

Dimension Dependent Silicon Photonics Rib Waveguide Characterisation

A.T.C.Chen*, M. Rakib Uddin**, F. K. Law and Nurazmina Lingas

Electrical and Electronic Engineering Programme Area

Faculty of Engineering

Universiti Teknologi Brunei (UTB)

Gadong, Brunei Darussalam

Email: *angie_teo236@hotmail.com; **rakib.uddin@utb.edu.bn

Abstract— In this paper, SOI rib waveguides with the variation of core dimensions have been demonstrated. The analysis of a silicon rib waveguide is performed by simulating the SOI waveguide containing a forward biased PN junction by applying the electro-optic carrier – injection effect via electric voltage changes. The dimensions of the waveguide/ring resonator have been altered. The dimensions of the waveguide/ring resonator include the width of the core waveguide (W), the height of the core waveguide (Hc), the rib thickness (Hr) and the height of buried oxide (Ho). Thus, in this research, the dimensions of the waveguide/ring resonator will be varied at distinct value with a specific interval in order to investigate the performance of the micro-ring resonator. This is because as the dimensions of the waveguide vary, its resonance wavelength will be change and thus shifting of resonance will occur. The simulation generates refractive index of the waveguide with respect to the applied voltage and refractive index, loss, gain and dispersion of the waveguide with respect to wavelength.

Keywords— Silicon, rib waveguide, PN junction, ring resonator.

I. INTRODUCTION

In recent times, silicon photonics has become a great attraction as it offers an opportunity for economical optoelectronic solutions for several applications varying from telecommunications down to chip-to-chip interconnects. Previously, there have been compelling advances in pushing the performance device for CMOS-compatible silicon building blocks required in development of silicon integrated photonic circuits [1]. In addition, a group IV element situated just below carbon in the periodic table known as silicon is the key building block in modern electronics which lead us into the information age through the digital revolution. Silicon is recognized as a choice of semiconductor material in fabricating transistors, a key component in integrate electronic circuits [2]. This is due to its transparency and low loss at the wavelength ranges of 1.3 μ m to 1.55 μ m, and fabrication compatibility with CMOS technology on SOI platform [3-5]. In addition, Silicon is very applicable for micro-optical applications due to special characteristics: 1) hard material; 2) high thermal conducting; 3) high tensile stress [6]. Even though, silicon might not be the best material with the best electronic properties for the job as

compare to gallium arsenide (GaAs) which has remarkable key electronic properties for fast electronics, but silicon makes up for its shortcomings by several factors. The factors include: 1) it is non-toxic; 2) it has high thermal conductivity; 3) it can form a well insulating oxide (SiO₂) and 4) it is cheap [2]. As a result, silicon can be an option for the formation of PIN diode. A silicon waveguide can be constructed with core waveguide in intrinsic region of a laterally formed PiN diode [7]. In this case, it allows the charge carrier concentration to be modulated at extreme speed. Moreover, the increase of free charge carriers will lead to an increase in silicon refractive index [8]. The purpose of high refractive index in silicon is to modulate light in silicon waveguide at extreme speed with low consumption of power [9].

This eventually lead to the design of optical filter based Micro-Ring Resonator. Optical filter based MRR had become one of the most well-known research in the past few years in integrated optics due to their compactness, high wavelength selectivity, on chip structure and it is less difficult to fabricate as compared to other devices [10 and 11].

II. RIB WAVEGUIDE

In photonics world's, there are two type of modes namely the single mode and multiple mode. Single mode can be done by using silica waveguides and it is easy to design as compared to SOI waveguide which support multiple modes. This type of SOI waveguide has a cross section of dimensions larger than a few hundred nanometers. But a problem arise as such multimode waveguides are troublesome in photonic circuits as their operation can be seriously compromised by the existence of multiple modes [12 and 13].

Nevertheless, it is proved that SOI waveguide with large rib waveguides could be designed to be single mode. Furthermore, several researchers have been investigated greatly these waveguides in order to find the behavior of single mode and low propagation loss. Large rib waveguides are attracting due to their multi-micron in cross sectional dimensions in order to

promote low loss coupling to and from optic fibers. A simple expression for single mode condition (SMC) of large rib waveguides is first proposed by Soref et al;

$$\frac{W}{H} \leq 0.3 + \frac{r}{\sqrt{1-r^2}} \quad (\text{for } 0.5 < r < 1) \quad (1)$$

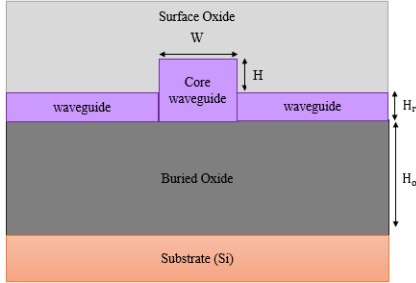


Figure 1 Cross section of an SOI rib waveguide

Where,

r is the ratio of rib height (H_r) to overall rib height (H).

W/H is the ratio of waveguide width to overall rib height.

In their investigation, it is seen that the waveguides were restricted to shallow etched ribs in which $r > 0.5$ and the dimensions of the waveguide were assumed to be larger than the operating wavelength. This investigation was based on the hypothesis in which vertical modes of high order confined under the rib were coupled to the outer slab region during propagation, thus accommodating high propagation losses for a higher order mode. As a result, the waveguide act as a single mode waveguide while all the other modes are lost.

For relatively small rib waveguides, Chan et al. had composed single mode and polarization independence equations;

$$\frac{W}{H} \leq 0.05 + \frac{(0.94+0.25H)r}{\sqrt{1-r^2}} - 2 \quad (2)$$

$$(\text{for } 0 \leq r \leq 0.5 \text{ and } 1.0 \leq H \leq 1.5\mu m)$$

$$D_{min} = 0.06 \times 10^{-6} + 0.556H \quad (3)$$

The quasi-TM single mode boundary is defined by equation 2 which implement the guidance on the geometric limitations in order to retain the behaviour of single mode while the minimum etch depth D_{min} is defined by equation 3 in order to retain polarisation independence. The protocol of both equation 2 and 3 are for waveguides with a top cladding layer made up of air.

Nonetheless, the deposition of the top cladding layer is for the reduction of influence of surface contamination in order to passivate the surface or provide electrical isolation.

III. DESIGN OF RIB WAVEGUIDE STRUCTURE

We have designed our rib waveguide based on SOI in which the following dimensions is set as a reference;

1. Core waveguide at a width of 450nm
2. Core waveguide at a height of 250nm
3. Rib waveguide at a height of 500nm
4. Buried oxide at a height at 1000nm

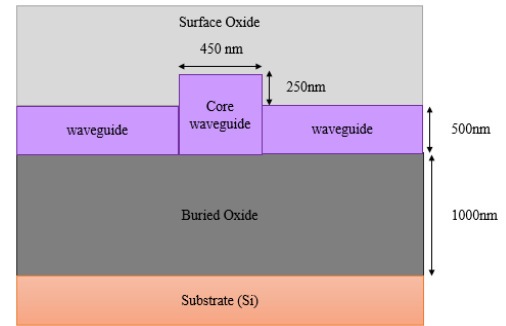


Figure 2 Cross section of an SOI rib waveguide

In this paper research, the dimensions of the waveguide/ring resonator such as width and length of core waveguide, height of rib waveguide and height of rib waveguide will be varied one by one by fixing the other three dimensions. As we know that the dimensions of the waveguide/ring resonator might be vary during fabrication which causes the initial design performance and actual device performance to be vary. Thus simulations were carried out in order to conclude the actual fabricated device outputs. Each of the dimension will be varied at distinct value with a specific interval and the results are plotted into graphs.

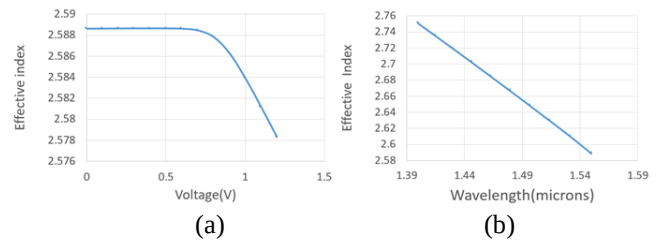


Figure 3 Effective index against voltage and wavelength at fixed dimensions

Based on Figure 3(a), it is seen that as the voltage increases from 0V to 0.6V, there is no effect on change of effective index. This is because since our design is electro-optic carrier –

injection based, it takes stronger voltage in order for the free carriers to go into the waveguide core. The change of effective index started to increase slowly by 0.00016 as voltage increased up to 0.7V. Continually increased of voltage lead to the increased of change of effective index until it reached a voltage of 0.9V, where the change of effective index came into a constant value. From Figure 3(b), it is seen that as the wavelength increases, the value of effective index will be decreased.

IV. CORE WAVEGUIDE WIDTH CHANGE

The width of the core waveguide is varied from 500nm to 1000nm at the interval of 100nm in which all other parameters are kept constant as shown in Figure 2.

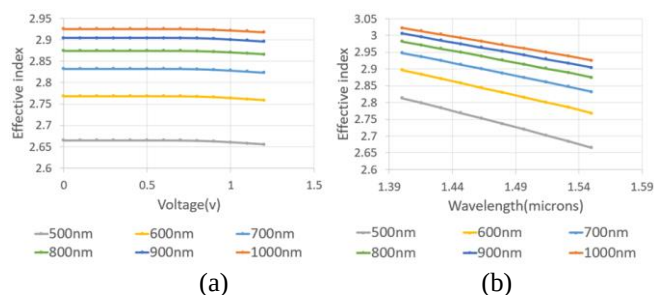


Figure 4 Effective index against voltage and wavelength for different waveguide width

Based on Figure 4 (a), it is seen that the change of effective index remains constant as voltage increased from 0V to 0.7 V for all changes in the width of waveguide as a larger voltage is required for the free carriers to go into the waveguide core. But as the voltage continued to increase 1.2V, the results show that bigger waveguide width will results in bigger change in effective index. Figure 4(b) shows that as the rising of waveguide width lead to the increase in change of effective index as the wavelength increased.

V. CORE WAVEGUIDE HEIGHT CHANGE

The height of the core waveguide is varied from 190 nm to 250 nm at the interval of 20 nm in which all other parameters are kept constant as shown in Figure 2.

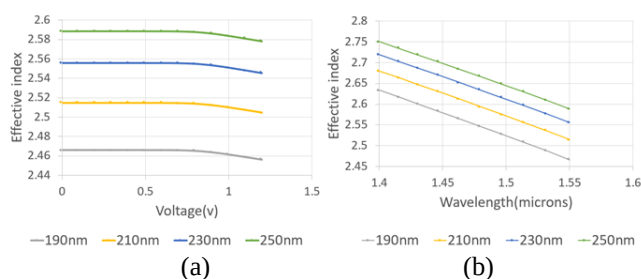


Figure 5 Effective index against voltage and wavelength for different core waveguide height

Based on the results shown in Figure 5(a), it is seen that as voltage increased from 0V to 0.7 V, the change of effective index remains constant for all changes in the width of waveguide. This is because since our design is electro-optic carrier – injection based, it takes stronger voltage in order for the free carriers to go into the waveguide core. From the results, as the voltage increased until 1.2V, it is seen that the change of the effective index is the largest when the waveguide height is at 250nm. Figure 5(b) shows that as the wavelength increased, the effective index will decrease.

VI. RIB WAVEGUIDE HEIGHT CHANGE

The height of the rib waveguide is varied from 50 nm to 110 nm at the interval of 20 nm in which all other parameters are kept constant as shown in Figure 2.

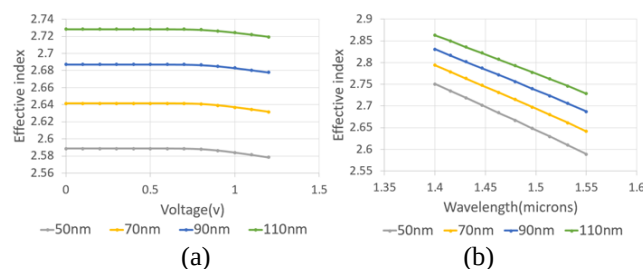


Figure 6 Effective index against voltage and wavelength for different rib waveguide height

Figure 6(a) shows that as voltage increased from 0V to 0.7 V, the change of effective index remains constant for all changes in the width of waveguide as a larger voltage is required for the free carriers to go into the waveguide core. The voltage is then continued to increase up to 1.2V and it is seen that the change of effective index decreases as the rib waveguide height increased. Figure 6(b) shows that as the wavelength increased, the effective index will decrease.

VII. BURIED OXIDE HEIGHT CHANGE

The height of the buried oxide is varied from 500 nm to 2000 nm at the interval of 500 nm in which all other parameters are kept constant as shown in Figure 2.

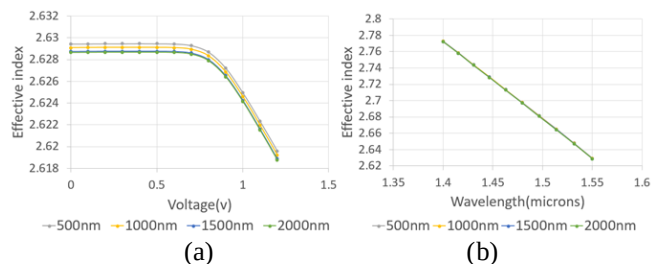


Figure 7 Effective index against voltage and wavelength for different buried oxide height

Based on Figure 7(a), it is seen that the change of effective index remains constant for all changes in the width of waveguide as voltage increased from 0V to 0.6 V as a larger voltage is required for the free carriers to go into the waveguide core. Then as the voltage increases, it is seen that effective index will decrease. Figure 7(b) shows that when the buried oxide is varied from 500nm to 2000 nm at the interval of 500 nm, the graph of effective index against wavelength is the same for all height.

VIII. CONCLUSION

This paper had demonstrated the simulation and analysis of SOI rib waveguides with the variation of core dimensions such as the width of the core waveguide (W), height of the core waveguide (H), rib thickness (H_r) and height of buried oxide (H_o). The simulation of the silicon rib waveguide is performed by varying the voltage from 0V to 1.2V at an interval of 0.1V. The results from the simulation are plotted into graphs in which refractive index of the waveguide is plotted with respect to the applied voltage and refractive index of the waveguide is plotted with respect to wavelength. Based on all results, it is seen that the change of effective index remains constant as voltage increased from 0V to 0.7 V for all changes which include the width of the core waveguide (W), the height of the core waveguide (H), the rib thickness (H_r) and the height of the buried oxide (H_o). This is because a larger voltage is needed in order for the free carriers to go into the waveguide core as in this paper carrier injection method is applied. As the voltage continued to increase, the effective index will decrease. While for the graph of effective index against wavelength for all changes, it is shown that as the wavelength increased, the effective index will decrease. Therefore, from the results on the simulation of the dimensions of the waveguide/ring resonator, the impact of each of the device design parameters are clearly shown. As a conclusion, the performance of the micro-ring resonator can be investigated.

ACKNOWLEDGMENT

We would like to thank Universiti Teknologi Brunei (UTB) for financial support to carry on this research.

REFERENCES

- [1] Liu, A., Liao, L., Rubin, D., Nguyen, H., Ciftcioglu, B., Chetrit, Y., Paniccia, M. (2007). High-speed optical modulation based on carrier depletion in a silicon waveguide. *Optics Express*, 15(2)
- [2] Fabrication and Characterisation of Silicon Waveguides for High-Speed Optical Signal Processing. DTU Fotonik, 2015, p. 18.
- [3] Rickman, A. G., Reed, G. T., & Namavar, F. (1994). Silicon-on-insulator optical rib waveguide loss and mode characteristics. *Journal of Lightwave Technology*, 12(10), 1771–1776.
- [4] R. Soref (1993). Silicon-based optoelectronics. *Proceedings of the IEEE*, 81(12), 1687–1706.
- [5] Bogaerts, W., Fiers, M. and Dumon, P. (2014). Design Challenges in Silicon Photonics. *IEEE JOURNAL*, [online] 20(4), p.1.
- [6] Parker, G. J., & Rahman, A. Z. M. S. (2017). Guided-Wave Optical Communications: Materials. Reference Module in Materials Science and Materials Engineering.
- [7] S.Akiyama and T.Usuki, "High-speed and efficient silicon modulator based on forward-biased pin diodes," *Frontiers in Physics*, vol. 2, no. November, pp. 1-7, 2014.
- [8] R. Soref and B. Bennett, "Electrooptical effects in silicon," *IEEE Journal of Quantum Electronics*, vol. 23, no. 1., pp. 123-129, 1987
- [7] V. Chandra and R. Ranjan, "Analysis of Propagation Loss in Silicon-on-Insulator based Photonic Rib Waveguide with Small Cross Section", 2019, p. 1.
- [9] A. Liu, L. Liao, D. Rubin, H. Nguyen, 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, no. 2, p. 660, jan 2007.
- [10] B.E. Little, S.T.Chu, H.A.Haus, J.Foresi, and J-P Laine, "Microring Resonator Channel Dropping Filters," *IEEE J.Lightwave Technl.*(2005)
- [11] A. Nikoukar et al., "Theoretical and simulation analysis of the add drop filter ring resonator based on z transform", 2014, pp. 1, 3.
- [12] Mashanovich, G. Z., Milosevic, M., Matavulj, P., Stankovic, S., Timotijevic, B., Yang, P. Y, Reed G. T. (2008). Silicon photonic waveguides for different wavelength regions. *Semiconductor Science and Technology*, 23(6).
- [13] Milan M. Milosevic, Petar S. Matavulj, Branislav D. Timotijevic, Graham T. Reed, and Goran Z. Mashanovich (2008).Design Rules for Single-Mode and Polarization-Independent Silicon-on-Insulator Rib Waveguides Using Stress Engineering. *Journal of Lightwave Technology*, Vol.26, Issue 13, pp. 1840-1846.



Ms. A. T. C. Chen is with the Universiti Teknologi Brunei as PhD student since January 2019. She got her bachelor degree with first class honors and received Excellent Student Award from the Ministry of education, Brunei Darussalam. Her research interest is in future high speed communication system by photonics.



M. Rakib Uddin (M'15). This author became a Member (M) of IEEE, USA in 2015. He was born in Bangladesh on February 18, 1978. He received his PhD degree in the area of communication engineering from KAIST, Daejeon, Korea in 2010. He received his MSc in Electrical and Electronic Engineering from Bangladesh University of Engineering and Technology, Dhaka, Bangladesh in 2005 and BSc in Electrical and Electronic Engineering from Chittagong University of Engineering and Technology, Chittagong, Bangladesh in 2002. He is working as ASSOCIATE PROFESSOR with Electrical and Electronic Engineering Programme Area, University Teknologi Brunei (UTB), Bandar Seri Begawan, Brunei Darussalam since December 2014. He worked for Samsung Electronics/Samsung Advanced Institute of Technology, Hwaseong/Geheung, Korea as research staff Member/Senior Engineer from 2011 to 2014. He worked as Post-doctoral fellowship with KAIST from 2010 to 2011. He has more than 60 articles in international journals and conference proceedings along with seven international patents. Dr Rakib Uddin is a Senior member of IEEE, USA and Member of IET, UK. He got Korean government IITA full scholarship for his PhD programme from 2006 to 2010 at KAIST. He also got Korean Government Brain Korea 21 (BK21) fellowship for his post-doctoral research with KAIST, Korea. Dr Rakib Uddin received University Teaching as well as Research Excellence Awards (special Mention) in 2017 at UTB, Brunei Darussalam.



Law Foo Kui is with the Universiti Teknologi Brunei (UTB), Bandar Seri Begawan, Brunei Darussalam as a PhD student since January 2017. He got his bachelor degree in Electrical and Electronic Engineering with first class honors and received Excellent Student Award from the Ministry of education, Brunei Darussalam. His research interest is in future high speed computer and communication by photonics.



Nurazmina Lingas received her BEng in Electrical and Electronic Engineering from the University of Glasgow, Scotland in 1995 and MSc in networked communication from Loughborough University in 2011. She also received Master of Teaching from Universiti Brunei Darussalam in 2013. Immediately after graduate in 1995, she worked at the telecommunication industry before joining Universiti Teknologi Brunei in 2008 as a lecturer. She is currently pursuing her part time PhD Degree in the

area of communication engineering. Her research interests include broadband access networks, photonics, telecommunication networks and computer networking.