microring as the optical structure to increase the 3-dB bandwidth for high bit rate signals transmission. In order to obtain high extinction ratios, the coupling strength between the microring and the bus waveguide should be carefully optimized to achieve the critical coupling state.

Figure 1(c) shows the schematic cross-section of the ring waveguide surrounded by a lateral p-i-n diode. The manipulations of the waveguide's refractive index are implemented by the electrical signals forward applied to the p-i-n junction. As the operation speed of a p-i-n diode significantly depends on the carrier transport distance across the waveguide [13, 14], reducing the width of the intrinsic region becomes the essential way to decrease the diode's response time. We located both the p+ and n+ regions 300 nm away from the ring waveguide edges by EBL and ion-implantation processes. A
location mismatch error of only ~ 40 nm was achieved by EBL. The p+ and n+ doping concentrations are both ~ $10^{19}$ cm$^{-3}$ for an acceptable dopant absorption loss. In order to ensure good metal contacts, highly doping regions p++ and n++ with > $10^{20}$ cm$^{-3}$ implantation concentrations are both defined 2 μm away from the waveguide ridge by optical lithography.

3. Measurement and results

3.1. Measurement setup
With the help of the grating couplers integrated at the devices’ input and output ports, we have realized wafer-scale measurements without wafer cleaving and facet polishing. Before the fabrications, we used the software CAMFR to design the grating period $\Lambda$ [15]. When the grating period is 620 nm and the duty cycle is 50%, simulation predicts an over 50% coupling efficiency and an 80nm 3-dB bandwidth for a single grating coupler. Figure 2(a) is the top-view SEM image of the grating coupler fabricated together with the waveguides. The coupler surface is about $14 \times 19$ μm$^2$ which is slightly larger than a single-mode fiber. The moderate surface size ensures a lot of tolerance to the fiber-coupler alignment. Figure 2(b) shows the detailed structure of the fabricated grating coupler. The measured grating period is 620 nm and the duty cycle agrees with the designed value very well.

![Figure 2. (a) Over-view and (b) detail SEM image of the grating coupler. The grating coupler is 14 μm in width and 19 μm in length. The grating period is 620 nm and duty cycle is ~ 50%.](image)

We set up the fiber-to-fiber transmission measurements to characterize the insertion loss of the microring devices integrated with grating couplers. During the experiment, light was coupled into and out of the chip by two single-mode fibers which were positioned at an angle of about 10° to the sample normal. The corresponding fiber-to-fiber transmission for TE-mode light measured as shown in figure 3. The 3-dB bandwidth is measured to be 60 nm (1527–1587 nm) fully covering the C-band. The minimal total insertion loss is measured to be 12.2 dB around 1550 nm which includes the waveguide propagation loss, alignment mismatch loss and polarization induced loss. As the maximal output of the laser source was 10 dBm and the output power from modulator was normally over -5 dBm, so the insertion loss was acceptable for the device characterizations even without erbium-doped fiber amplifier (EDFA).
Figure 3. Measured (blue) and simulated (red) coupler-to-coupler transmission spectra. The spectral drops in the measured curve are the microring resonances.

3.2 Results of the microring switch

For the switch, an asymmetric dual-coupled microring was employed due to the characteristics of large through-port extinction and low crosstalk [16]. Figure 4(a) shows the top-view microscope image of the fabricated switch with electrodes. The gray lines highlight the 20 μm-radii microring and the straight bus waveguides. Under forward bias, carriers are injected into the intrinsic waveguide by the embedded p-i-n diode. The variation of the carrier density brings to the refractive index change due to the plasma dispersion effect in silicon. In this way, the driving electrical signal shifts the microring resonance and thus controls the on/off state of the optical signals outputting from the through-port and drop-port. Figure 4 shows the optical transmission spectra before and after a DC bias with the inset showing the current-voltage characteristics of the p-i-n diode. The forward differential resistance of the p-i-n diode is ~ 75 Ω, indicating a very good metal contact. A 1.4 V forward DC bias blue-shifted the resonant wavelength for ~ 0.23 nm which was sufficient for the switching due to the high Q factor of 11,000. Extinction ratios at the through-port and the drop-port were measured to be 25 dB and 13 dB, respectively, while the in-band add-drop crosstalk was less than -23 dB.

Figure 4. (a) Top-view microscope image of the add-drop microring switch. (b) Transmission spectra of the microring resonator at the bias voltages of 0 V and 1.4 V. Inset: Current-voltage curve of the microring switch.

Pre-emphasis signals have been demonstrated to greatly reduce the p-i-n diode's state transition time [3, 17]. In our case, the electrical pre-emphasis signal is adopted to accelerate the switch which is
generated by combining two square wave signals. Figure 5(a) shows the waveform of the pre-emphasis driving signal with 500 ps wide emphasis pulses. We choose the switch on/off voltages to be 1.4/0.7 V, respectively. The forward and reverse pre-emphasized voltages are respectively 2.5 V and 0.5 V. Figure 5(b) and (c) are the corresponding normalized optical power measured from the through-port and drop-port. As the switch-off voltage is set close to the p-i-n junction’s turn-on voltage (~ 0.7 V), the carrier density (as well as refractive index) would immediately change when the forward pre-emphasis pulse is applied and leads to a short switch-on time. When carrier density starts to stabilize, the driving voltage would then decrease to 1.4 V to maintain switch-on state with the least carrier densities. When the reverse emphasis pulse is applied to the switch, the carriers in the waveguide would be quickly swept by the reverse electric filed. According to the output optical waveforms, a 380 ps switch-on and 300 ps switch-off time are finally achieved by tailoring the driving signal’s waveform.

Figure 5. Dynamic responses of the microring switch driven by pre-emphasized square wave signals. (a) Measured waveform of the pre-emphasis square wave signal. (b) Measured optical output at the through-port. (c) Measured optical output at the drop-port.

3.3 Results of the microring modulator
For a high modulation speed, the Q factor has to be moderately increased. We adopt a notch type microring structure as shown in figure 6(a). Figure 6(b) shows the microring’s transmission spectra curves under different bias voltages. When the modulator is zero-biased, the Q factor is measured to be ~ 23,000 ensuring fast electro-optical responses. By optimizing the bus-microring coupling to the critical coupling state, a 30 dB extinction ratio of is achieved under 1.2 V forward biased voltage.
In order to realize 10 Gbit/s modulation, we amplified the emphasis signals by a high bandwidth microwave amplifier. Figure 7(a) shows the 10 Gbit/s driving signals composed of an NRZ signal with $V_{pp} \sim 2.2$ V and pre-emphasis pulses with ~ 4 V peak amplitude occurring at each transition edges. Figure 7(b) illustrates the corresponding modulated output when the driving signals applied to the modulator. Actually, the electrical driving power would be greatly decreased if the modulation efficiency is improved which could be realized with the standard CMOS process.

Figure 7. (a) Waveform of 24-bit electrical pre-emphasis signal at 10 Gbit/s. (b) Corresponding optical signal output from the modulator.

4. Conclusion
In conclusion, we have demonstrated a SOI microring switch and a microring modulator which are integrated with grating couplers. The grating couplers, which were exposed and etched together with the active microring devices, have enabled the wafer-level online measurements without wafer cleaving and facet polishing. In order to realize high speed operation of the forward p-i-n diode type
devices, pre-emphasis driving signals were generated by combining two channels of NRZ signals. By optimizing the driving signals, switch on and off time of 300 ps and 380 ps are realized. Our measurements on the microring modulator demonstrated 10 Gbit/s NRZ modulation with the amplified pre-emphasis driving signals. This cost-efficient integration of active microring and grating couplers would have enormous potential in future photonic networks-on-chip.

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