Design and Measurement of the Silicon Slab Optical Waveguide

Dissertation Abstract

Design and Measurement of The Silicon Slab Optical Waveguide

シリコンスラブ光導波路の設計と測定

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ABSTRACT

The optical waveguide is one of the good supporting elements in the integrated circuits, because optical waveguide has brought advantages in terms of efficiency, energy consumption and size of the devices. The development of technology in the optical waveguide can be explored for many applications and purposes. Two of the most common types of optical waveguide are channel waveguide and optical slab waveguide. The quality factors of an optical waveguide are usually measured as propagation loss and scattering loss in the optical waveguide.

The silicon-based optical slab waveguide has been intensively studied at 1550 nm wavelength of light. The optical slab waveguide designed in our laboratory is built of silicon as a core, SiO_2 as the bottom layer (substrate) and air as the top cladding layer respectively. In this case, the incident light will be confined and guided in silicon core region. Based on total internal reflection (TIR), we positioned a mirror at 45 degrees from horizontal parallel to light propagation. Furthermore, the effects of the mirror size, curvature radius, length of the slab waveguide and optimization of the coupling system are studied. The loss due to several components such as roughness and imperfectness of the design was comprehensively analyzed. The effect of the mode propagation to the losses are also reviewed. According to the experimental data on the TE mode propagation, the mirror loss on our slab waveguide is 0.011 dB/mirror and the calculation on the TM mode is 0.007 dB/mirror. The mirror loss can indicate that there has been a slight loss on the mirror which might have been caused by the imperfection of the design of a slab waveguide.

Introduction

Current and future technological developments will be greatly influenced by the progress of integrated circuits, both in the electronic, optical or a combination of both. One thing that is very supportive in the development of integrated circuits is the optical waveguide, this is because the optical waveguide has brought increased efficiency, energy consumption and size of the device. The comparison between the development of circuits functionality and the cost per circuit becomes an interesting issue to discuss

Currently the development of optical waveguide can be enjoyed in a variety of applications and purposes. The two most prominent things about the types of optical waveguide that are widely used are channel waveguide and slab or planar waveguide. The quality of an optical waveguide is usually determined by propagation loss and scattering loss. But because the optical waveguide will be connected to an emitter device such as a laser or LED, there is usually loss due to connectivity, usually called coupling loss. As we all know that the waveguide channel has an advantage in confinement factor but the slab waveguide has other characteristics such as interference and scattering when two propagation lights do not intersect.

A slab waveguide allows light guiding through its volume without significant changes on its properties, thus opening the door to many high technology applications which include the communications, sensors, lasers and optics industrial sectors, among many others. Moreover, a number of new devices may be developed based on optical interconnects to implement distribution systems in parallel or cross-optical signals. The possibility of fabricating slab waveguides using inexpensive and simple technology opens a very interesting field of science.

In the optical slab waveguide, some references have discussed about how to focus light propagation into a waveguide slab, which is by utilizing a fine trapezoidal design which is commonly called a taper. The tapered design also can be applied in many applications in waveguides. Beside the tapered design, other application of slab waveguide that needs to be further developed is the mirror design. A mirror is usually constructed from differences of the refractive index between the optical waveguide and mirror edge.

The silicon-based optical slab waveguide has been intensively studied at 1550 nm wavelength of light. The optical slab waveguide designed in our laboratory is built of silicon as a core, SiO_2 as the bottom layer (substrate) and air as the top cladding layer respectively. In this case, the incident light will be confined and guided in silicon core region.[23-32)] Based on the refractive index differences between the core, substrate and upper cladding, the mirror in the optical slab waveguide with a 45-degree angle is fabricated and analyzed the mirror loss.[33-36)]

However, inputting the light from the optical fiber into optical slab waveguide is difficult. It is also difficult to collimate this input light during propagation in slab waveguide. To solve

these problems, the light propagation is introduced to the slab waveguide through additional taper waveguide to collimate the input light.

In this article, we propose to analyze some optical properties such us propagation loss, coupling loss and the mirror loss for the transverse electric (TE) and transverse magnetic (TM) modes. The characteristic of TE and TM modes when the light source propagates to the waveguide will determine the quality of the waveguides.

The main objective of this research is to design, construct, and test by simulation for optical silicon slab waveguide. The design of the slab waveguide consists of the taper design, curve mirror design, half-mirror design and retro reflector design. however, the optical integration in slab waveguide has never been analyzed in detail. The purpose of this research is to measure and analyze in detail about an optical slab waveguide in terms of propagation loss and loss of mirrors. The waveguides must be characterized to know their guiding properties. Furthermore, we also carry out simulations with the FDTD solution in the same design and compare the simulation with the experimental results.

Design

The slab waveguide consists of three layers of materials with different dielectric constants, extending infinitely in the directions parallel to their interfaces. The light may be confined in the middle layer by total internal reflection. This occurs only if the dielectric index of the middle layer is larger than that of the surrounding layers. In practice slab waveguides are not infinite in the direction parallel to the interface, but if the typical size of the interfaces is much larger than the depth of the layer, the slab waveguide model will be an excellent approximation.

- ## Taper

The function of the taper is to obtain an efficient coupling between two different optical waveguides which are channel waveguide and the slab waveguide. Normally, the function of the taper is to change the size and the shape of the optical propagation. The linear taper is adapted to this design as shown in Fig. 1.

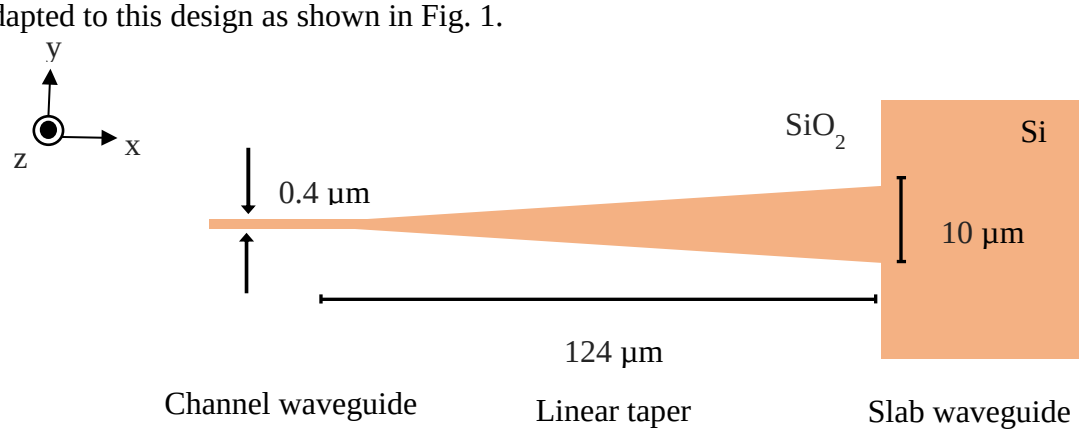

Figure 1. Design of the taper on top view in the slab waveguide.

The taper design with 124 µm in length, 0.4 µm of the input port, and 10 µm of the output port is designed after the channel waveguide to control the divergence angle of the input light of slab waveguide. Using taper structure, the divergence angle of the input light of slab waveguide can be kept small. The tapered design carries out the parallel pattern of the light with small divergence angle, even though the output beam size is larger than the input.

- **Curve mirror**

The light is needed to be reflected in the slab waveguide. One of reflecting mechanism to guide the light is by using mirror. The mirror's function is to reflect all incident light that propagates in slab waveguide. Our proposed design of the mirror adapted curvature with certain radius as shown in Fig. 2. The curvature design follows the concave mirror rule, that has focus point half of radius.

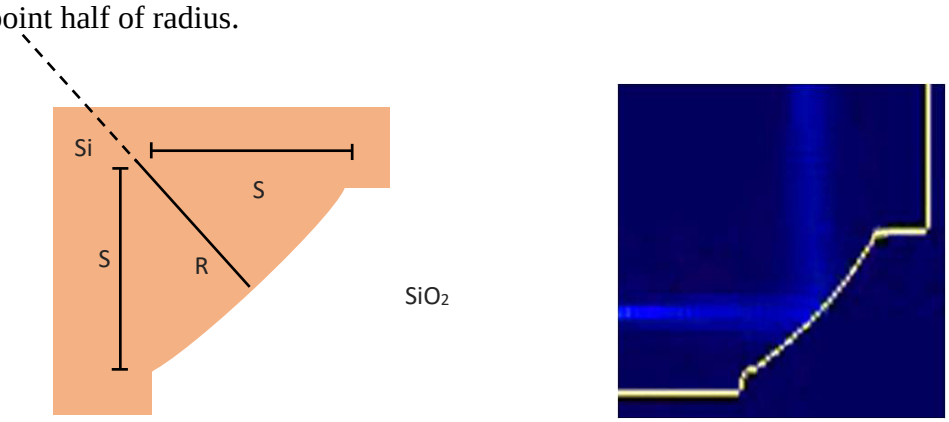

Figure 2. Design and the simulation result of the curved mirror on slab waveguide.

The radius (R) of the mirror should be correlated with the distance between the two mirrors. The radius of the mirror is 110 µm and the width (S) of the mirror is 24 µm. The distance between two mirrors are varied to be 50 µm, 100 µm, and 200 µm. By these dimensions, the performance of the mirror is expected to be optimal. Furthermore, the performance of this mirror is measured by the mirror loss.

Experimental Method

The propagation loss measurements are performed by inserting light from a laser to the optical power meter through the slab waveguide as can be seen from Fig. 3. The Polarizing Maintenance Fiber (PMF) is used to keep the polarization direction in the system. PMF ensures the propagation of polarized light is in the same direction. We also use a lens fiber before slab waveguide to minimize the coupling loss. Usually, the coupling loss occurs due to the different sizes of the input port and output port of the slab waveguide and optical fiber.

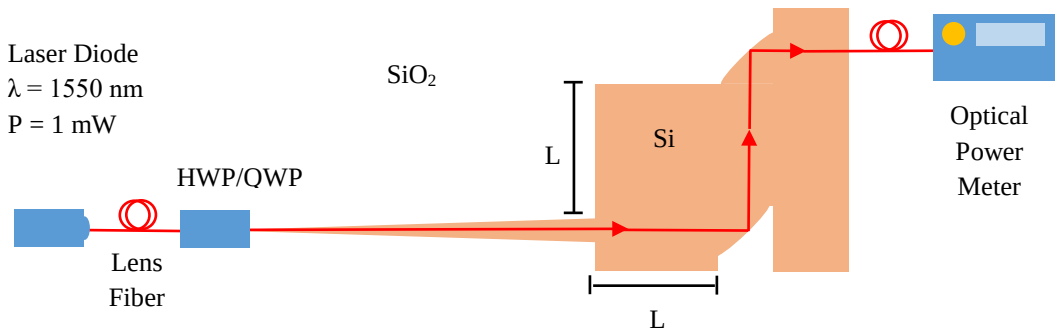

Figure 3. Experimental setup of the propagation loss measurement in slab waveguide.

The rotational wave plate imposes the incident light to become the TE polarization or TM polarization. The rotational wave plate consists of Half-Wave Plate (HWP) and Quarter-Wave Plate (QWP), as shown in Fig. 3. The combination of HWP and QWP generates one polarization mode. In this experiment, we use the tunable semiconductor laser with a wavelength of 1550 nm and an output power of 1 mW as the light source.

The incident light is reflected by the mirror in the slab waveguide, which causes the mirror loss. Commonly, the mirror loss is difficult to be measured directly. This experiment uses 2, 4, and 6 mirrors at the same distance between two mirrors (L) in the slab waveguide to measure the mirror loss. Furthermore, we conduct an experiment scenario of various L to measure the waveguide loss. The variant of L is 50 μm, 100 μm, and 200 μm at the same number of mirrors.

From the experimental results, the total loss of the slab waveguide is calculated from the value of optical power which is measured by the optical power meter after the propagation of light through slab waveguide and optical power which is measured before the propagation in slab waveguide as:

$$\text{Total loss} = 10 \log \frac{P_{out}}{P_{in}} \quad . \qquad (1)$$

In this calculation, P_{out} and P_{in} are the output and the input of the optical power in the slab waveguide, respectively. However, this total loss consists of some elements such as coupling loss, waveguide loss and mirror loss as can be seen from eq. (2):

$$\text{Total loss} = \text{Coupling loss} + \text{Waveguide loss} + \text{Mirror loss} \ . \qquad (2)$$

The coupling loss occurs at the mounting point between lens fiber and slab waveguide and between the slab waveguide and optical power meter. The waveguide loss might occur due to the scattering loss in the slab waveguide. The mirror loss occurs due to mirror design or size. This mirror loss includes the loss due to mismatch between the size of the mirror and the wave front of the propagated light (mirror mismatch loss) and the scattering at the reflection on the mirror (mirror scattering loss).

Result

Experiments with three different numbers of mirrors in slab waveguide for the TE and TM polarizations of input light are conducted. The experiments result are shown in Fig. 4.

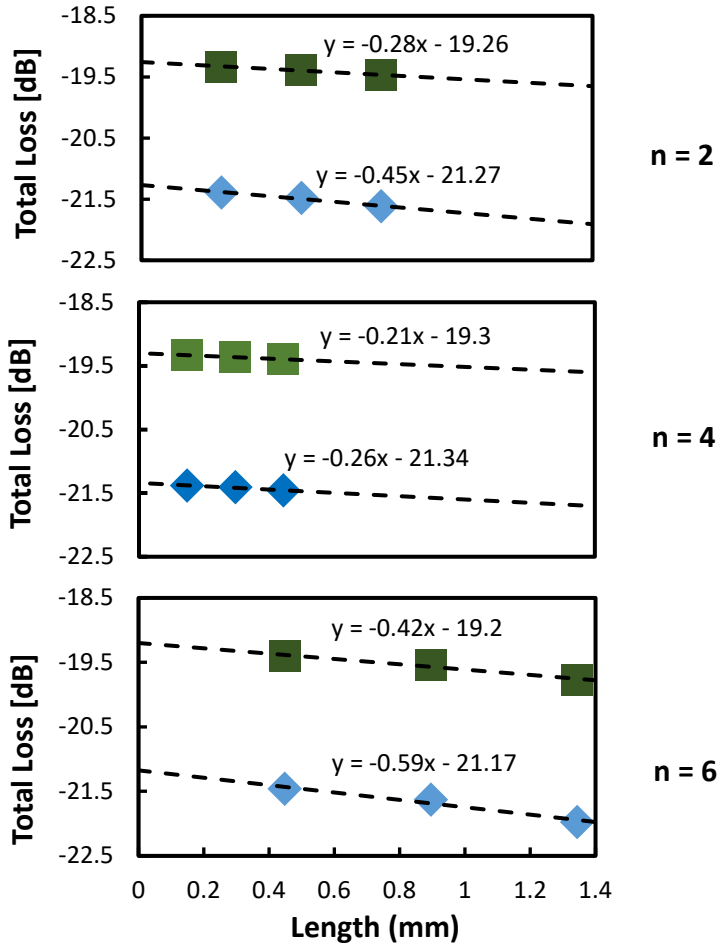

Figure 4. The dependence of total loss on the waveguide length in the slab waveguide. "n" is the number of mirrors. ■ and ◆ are the TE and TM polarizations, respectively.

Total waveguide length can be calculated as the total length between mirrors and the size of mirrors itself. The total waveguide length for 2 mirrors are varied to be 148 μm, 248 μm and 448 μm for 50 μm, 100 μm and 200 μm distance between mirrors respectively. The total lengths of the waveguide for 4 and 6 mirrors in slab waveguide are 296 μm and 444 μm (for 50 μm distance between mirrors), 496 μm and 744 μm (for 100 μm distance between mirrors) and 896 μm and 1344 μm (for 200 μm distance between mirrors) respectively. From Figure 6, the coupling losses of slab waveguide with 2, 4 and 6 mirrors can be calculated on the TE mode are 21.34 dB, 21.27 dB and 21.17 dB respectively, and on the TM mode the coupling losses are 19.3 dB, 19.26 dB and 19.2 dB.

The analysis based on experiment results shows that total loss increases as the number of mirrors and distances between mirrors increase. As shown in Fig. 6, the propagation loss is strongly influenced by waveguide length and number of mirrors. Furthermore, from the experimental results, the net waveguide loss is obtained to be 0.10 dB/mm and 0.09 dB/mm on the TE and TM mode respectively. Note that, net waveguide loss is the loss caused by the light propagation in slab waveguide and does not include mirror loss, on the other hand, in this analysis, the term "propagation loss" refers to the losses caused by the light propagation passing through the slab waveguide including mirror loss.

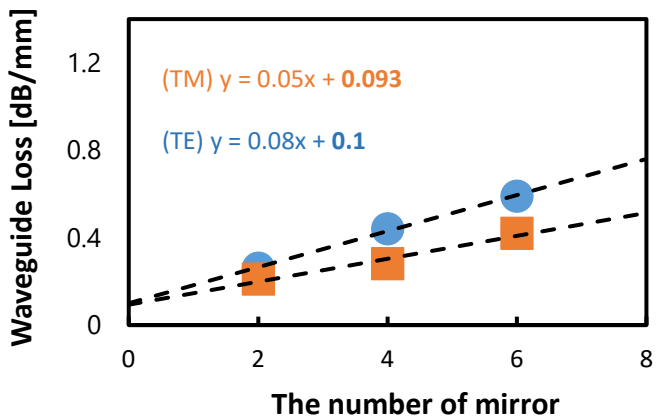

Figure 5. The linear regression to determine the waveguide loss.

The propagation length of light at each mirror was 24 μm. The distances between mirrors are 50 μm, 100 μm and 200 μm. Hence, in the slab waveguide with 2 mirrors, that the total waveguide lengths are 148 μm, 248 μm, and 448 μm. By the same calculation, the total waveguide length for slab waveguide with 4 and 6 mirrors are 296 μm and 444 μm, 496 μm and 744 μm, 896 μm and 1344 μm, respectively. From Fig. 7, loss condition at zero waveguide length is the coupling loss value. In TE polarization, the coupling loss values are 21.34 dB, 21.27 dB, and 21.17 dB for slab waveguide with 2, 4, and 6 mirrors, respectively. In TM polarization, the coupling loss values are 9.3 dB, 19.26 dB, and 19.2 dB for slab waveguide with 2, 4, and 6 mirrors, respectively. From Fig. 4, it is found that the total loss increases along with the increases of waveguide length and the number of mirrors.

Furthermore, from the gradient in Fig. 5, the net waveguide losses obtained are 0.10 dB/mm and 0.09 dB/mm for the TE and TM polarizations, respectively. Note that, the net waveguide loss is the loss caused by the light propagation in slab waveguide but excludes the mirror loss. The waveguide loss parameter in eq. (2) can be identified as:

$$\text{Waveguide Loss} = \text{net waveguide loss} \times \text{propagation length} \qquad (3)$$

Moreover, we can assume that the mirror loss is equal to the total loss subtracted by the coupling loss and the waveguide loss.

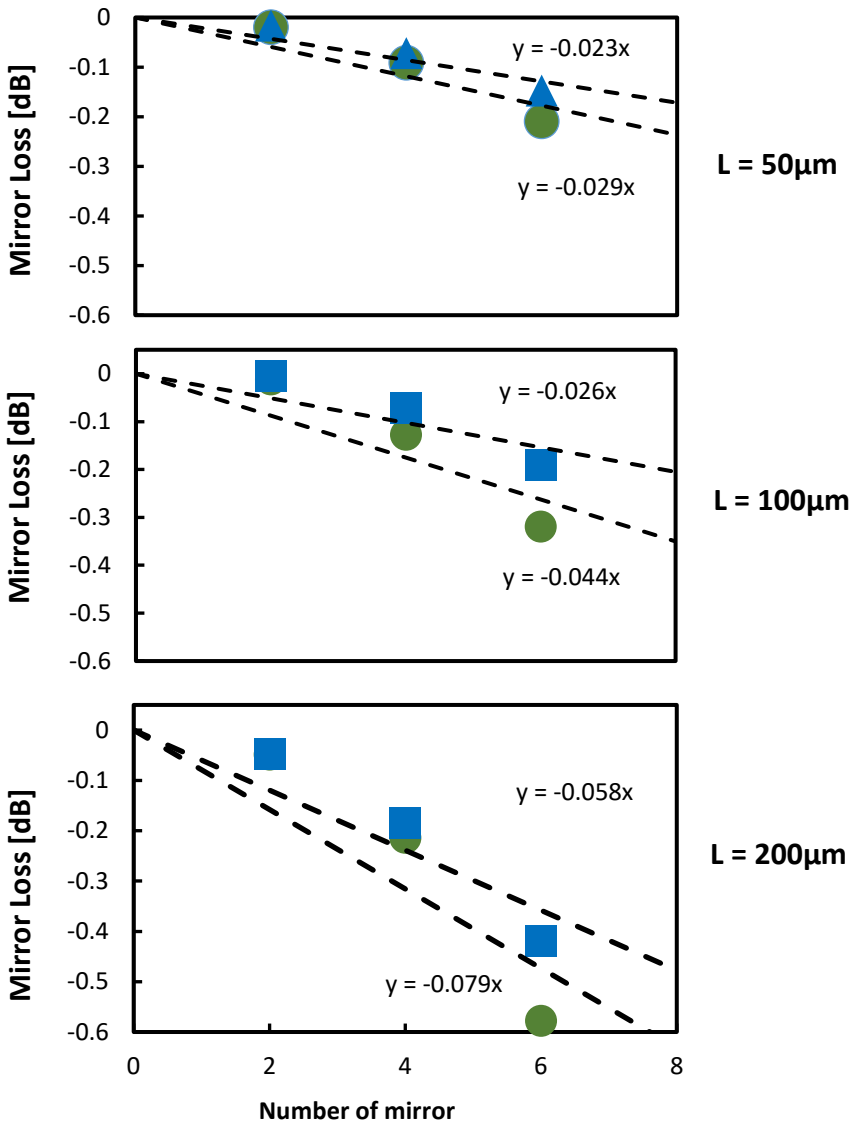

Figure 6. The dependence of the mirror loss on number of mirrors in the slab waveguide. "*L*" is the distance between mirrors, ■ and ● are the TE and TM polarizations, respectively.

The waveguide loss is strongly influenced by the waveguide length so that the calculation of the net waveguide loss must be adjusted. After the net waveguide loss is obtained, the mirror loss is defined. Furthermore, the calculation of the mirror loss which is shown in Fig. 9, does not involve the waveguide length variable anymore. The remaining variable affecting mirror loss is the number of mirrors. Figure 6 shows the mirror loss value, which is not influenced by the number of the mirror. The linear regression in Fig. 6 should be adjusted to force the mirror loss of zero mirrors to become zero value.

The mirror loss increases while the distance between mirrors becomes longer. This condition is affected by the waveguide loss and mismatch position. The mismatch position

might be related to the mirror size and the mirror position. Figure 6 also shows the mirror loss increases in the same trend in 4 and 6 mirrors scenarios. The highest mirror loss occurs while n=6 and L=200μm. The reason for the highest mirror loss is influenced by the waveguide length and the curvature radius of the mirror.

Furthermore, we calculate the average mirror scattering loss on each mirror in the slab waveguide. The average mirror loss is calculated from each value of 2, 4, and 6 mirrors. By the linear regression in Fig. 6, we describe the average mirror loss of each mirror as shown in Fig. 7.

The experimental result of mirror loss has been confirmed by FDTD simulation, in terms of the value and the image of the propagation direction. Based on the simulation, the curved mirror is better than the flat mirror in terms of directing the light in the slab waveguide.

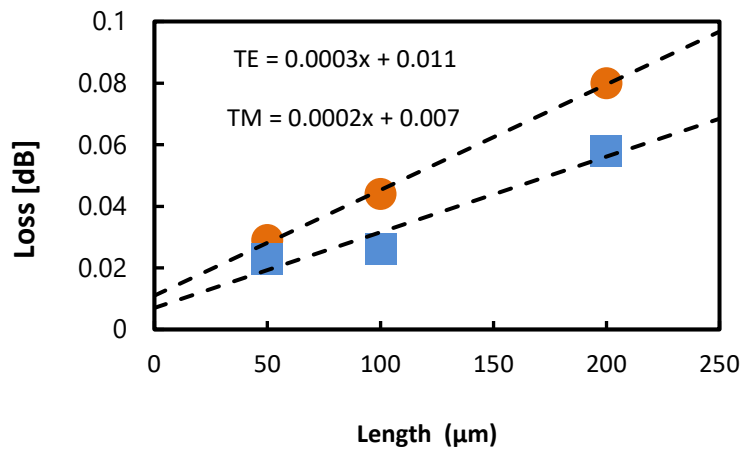

Figure 7. The calculation of the average mirror loss in the slab waveguide.

According to the experimental data, the mirror loss of our slab waveguide is 0.011dB/mirror and 0.007dB/mirror for the TE and TM polarizations, respectively. The mirror scattering loss indicates that there is a slight loss on the mirror which might be caused by the imperfection of the slab waveguide design. Both of the TE and TM polarizations, the results of the calculations give the good tendencies which are proved by the small value of the mirror scattering loss in the slab waveguide.

Conclusion

We investigated all properties of propagation loss in our proposed slab waveguide designed with mirror structures. In this analysis, we describe the propagation loss as the total of the coupling loss, waveguide loss, and the mirror loss. The coupling losses at the input and the output ports are the dominant factors in the total loss, but the coupling losses can be reduced by using a lens fiber at the input port. Moreover, the position and the size of the mirror also influence the mirror loss. The mirror scattering losses caused by the scattering of the light at the reflection on the mirror are 0.011 dB/mirror and 0.007 dB/mirror for the TE

and TM polarizations, respectively. The TE polarization is commonly used in the optical waveguide measurement. However, based on these results, the TM polarization can also be used for giving a similar result. From all the results, we conclude that our design can be applied.

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令和　2年　8月　3日

学位論文審査報告書（甲）

1．学位論文題目（外国語の場合は和訳を付けること。）

~~The~~ Design and Measurement of the Silicon Slab Optical Waveguide

(シリコンスラブ光導波路の設計と測定)

2．論文提出者　(1) 所　　属　電子情報科学　　専攻

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3．審査結果の要旨（600～650字）

当該学位論文に関し、令和2年（2020年）8月3日に第1回論文審査委員会を開催し、提出された学位論文及び関係資料について詳細に検討した。さらに同日に行われた口頭発表後に第2回論文審査委員会を開き、協議の結果、以下のように判定した。

本論文はシリコンスラブ光導波路を用いた光回路における、各光素子の提案及び設計、ファウンドリーサービスによる試作、光素子の測定と評価についての報告である。まず、空間光学系を集積化するためにはスラブ光導波路が有利であることを明らかにし、光回路で必要な、集光、コリメーション、反射、分岐に関する光素子をFDTD（時間領域差分）法を用いて設計した。ビームのコリメーションには長さ125μmのテーパー構造が有効であり、反射鏡には曲率（曲率半径56μm）を付加することでビームの広がりが抑制できることを明らかにした。また光分岐に用いるハーフミラーは空隙厚110nm（TEモード）、140nm（TMモード）とすることで得られる。これら設計した素子をCADファイルにし、ファウンドリーサービスで試作した。試作チップを測定することで、導波路損失0.1dB/mm、反射率99.7%以上が得られた。またモード（TE及びTM）による差異はなかった。

以上のように、本論文はシリコンスラブ光導波路を用いた光集積回路に関して有用な知見を得ており、学術的及び工学的な価値が高く、当該研究分野における十分な知識と自立して研究活動を行う能力を有することが論文の中で証明されていることから、博士（工学）に値するものと判定した。

4．審査結果　(1) 判　　定（いずれかに○印）　(合　格)・　不合格

(2) 授与学位　博　士（　工　学　）