Comparative Studies of Rib Waveguide Material for Quantum Communication Application

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Abstract. Recently, the needs to achieve a very high traffic capacity and superfast quantum computing led to advancement in optical waveguide technology. The selection of material with a high refractive index and transparent within the telecommunication wavelength range are crucially needed to achieve these. In this paper, the performance of two promising quantum materials, Silicon on Insulator (SOI) and Lithium Niobate on Insulator (LNOI) rib waveguide were studied. The mode analysis was conducted by using a finite element method to observe the confinement electromagnetic wave across rib waveguide. Apart from the variation of a material index, the width and height of core were optimized to achieve single mode propagation at the wavelength of 1550 nm. Based on the simulation work, it is shown that both material structures were able to produce single mode propagation with SOI showing higher confinement compared to the LNOI rib waveguide structure. LNOI structure was able to provide wide range of propagation signal wavelength.

1. Introduction

Currently, the rapid advancement in integrated optics has led to the acknowledgment of optical waveguides as one of the key element in optical integrated circuits. The optical waveguide has been used extensively in a telecommunication system to carry the information in a form of photon efficiently compared to copper-based interconnecting system. With an ability to produce more broadband, low loss and minimal power consumption these promising optical devices offer a bright future for quantum communication. For the past decades, research on optical waveguide has been conducted comprehensively for various applications such as switches, filter, and detectors[1-3]. These waveguide functions are determined by their design structure and material. Rib optical waveguide is one of the practical and extensively used solutions for the past few years compared to other optical waveguides such as a ridge, buried and planar waveguide [4]. It consists of three elements which are a substrate, a thin buffer layer on top of the substrate and a rectangular confinement layer as shown in Figure 1.

The refractive index of the rectangular layer has to be larger than the surrounding area (buffer layer) in order to produce light confinement based on total internal reflection phenomena. Relative refractive index contrast, $\Delta n$ is given by the ratio of the index between the rectangle confinement layer and the buffer layer. The bending structure is one interest since there where a critical point of total internal reflection and centripetal force of electromagnetic wave. As the refractive index increase, the
minimum bending radius is reduced. Selection of high index material such as Silicon and Lithium Niobate is an alternative to improve the performance of quantum communication. Additionally, the rib waveguides structure must be designed to operate within fundamental mode either TE00 or TM00. On the contrary, the higher order model led to higher propagation loss[4]. This work aims to compare and analyze single mode propagation of rib waveguide for two different material which are Silicon on Insulator and Lithium Niobate on Insulator.

1.1 Rib waveguide structure
Rib waveguide structure consists of 3 important elements: substrate (A), buffer layer (B) which act as a cladding and confinement layer (C) with a micro-thick slab of height (h) which acts as a core. In a quantum communication system, it is crucially required to obtain a single mode propagation across the waveguide. The selection of material and geometrical optimization are the key element to achieve this. Based on Figure 1, width (W) and height (H) of the core, height of slab (h) and an etched depth are among the important parameters to be optimized in order to achieve single mode fiber geometries.

![Figure 1. Rib waveguide cross section.](image)

1.2 Silicon on insulator
Silicon is known as an ultimate semiconductor material with a broad transmission region within Infrared wavelengths. Due to its low absorption loss at 1310nm and 1550nm, silicon becomes a very promising material for quantum communication. Due to its high refractive index contrast, silicon is able to provide strong light confinement. Silicon is highly compatible with integrated circuit manufacturing processes known as CMOS fabrication[4,6]. In order to operate within fundamental mode properties at a minimal propagation loss, the thickness of the silicon core has to be sufficiently small.

1.3 Lithium Niobate on Insulator
Recently, research on Lithium Niobate (LN) based photonic devices has been conducted due to its wide transmission window spanning from UV to mid-IR wavelength region and strong electro-optical coefficient. With an ability to produce high second-order optical nonlinearity, it leads to the tremendous progress in nonlinear nanophotonics technology. Unfortunately, the small index contrast between waveguide core and cladding results in large device dimensions and large bending radii which limits the ability for dense integration. Recently, the commercialization of LN on insulator (LNOI) substrate offers a brighter alternative to enhance the performance of LN [7-9] mainly for microscale LN waveguides and its application in nonlinear wavelength conversions.
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Figure 2 (a) (i) SOI and (ii) LNOI rib waveguide structure consist of Silicon Substrate, SiO$_2$ layer and Si (a) and LiNbO$_3$ (b) which act as a confinement layer. Figure 2 (b) 2D rib waveguide structure consist of SiO$_2$ structure and confinement layer (Si or LiNbO$_3$). The condition is set under the standard air condition ($n_{\text{air}} = 1$) on top of confinement layer.

1.4 Mode Analysis

In order to identify the modes of the waveguide, we have employed the eigen-mode solutions to the Maxwell equations with an appropriate boundary condition of the waveguide geometry. Currently, a number of numerical techniques can be used to analyze the waveguide modes such as the beam propagation method, effective index method and finite element method [6]. In this work the finite element method is used to conduct mode analysis as this method is used to obtain the polarization independence single mode waveguide with a small cross section as shown in Equation 1.1. This method has been introduced by Chan et al [5].

$$\frac{W}{H} \leq 0.05 + \frac{(0.94+0.25H)r}{\sqrt{1-r^2}}$$ (1.1)

where $r = h/H$ ($h/H < 0.5$ for small cross section), 1.0 um $\leq H \leq 1.5$ um

The thickness of the core, $H$ must be greater than the thickness of the slab, $h$ ($H > h$) to allow light confinement at the ridge. Apart from that, the variation of thickness and width of core affect the effective indices of refraction, $n_{\text{eff}}$ of the structure.

2. Geometrical and material optimization

The simulation of 2D rib waveguide has been performed to observe and analyze the mode propagation across the structure by using finite element analysis software. In this simulation, the dimension of the core is given by 0.5 $\mu$m x 0.3 $\mu$m (WxH) and the thickness of the slab, $h$ was set at 0.2 $\mu$m. The value of $h$ is set smaller than $H$ to optimize the mode confinement at the core. Based on Equation 1.1, width, $W$ of the core was varied from 0.5 $\mu$m to 1 $\mu$m to obtain a small cross section polarization independent single mode properties. Based on Figure 3, the refractive index of Silicon, $n_S$ and Silicon Oxide, $n_{SiO_2}$ are set at 3.5 and 1.5, respectively. Whereas for LNOI based waveguide structure, the refractive index of LN, $n_{LN}$ and Silicon Oxide, $n_{SiO_2}$ are set at 2.2 and 1.5, respectively. Hence, the value of refractive index differences, $\Delta n$ for both structures are given by 2.0 and 0.7, respectively.

The operating free space wavelength, $\lambda$ is set as 1550 nm for both SOI and LNOI structure. Alternatively, it has been optimized to 755 nm for LNOI, respectively as these material are optimally operated within this region. The mode analysis study was conducted to compute the propagation constant, wave number and mode confinement within the core area for a given frequency, $f_w$. These fundamental mode values are obtained based on the largest propagation constant and electric field distribution.
3. Results and Discussion

From the simulation of 2D SOI and LNOI rib waveguide, the geometrical structure has been optimized to obtain fundamental mode. The optical operation wavelength of SOI was set at 1550 nm whereas for LNOI was set at a pump wavelength of 1550 nm and second harmonic wavelength of 755 nm, respectively.

![Mode distribution across the (i) LNOI waveguide at 755 nm, (ii) LNOI waveguide at 1550 nm and (iii) SOI waveguide at 1550 nm as the width is varied to 500 nm, 700 nm, 900 nm and 1000 nm (from left to right).](image)

![Graph of effective refractive index versus width of core for the confined mode of SOI and LNOI rib waveguide.](image)

Figure 3 (a) Mode distribution across the (i) LNOI waveguide at 755 nm, (ii) LNOI waveguide at 1550 nm and (iii) SOI waveguide at 1550 nm as the width is varied to 500 nm, 700 nm, 900 nm and 1000 nm (from left to right). Figure 4(b) Graph of effective refractive index versus width of core for the confined mode of SOI and LNOI rib waveguide.

Figure 3 shows the cross section view of optical mode field distribution across the waveguide structure for (a) LNOI at 755 nm (b) LNOI at 1550 nm and (c) SOI at 1550 nm with a variation of cores’ width, W from 500 nm to 1000 nm. Consequently, the correlation between effective refractive indices and a variation of the width of the core are shown in Figure 4 (b). Based on Figure 4 a(i) and a(iii), the optimum single mode distributions were found consistently across the SOI waveguide structure. However, in LNOI waveguide at 1550 nm, the single mode distributions were only found as the minimum width, W of 900 nm was applied. These optical modes were presented as a solution of eigenvalue problem derived from Maxwell’s equation. From the simulation, the fundamental mode is selected based on the highest propagation constant, $\beta$ which reflected the maximum confinement of an electric field across the structure. The normalized propagation constant is interpreted in a form of a modified effective refractive index, $n_{\text{eff}}$. As shown in Figure 4(b), as the width of the core was optimized, the value of $n_{\text{eff}}$ varied. The graph shows that the value of $n_{\text{eff}}$ increase significantly as the width of core increased and it seems to be less sensitive to the wavelength variation especially for SOI waveguide. As the wavelength is varied at 1310 nm and 1550 nm for SOI and 755 nm and 1550 nm for LNOI, there are only a slight variation. The maximum value of $n_{\text{eff}}$ for SOI waveguide at 1310 nm and 1550 nm are given by 3.4786 and 3.4469, respectively. Whereas for LNOI waveguide at 755 nm and 1550 nm are given by 2.1890 and 2.1384, respectively. Equation 1.1, it indicates that the single mode condition is dependent on the size of waveguide but independent to the propagation length.

4 Conclusions

From the studies, it can be conclude that both material structures were able to produce single mode propagation with SOI showing higher confinement compared to the LNOI rib waveguide structure. Secondly, geometrical structure optimization is crucially required in order to obtain single mode
propagation. The LNOI rib waveguide gives the flexibility of wavelength range for single mode waveguide structure design. In this design structure, usually Second Harmonic Generation (SHG) or Spontaneous Parametric Down Conversion have modal phase matching so if the fundamental is single mode then the SHG should also be a single mode eventhough the waveguide supports a multimodes at this wavelength[13].

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