Study of the Local Oxidation of Silicon Waveguide for Realizing the Intra-Guided Mode Conversions

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Abstract. The impressive achievements in research and developments of silicon-on-on-insulator (SOI) based silicon photonic integrated (PIC) devices have been made, but the coupling loss between the fibre and SOI waveguide is still a fatal problem. As well known, the butt coupling between a fibre and a low index-contrast silica-on-silicon (SOS) waveguide only causes a much lower optical loss, however, such a process between a fibre and a high index-contrast SOI waveguide creates a much higher optical loss. In this work, a 2-step intra-guide mode conversion of fibre-SOS-SOI structure is modelled and studied, in which a mitigating structure of SOS waveguide is created via a local oxidation of silicon (LOCOS) technique. The LOCOS method is an in-situ chemical process during the waveguides are fabricated without causing any extra fabrication, but it can control the physical parameters of the SOS waveguide through a chemical process. In such a 2-step intra-guide mode conversion, the total optical efficiency of the fibre-SOS-SOI structure is modelled, and the optical efficiencies of both the fibre-SOS mode conversion and the SOS-SOI mode conversion are systematically studied, and the broad dependences of guided mode profile on the chemical parameters of the LOCOS process are discussed. As a result, a total optical loss of <0.5dB for a butt coupling process between fibre and single-mode SOI-waveguide is achieved. So far, no similar practical butt-coupling method has been reported yet.

1. Introduction

In the past two decades, the impressive establishments in research and development of the photonic integrated components and systems with various silicon based optical waveguides have covered a broad range of advanced functions and applications [1,2]. Aimed at the applications, the silicon based waveguides, including earlier mature silica-on-silicon (SOS) strip or channel waveguide and the warming-up silicon-on-insulator (SOI) rib or strip waveguide, have formed a new technical area of optoelectronic integrated circuits (OEIC) and photonic integrated circuits (PIC) for fibre-optic telecommunications, computer data-communications, etc [3]. Therefore, it is clearly noticed that the era of silicon photonics with the high-performance costly functional components/systems and the advanced technologies is coming, driving the broad innovations and the extensions of applications. During various advanced PIC devices and systems are showing their potentials to the aforementioned areas of modern industrial applications, the realistic ‘bottle-neck’ stopping the high-performance photonic components and systems from the mass productions of industries is finally exposed out, especially, blocking the averaged-efficiency coupling between fibre and the chips of widely emphasized SOI PIC components and systems [4].
SOI waveguides are high index-contrast waveguides composed of the core of Si material having a much higher refractive index (~3.45) and the substrate/cladding layer material of material SiO₂ having much lower refractive index (~1.45), leading to small cross waveguide-size for single-mode [5]. So, the big discrepancies between fibre and SOI waveguide exist in both the dimensions and mode distribution. As a result, the much higher optical loss is unavoidable caused by the coupling process between the single-mode SiO₂ fibre and the single-mode SOI waveguide. Among the competitive technologies and methods that are reported to have compressed the waveguide-fibre coupling caused optical losses, the guided-mode conversions are the commonly aimed to solve, and various new structures and techniques have been developed to show the interesting benefits. The key fibre-waveguide coupling techniques are proposed and investigated, which are mainly the vertically coupled and the horizontally coupled gratings. The former has been widely exploited for the experiments in labs and the latter is still at the research stage. Each butt-coupling between fibre and SOS waveguide generally causes an optical loss lower than 0.3dB, but the coupling techniques between fibre and SOI waveguide that cause an optical loss lower than 1.0dB are seldom reported [6].

In this work, we propose a two-step mode conversion scheme of fibre-SOS-SOI system where an SOS mitigating waveguide is fabricated with a new technique of silicon waveguide fabrication, the local oxidation of silicon (LOCOS), to change a small-size high index-contrast SOI waveguide to a large-size low index-contrast waveguide at the input/output ends of SOI circuits. Thus, the butt coupling between fibre and SOI-waveguide is replaced with the two intra-guide mode conversions: a. from a fibre mode to an SOS mode and b. from the SOS mode to an SOI mode.

2. Configuration of fibre-SOS-SOI system with the intra-guide mode conversions

2.1. Theoretical model for the optical field transferring processes of an intra-guide mode conversion

As described in Introduction, the new theories and techniques of the coupling and mode conversion between the fibre and SOI waveguides are the drastic topics in the past decades. In order to completely solve this big coupling loss problem, in this work we propose a new configuration of an intra-guide mode conversion realize the low optical loss butt-coupling between fibre and SOI waveguide.

The butt-coupling configuration of fibre-SOI waveguide shown in Fig. 1 is composed of fibre, SOS waveguide and SOI waveguide, where the SOI taper type waveguide connecting the SOI strip or rib waveguide to the SOS waveguide. So, this configuration is referred to as the fibre-SOS-SOI system with which all the mode conversions from fibre mode to rib SOI waveguide are finished within guided channels without passing through any gap area, so the mode conversion is called intra-guide mode conversion. By defining \( E_x, E_{SOS}(I), E_{SOS}(O), E_{SOS}(tap-I), E_{SOS}(tap-O), \) and \( E_{SOS}(rib-I) \) to be normalized electric fields of the fibre mode at the output plate, the SOS waveguide mode at the input.
plate, the SOS waveguide mode at the output plate, the guided-mode of the SOI taper structure at the input plate, the guided-mode of the SOI taper structure at the output plate, and the guided-mode of the SOI rib waveguide, respectively. So, if the optical input power and the output power are $P_{in}$ and $P_{out}$, respectively, and the optical power of input from fibre is normalized, namely, $P_{in} = \int \int |E(x, y)|^2 dx dy = 1.0$, we have an optical butt-coupling efficiency between the fibre and SOI waveguide as defined by Equation (1) as

$$\eta(z) = \frac{P_{out}}{P_{in}} = (EC_1) \cdot (EC_3) \cdot \eta_{tap} \cdot (EC_3)$$

where the three field conversion efficiencies at the three interfaces are defined by [7]

$$EC_1 = (1 - R_1) \frac{\int \int |E(x, y)|^2 E_{SOS} (I : x, y, z) dx dy}{\int \int |E_{SOS} (I : x, y, z)|^2 dx dy}$$

$$EC_2 = (1 - R_2) \frac{\int \int E_{SOS} (x, y, z) \cdot E_{SOI}^* (tap - I : x, y, z) dx dy}{\int \int |E_{SOS} (x, y, z)|^2 dx dy \cdot \int \int |E_{SOI} (tap - I : x, y, z)|^2 dx dy}$$

$$EC_3 = (1 - R_3) \frac{\int \int E_{SOI} (tap - O : x, y, z) \cdot E_{SOI}^* (I : x, y, z) dx dy}{\int \int |E_{SOI} (tap - O : x, y, z)|^2 dx dy \cdot \int \int |E_{SOI} (I : x, y, z)|^2 dx dy}$$

$R_1$, $R_2$, and $R_3$ are the Fresnel reflections at the three interfaces. In this fibre-SOS-SOI system, the mode conversion efficiency $\eta_{tap}$ of the SOI taper waveguide is a complex function, so we use the finite difference beam propagation method (FD-BPM) to simulate and optimize this value.

2.2. The structure conversions from the SOI rib waveguide to SOS waveguide via LOCOS method

What need to be emphasised here is that in the fibre-SOS-SOI mode conversion system, the mitigating structure, the single-mode SOS waveguide connecting the fibre and the SOI waveguide is created with the LOCOS technique.

![Figure 2(a)](image1.png) **Figure 2(a).** Schematic configuration of the mode converter 1 (MC1) before the silicon strip is oxidized.

As shown in Figure 2(a), a small-size silicon strip is designed and fabricated on the SOI platform together with the same techniques as all the other SOI waveguides, and then oxidize this silicon strip to a large-size SiO$_2$ strip with the LOCOS technique to form the SOS waveguide core. So, after the top
SiO$_2$ layer is coated, a single-mode SOS waveguide is formed. In fact, the LOCOS technique was first developed to conveniently create the insulation lines and zones in the very large-scale electronic circuits (VLSC) around the begin of this century [8]. Update to 2010, the LOCOS technique was investigated again as a new waveguide fabrication approach by directly oxidizing the silicon layer to the silicon dioxide cladding layer to compress the sidewall roughness of the etched waveguides.

To create the single-mode SOS strip waveguide in Figure 2(b), the index-contrast of SOS waveguide is aimed to 0.75-2.0%, so we design the SOI strip dimension in Figure 2(a) to be the value that can become the SOS physical structure after being processed with LOCOS technique. The intrinsic relationship between these two waveguides is studied below. In the LOCOS process, the chemical reaction from Si layer to SiO$_2$ layer should meet the following chemical relation as

$$Si(solid) + 2H_2O(vapor) = SiO_2(solid) + 2H_2(vapor)$$

(3)

where the chemical solvent is the water at vapor state. If the dimensions of Si strip and SiO$_2$ strip are expressed with $X_{Si}$ and $X_{SiO_2}$, respectively, they can be either the width or height of a strip, we have the following intrinsic relation as [9,10]

$$R_{thick} = \frac{X_{Si}}{X_{SiO_2}} = \frac{V_{Si}}{V_{SiO_2}} = \frac{N_{Si}^S / \rho_S}{N_{SiO_2}^S / \rho_{SiO_2}} = \frac{28.08(g/mol)}{60.08(g/mol)} \times \frac{2.33(cm^3)}{2.21(cm^3)} = 0.44,$$

(4)

where $V_{Si}$ and $V_{SiO_2}$ stand for the volumes of Si strip and SiO$_2$ strip, respectively.

3. Simulations for optical mode conversions of the fibre-SOS-SOI system

At first, for the single-mode operations of both the SOI and SOS waveguides, we select the SOI substrate to have a 2.0μm thick BOX layer and a 1.5μm thick Si film, then design a rib waveguide with a 4.0μm width and a 0.5μm height; similarly we select the SOS waveguide core to have a width of 5.4μm and a height of 6.0μm. Then, at $\lambda$=1550nm wavelength and with the FD-BPM tool and the theoretical model Eq. (2), by setting a waveguide-fibre transverse shift of 0.5μm during coupling process, we obtain the simulations results of the waveguide-fibre butt coupling losses as shown in Figures 3(a) and 3(b), respectively. In simulations, what needs to be clarified is that the Fresnel reflection is considered, while the mode mismatching is not.

![SOI-FIB butt coupling loss vs end-gap](image1)

**Figure 3(a).** Simulations for the optical loss of butt coupling process between fibre and SOI-waveguide vs the fibre-chip gap size.

![SOS-FIB butt coupling loss vs end-gap](image2)

**Figure 3(b).** Simulations for the optical loss of butt coupling process between fibre and SOS-waveguide vs the fibre-chip gap size.
Note from Figure 3(a) that when the end-gap is approaches to 2.0μm, the coupling caused optical loss of one side is over 1.0dB albeit the mode mismatching is not considered. We know, a Corning SMF-28 fibre’s output beam generally has a distance of 2.0μm from the output end to the beam waist, and at the waist position the fibre guided mode has the smallest mode size, so optical loss from the direct butt coupling from the fibre to an SOI waveguide should be much higher than 1.5dB and the difference of the optical loss between TE and TM modes, namely, the polarization dependent loss (PDL) is also very high. In contrast with the SOI waveguide, if the waveguide end is changed to a single mode SOS waveguide, as shown in Figure 3(b), at the 2.0μm end-gap, the butt coupling optical loss should be lower than 0.5dB and the PDL is much lower. At this scenario, if we build an intra-guide mode conversion fibre-SOS-SOI system as shown in Figure 1, the end-gap will become a very small value, and even can be taken to be close to zero, so the optical loss is only from the mode conversion process.

In order to investigate the intra-guide mode conversion process of the taper structure shown in Figure 1, we must process the solutions of Maxwell’s equations for the guided mode to the two-dimensional (2-D) form below. As shown Figure 2(b), after the SOS waveguide section is formed via the LOCOS technique, the taper structure is also changed from a one-dimensional (1-D) taper to the horizontal direction (X-coordinate) to a 2-D taper at both the horizontal and vertical (Y-coordinate) directions. Thereby, the optical field of guided mode constantly changes during the propagation process and the solutions of Maxwell’s equations for this section should consider the interaction between the two mode components at X and Y coordinates, and the partial derivatives of the electric fields with respect to the position Z should be involved [11]. In the finite difference of BPM process, a slowly varying envelope approximation (SVEA), in a waveguide structure with the core material with a refractive index of $n$ and the cladding material with a refractive index of $n_c$, an optical field can be expressed by $E_{x,y}(x, y, z) = E_{x,y}(x, y)e^{-j n_k z}$, so the 2-D solutions can be expressed as [12]

$$2jn_k\frac{\partial E_z}{\partial z} = \frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_z}{\partial y^2} + \frac{1}{n^2} \frac{\partial}{\partial y} \left( \frac{\partial n^2}{\partial x} E_x + \frac{\partial n^2}{\partial y} E_z \right) + k_0^2 (n^2 - n_c^2) E_z$$

$$2jn_k\frac{\partial E_y}{\partial z} = \frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_y}{\partial y^2} + \frac{1}{n^2} \frac{\partial}{\partial y} \left( \frac{\partial n^2}{\partial x} E_x + \frac{\partial n^2}{\partial y} E_y \right) + k_0^2 (n^2 - n_c^2) E_y$$

\[ (5) \]

Figure 4(a). Simulation results for the TE mode distribution and changing of SOI taper structure in the XZ plane, where the arrow indicates the beam propagation direction. Figure 4(b). Simulation results for the TE mode distribution and changing of SOI taper structure in the YZ plane, where the arrow indicates the beam propagation direction.
Accordingly, with the FD-BPM powerful simulator that runs the equations of optical field of guided mode at any position of the taper structure in Figure 1(b), by selecting TE-mode, we obtain the mode amplitudes at two coordinate directions $E_x$ and $E_y$ from the light beam input end (from the SOS strip waveguide) to the output end (to the SOI rib waveguide) as shown in Figures 4(a) and 4(b), respectively. Note that the horizontal mode distribution ($E_x$) slowly stabilizes, while the vertical mode distribution ($E_y$) quickly stabilizes, and fortunately both $E_x$ and $E_y$ have reached the stable statuses in the set length of 400μm. In fact, the intra-guide mode conversion efficiency of fibre-SOS-SOI structure for the fibre-SOS-SOI chip butt-coupling can further be optimized.

4. Studies for the LOCOS technique
As a key stage to the fibre-SOS-SOI structure, the conditions of LOCOS for realizing the dimension extension (DE) and refractive index (RI) of the transferred SOS strip waveguide are studied as depicted in Table 1, where the accurate values of the parameters will be experimentally studied.

| Temperature | Reactive Time | Water gap density |
|-------------|---------------|-------------------|
| DE          | Yes           | Yes               | NA                |
| RI          | No            | No                | NA                |

5. Discussions and conclusion
To improve the butt-coupling efficiency between fibre and chip of SOI-waveguide chip, this work provides an intra-guide mode conversion scheme to replace the overlap interaction in the gap area between fibre and SOI-waveguide ends. In fabricating the mode convertors of waveguides, a LOCOS technique is employed to realize the changes of both the refractive index and dimension of SOI waveguide to the matching SOS waveguide. Therefore, this method has more room to be optimize.

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