

Transverse Electric (TE) and Transverse Magnetic (TM) Modes Dependent Effective Index Analysis for a Nano-scale Silicon Waveguide

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Abstract—In this paper, we propose and demonstrate the effect of effective index on silicon waveguide thickness by using MODE solution. The effect of effective index variations is presented for two different fixed core height of 220nm and 200nm, and with each the core width was from 300nm to 600nm at the steps of 100nm for Transverse Electric (TE) and Transverse Magnetic (TM) mode. With the simulation results, the thickness of the core width is used for the determination of fundamental or higher order mode design. It is seen that higher effective index can be achieved as the core width and core height increases. The determination of fundamental or higher order mode design can be achieved by analysing the graphs of effective indices for TE₀, TM₀, TE₁ and TM₁ modes at varying core height and width. Based on the analysis, it is concluded that fundamental order can only be achieved when the silicon core width is kept at a value of approximately 500nm while higher mode order can be achieved if the silicon core width is kept more than 500nm. At a higher order mode, excess noise and losses can be introduced.

Keywords—Effective index, Rib Waveguide and Silicon

I. INTRODUCTION

For the past few years, Silicon waveguides based on Silicon-on-Insulator (SOI) platform have become a famous research field in the interest of their high capability in optoelectronic circuits. SOI technology is a good choice for optical waveguide owing to its very high index contrast between silicon and silicon dioxide [1-3]. With high index contrast, the fabrication of dimensions of a few $\mu\text{m} \times \mu\text{m}$ ultra-compact silicon photonic devices and circuits can be achieved [4-6]. In addition to that, low-loss optical waveguide can be implemented with the use of silicon material [1 and 7-9]. Apart from these, various technologies like light sources, guiding of light, modulation of light and detection of light can be incorporated into a single chip with the support of integration of Photonics along with microchip technology [1 and 8]. Effective index is one of the most significant characteristics in silicon waveguides especially in designing of an optical system as it determines the propagation constant of an optical field, although in high-speed communication in which dispersion might be a limiting factor [1].

Waveguide polarizations are defined as the characteristic of a particular waveguide structure which consists of TE and TM

mode. For a particular mode, only waveguides with a specific cross-sectional area can support the entire mode. In optical communication applications, the fundamental TE mode is mainly used in the transmission of information. The most frequently used cross-sectional area for a waveguide that can support the fundamental TE mode at negligible loss are usually at a height of 200nm and a width of 500nm [10]. If the waveguide has a smaller cross-sectional area, the entire fundamental mode cannot be supported as the mode will be partially distributed in the outer region of the waveguide. Whereas, if the waveguide has a larger cross-sectional area, undesirable higher order modes will be easily excited [11].

II. THEORY ON SOI RIB WAVEGUIDE

To the greatest extent, Silicon waveguides based on SOI platform can be easily built from SOI wafers as shown in Figure 1 by employing Complementary Metal-Oxide Semiconductor (CMOS) processes [10].

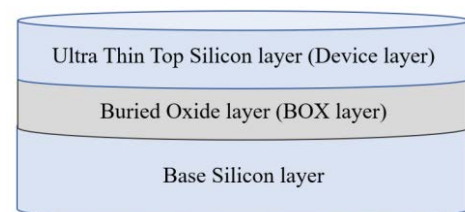


Figure 1. SOI wafers

Standard SOI wafers are made up of a layer of buried oxide (BOX) centrally located in between an ultra-thin top silicon layer and base silicon layer. The techniques used to design Silicon-based type waveguides are optical lithography and etching process [12]. In an SOI based-type waveguide, guiding of light will occur in the core of silicon in which it is separated from the silicon substrate with a layer of silicon oxide that acts as lower cladding [13]. An example of the commonly used waveguide is the rib waveguide in which the geometry of the waveguide is shown in Figure 2.

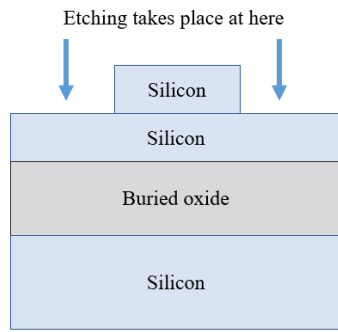


Figure 2. The geometry of rib-type based waveguide on SOI platform

III. PROPOSED DESIGN OF RIB-TYPE BASED WAVEGUIDE

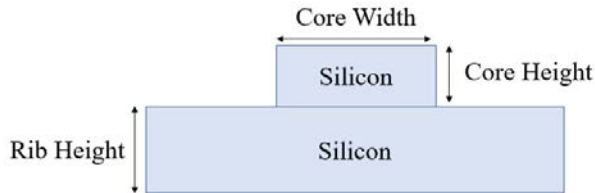


Figure 3. Cross section of core section of the rib waveguide

A cross section diagram of a core part of the rib waveguide is shown in Figure 3. This paper is divided into two sections. In the first section, the core of the rib waveguide is designed to be at a fixed height of 220nm, a fixed rib height of 50nm and varied core width from 300nm to 600nm in the steps of 100nm. Next, the core of the rib waveguide is designed at a fixed core height of 200nm, a fixed rib height of 50nm and varied core width from 300nm to 600nm at the steps of 100nm.

IV. SIMULATION AND RESULTS

In this work, the cross-section rib-type based waveguide is simulated by using the MODE solution to generate the waveguide characteristics such as the effective index for the different polarization mode. The mode profiles of core waveguide for the first section are shown in Figure 4 to Figure 7 respectively, in which the height of the core is at a fixed value of 220nm with varied width of 300nm to 600nm.

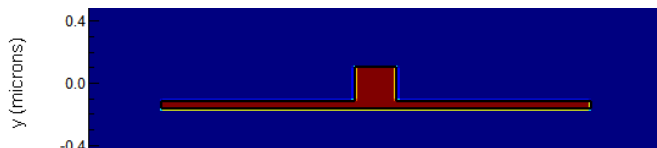


Figure 4. Mode profile at core height of 220nm and core width of 300nm

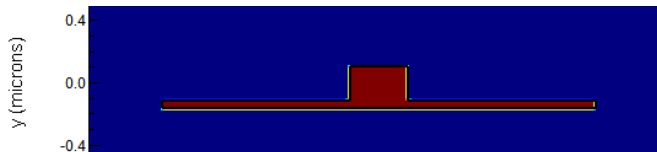


Figure 5. Mode profile at core height of 220nm and core width of 400nm

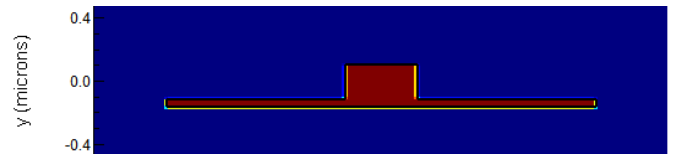


Figure 6. Mode profile at core height of 220nm and core width of 500nm

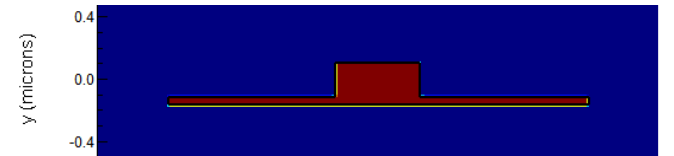


Figure 7. Mode profile at core height of 220nm and core width of 600nm

In this simulation, the results of the effective index at a fixed height of 220nm with varied width are shown in Figure 8 to 11, respectively. From the results, it is clearly shown that as the wavelength increases, effective index also increases for the 4 modes. It is also observed that core waveguide width variations will have impacts on effective index. Thus, based on the results, it is deduced that as we increased core waveguide width, the value of effective index also increases.

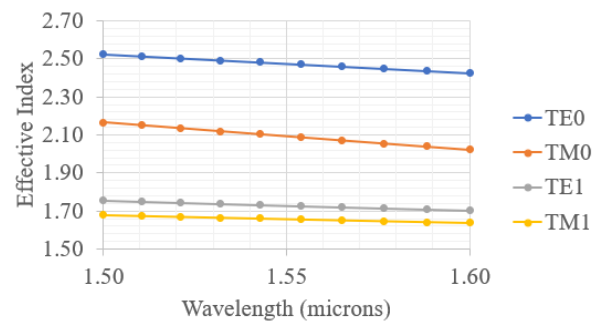


Figure 8. Graphs of Effective index at height of 220nm with width of 300nm for 4 modes

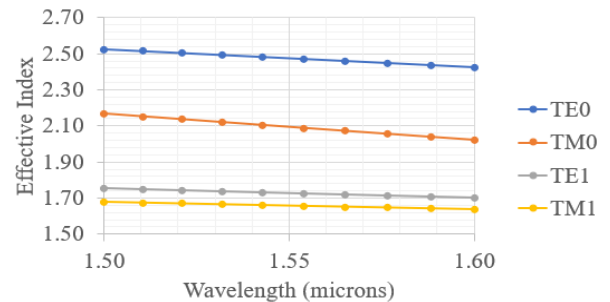


Figure 9. Graphs of Effective index at height of 220nm with width of 400nm for 4 modes

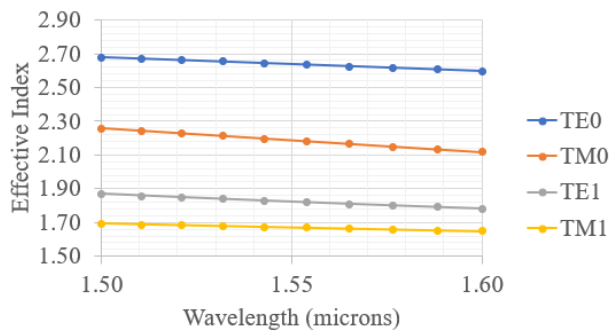


Figure 10. Graphs of Effective index at height of 220nm with width of 500nm for 4 modes

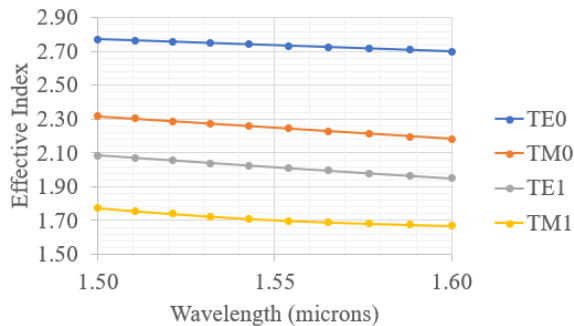


Figure 11. Graphs of Effective index at height of 220nm with width of 600nm for 4 modes

The mode profiles of core waveguide for the next section are shown in Figure 8 to Figure 11, respectively, in which the core height is fixed at 200nm with a variation of width from 300nm to 600nm.

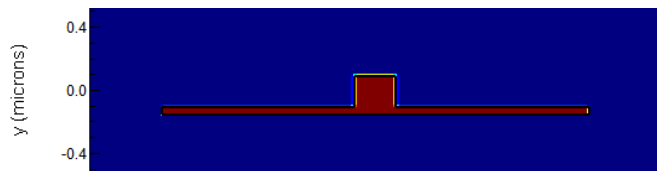


Figure 12. Mode profile at core height of 200nm and core width of 300nm

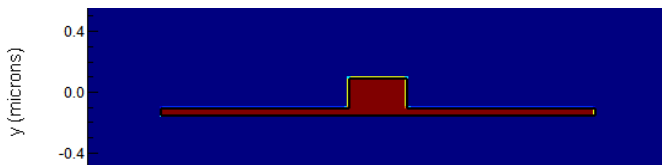


Figure 13. Mode profile at core height of 200nm and core width of 400nm

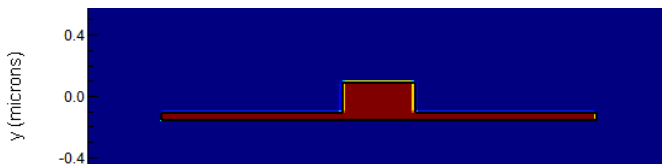


Figure 14. Mode profile at core height of 200nm and core width of 500nm

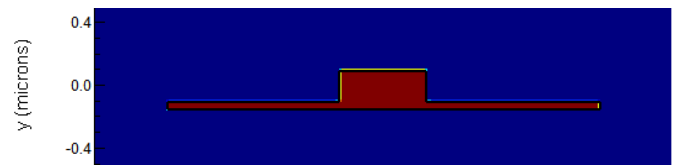


Figure 15. Mode profile at core height of 200nm and core width of 600nm

Figure 16 to 19 shows the graphs of the effective index at a fixed height of 200nm with varied width of 300nm to 600nm. From the results, it is clearly shown that as the wavelength increases, effective index also increases for the 4 modes. It is also noticed that core waveguide width variations will have impacts on effective index. Thus, based on the results, it is deduced that effective index increases gradually as we increased the width of the core.

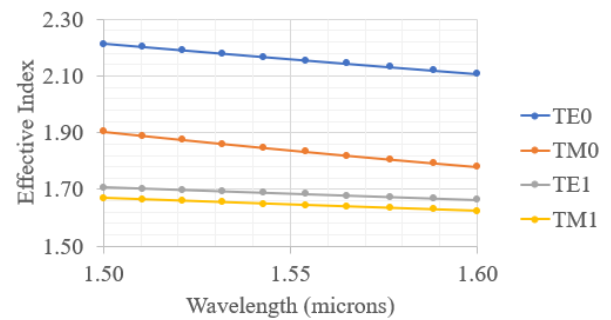


Figure 16. Graphs of Effective index at height of 200nm with width of 300nm for 4 modes

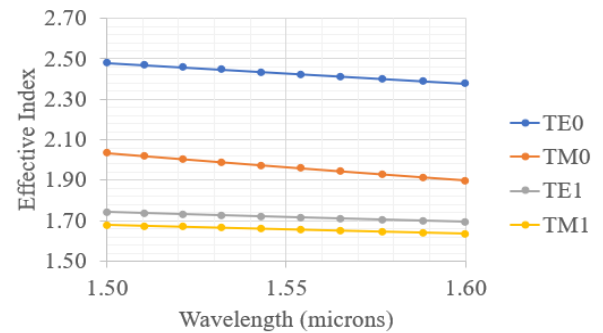


Figure 17. Graphs of Effective index at height of 200nm with width of 400nm for 4 modes

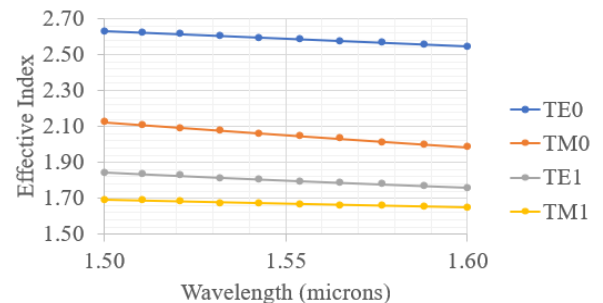


Figure 18. Graphs of Effective index at height of 200nm with width of 500nm for 4 modes

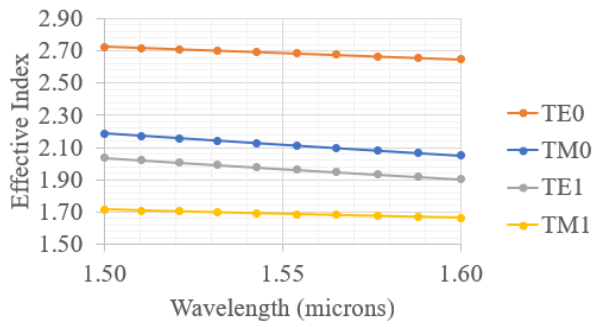


Figure 19. Graphs of Effective index at height of 200nm with width of 600nm for 4 modes

According to graphs of the effective index for dimension variables, the value of the effective index at $\lambda = 1.55 \mu\text{m}$ / 1550nm for core height of 220nm and 200nm are deduced, tabulated, and shown in Table 1 and Table 2, respectively. Based on the results from both Table, graphs of effective indices for 4 modes with respect to the varied core width to core height of 220nm and 200nm are shown in Figure 20 and 21, respectively.

Table 1. Effective index at $\lambda = 1.55 \mu\text{m}$ / 1550nm for core height of 220nm with varied core width

Width of the Core	Effective index at $\lambda = 1.55 \mu\text{m}$ / 1550nm for TE and TM Mode			
	TE0	TM0	TE1	TM1
300nm	2.19	1.95	1.69	1.64
400nm	2.47	2.09	1.73	1.66
500nm	2.63	2.18	1.82	1.67
600nm	2.73	2.24	2.01	1.70

Table 2. Effective index at $\lambda = 1.55 \mu\text{m}$ / 1550nm for core height of 200nm with varied core width

Width of the Core	Effective index at $\lambda = 1.55 \mu\text{m}$ / 1550nm for TE and TM Mode			
	TE0	TM0	TE1	TM1
300nm	2.16	1.83	1.68	1.64
400nm	2.42	1.96	1.72	1.66
500nm	2.58	2.05	1.80	1.67
600nm	2.68	2.11	1.96	1.69

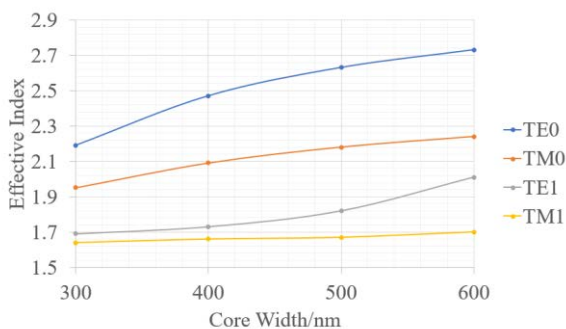


Figure 20. Effective indices for TE0, TM0, TE1 and TM1 modes at core height of 220nm with width variation

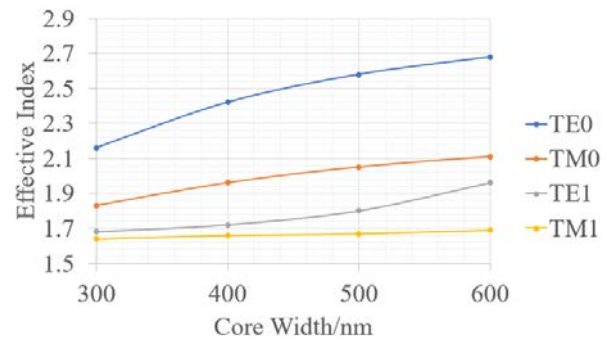


Figure 21. Effective indices for TE0, TM0, TE1 and TM1 modes at core height of 200nm with width variation

From Figure 20 and 21, it is observed that as the silicon core width is made thinner, the effective index will be reduced. But if the silicon core width is made thicker, it is seen that effective index will eventually increase. Whereas for core height variations, it is noticed that thicker height will lead to higher effective index. As seen from both Figures, it is deduced that a width of 500nm is recommended when come in designing waveguide. This is because when the width of the core is more than 450nm, it is observed that the effective index for higher order (TE1) mode has been gradually increasing. Thus, the waveguide is said to be multimode and supports not only the fundamental mode but also higher order modes. At higher order mode, more noise and losses will be obtained. Thus, it is recommended that the silicon core width is set to be around 500nm to achieve a fundamental mode design which include TE0 and TM0 mode only. Based on the results, it is precisely presented that a good compromise between effective index and polarization can be achieved with this design.

I. CONCLUSION

This paper has presented the simulation and analysis of the effect of effective index on silicon waveguide thickness by using MODE solution. In this paper, two different fixed core height of 220nm and 200nm, respectively, with varied core width of 300nm to 600nm at the steps of 100nm are presented in both TE and TM MODE. Based on the simulation results, we can clearly see the impact of each design parameter on effective index. It is seen that with a thicker silicon core height and core width, higher effective index can be achieved. By analyzing the graphs of effective indices for 4 modes, the determination of fundamental or higher order mode can be accomplished. From the simulation results, it is observed that TE polarization mode has a much higher effective index than TM polarization. From the analysis of both graphs, it is seen that as the silicon core width with a value greater than 450nm will easily excite undesirable higher-order modes and may results in more noise and losses. Thus, it is deduced that silicon core width is recommended to be set at around 500nm in order to achieve a good compromise between effective index and polarizations. The desired core width is chosen to be at 500nm as the entire fundamental mode cannot be supported at a smaller

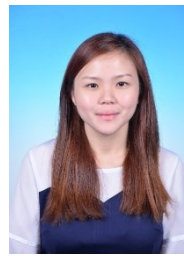
dimension while undesirable higher mode will get easily excited at a larger dimension. Based on the simulation results, it is concluded that the impact of each design parameters will lead to huge effect on the value of effective index.

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REFERENCES

- [1] Y. Dattner and O. Yadid-Pecht, "Analysis of the Effective Refractive Index of Silicon Waveguides Through the Constructive and Destructive Interference in a Mach-Zehnder Interferometer," in *IEEE Photonics Journal*, vol. 3, no. 6, pp. 1123-1132, Dec. 2011, doi: 10.1109/JPHOT.2011.2171678.
- [2] Troia, B., De Leonardis, F., Lanzafame, M., Muciaccia, T., Grasso, G., Giannoccaro, G., ... Passaro, V. M. N. (2014). Design and Optimization of Polarization Splitting and Rotating Devices in Silicon-on-Insulator Technology. *Advances in OptoElectronics*, 2014, 1-16. doi:10.1155/2014/490405
- [3] Dwivedi, S., Ruocco, A., Vanslembrouck, M., Spuesens, T., Bienstman, P., Dumon, P., ... Bogaerts, W. (2015). Experimental Extraction of Effective Refractive Index and Thermo-Optic Coefficients of Silicon-on-Insulator Waveguides Using Interferometers. *Journal of Lightwave Technology*, 33(21), 4471-4477. doi:10.1109/jlt.2015.2476603
- [4] W. Bogaerts, P. Dumon, D. Van Thourhout et al., "Compact wavelength-selective functions in silicon-on-insulator photonic wires," *IEEE Journal on Selected Topics in Quantum Electronics*, vol. 12, no. 6, pp. 1394-1401, 2006. (GOOD GOT TE AND TM MODE)
- [5] Ding, Y., Liu, L., Peucheret, C., & Ou, H. (2012). Fabrication tolerant polarization splitter and rotator based on a tapered directional coupler. *Optics Express*, 20(18), 20021. doi:10.1364/oe.20.020021
- [6] Dwivedi, S., Van Vaerenbergh, T., Ruocco, A., Spuesens, T., Bienstman, P., Dumon, P., & Bogaerts, W. (2015). Measurements of Effective Refractive Index of SOI Waveguides using Interferometers. *Advanced Photonics* 2015. doi:10.1364/ipsn.2015.im2a.6
- [7] Muñoz, P., Micó, G., Bru, L., Pastor, D., Pérez, D., Doménech, J., ... Domínguez, C. (2017). Silicon Nitride Photonic Integration Platforms for Visible, Near-Infrared and Mid-Infrared Applications. *Sensors*, 17(9), 2088. doi:10.3390/s17092088
- [8] Kim, S., & Qi, M. (2015). Mode-evolution-based polarization rotation and coupling between silicon and hybrid plasmonic waveguides. *Scientific Reports*, 5(1). doi:10.1038/srep18378
- [9] Bian, Y., & Gong, Q. (2015). Metallic-nanowire-loaded silicon-on-insulator structures: a route to low-loss plasmon waveguiding on the nanoscale. *Nanoscale*, 7(10), 4415-4422. doi:10.1039/c4nr06890d
- [10] Mu, Xin; Wu, Sailong; Cheng, Lirong; Fu, H.Y. (2020). Edge Couplers in Silicon Photonic Integrated Circuits: A Review. *Applied Sciences*, 10(4), 1538-. doi:10.3390/app10041538
- [11] He, Y.; Zhang, Y.; Zhu, Q.; An, S.; Cao, R.; Guo, X.; Qiu, C.; Su, Y. Silicon High-Order Mode (De)Multiplexer on Single Polarization. *J. Lightwave Technol.* 2018, 36, 5746-5753.
- [12] Steglich, P. (2018). Silicon-on-Insulator Slot Waveguides: Theory and Applications in Electro-Optics and Optical Sensing. *Emerging Waveguide Technology*. doi:10.5772/intechopen.75539
- [13] Ye, W. N., Xu, D.-X., Janz, S., Cheben, P., Picard, M.-J., Lamontagne, B., & Tarr, N. G. (2005). Birefringence control using stress engineering in silicon-on-insulator (SOI) waveguides. *Journal of Lightwave Technology*, 23(3), 1308-1318. doi:10.1109/jlt.2005.843518



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