Hybrid Integration Technology of Silicon Optical Waveguide and Electronic Circuit

Daisuke Shimura **Kyoko Kotani** **Hiroyuki Takahashi**
Hideaki Okayama **Hiroki Yaegashi**

Due to the proliferation of broadband services in recent years, the volume of information transmitted across the Internet is growing steadily. As a result, data processing capacity of information processing systems are expected to significantly increase. Signal processing in an information processing system can be classified as between equipment, between boards inside the equipment, and between chip and module inside the board. Currently, the use of optical fibers and optical waveguides are on the rise for inter-equipment and in some cases inter-board connections. The use of electrical wirings to make high-speed connections between the closely spaced chips in the board poses problems of noise interference, number of wirings and wiring size. Furthermore, judging from the yearly increases in information traffic, electrical wirings will no longer be adequate for interconnections, thereby raising the expectations of optical interconnection technologies.

Among the optical interconnection technologies, polymer waveguides and silicon photonics are being studied for use as optical circuit boards. Silicon photonics have extremely high refractive index compared to silicon oxide films or polymer waveguides meaning they have strong confinement of light and are less susceptible to bending loss. Therefore, silicon photonics can be used to form optical circuits with small radius curvatures. The recent advances in silicon process that make nm order processing possible and the availability of high-quality SOI (Silicon on Insulator) substrates have prompted many studies in silicon photonics. In particular, we are researching and developing silicon-wire waveguides. This article will first report on the silicon-wire waveguide design and evaluation of its basic properties. This will be followed by the simulation and evaluation of the wavelength mux/demux, a vital component in configuring an optical circuit. Finally, the article will report on a sample chip fabricated for a bi-directional optical module.

Silicon-wire waveguides

Silicon waveguides have been researched and developed in the past, and mainly there are two types of structures as shown in **Figure1**. Considering the difficulties of microfabrication, rib waveguide (3-5μm waveguide width) in **Figure 1 (a)** was often studied. However, with the rib waveguide, the circuit itself is large, and there is little benefit over conventionally developed polymer waveguides. On the other hand, the wire waveguide in **Figure 1 (b)** has a cross sectional area that is 1/100th of the rib waveguide making it a very useful structure for circuit integration and miniaturization. Since the goals of the study reported in this article were integration and miniaturization, the wire waveguide was adopted. To evaluate the basic properties of silicon-wire waveguide, design criteria was explored for the 1.31μm and 1.49μm bands used in FTTH (Fiber To The Home), a typical bi-directional optical component. Core size thickness of 300nm and width of 300nm was selected so that operation will be single mode at both 1.31μm and 1.49μm wavelengths and to achieve polarization independence. **Figure 2** shows the cross section of a fabricated silicon waveguide observed with a Scanning Electron Microscope (SEM).

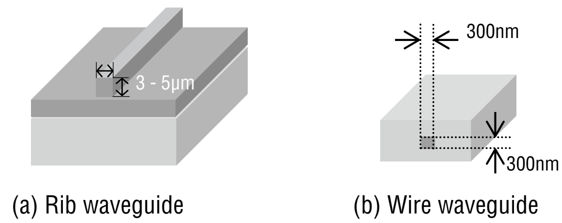


Figure 1. Waveguide Structures

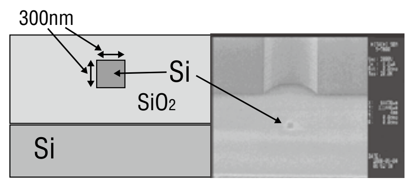


Figure 2. Actual Fabricated Silicon Waveguide
Left: Schematic Right: SEM image

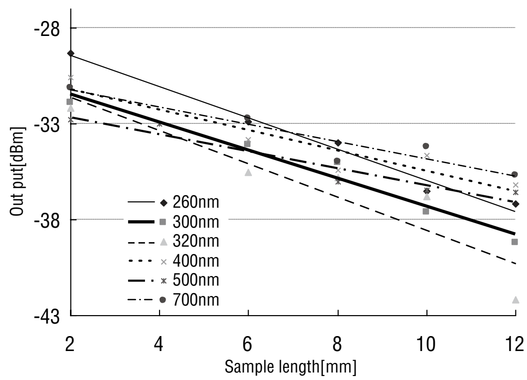


Figure 3. Straight Waveguide Propagation Losses

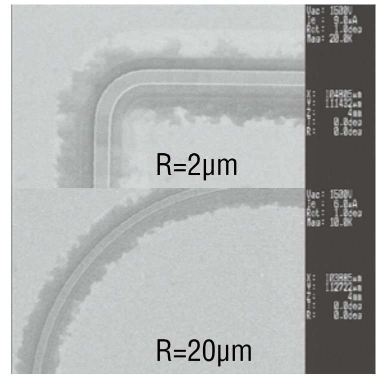


Figure 4. SEM Images of Curved Waveguides for R = 2 and 20μm

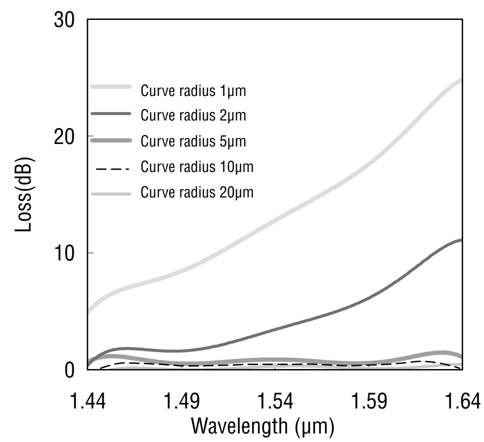


Figure 5. Loss Measurements for Curved Waveguides Curved waveguides of radius 1-20μm

Characteristics of basic waveguide

To examine whether the silicon waveguide is useful for the optical circuit, straight waveguides were fabricated and measured. In the experiment, lensed fibers and waveguides were actively aligned for maximum coupling efficiency. The light source was a tunable laser, and output was captured with a spectrum analyzer. Because the waveguides exhibited maximum Polarization Dependent Loss (PDL) of 2.0dB due to fabrication errors, measurements were taken after polarization was adjusted for maximum optical reception. In order to evaluate propagation losses of the standalone waveguides, cutback method was used to exclude connection losses. Measurement procedure was started with a 12mm long waveguide and shortened 2mm at a time. Measurements were taken for core widths of 260, 300, 320, 400, 500 and 700nm at each waveguide length.

Figure 3 shows the propagation loss for each waveguide width at a wavelength of 1.54μm. Propagation loss of 0.75dB/mm obtained for the 300nm width is a good value.

The losses of the curved waveguides were measured with the same experimental system as the straight waveguides. The five curved waveguide patterns tested consisted of fourteen 90-degree arcs linked by straight-line segments for each radius of 1, 2, 5, 10, 20μm. **Figure 4** shows the SEM images of curved waveguides with a radius of R=2 and 20μm, respectively.

Measurements of excess losses compared with straight waveguides of the same length are presented in **Figure 5**. Almost no curvature losses are observed above the radius of 5μm suggesting filter miniaturization will be possible during manufacturing.

Design and implementation of wavelength mux/demux

Wavelength mux/demux is one of the key elements in an optical circuit. The following properties and design guides are expected from the wavelength mux/demux.

- Polarization independent operation
- Reduced waveguide optical loss during multiplexing/demultiplexing
- Wavelength mux/demux size below 1mm to reduce propagation loss of entire circuit
- Form design possible with generally available machining process
- Wide tolerance for dimension errors and temperature changes

Multistage Mach-Zehnder, Arrayed Waveguide Grating (AWG) and multimode interference (MMI) are wavelength mux/demux for silicon-wire waveguides. Schematic of each wavelength mux/demux is shown in **Figure 6**.

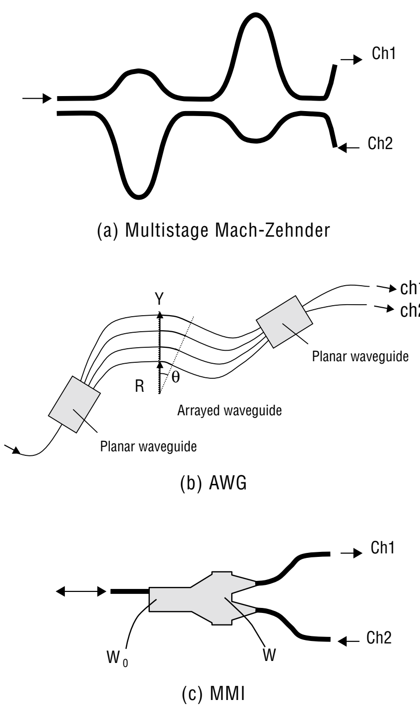


Figure 6. Overview of Wavelength Mux/Demux

Even if a 20μm bending radius is chosen to take into consideration bending loss, with the Mach-Zehnder wavelength mux/demux shown in Figure 6 (a), the total length is only 300μm thus designing very compact devices are possible.

Wavelength properties for the designed four-stage Mach-Zehnder wavelength mux/demux were calculated using two-dimensional FDTD (Finite Difference Time Domain) simulation and are shown in **Figure 7**. Crosstalk in the 1.31μm and 1.49μm band were 25-40dB (in same propagation direction). When this wave filter is used for a two-way communication module, transmitted light and received light propagates in opposite directions to each other. Of the crosstalk propagating in the same direction, the portion that is reflected back contributes to the actual crosstalk, therefore it is expected the effective crosstalk can be held to less than 40dB when applied to an optical transceiver module.

However, there are drawbacks. From the results of the straight and curved waveguide evaluations, it was found that polarization dependence could occur due to errors during fabrication. In case of the multistage Mach-Zehnder, if fabrication errors cause the two waveguides to differ in width, the desired mux/demux properties cannot be obtained. The AWG type of **Figure 6 (b)** and MMI type of **Figure 6 (c)** are also under study since they are relatively resistant to fabrication errors. With the AWG,

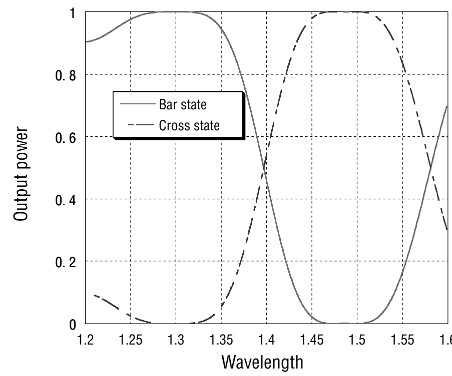


Figure 7. Four-stage Mach-Zehnder Wavelength Mux/Demux Two-dimensional FDTD Simulation Results

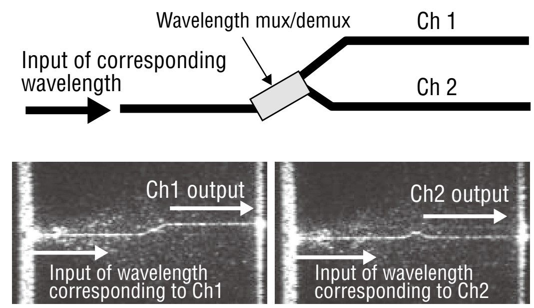


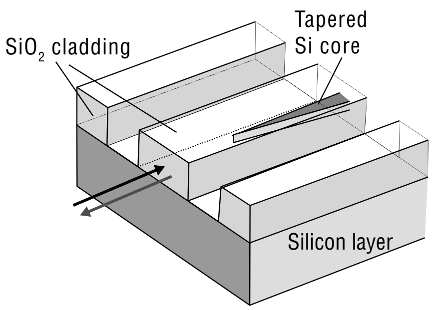
Figure 8. Observed Light Trajectories of Wavelength Mux/Demux

if a symmetric structure around the center point of the element is adopted, it can be made compact and made to fit into a 200μm×200μm square area. In case of the MMI, tapered waveguide widths were arranged making the gaps between the two waveguides that connect to optical transceiver element relatively small. This reduces light escaping from the gaps. AWG and MMI wavelength mux/demux are also currently under evaluation.

Figure 8 shows the operational overview and observations made with an actual wavelength mux/demux. Light trajectory of the optical waveguide was observed from the substrate surface using an infrared camera. When wavelength corresponding to channel 1 enters the input port, wavelength mux/demux selects the output port, and light is guided only to channel 1. A similar result was confirmed when wavelength corresponding to channel 2 was entered.

Bi-directional optical module

As an example of a silicon waveguide application, a bi-directional (BIDI) optical module is proposed. Normally, BIDI modules have many passive elements, which include ball lenses for spot-size converters and wave division multiplexing (WDM) filter. Since WDM filter and spot-size converters can be integrated in silicon waveguide circuits, the proposed module can be a simplified structure. Therefore, the proposed optical module significantly reduces total parts count and costs compared with Oki's μBOSA (Bi-directional Optical Subassembly) module[1]. The fabricated waveguide circuit for bi-directional optical module has a WDM filter and two types of spot-size converters. One is a tapered spot-size converter used between LD and waveguide shown in **Figure 9** (**a**). The other is a grating coupler used between PD and waveguide coupling shown in **Figure 9** (**b**).



(a) Tapered spot-size converter

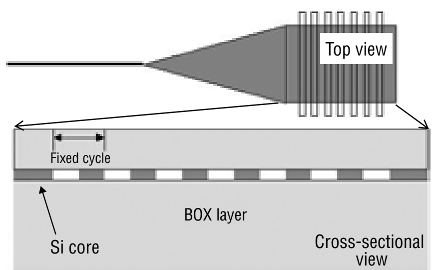


Figure 9. Couplers for Different Optical Elements

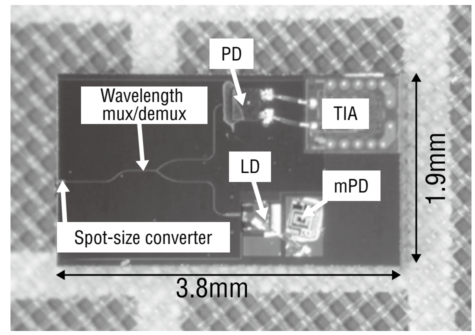


Figure 10. Sample of a Bi-directional Communication Module Silicon waveguide substrate mounted with LD/PD/mPD/TIA

Figure 10 shows the fabricated chip. The WDM filter and two converter types are integrated in a 1.9mm x 3.9 mm silicon optical bench (SiOB). First, the LD chip and PD chip were precisely mounted on the SiOB using Surface Mount Technology (SMT). Then the monitor PD (mPD) chip and transimpedance amplifier (TIA) were mounted. Average shear strengths for the LD chip and PD chip were excellent with more than twice the value specified in MIL standard (MIL-STD-883G)[2]. Through integration of the fabricated chip with external electrical circuits and packaging, compact optical modules will become possible.

TIPS

【Glossary】

Silicon Photonics
Silicon photonics is a general term referring to optical device technologies that utilize silicon as the optical medium. Compound semiconductors such as gallium arsenide and indium phosphide, or dielectric material such as quartz were commonly used in conventional optical devices. Miniaturized optical devices, integration of optical devices with silicon LSI, and improvement in production efficiency are some of the benefits that can be expected by switching to silicon material.

SOI(Silicon on Insulator)substrate
SOI substrate has a structure where thin films of quartz and silicon crystal are sequentially formed on top of a silicon substrate. Process for mass production is already established, and it is an inexpensive material for the manufacturing of silicon-wire waveguides.

Spot-size converter
Spot-size converter is a device with a function to convert the spot size of a light beam. It is used to reduce optical power loss at the light input/output.

Silicon-wire waveguide
Silicon-wire waveguide is an optical waveguide composed of a silicon core and quartz cladding. Optical waveguide is a pathway in which light is confined and propagated along a desired path. Silicon-wire waveguide can be bent sharper than conventional silica waveguide (minimum radius of 5 microns, approximately 1/1000 of what is possible with silica waveguide) enabling it to be placed in smaller areas.

FTTH(Fiber to the Home)
FTTH is a broadband network that provides optical connection to the subscriber's home.

Wavelength Mux/Demux
Wavelength mux/demux is an optical device that either combines light of varying wavelengths arriving from different paths into a single path or separates combined light of varying wavelength from a single path into different paths according to wavelength.

Conclusion

The status of our silicon-wire waveguide development has been reported in this paper. Various optical components of silicon wire waveguide were designed and fabricated. Upon evaluating fabricated waveguide, there is the issue of polarization dependence. We evaluated the results by simulation taking into account fabrication errors. Calculation results including the fabrication errors revealed that such errors strongly affect the polarization dependence. Through the improvement of fabrication process, this problem can be resolved. We demonstrated and fabricated bi-directional optical module using a waveguide circuit. Because the waveguide includes WDM filter and two coupling ports, this chip enables significant cost reduction both by reducing the part count used and by simplifying the assembly process. Besides aiming for further integration, future actions include consideration of arrangement patterns for the various elements to handle multiple optical elements and the study of wavelength mux/demux and input/output ports to support those arrangement patterns. ◆◆

■ References

1) Kyoko Kotani, et al., "μBOSA Chip Utilizing Si Lens for Low Cost FTTH", OKI Technical Review No. 207, Vol. 73 No.3, pp. 30-33, 2006

2) MIL Standards, MIL-STD-883G, pp. 354-355

● Authors

Daisuke Shimura, Network Technology Laboratories, Corporate Research & Development Center

Kyoko Kotani, Network Technology Laboratories, Corporate Research & Development Center

Hiroyuki Takahashi, Network Technology Laboratories, Corporate Research & Development Center

Hideaki Okayama, Network Technology Laboratories, Corporate Research & Development Center

Hiroki Yaegashi, Network Technology Laboratories, Corporate Research & Development Center