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# S-Bend Silicon-On-Insulator (SOI) Large Cross-Section Rib Waveguide for Directional Coupler

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**ABSTRACT**

S-bend contributes the high losses in the silicon-on-insulator (SOI) large cross-section rib waveguide (LCRW). The objective of this work is to investigate S-bend SOI LCRW with two different single-mode dimensions named symmetrical and asymmetrical. The S-bend SOI LCRW has been simulating using beam propagation method in OptiBPM software. The asymmetrical waveguide with two different dimension arc given the best performance if compared to others dimension with 3 µm of waveguide spacing. It achieved 92.24% and 91.10% of normalized output power (NOP) for 1550 nm and 1480 nm wavelength respectively. Moreover, the minimum of S-bend spacing between the two cores is 0.9 µm for both 1550 nm and 1480 nm. Therefore, asymmetrical waveguide with two different dimension arc and 0.9 µm of S-bend spacing are chosen. This analysis is important to determine the right parameter in order to design the SOI passive devices. However, future work should be done to see the performance by designing the coupler and implement in the real system.



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## 1. INTRODUCTION

Apart from being used as a material for designing transistors [1], silicon-on-insulator is also widely used as a material in optical waveguides. Silicon-on-insulator waveguide is one of the basic elements of silicon photonic devices including straights and bends waveguide which need to have extremely low propagation loss and low power consumption for large-scale integration [2]. Bend waveguide is well known to change optical propagation direction and allow reduction in device length. It is the most critical part in the design of large cross section rib silicon-on-insulator (SOI) coupler, splitter or taper. In fact, the mode profile inclines to shift toward the outer edge of the waveguide in a waveguide bend which creating loss. Fortunately, the high index contrast (HIC) in SOI allows the low bending loss due to the strong mode confinement if compared to a conventional low index contrast waveguide thus reduce the total size of the planar lightwave circuit (PLC).

Large-cross section SOI rib waveguide (LCRW) is tended to bend with millimeter (mm) scale dimensions which leads to even several centimeter scale circuits. The rib waveguide has low lateral index contrast which limits the minimum bending radius but enables single-mode operation. Even though the bending radii of LCRW is larger than silicon wire in SOI waveguide, the benefits of having LCRW are such as robustness to fabrication errors, minimum roughness of the etched surface, small birefringence, low-loss crossing, reduced fabrication cost, small polarization effect and efficient coupling to standard single-mode fibers [3]. Therefore, by reducing the size of bending radius of LCRW would enhance their benefits such as smaller size and reduction of cost. Currently, the optimum bends are being actively developed.

In general, the bending loss of SOI rib waveguide will decrease with the increment of bending radius and waveguide width while increase with the increment of the step factor. When the bending radius increased, more optical energy is confined in the waveguide layer due to decrement of the width of propagation mode field. The larger the waveguide width also results to the more difficult for the radiated energy to get out of the confinement layer. Therefore, radiated energy is reduced. However, the smallest bending radius is important in order to achieve denser integration in the PLC. Consequently, the size reductions of bending radius are being continuously investigated to increase the density of the integration. Moreover, the decrement of step factor can make the index of cladding decrease. It increased the index different between the core and cladding and as a result, strong confinement occurred.

There are several types of bend that are usually used in SOI design namely spline bend, S-bend, 90°-bend [4], 60°-bend, multimode bend [5] and adiabatic bend [6]. The selection of the bend is according to the design of the device and the application that requires the use of the particular bend. In this research, S-bend is selected. It is suitable for optical field input and output in series. In fact, there are many research focuses only on S-bend [7],[8] such as those investigating the effect of pure bending loss, transition loss [2], mode mismatch between straight and bend waveguide and higher order mode in large dimension bend waveguide.

The pure bending loss occurs when light at certain wavelength travels down a bend of constant radius which causes power dissipation and radiation. It can be reduced by increasing the rib width. However, when the rib width reaches a certain value, the pure bending loss cannot be reduced much further [5]. The transition loss is referred as the loss due to the modal mismatch between straight and bend modes. There are various methods to reduce transition loss. One of them is to change the lateral offset between the straight and the bend where precise control of the junction offset down to as small as 0.02 µm is required and the field distortion does not reduce [9]. In [10], the ideal lateral offset is reported as 2.7µm with 2.52% normalized output power improvement. Other method is to use an adiabatic mode transition between the straight and the bend waveguide which requires extensive design computation. The width and the curvature of the waveguides can be adapted continuously to mitigate the transition loss [11]. Large dimension bend waveguide also produced higher order mode (HOMs) by inducing significant coupling between different modes. Light is coupled from the fundamental mode in a straight input waveguide to the HOMs of a straight output waveguide which is placed after the bend. Therefore, bent waveguide must be single-mode to avoid unwanted coupling to HOMs when realization for small footprint and low propagation losses.

The bending losses will diminish the performance and reduce the function of the SOI devices. Numerous efforts are done to minimize bending losses. Some researchers use the different dimension of arm along the S-shape [8] and others used trench [12], additional groove, increase lateral index contrast on bend [13], reflection mirrors, corner mirrors [14], adding the spline bend between bend and straight waveguide [6] and phase-compensated micro-prism [15]. It is such a trade-off between the complexity of design, performance and the cost. However, the method is depending on the device to be developed and its application.

The purpose of doing this analysis is to compare the performance of S-bend at difference slab length. The S-bend design of the LCRW includes symmetrical and asymmetrical design which are similar in terms of width (W), height (H) and length (L) of the waveguide. Moreover, the analysis of waveguide spacing between two selected S-bend also has been done. The motivation of doing this work is to choose the right S-bend design with minimum loss and simple features which significant to enhance the performance of overall PLC coupler. The simulation is done using beam propagation method in OptiBPM 10 software.

## 2. RESEARCH METHOD

The operation of the micro-photonic devices commonly needs a single-mode (SM) behavior. It is important to ensure the optical waveguide allows light propagation in single-mode to avoid high loss. According to Soref [16],[17], the single-mode waveguide can be realized by the Eq. (1) below:

$$\frac{W}{H} \le 0.3 + \frac{r}{\sqrt{1-r^2}}, where r = \frac{h}{H} \ge 0.5 \qquad (1)$$

The height (H), width (W) and depth (d) is fixed where H and W are 5 µm while d is 2 µm. These values satisfied the single mode condition in (1) and to match with 5 µm single mode silica optical fiber. The value of silicon dioxide (SiO2) is usually from 1 to 3 µm to avoid penetration of light from core to substrate.

Figure 1 shows the SOI LCRW with refractive index of silicon, substrate and air are 3.5, 1.5 and 1 respectively.

There are basically three types of S-bend waveguide in OptiBPM layout designer which are arc, sine and cosine. In this work, S-bend arc waveguide is chosen. Instead of select the S-bend arc waveguide directly from draw menu, S-bend arc can be also made by two arms of arc waveguide. This is to allow the implementation of different dimension along the bend waveguide.

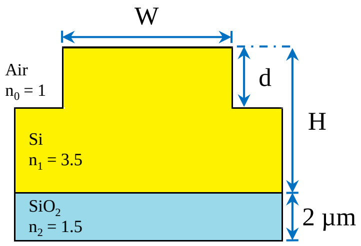


Figure 1. Large cross-section SOI rib waveguide

Figure 2 shows the S-bend waveguide in general. S-bend waveguide is divided into two arms named first arm and second arm in this analysis to make justification of each arm easier. R is the radius of curvature. S-bend offset must be higher than 62.5 µm to ensure the single-mode fiber can be couple at the output. The radius is selected based on the maximum power exit at the output with the change of length. Table 1 summarized the length, radius and offset of the S-bend used in this work.

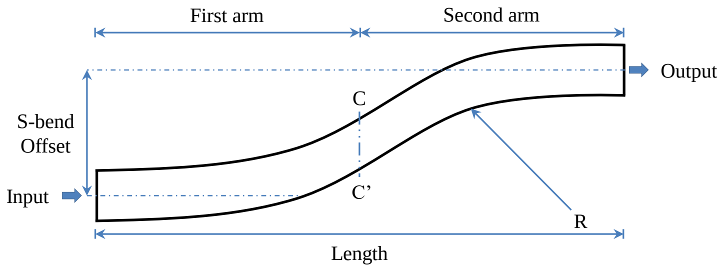


Figure 2. S-bend waveguide

Table 1. Summarized of S-bend specification

| S-bend specification | |
|---|---|
| Length, L | 3442 µm |
| Radius of curvature, R | ~40000 µm |
| S-bend offset, O | 64 m |

### 2.1. Symmetrical and asymmetrical S-bend

The analyses on symmetrical and asymmetrical waveguide have been done continuously for straight and S-bend waveguide. It is performed to investigate which dimension of the waveguide is suitable for straight and S-bend waveguide and also depends on its function. The S-bend waveguide can be designed by looking at the symmetrical-asymmetrical dimension and combined the various asymmetrical dimensions for better performance [8].

Three symmetrical dimensions of S-bend waveguides selected are shown in Figure 3. The rib height (H), rib width (W) and etch depth (d) of the rib are fixed while slab width has three different values which are 1.5 µm, 3.5 µm and 5.5 µm. Four different dimensions of asymmetrical S-bend waveguides are indicated in Figure 4. The rib height (H), rib width (W) and etch depth (d) of the rib are also fixed. First and second dimension are without outer and inner slab respectively with 1.5 µm of slab. Third design consists of two different dimension arcs without outer slab with 5.5 µm of inner slab. The last design is two different dimension arcs with 1.5 µm of outer slab and 5.5 µm of inner slab. Here, inner slab is a slab within the curve whereas outer slab is opposite with inner slab. Figure 5 shows the 3D waveguide layout in OptiBPM software for the fourth asymmetrical design.

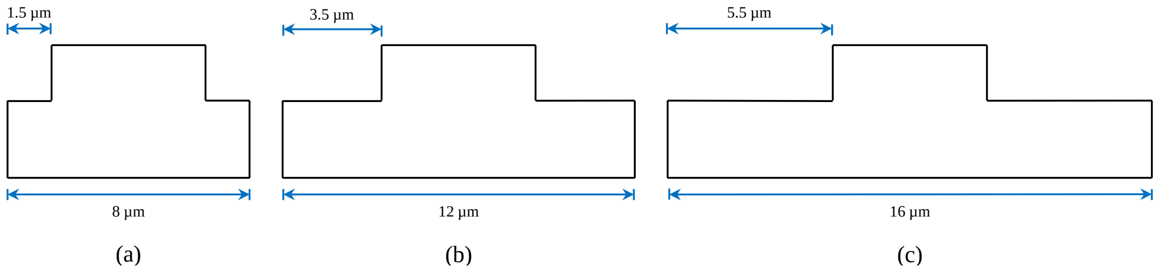


Figure 3. Symmetrical rib waveguide with (a) 1.5 µm (b) 3.5 µm and (c) 5.5 µm of slab length

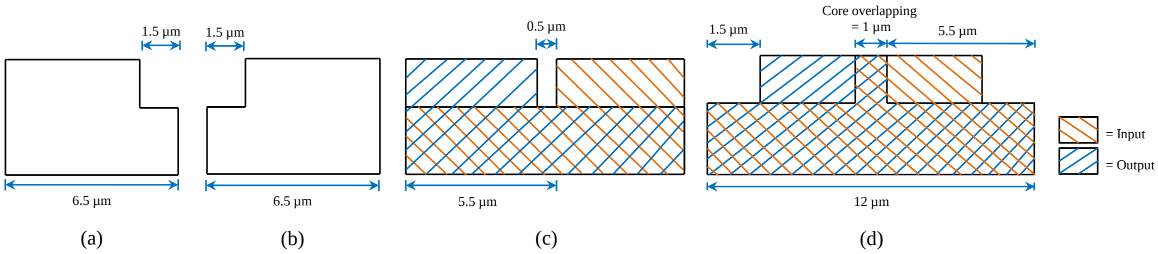


Figure 4. Asymmetrical rib waveguide (a) without outer slab (b) without inner slab (c) two different dimension arcs (without outer slab) and (d) two different dimension arcs (outer slab = 1.5 µm)

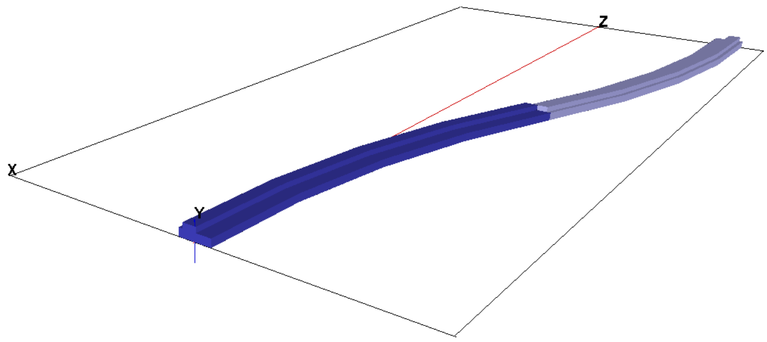


Figure 5. 3D waveguide viewer by OptiBPM software for two different dimension arc (outer slab = 1.5 µm)

### 2.2. Two asymmetrical S-bend

Two S-bends which represent two outputs as shown in Figure 6 must be considered in order to investigate the effect of the parallel path at the S-bend. The parallel path can couple the optical field from upper to the lower waveguide when these paths are close enough. Therefore, the S-bend spacing analysis is significant to observe light coupling and provide the minimum spacing between the S-bend waveguide. The S-bend spacing is referring to spacing between S-bend slabs. The dimension of asymmetrical S-bend as shown in Figure 4 (d) is used. The minimum waveguide spacing is identified when there is no optical signal leaving to the lower waveguide output.

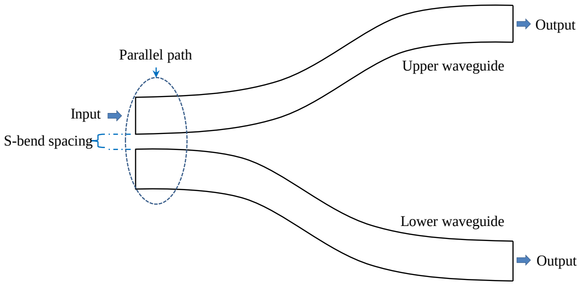


Figure 6. Two asymmetrical S-bend waveguide

## 3. RESULTS AND ANALYSIS

### 3.1. Analysis of symmetrical and asymmetrical S-bend

Table 2 indicates the normalized output power (NOP) for different dimension of S-bend. The result shows that the longer slab of the rib waveguide gives the larger NOP for the symmetrical waveguide. It provides up to 20% more power at 16 µm waveguide width if compared to 8 µm waveguide width. It is due to the longer slab feature which will confine the light better than the shorter slab which avoid light scattering outside the waveguide. However, longer slab is not suitable for light coupling with straight waveguide in coupler devices. If the waveguide spacing between two straight waveguides is too large in order to match with longer slab of S-bend waveguide, the length of parallel straight waveguide will become too long which can be several centimetres.

Table 2. Normalized output power for symmetrical and asymmetrical waveguide

| Types of S-bend arc | Normalized output power, NOP (%) 1550 nm | 1480 nm |
|---|---|---|
| Symmetrical | | |
| S-bend arc (slab=1.5 µm) | 75.22 | 77.92 |
| S-bend arc (slab=3.5 µm) | 91.68 | 91.17 |
| S-bend arc (slab=5.5 µm) | 95.60 | 94.98 |
| Asymmetrical | | |
| S-bend arc (without outer slab) | 88.32 | 89.47 |
| S-bend arc (without inner slab) | 88.32 | 89.47 |
| Two different dimension arc (without outer slab) | 88.02 | 87.55 |
| Two different dimension arc (outer slab = 1.5 µm) | 92.24 | 91.10 |

Alternative to symmetrical waveguide is the asymmetrical waveguide. Asymmetrical waveguide with two different dimension arcs will give the best result if compared to others asymmetrical dimension. These asymmetrical waveguide with two different dimension arcs will give 92.24% and 91.10% of NOP for 1550 nm and 1480 nm wavelength respectively. Here, the waveguide spacing between parallel straight waveguide can be made approximately 3 µm which can be accepted to minimize the size of the coupler device. Therefore, the overall S-bend width also can be diminished as much as 4 µm.

### 3.2. Analysis of two S-bends

Regarding to Figure 7, the minimum of S-bend spacing between the two waveguide cores is 0.9 µm for both 1550 nm and 1480 nm wavelength. If the S-bend spacing is less than 0.9 µm, undesired light coupling from launch waveguide to opposite waveguide will affect the percentage of transmission wavelength. Therefore, to design the coupler with the S-bend spacing less than 0.9 µm, the parallel path must be shorter in order to get the desire coupling ratio. There is almost 10% of light coupling to opposite waveguide for the zero S-bend spacing. The optimum value of NOP for 1550 nm and 1480 nm are 90.71% and 91.04% respectively with the minimum of 0.9 µm S-bend spacing.

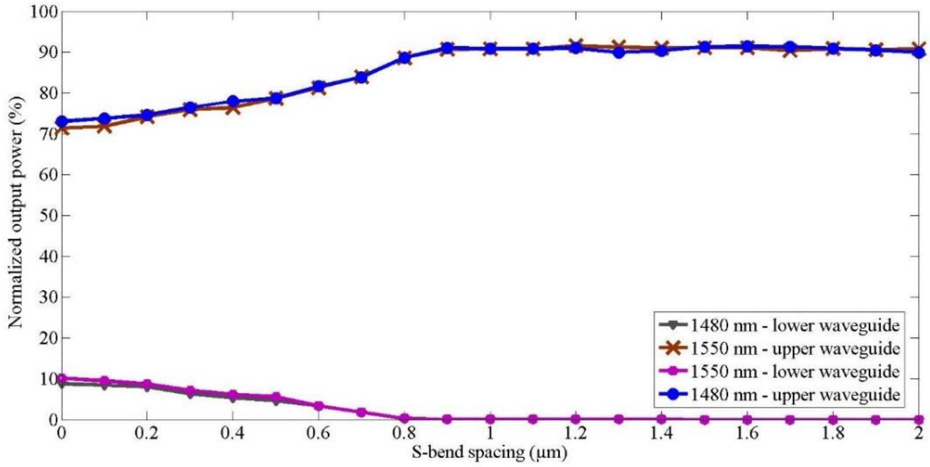


Figure 7. Normalized output power versus S-bend spacing for 1550 nm and 1480 nm wavelength

## 4. CONCLUSION

Asymmetrical waveguide with two different dimension arcs (outer slab = 1.5 µm, inner slab = 5.5 µm) is suitable for the coupler/splitter device design due to lower loss as compared to other dimensions. These waveguide designs allow transmission more than 90% NOP for both 1550 nm and 1480 nm wavelengths. In addition, the 0.9 µm of S-bend spacing is identified as a minimum value and a guideline to combine straight and S-bend waveguide for an effective coupler design.

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