12.5 Gbit/s carrier-depletion based silicon Mach-Zehnder modulator with a 2 V driven voltage

H. Yu,[1] W. Bogaerts,[1] K. Komorowska, [1] J. V. Campenhout,[2] P. Verheyen,[2] P. P. Absil,[2] and R. Baets[1]

[1] Dept. of Information Technology, Ghent University-imec, Center for Nano- and Biophotonics (NB Photonics), St.-Pietersnieuwstraat 41, 9000 Gent, Belgium
[2] imec, Kapeldreef 75, 3001 Leuven, Belgium

We demonstrate a carrier-depletion based silicon optical modulator with a figure of merit of 1.3 V·cm. The device is based on a Mach-Zehnder interferometer whose two arms incorporate lateral PN junctions and lumped electrodes. With a 3mm phase shifter, the modulator can be driven by a signal of 2 V peak-to-peak voltage. The modulation depths at 5 Gbit/s, 10 Gbit/s and 12.5 bit/s are 5.92 dB, 4.51 dB and 3.73 dB, respectively. The total insertion loss of the device is 8 dB.

Introduction

A power efficient and high-speed silicon modulator is a key building block in optical interconnects which can overcome the bottleneck of current electrical interconnect systems. Various silicon optical modulations have been demonstrated during the last decade based on different effects [1]. Among these candidates the carrier-depletion based modulator is the most common scheme due to its CMOS compatibility, fabrication simplicity and high operation speed. This structure incorporates a PN junction inside a silicon waveguide and manipulates the refractive index of silicon by reverse biasing the PN junction. However, as a result of the small overlap between the carrier depletion region and the optical mode, the carrier-depletion based modulator exhibits poor modulation efficiency provided that a Mach-Zehnder (MZ) interferometer is used to convert the refractive index modulation to the optical intensity modulation. Therefore a large driving voltage is necessary which cannot be generated directly by a CMOS driver circuit. An alternative is to enhance the interaction between the carrier depletion region and the optical mode by an optical resonator. In order to make the resonator operate at the right wavelength, a thermal tuner together with a control circuit is required which increase complexity of the system. In this paper, we cut the driving voltage of carrier-depletion based silicon MZ modulator by adjusting the length of the phase shifter. With a phase shifter of 3 mm, the modulator can be driven by a voltage swing of 2 V_{pp} up to 12.5 Gbit/s.

Device design and fabrication

The device is an asymmetrical MZ interferometer with a path difference of 40 µm. Two compact 1×2 multi-mode interferometers (MMI) are used to split and combine the beam. The phase shifter on each arm of the MZ interferometer is formed by embedding a lateral PN junction in a rib waveguide. Schematic 3D and top views of the phase shifter are presented in Fig. 1. The width and height of the rib waveguide are 500 nm and 220 nm respectively. The slab height is 150 nm in order to be compatible with the processing of the fiber grating coupler. The thickness of the buried oxide layer is 2 µm. The doping pattern in Fig. 1 is optimized so as to reduce the optical loss without impairing the modulation efficiency and the operation speed [2]. The nominal doping concentration is 1e18/cm^3 for both P and N type silicon, while the P++ and N++ regions which reside 1 μm away from the rib edge are heavily doped to 1e20/cm^3 in order to form the ohmic contact. The width *w* of the two strips which form the PN junction in the centre of the waveguide is 300 nm. The pitch *L* of periodically loaded bridges between the PN junction and the heavily doped contacting area is 1000 nm. Lumped electrodes with GSG pads are used to drive the two phase shifters.

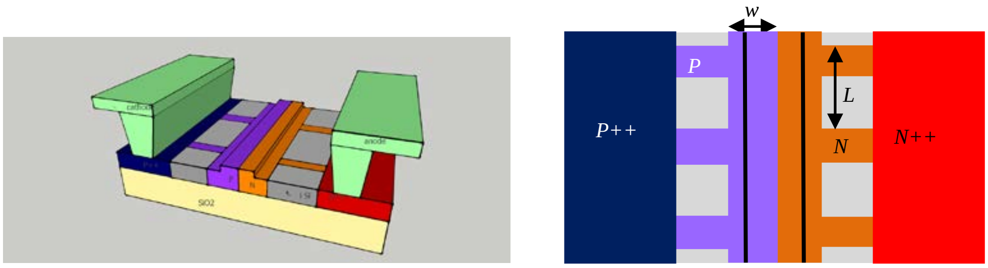

Fig. 1. Schematic 3D (left) and top (right) views of the phase shifter

The optical modulator was fabricated on 200 mm SOI wafers. 193 nm optical lithography and silicon dry etching were used to define the optical waveguide. The implantation window was opened by 248 nm lithography. Subsequently ion implantation was carried out with a sweep of different implantation conditions in the wafer matrix so as to optimize it. After that a thin layer of Ni was deposited using an oxide hard mask to form a local silicide. This was followed by wafer dicing. The diced sample was spin coated with a BCB layer. After via etching through the BCB, a Pt/Au electrode was patterned by the lift-off technology.

Static and dynamic measurement

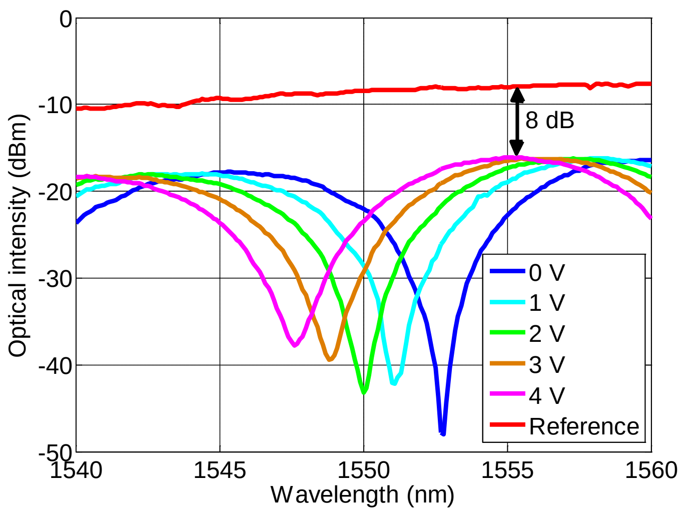

Fig. 2. Transmission spectrum of the modulator for different reverse biases

The transmission spectrums of the asymmetrical MZ modulator as a function of the wavelength are shown in Fig. 2 for different reverse biases. What is shown together is the spectrum of the reference straight waveguide with the same length. The figure of merit $V_\pi L_\pi$ of the modulator can be extracted from the spectral shift and the free spectrum range (FSR), whose value is 1.32 V·cm for a reverse bias from 0 V to 1 V. This value slightly degrades to 1.68 V·cm if we compare the spectrums of 0 V and 4 V. The on-chip insertion loss of the modulator is 8 dB which includes a loss of 1.5 dB from 2 MMIs and 4 rib/wire waveguide transitions. We estimate that loss of the phase shifter itself is about 2.2 dB/mm.

The dynamic measurement is carried out by driving the modulator with a pseudorandom bit sequence (PRBS) of 2^7-1 pattern length. The 2 V_{pp} PRBS output of the pulse pattern generator is sent to the modulator by a GSG probe without any RF amplification. A bias tee is used to add a DC bias voltage to the RF signal. Before being sent to the digital communication analyser, the optical output from the modulator passes through an EDFA and a band pass tuneable filter. Eye diagrams obtained at 5 Gbit/s, 8 Gbit/s, 10 Gbit/s and 12.5 Gbit/s are presented in Fig. 3 where the optical wavelength and the DC reverse bias are fixed at 1550 nm and 5.3 V respectively. Clear eye open is observed up to 12.5 Gbit/s which is the upper limit of our measurement system. The extinction ratio at 5 Gbit/s, 8 Gbit/s, 10 Gbit/s and 12.5 Gbit/s are 5. 92 dB, 4.88 dB, 4.51 dB and 3.73 dB respectively.

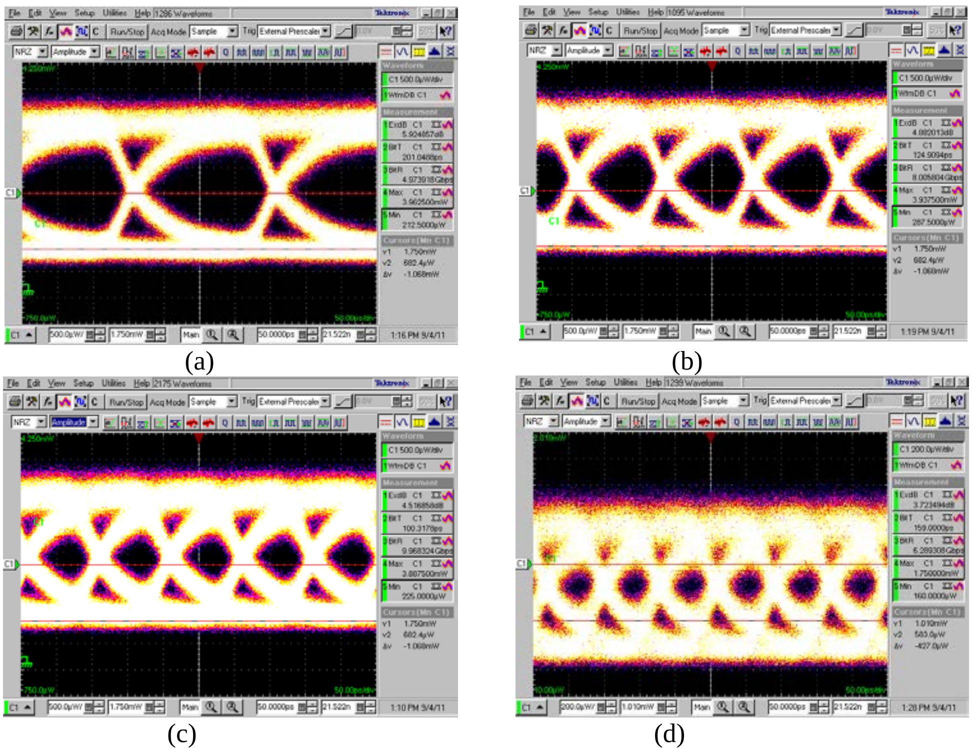

Fig. 3. Eye diagrams at different bit rates: (a) 5 Gbit/s (a), (b) 8 Gbit/s, (c) 10 Gbit/s (d) 12.5 Gbit/s

Conclusion

It is well know that for a MZ modulator the phase shifter length determines the modulation speed because of the RC constant, so most reported MZ modulators resort to short phase shifters for 10 Gbit/s operation when they are driven by a lumped electrode [3-5]. This approach imposes a high requirement on the driven voltage (V_{pp} > 5 V) in order to have sufficient modulation depth. In this paper we show that with a lumped electrode, a phase shifter as long as 3 mm could still supports a bit rate of up to 12.5 Gbit/s. Due to the long phase shifter, the modulator can be driven by a signal with

2 V_{pp} voltage swing. Further experiment result show that the operation speed can be boosted to 40 Gbit/s by a travelling wave electrode.

References

[1] G. T. Reed, G. Mashanovich, F. Y. Gardes and D. J. Thomson, “Silicon optical modulators,” Nature Photon. vol. 48, 518-526, 2010.

[2] H. Yu, W. Bogaerts, and A. D. Keersgieter, “optimization of ion implantation condition for depletion-type silicon optical modulators,” IEEE J. Quantum Electron. vol. 46, 1763-1768, 2010.

[3] M. R. Watts, W. A. Zortman, D. C. Trotter, R. W. Young and A. L. Lentine, “Low-voltage, compact, depletion-mode, silicon Mach-Zehnder modulator,” IEEE J. Sel. Top. Quantum Electron. vol. 16, 159-164, 2010.

[4] G. Rasigade, D. M. Morini, M. Ziebell, J. M. Fédéli, F. Milesi, P. Grosse, E. Cassan, and L. Vivien, “10 Gbit/s silicon optical modulator with 8 dB extinction ratio,” in Proceedings of 8-th IEEE International Conference on Group IV Photonics, 269-271, 2011.

[5] N. N. Feng, S. Liao, D. Feng, P. Dong, D. Zheng, H. Liang, R. Shafiiha, G. Li, J. E. Cunningham, A. V. Krishnamoorthy, and M. Asghari, “High speed carrier-depletion modulators with 1.4 V-cm $V_{\pi}L$ integrated on 0.25μm silicon-on-insulator waveguides,” Opt. Express. vol. 18, 7994-7999, 2010.