

Design of a micro-ring resonator electro-optical modulator embedded in a reverse biased PN junction

A. Brimont¹, F.Y. Gardes², P. Sanchis¹, D. Marris-Morini³, P. Dumon⁴, J.M. Fedeli⁵,
L. O'Faolain⁶, W. Bogaert⁴, L. Vivien³, J. Martí¹, G.T. Reed², T.F. Krauss⁶

¹Nanophotonics Technology Center - Universidad Politécnica de Valencia (Spain)

abrimont@ntc.upv.es

²Advanced Technology Institute, University of Surrey (UK)

F.Gardes@surrey.ac.uk

³Institut d'Electronique Fondamentale, CNRS, Université Paris Sud (France)

⁴Ghent University – IMEC (Belgium)

⁵CEA-Leti (France)

⁶School of Physics & Astronomy, University of St Andrews (UK)

Abstract. *In this paper, the design of a micro-ring resonator electro-optical modulator using a PN junction embedded in a rib waveguide is reported. A reverse bias of 10V is applied to the junction and shows the possibility to achieve a high modulation depth. The figure of merit of this compact depletion modulator is estimated to be $L_p.V_p=3.46$ V.cm for a loss varying from about 5 dB/cm to 8.6 dB/cm depending on the voltage applied.*

1. Introduction

Silicon photonics aims at scaling down dramatically the dimensions of optical components so electronic and optical functionalities could be integrated monolithically into an all-silicon chip at very low cost. Most of research activities in the field of silicon have been so far focused on passive structures, light emitting devices, detectors and modulators. Significant progress has been made, pushing physical limits of silicon beyond initial expectations. In the field of light modulation in Silicon, the challenging aspect is to alter the refractive index as silicon does not exhibit any linear electro-optic (Pockels) effect, usually used in III-V semiconductors. Alternative ways to alter the refractive index in all-silicon structures have been proposed. So far, the last experimental evidences shown that the only viable mechanism to achieve multi-GHz modulation in all-silicon devices is proven to be the plasma dispersion effect. This physical effect is basically based on free carrier concentration variation in a semiconductor, which alters both the real and imaginary part of the refractive index, respectively known as electrorefraction and electroabsorption. These parameters were derived experimentally by R.A.Soref [1] from the Drude-Lorenz equations at the specific telecommunication wavelengths (1.3 μm and 1.55 μm). His conclusions led to the following empirical equations:

At $\lambda=1.55 \mu\text{m}$:

$$\Delta n = \Delta n_e + \Delta n_h = -[8.8 \times 10^{-22} \Delta n_e + 8.5 \times 10^{-18} (\Delta n_h)^{0.8}]$$

$$\Delta \alpha = \Delta \alpha_e + \Delta \alpha_h = 8.5 \times 10^{-18} \Delta n_e + 6.0 \times 10^{-18} \Delta n_h$$

Where Δn_e is the change in refractive index resulting from change in free electron concentration; Δn_h is the change in refractive index resulting from change in free hole concentration; $\Delta \alpha_e$ is the change in absorption resulting from change in free electron concentration; $\Delta \alpha_h$ is the change in absorption resulting from change in free hole concentration

Combining these equations with a mode solver it becomes possible to work out the effective index change of a mode and therefore the resulting phase shift for a given voltage. Experimental demonstrations of high speed modulation in free carriers depleted silicon-based structures was demonstrated theoretically by [2,3] and experimentally by [4-7] to work in the multi-GHz regime. However, the need for compactness, the key for VLSI integration motivated researchers to move toward resonating structures among other alternatives. The use of a ring resonator to modulate an optical signal was already shown by [8] to reach bit rates as high as 12.5 Gbit/s under a pre-emphasized voltage driving scheme. In this paper, we propose also the use of a ring resonator modulator, in which modulation is achieved shifting the resonance peaks by means of carrier depletion within a PN junction.

2. Device description

The proposed ring resonator modulator (Fig. 1) is based on a 300nm wide, 150nm etch depth and 200 nm high rib waveguide, which enables to achieve single mode transmission.

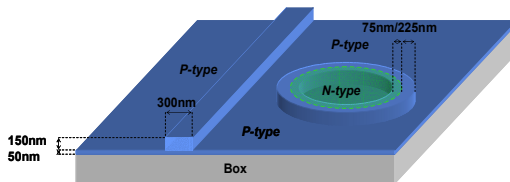


Fig1. Schematic of the proposed ring resonator modulator showing the positioning of the junction inside the ring modulator

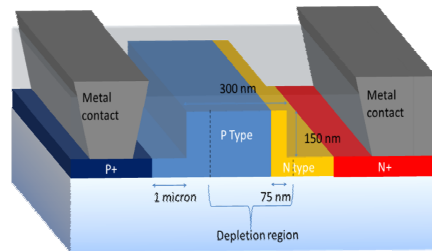


Fig2 : Electrical structure of the modulator

As shown on Fig .2, the PN junction is asymmetrical in size and in doping concentration in order to maximize the holes depletion area overlapped by the optical mode. The n-type region is 75 nm wide and the p type 225 nm wide, the net doping concentration of this particular junction is varying between $6E17/cm^3$ and $2E17/cm^3$, for n and p type respectively. The resistive contacts are formed by highly doped regions ($1E20/cm^3$) in order to form a good resistive contact and are placed $1\mu m$ away from the junction to minimise interaction with the optical mode and thus absorption losses. The position of the contacting electrodes is a key aspect in the case of a reverse biased PN based-modulator because the RC constant cut off frequency, which results from capacitive effects within the junction, limits the modulation speed.

The modulator performance was simulated using Athena for the process development and ion implantations and Atlas for DC and transient analysis, both part of the

semiconductor CAD software Silvaco. Optical Characteristics for the optical loss, efficiency and transient analysis were calculated using an in house mode solver. Fig. 3 represents the variation of the effective index for different reverse voltages; the loss of the active area is also displayed, and varies from 8.6dB/cm when no bias is applied, to about 5 dB/cm with a reverse bias of 10 volts. The efficiency of this specific modulator is $L_p.V_p=3.46 \text{ V.cm}$. meaning that a length of 3.46 mm would be necessary to obtain a π -phase shift with a 10 volt reverse bias in a Mach Zehnder interferometer.

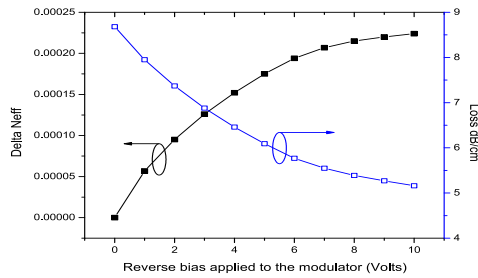


Fig3. Simulated effective index change and loss of due to the carrier for different reverse voltage bias

As the active part of the modulator is inserted in the ring resonator, the response of the ring modulator is calculated by combining the results in figure 3 in the equation below ([9], [10])

$$|b_i|^2 = \frac{K^2 + |t|^2 - 2K|t|\cos\left(\frac{2\pi}{\lambda}NL\right)}{1 + K^2|t|^2 - 2K|t|\cos\left(\frac{2\pi}{\lambda}NL\right)}$$

Where N is the total effective index including dispersion or group index, K is loss factor of the ring ($K=1$ is lossless), L is total physical length of the ring (nm), t is transfer or coupling coefficient of the coupler, λ is the wavelength.

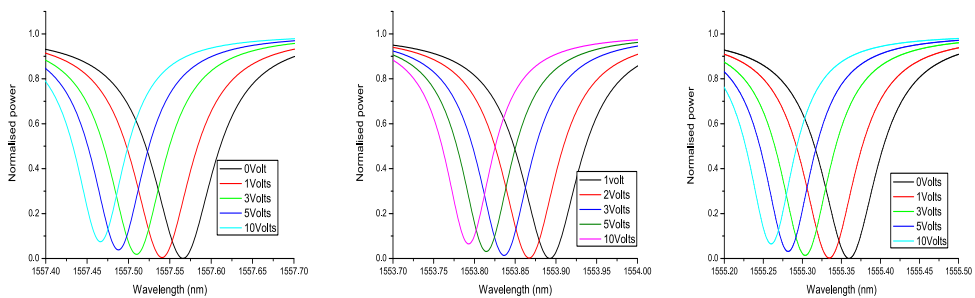


Fig4. Simulated ring response for different radius 10, 30 and 50 μm and reverse bias voltage varying between 0 and 10 volts.

The results are displayed in Fig4 for three different ring radii. Those results are derived from an ideal coupling factor matched to the loss factor of the ring in order to obtain the best response, also only the loss induced by the free carriers inside the waveguide is taken into account. The interesting result here is to show that for a similar PN junction

design, a similar extinction ratio can be achieved regardless of the ring size. This is due to the fact that as the ring decreases in size, the free spectral range (FSR) increases hence a small change in refractive index inside the waveguide will induce a bigger shift in wavelength compared to larger rings where the FSR is smaller. Nevertheless, it is important to note that decreasing the bend radius increases the intrinsic losses inside the ring due to the waveguide wall roughness, hence increasing the loss factor and the extinction ratio of the ring.

Conclusion

This paper shown the theoretical possibilities of modulating efficiently an optical signal propagating through a ring resonator and using a PN junction embedded in rib waveguide. Due to the intrinsic possibilities offered by a PN junction, high speed modulation can then be achieved by shifting the ring resonance peak under a reverse biased voltage, canceling the need of using complicated pre-emphasized voltage driving schemes. Furthermore such a device would be beneficial and a major improvement in terms of power requirements as well as real estate of the device compared to depletion modulators inserted in MZI.

Acknowledgments

Authors acknowledge financial support by EC under NoE ePIXnet.

References

- [1] R A. Soref, B.R. Benett, "Electrooptical effects in Silicon" *IEEE J. Quantum Electron.* QE-23, pp. 123-129, 1987.
- [2] F. Y. Gardes, G. T. Reed, N. G. Emerson, and C. E. Png, "A sub-micron depletion-type photonic modulator in silicon on insulator," *Optics Express*, vol. 13, pp. 8845-8854, 2005.
- [3] D. Marris, E. Cassan, L.Vivien, "Response time analysis of SiGe/Si modulation-doped multiple-quantum-well structures for optical modulation", *Journal of applied physics*, Vol 96, n°11, pp 6109-6111, 2004.
- [4] A. Lupu, D. Marris, D. Pascal, J-L. Cercus, A. Cordat, V. Le Thanh, S. Laval, "Experimental evidence for index modulation by carrier depletion in SiGe/si multiple quantum well structures", *Applied physics letters*, Vol 85, n° 6, pp. 887-889, 2004
- [5] D. Marris-Morini, X. Le Roux, L. Vivien, E. Cassan, D. Pascal, M. Halbwx, S. Maine, S. Laval, J. M Fedeli, and J. F. Damlencourt, "Optical modulation by carrier depletion in a silicon PIN diode," *Optics Express*, vol. 14, pp.10838-10843, 2006.
- [6] L. Ansheng, L. Ling, D. Rubin, N. Hay, B. Ciftcioglu, Y. Chetrit, N. Izhaky, and M. Paniccia, "High-speed optical modulation based on carrier depletion in a silicon waveguide," *Optics Express*, vol.15, pp. 660-668, 2007.
- [7] D. Marris-Morini, L.Vivien, J.M. Fédéli, E. Cassan, P. Lyan, S. Laval, "Low loss and high speed silicon optical modulator based on a lateral carrier depletion structure", *Optics express*, vol.16, pp.334-339, 2008.
- [8] Q. Xu, S.Manipatruni, J. Shakya, M. Lipson, "12,5 Gbit/s carrier-injection-based silicon micro ring silicon modulators", *Optics express*, vol. 15, pp. 430-436, 2007.
- [9] J. M. Choi, R. K. Lee, and A. Yariv, "Control of critical coupling in a ring resonator-fiber application to wavelength-selective switching, modulation, amplification, and oscillation," *Optics Letters*, vol. 26, pp. 1236-8, 2001.
- [10] A. Yariv, "Critical coupling and its control in optical waveguide-ring resonator systems," *IEEE Photonics Technology Letters*, vol. 14, pp. 483-5, 2002.

Eindhoven, The Netherlands, June 11-13, 2008

Proceedings
14th European Conference
on Integrated Optics
Contributed and Invited Papers

ECIO₀₈
EINDHOVEN

June 11–13, 2008
Eindhoven University of Technology
The Netherlands

Organized by
COBRA Institute
Eindhoven University of Technology

Editor
X.J.M. Leijtens