12.5 Gbps optical modulation of silicon racetrack resonator based on carrier-depletion in asymmetric p-n diode

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Abstract: We present a high speed optical modulation using carrier depletion effect in an asymmetric silicon p-n diode resonator. To optimize coupling efficiency and reduce bending loss, two-step-etched waveguide is used in the racetrack resonator with a directional coupler. The quality factor of the resonator with a circumference of 260 um is 9,482, and the DC on/off ratio is 8 dB at -12V. The device shows the 3dB bandwidth of ~8 GHz and the data transmission up to 12.5Gbit/s.

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OCIS codes: (250.7360) Waveguide modulators; (130.3120) Integrated optics devices; (230.2090) Electro-optical devices; (250.5300) Photonic integrated circuits.

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Advancement of silicon photonic devices which can be monolithically integrated into a platform compatible with CMOS circuits, can provide high-performance, cost-effective optical communication and computation systems [1,2]. Recently, there has been noticeable progress in silicon optical modulators which are the key components in the electronic photonic integrated circuits [3-10].

The resonator modulator is one of the typical silicon modulators. The p-i-n diode or p-n diode structure is integrated into the resonator to change the carrier density. The refractive index in a silicon resonator can be modulated by either carrier injection in a p-i-n diode or

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carrier-depletion effect in a p-n diode [11]. The p-i-n diode based resonator can have the high modulation efficiency and small device area, whereas a special driving scheme is required for faster operation due to the inherently slow recombination of carriers in a p-i-n diode modulator. Recently, 12.5 Gbit/s operation of a p-i-n diode ring modulator with the pre-emphasized driving signal has been reported [3]. The p-n diode based resonator, on the other hand, can have a faster modulation operation by the fast carrier depletion effect. It can also achieve an effective modulation depth with a properly designed active region of the p-n junction.

In this paper, we have investigated the asymmetric p-n diode-based racetrack resonator modulator. The device was fabricated with a standard CMOS-compatible process. The fabricated device showed the relatively high Q-factor and the fast reverse bias operation. The simulation based on the realistic doping profile of the device has been carried out to compare with the experimental data.

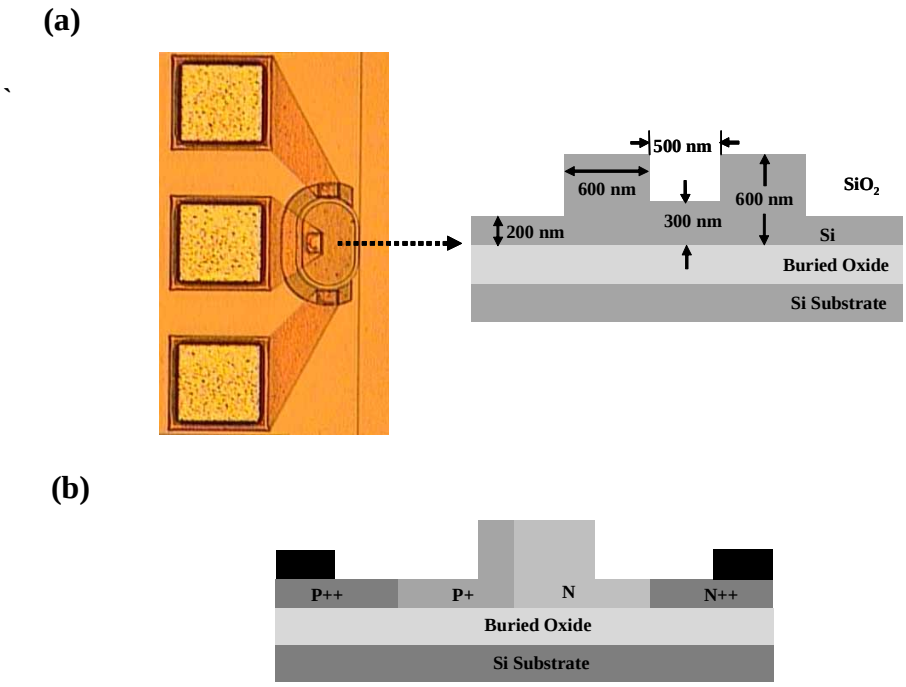

Fig. 1. (a) The top-view of microscopic picture of the fabricated silicon p-n diode racetrack resonator and the schematic diagram of the cross-sectional view of the directional coupler region. (b) The cross section of the racetrack waveguide.

The modulator consists of a racetrack resonator embedded in a p-n diode structure on a Silicon-On-Insulator (SOI) wafer with a 0.6 μm-thick layer of silicon above a 1 μm-thick buried oxide (BOX), as shown in Fig. 1. The ridge waveguide of the modulator is 600 nm wide and 600 nm thick. The slab height is 200 nm. Figure 1(a) shows the top-view microscopic picture of the fabricated modulator and the cross section of the directional coupler region. The 35 μm-long directional coupler of the racetrack is coupled to the straight waveguide with 500 nm gap, and the bending radius of the racetrack is 30 μm. The free carrier absorption loss is large in a p-n diode waveguide. The coupling between the straight waveguide and the racetrack should increase to obtain effective modulation depth in a relatively lossy p-n diode racetrack [12]. Two-step etching technique is used to optimize the

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coupling efficiency in the directional coupler and reduce the loss in the bending region. The directional coupler region was shallow-etched, and the rest was further deep-etched. The slab of the coupling region is 300 nm thick and that of the rest waveguide region is 200 nm thick. The simulation shows that this two-step etched resonator can enhance the coupling efficiency up to ~3 times and reduce the length of a directional coupler down to ~5 times compared to that of the single deep-etched case. Therefore, it can effectively reduce the total size of a device. In designing a p-n junction resonator, the electrical speed of the junction, the inner circulation factor (loss related term) [12], and the index change efficiency should be considered simultaneously. These factors are related with each other based on the device configuration. The hole depletion can give larger refractive index change, whereas the electron depletion can give faster electrical response. Following the Yariv's notation [12], larger total loss factor (inner circulation factor) α (closer to 1) in a resonant condition can result in larger Quality (Q) factor, and larger on/off ratio in the modulation of a resonator even for small index change at a proper coupling condition. The present asymmetric configuration of doping concentrations was designed to achieve a larger bandwidth (faster operation) with a relatively low absorption loss and less sacrificed refractive-index change for obtaining effective on-off ratio in a p-n diode resonator. Figure 1(b) shows the schematic cross-section of the asymmetric p-n junction racetrack waveguide. The target doping levels were 2 x 10^{18} cm^{-3} for p region and 3 x 10^{17} cm^{-3} for n region of the racetrack waveguide.

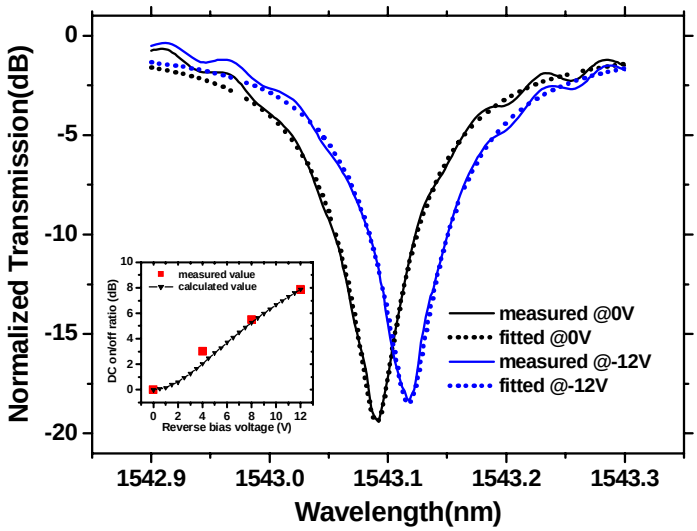

Fig. 2. Normalized transmission spectra of the modulator measured at 0 V and -12 V (solid curves). The calculated transmission spectra at 0 V and -12 V are depicted with the dotted curves. Inset shows the measured and calculated DC on/off ratios with varying bias.

Figure 2 shows the measured normalized optical transmission spectra of the resonator modulator. The black solid curve is the transmission spectrum of the unbiased resonator. The blue solid curve is transmission spectrum of the modulator biased at -12 V. The Q factor of the resonator is ~9,482. The shift of the resonance peak per unit voltage is 2.3 pm/V corresponding to the refractive index change of ~5.41x10^{-6}/V. The black dotted curve and the blue dotted curve are the calculated transmission spectra at 0V and -12 V, respectively. The measured DC on/off ratio is 8 dB at -12V. Following the Yariv's notation [12], the coupling factor κ is estimated as 0.519 from the fitted curve, and the total loss factor of the resonator, α is estimated as 0.883. This experimentally estimated value of α is lower than the expected value due to other losses such as, scattering loss due to side wall roughness and non-uniform

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doping profile, bending loss, etc. With above estimated parameters, the calculated on/off ratio was 2.04 dB at -4 V and ~ 6 dB at -8 V, which agrees relatively well with the measured values of ~ 3dB at -4V and ~6 dB at -8V. Inset shows the calculated (- - - curve) and experimental on/off ratios (scattered symbol ▪) with varying voltage. The experimental results indicate that the doping profile configuration can be further optimized to increase the index change and the inner circulation factor α (reduced loss) to improve the Q value in order to increase an on/off ratio without sacrificing the bandwidth of a device. The controlled shallow etching in the directional coupler region to meet the optimum coupling for the effective resonant condition of a resonator can also enhance the device performance.

The electrical speed of the modulator using a reverse biased p-n junction is limited by capacitance. The measured capacitance of the diode is < 0.7 pF. The doping profile of the asymmetric p-n diode racetrack waveguide was calculated with SILVACO simulator considering the actual implantation conditions of dopants. Based on the calculated doping profile, the predicted 3 dB electrical bandwidth of the asymmetric p-n junction device was ~14 GHz.

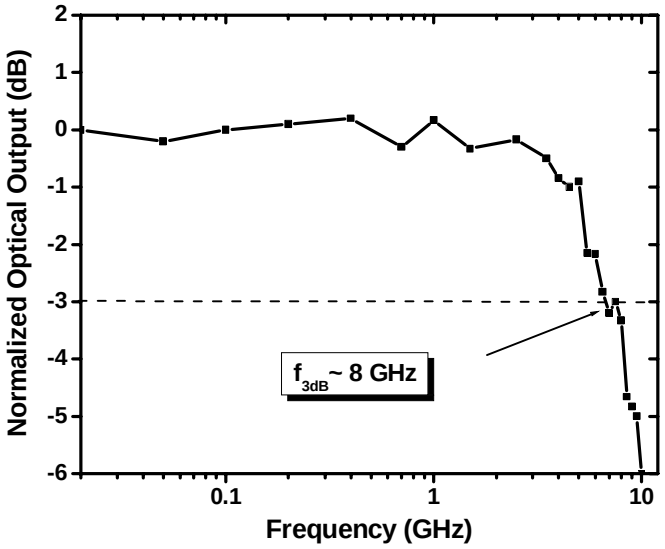

Fig. 3. The measured optical frequency response of the silicon p-n diode based racetrack modulator with a 30um-ring radius and 35um-directional coupler.

The frequency response measurement was carried out with Agilent 81940A tunable laser, HP8373A signal generator and HP8565E spectrum analyzer. An input optical beam from the tunable laser is coupled into the modulator chip via a lensed fiber. The output signal from the modulator chip is collected by a lensed fiber, amplified by EDFA, and detected with a Newport 20 GHz photodetector and the RF spectrum analyzer. The frequency response of a device is obtained by de-embedding the connecting cable response from the total response. Any losses from the impedance mismatch are not measured or compensated by this method. Fig. 3 shows the measured frequency response of the silicon optical modulator at -2 V bias. The wavelength of resonance is 1543.09 nm. As shown in the figure, the 3 dB bandwidth of the device is ~ 8 GHz.

Figure 4 shows the on-wafer measurement of eye diagram. The resonator modulator was biased at -2 V. The NRZ PRBS 2^7-1 signal (V_{pp} ~ 0.5V) from the Anritsu MP1775 Pulse pattern generator is amplified to V_{pp}~ 4 V which is the maximum voltage attainable by our 25 GHz RF amplifier, and applied to the modulator chip. The input optical beam from the tunable

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laser (λ ~ 1543.09 nm) is passed through a polarization controller and coupled to the optical modulator waveguide in a similar way as above. The output optical signal from the modulator is amplified by EDFA, and the eye-diagram is measured using the Agilent 86100C Digital communication Analyzer. The total loss including the coupling loss between two facets and lensed fibers was estimated greater than 26 dB. The measured eye diagram exhibits an extinction ratio of (a) 1.45 dB at 5 Gbps and (b) 1.16 dB at 12.5 Gbps data transmission for the driving signal with V_{pp} = 4 V. The degradation of the extinction ratio resulted from the ASE noise of EDFA. As shown in Inset of Fig. 2, the larger driving voltage can result in higher extinction ratio. The simulation and experimental results indicate that the modulation efficiency can be further improved with the optimized design of the doping profile and junction of the p-n diode resonator modulator.

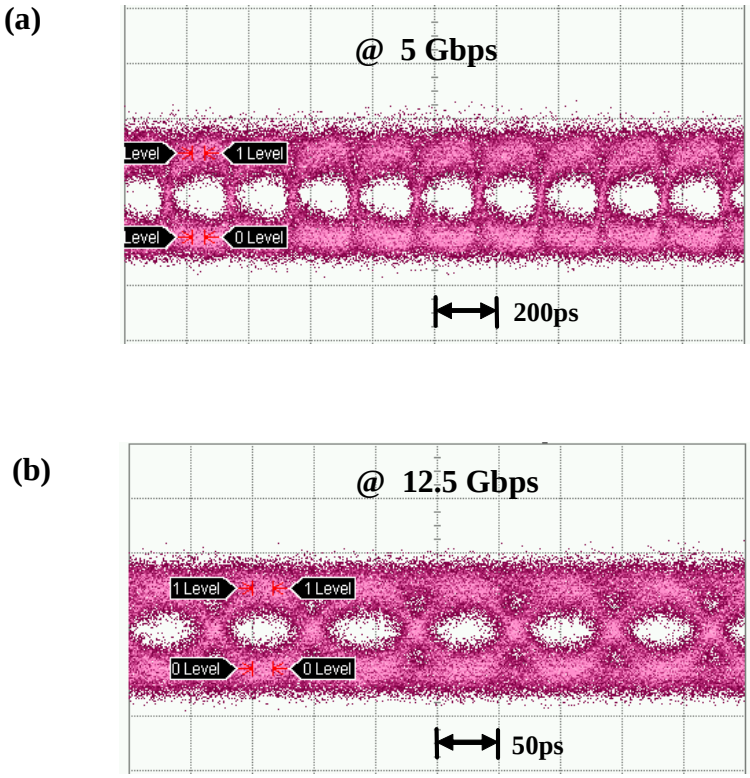

Fig. 4. On-wafer measurement of eye diagrams with NRZ signal (PRBS 2^7-1, V_{pp} = 4 V) (a) at 5 Gbps (b) at 12.5 Gbps

In conclusion, we present a high speed racetrack resonator modulator. The modulation was achieved by the carrier depletion effect in the asymmetric p-n diode structure. The two-step etched resonator with a directional coupler was used to optimize the coupling efficiency and reduce the bending loss. The quality factor Q of 9,482 was measured. The modulator exhibited the DC on/off ratio of 8 dB at -12V, the 3dB bandwidth of 8 GHz, and the data transmission up to 12.5 Gbit/s, which is the fastest operation based on p-n diode resonator modulator ever reported.

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