

Dimension Dependent Effective Index Analysis for a Nano-scale Silicon Waveguide in Transverse Mode

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Abstract—In this paper, we propose and demonstrate the effect of effective index on silicon waveguide dimensions by using MODE solution. The objective of this paper is to study the effect of effective index which is influenced by waveguide width variations and waveguide height variations. The effect of effective index variations is presented by fixing the core height at 200nm and varying the core width from 300nm to 600nm and by fixing the core width at 500nm and varying core height from 150nm to 300nm for Transverse Electric (TE) and Transverse Magnetic (TM) MODE. With the simulation results, the thickness of the core width and core height are 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 analyzing the graphs of effective indices for TE₀, TM₀, TE₁ and TM₁ modes at varied 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 and core height is kept at a value of less than 250nm. At a higher order mode, excess noise and losses can be introduced.

Keyword— Core Height, Core Width, Effective Index, Rib Waveguide and Silicon

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I. INTRODUCTION

In recent past, silicon photonics has been one of the most fascinating topics in the communication sector where tremendous impacts have been realized by utilizing Silicon-On-Insulator (SOI) platform with very thin top layer of silicon [1-3].

Silicon waveguides based on Silicon-on-Insulator (SOI) platform have become the famous research field in the interest of their high capability in optoelectronic circuits. SOI technology is a good choice for optical waveguiding owing to its very high index contrast between silicon and silicon dioxide [4-6]. With high index contrast, the fabrication of dimensions of a few $\mu\text{m} \times \mu\text{m}$ ultracompact silicon photonic devices and circuits can be achieved [7-9]. The most standard design of single mode SOI nanowire is that it has a cross section of approximately 500nm x 220nm [1]. It is well-known that effective index is one of the most significant characteristics in silicon waveguides especially in designing of optical system as it determines the propagation constant of optical field although, more essentially, in high-speed communication in which dispersion might be a limiting factor [4]. Usually, TE-polarization mode is used in this design as it has a stronger confinement of light compared to TM-polarization mode. Therefore, small bending radii can be achieved which lead to the fabrication of ultra-compact devices. Optical waveguide such as SOI based platform waveguide is acknowledged as the most extensive bridging element in optical integrated devices [10 and 11]. Therefore, a low loss optical waveguide is important in the design and fabrication of reliable and effective optical communication system. Low loss optical waveguides can be attained by applying or varying various parameters.

II. THEORY FOR 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 [12].

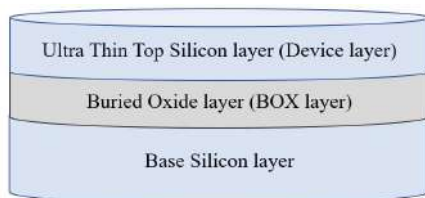


Fig. 1. SOI wafers.

A standardized SOI wafers are made up of a layer of buried oxide (BOX) centrally located to 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 occurs in the core of silicon in which it is separated from the silicon substrate by 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.

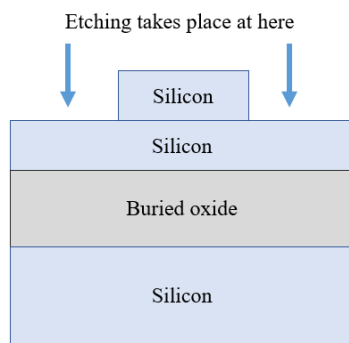


Fig. 2. The geometry of rib-type based waveguide on SOI platform.

III. PROPOSED DESIGN OF RIB TYPE WAVEGUIDE

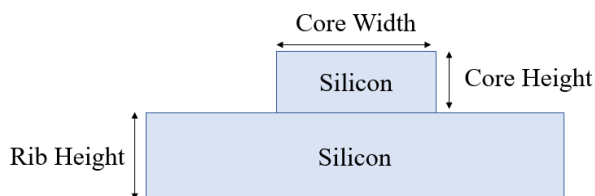


Fig. 3. Cross section of core section of the rib waveguide.

A cross section diagram of 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 in a fixed height of 200nm, a fixed rib height of 50nm and varied core width from 300nm to 600nm at the steps of 100nm. Next, the core of the rib waveguide is designed at a fixed core width of 500nm, a fixed rib height of 50nm and varied core height from 150nm to 300nm at the steps of 50nm.

IV. SIMULATION AND RESULTS ON VARIED WIDTH

In this work, the cross-section rib-type based waveguide is simulated by using MODE solution to generate the waveguide characteristics such as effective index for different polarization mode. The mode profile 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 200nm with varied width from 300nm to 600nm.

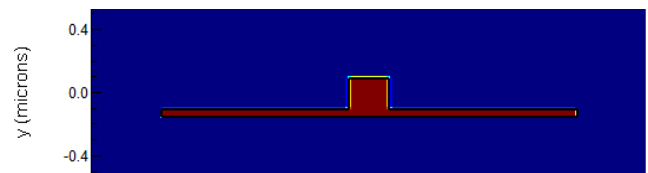


Fig. 4. Mode profile at core height of 200nm and core width of 300nm.

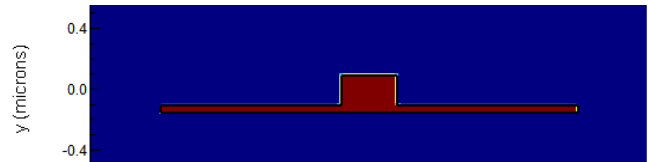


Fig. 5. Mode profile at core height of 200nm and core width of 400nm.

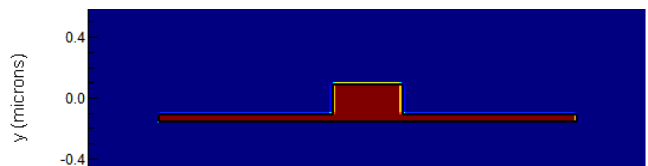


Fig. 6. Mode profile at core height of 200nm and core width of 500nm.

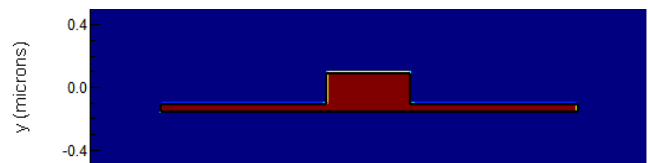


Fig. 7. Mode profile at core height of 200nm and core width of 600nm.

Figures 8 to 11 show the graphs of effective index at a fixed height of 200nm with varied width from 300nm to 600nm. The characteristic performance in terms of effective index have been noticed at core width of 300nm, 400nm, 500nm and 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.

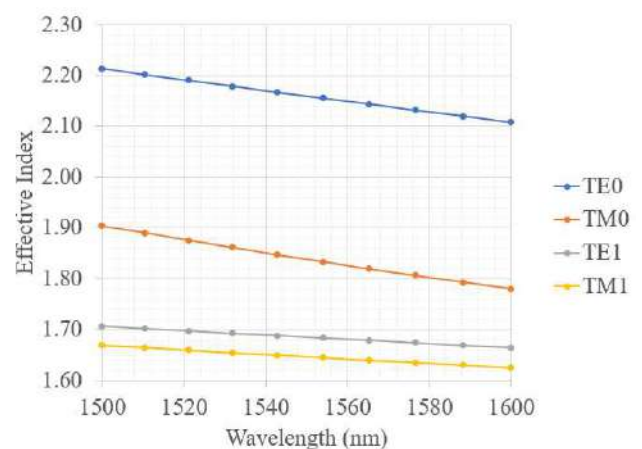


Fig. 8. Graphs of Effective index at height of 200nm with width of 300nm for 4 modes.

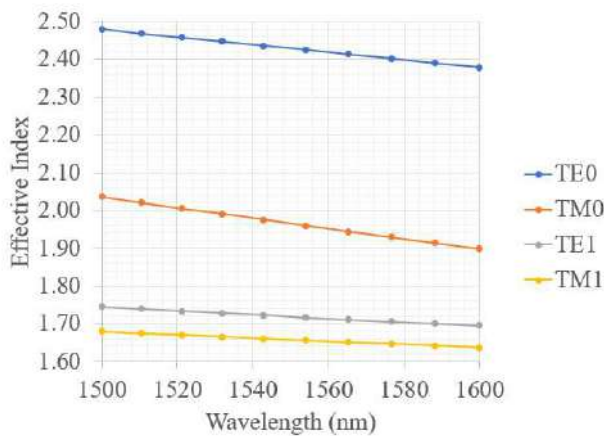


Fig. 9. Graphs of Effective index at height of 200nm with width of 400nm for 4 modes.

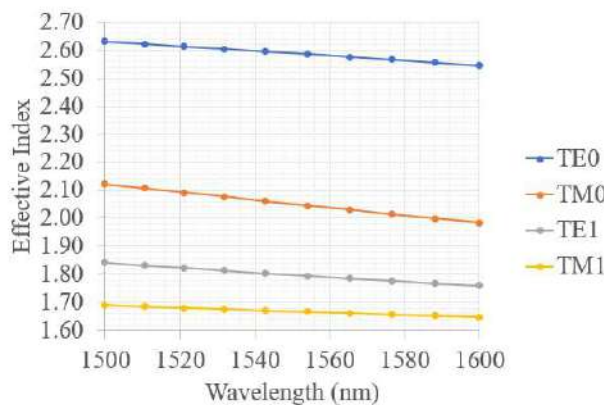


Fig. 10. Graphs of Effective index at height of 200nm with width of 500nm for 4 modes.

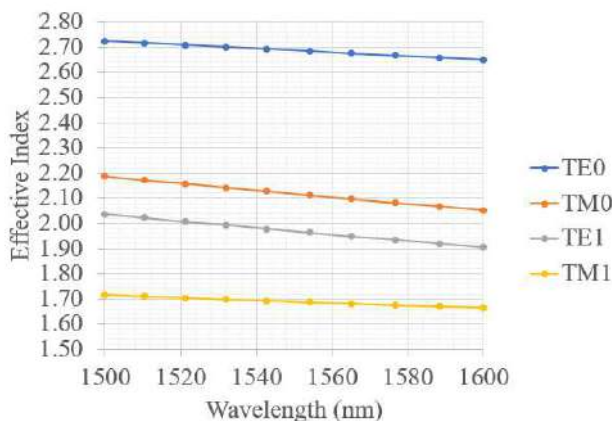


Fig. 11. Graphs of Effective index at height of 200nm with width of 600nm for 4 modes.

Based on the graphs of the effective index for dimension variables, the value of the effective index at $\lambda = 1550\text{nm}$ for core height of 200 nm are deduced, tabulated, and shown in Table I. Accordance with the results, graphs of effective indices for 4 modes with respect to the varied core width to core height of 200nm are shown in Figure 12.

TABLE I
EFFECTIVE INDEX AT WAVELENGTH OF 1550NM FOR CORE HEIGHT OF 200NM WITH VARIED CORE WIDTH

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

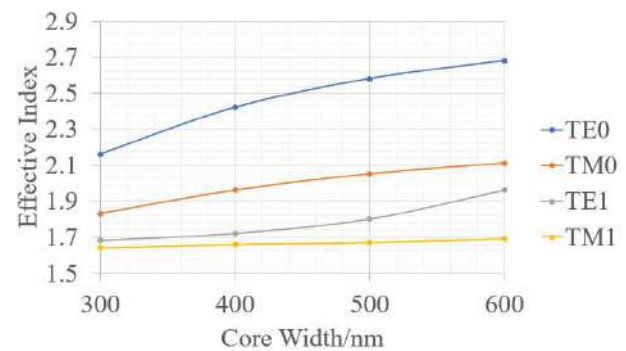


Fig. 12. Effective indices for TE0, TM0, TE1 and TM1 modes at core height of 200nm with width variation.

Based on the results shown in Figure 12, it is observed that as the silicon core width is made thicker, the effective index will increase. But if the silicon core width is made thinner, it is seen that effective index will eventually become smaller. Whereas for core height variations, it is noticed that thicker height will lead to higher effective index. As seen from the graph, it can be deduced that a width of 500nm is recommended when designing the 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 gradually increases. 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 modes only.

In addition to that, the percentage change in effective index of each width with respect to 500nm for the TE0 mode is calculated and recorded in Table II as referred to Table I.

TABLE II
PERCENTAGE CHANGE IN EFFECTIVE INDEX OF EACH WIDTH WITH RESPECT TO 500NM FOR TE0 MODE

Width of Core (nm)	Percentage Change (%)
300	-16.3
400	- 6.20
500	0
600	+3.88

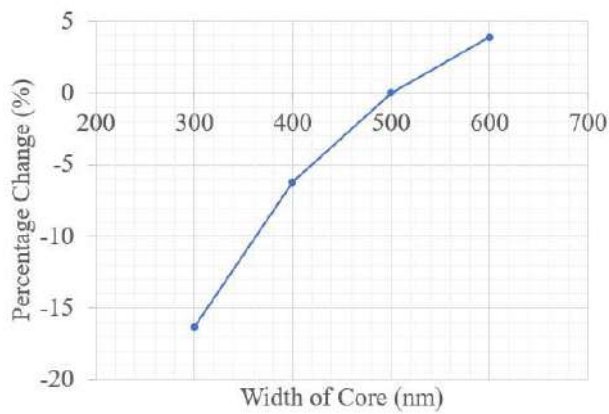


Fig. 13. Percentage Change in effective index of each width with respect to 500nm for TE0 mode.

In terms of effective index, higher effective index will lead to highest confinement of light and thus it is deduced that effective index is at the highest at core width of 600nm. In accordance with the analysis using the width of ± 100 nm and -200 nm from 500nm, it can be deduced that it is better for the design to have a core height of between 400nm to 500nm rather than more than 500nm as the balanced of high effective index and single order mode are maintained.

V. SIMULATION AND RESULTS ON VARIED HEIGHT

The mode profile of core waveguide for the next section are shown in Figure 14 to Figure 17, respectively in which the core width is fixed at 500nm with variation of height from 150nm to 300nm.

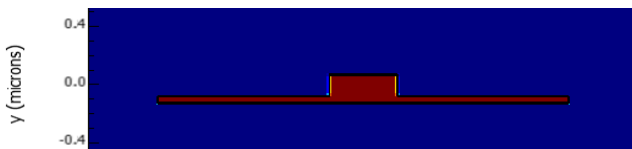


Fig. 14. Mode profile at core width of 500nm and core height of 150nm.

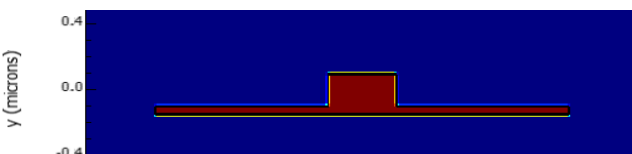


Fig. 15. Mode profile at core width of 500nm and core height of 200nm.

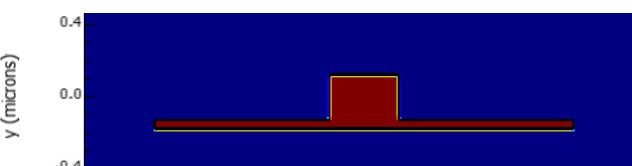


Fig. 16. Mode profile at core width of 500nm and core height of 250nm.

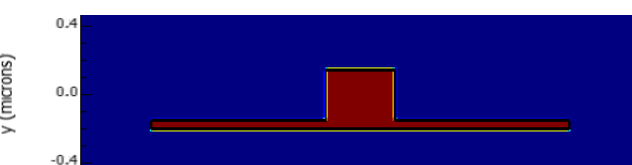


Fig. 17. Mode profile at core width of 500nm and core height of 300nm.

From there on, with fixed core width of 500nm, the core height of the waveguide is varied and the performances of various angle on fundamental and higher order mode effective index are observed and analyzed. The characteristic performance in terms of effective index has been noticed at core height of 150nm, 200nm, 250nm and 300nm. Based on the results, it is noticeable that effective index increases as wavelength increases. Furthermore, it is deduced that effective index increases with increased height.

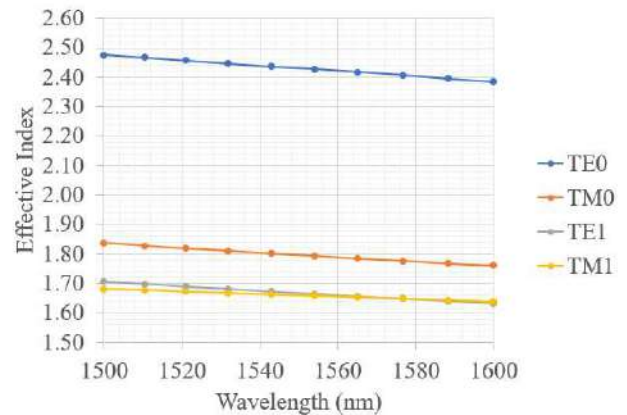


Fig. 18. Graphs of Effective index at width of 500nm with height of 150nm for 4 modes.

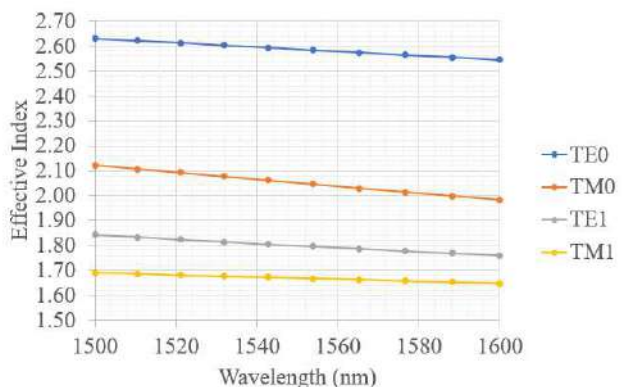


Fig. 19. Graphs of Effective index at width of 500nm with height of 200nm for 4 modes.

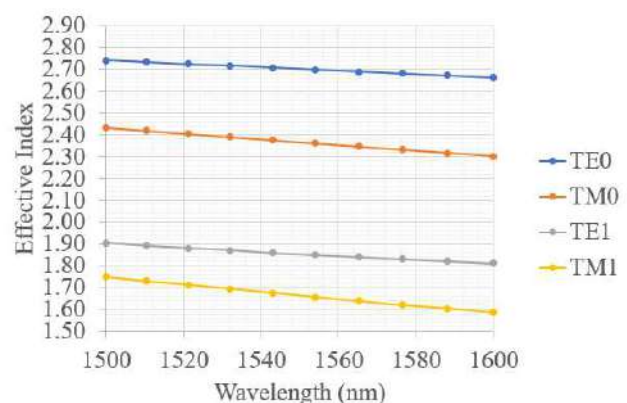


Fig. 20. Graphs of Effective index at width of 500nm with height of 250nm for 4 modes.

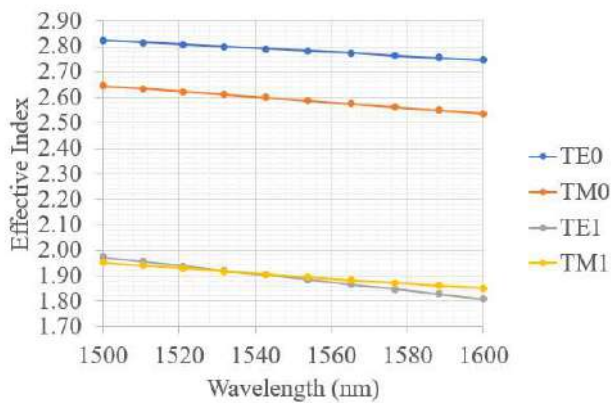


Fig. 21. Graphs of Effective index at width of 500nm with height of 300nm for 4 modes.

Based on the outcome results, summary of effective indices for TE0, TM0, TE1 and TM1 modes at fixed core width of 500nm over a range of core height dimensions is shown in Figure 22. Comparisons showing how polarization modes affect effective index as we varied core height from 150nm to 300nm are summarized, tabulate and shown in Table III.

TABLE III
EFFECTIVE INDEX AT WAVELENGTH OF 1550NM FOR CORE WIDTH OF 500NM WITH VARIED CORE HEIGHT

Height of the Core (nm)	Effective index at $\lambda = 1550\text{nm}$ for TE and TM Mode			
	TE0	TM0	TE1	TM1
150	2.43	1.79	1.66	1.66
200	2.58	2.05	1.8	1.67
250	2.7	2.36	1.85	1.66
300	2.78	2.59	1.88	1.89

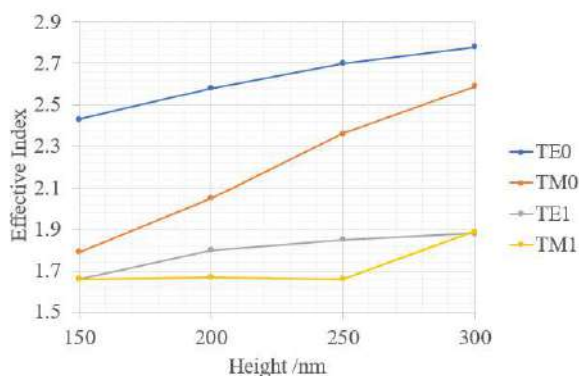


Fig. 22. Effective indices for TE0, TM0, TE1 and TM1 modes at core width of 500nm with height variation.

Based on the results shown in Figure 22, it is observed that effective index is inversely proportional to wavelength. Hence, as wavelength increases, effective index will decrease for all of the modes. In addition to that, with regards to core height, it is deduced that effective index increases with increased height.

From the simulation results shown, it is observed that as we increase the core height of the waveguide, the waveguide is said to be in higher order mode instead of fundamental mode only. It is also noticed that the effective index at fundamental mode is higher as compared to higher-order mode. Thus, it is deduced that the core height is recommended to be lesser than 250nm when designing waveguide as multi-order mode will

come in if the core width is higher than 250nm. Higher-order mode will tend to introduce some excess loss and crosstalk, therefore only fundamental mode is preferred. In consequence, the dimension of the waveguide needs to be carefully designed to prevent the excitation of higher order mode.

Moreover, the percentage change in effective index of each height with respect to 250nm for the TE0 mode is calculated and recorded in Table IV as referred to Table III.

TABLE IV
PERCENTAGE CHANGE IN EFFECTIVE INDEX OF EACH HEIGHT WITH RESPECT TO 250NM FOR TE MODE

Height of Core (nm)	Percentage Change (%)
150	-10.0
200	-4.44
250	0
300	+2.96

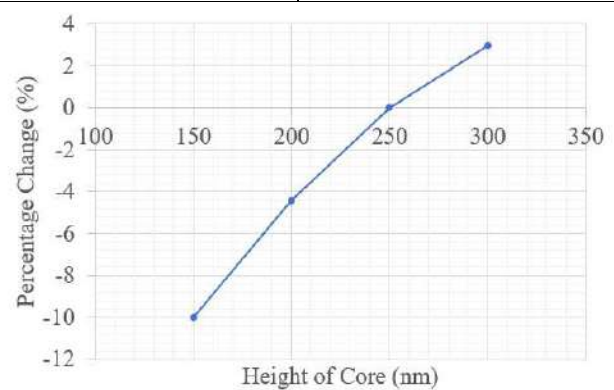


Fig. 23. Percentage Change in effective index of each height with respect to 250nm for TE0 mode.

In terms of effective index, higher effective index will lead to highest confinement of light and thus it is deduced that effective index is the highest at core height of 300nm. Based on the analysis using the height of $\pm 50\text{nm}$ and -100nm from 250nm, it can be deduced that it is better for the design to have core height between 200nm to 250nm rather than more than 250nm as the balanced of high effective index and single order mode are maintained.

VI. CONCLUSION

The simulation and analysis of the performance of polarization modes for a nano-scale silicon rib waveguide with respect to the dimensions of the waveguide have been presented. The performances of the polarization modes (fundamental mode and higher order mode) are observed and analyzed by using effective index. The study and analysis of polarization modes is to avoid the excitation of higher order modes that can cause excess loss and crosstalk. From the results, it is worth noting that as core width and core height increases, effective index also increases. Thus, it is said that core width and core height is directly proportional to the effective index. From this analysis, it is concluded that silicon core width is recommended to be set at around 500nm and core height is recommended to be set at around 250nm in order to achieve a good compromise between effective index and polarizations. This is because as the core width and core

height are more than 500nm and 250nm, respectively, it is seen that higher order mode started to come in and caused additional losses and crosstalk. As a conclusion, the study of waveguide dimensions and polarization mode is important in the realization of novel and optical devices with optimized performance.

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