

## New Waveguide Fabrication Techniques for Next-generation PLCs

*Masaki Kohtoku<sup>†</sup>, Toshimi Kominato, Yusuke Nasu, and Tomohiro Shibata*

### Abstract

New waveguide fabrication techniques will be needed to make highly functional next-generation planar lightwave circuits (PLCs). After first reviewing the basic PLC fabrication process, this article describes recent progress in waveguide fabrication techniques. In particular, it describes a fabrication technique designed to make an ultralow loss waveguide for large-scale optical circuits, a fabrication technique that can produce ultra-compact optical circuits for high-density integration, and a laser direct writing waveguide fabrication technique whose goal is flexible waveguide formation and high-density integration.

### 1. Basic PLC fabrication process

Next-generation planar lightwave circuits (PLCs) will need circuits that have greater functionality and are larger in scale, but they must also be less expensive to make. To achieve this, we must continue improving the waveguide fabrication process and develop new ones. A PLC fabricated using a technique for fabricating optical fibers can provide a high-quality lightwave circuit on a substrate. This means that both PLCs and optical fiber use the same silica-based glass material, buried waveguide geometry, and glass forming method. The fundamental PLC fabrication process is shown in **Fig. 1**. First, SiO<sub>2</sub> and GeO<sub>2</sub> glass particles are deposited on a Si substrate by flame hydrolysis deposition (FHD). SiO<sub>2</sub> particles are deposited to form the under-cladding layer and GeO<sub>2</sub>-doped SiO<sub>2</sub> particles are deposited for the core layer. The photograph on the left of **Fig. 1** shows the oxy-hydrogen flame used to generate the glass particles used in the FHD process. Then, the substrate is heated to 1000°C, which consolidates the glass particles into a transparent glass film. Next, a rectangular core is formed by reactive ion etching. Finally, over-cladding glass is

deposited by FHD. The photograph in the bottom right of the figure shows that a well-defined rectangular core is embedded in the cladding glass.

PLCs employ low-cost Si substrates, so they have the potential to provide inexpensive circuits. Moreover, they have excellent mass-production characteristics, a low propagation loss, high stability, and good design flexibility. We are now developing new waveguide fabrication and design techniques with a view to producing lightwave circuits for new highly functional large-scale integrated optical circuits.

### 2. Ultralow-loss waveguide

To make large-scale optical circuits, we will need a waveguide with low loss. PLCs exhibit extremely low propagation losses compared with other waveguide materials such as polymers and semiconductors. However, PLCs have higher losses than optical fiber, so there is room for further improvement. The propagation loss spectra for a PLC waveguide are shown in **Fig. 2**. Previously, a PLC had a propagation loss of about 1.6 dB/m at a wavelength of 1.55 μm. We have improved the waveguide fabrication process to reduce the surface roughness of the waveguide, which in turn has reduced the propagation loss to 0.6 dB/m. A bent waveguide is indispensable if we are to make a long waveguide on a small area of wafer, but

<sup>†</sup> NTT Photonics Laboratories  
Atsugi-shi, 243-0198 Japan  
E-mail: kotoku@aecl.ntt.co.jp

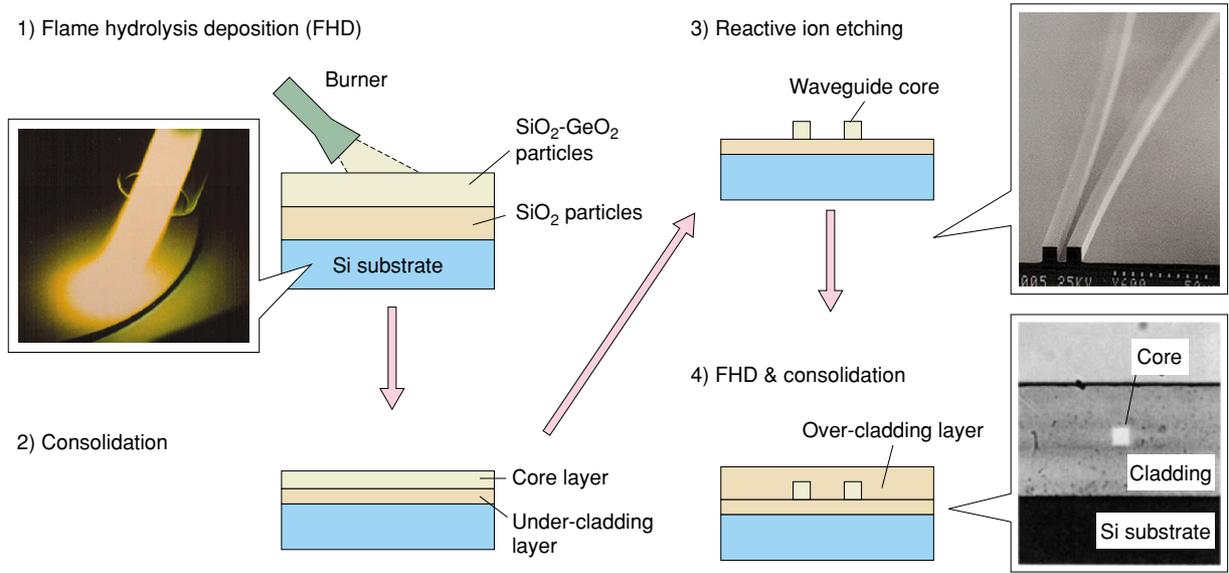


Fig. 1. Basic PLC fabrication process.

the bent waveguide becomes a source of propagation loss. Waveguide junctions between straight and bent waveguides are schematically shown in **Fig. 3** for (a) conventional and (b) newly developed structures. In the conventional structure, a straight waveguide and a bent waveguide are joined with a small optimized offset. Nevertheless, the field distributions for the straight and curved waveguides are slightly different. The loss at each junction is very small, but since a large-scale circuit usually has more than one hundred junctions, the loss accumulates and becomes high overall. With our new approach, we connected the straight and curved waveguides by introducing a clothoid function, which gradually reduces the bending radius in the bending direction. This method can yield an ultralow-

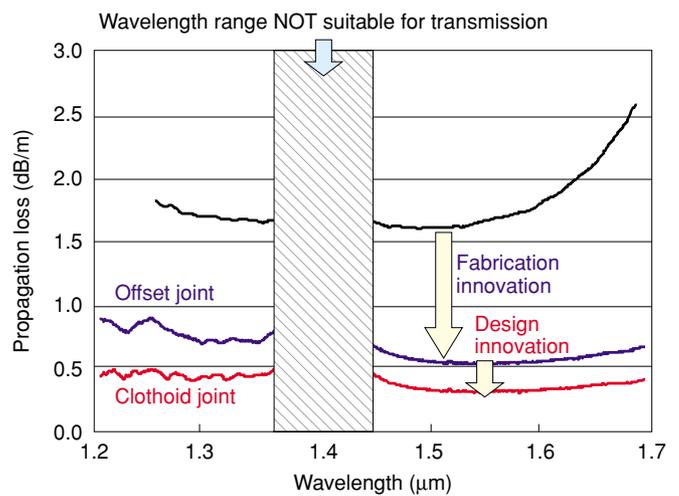


Fig. 2. Propagation loss spectra of waveguide.

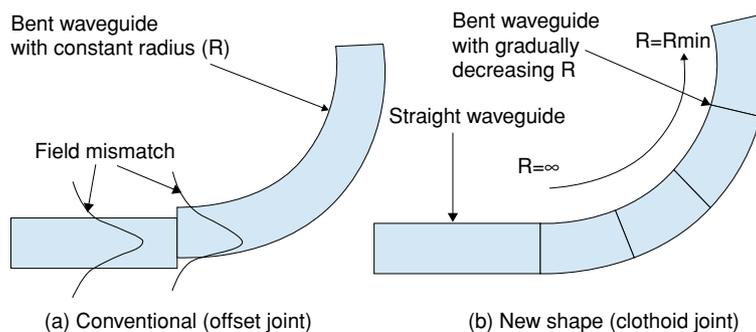


Fig. 3. Schematic views of waveguide joint.

loss waveguide with a propagation loss of 0.3 dB/m [1]. This waveguide will enable us to obtain optical circuits with a larger scale and a lower loss.

### 3. Waveguides for compact devices

We must consider reducing the chip size in order to construct a large-scale optical circuit at low cost. First, we must reduce the bending radius of the waveguide. For example, conventional optical fiber cannot be bent with a curvature of less than a few centimeters, so the circuit size becomes very large. Using a PLC decreases the minimum bending radius by increasing the relative index difference  $\Delta \cong (n_1 - n_2)/n_1$  ( $n_1$ : core index,  $n_2$ : clad index). The minimum bending radius for a  $\Delta$  of 0.75% (high  $\Delta$ : H $\Delta$ ) is 5 mm and that for a  $\Delta$  of 1.5% (super-high  $\Delta$ : SH $\Delta$ ) is 2 mm. To achieve a further reduction, we use a deep-ridge waveguide, as shown in **Fig. 4**. The deep-ridge waveguide consists of a core layer sandwiched between a SiO<sub>2</sub> cladding layer and the substrate; both sides of the waveguide are etched. This means that the waveguide is strongly confined by the air in the lateral direction. We increased the relative index difference for the lateral direction to 25% and achieved a minimum bending radius of less than 250  $\mu$ m.

The AWG (arrayed-waveguide grating) chip sizes of conventional  $\Delta$  and deep-ridge waveguides are compared in **Fig. 5**. An AWG with a deep-ridge waveguide has a chip size of about  $5 \times 7$  mm, which is about 1/20 that of the H $\Delta$  waveguide and 1/6 that of the SH $\Delta$  waveguide [2].

It has recently become easier to fabricate compact AWGs; however, the losses of these AWGs tend to be

higher than those of conventional PLCs. We reduced the AWG loss by introducing a vertically tapered waveguide at the junction between slab and arrayed waveguides [3]. The AWG has a loss of about 1.85 dB, which is almost the same as that of a conventional PLC-based AWG. This result shows we can achieve excellent characteristics even when fabricating a compact AWG, which will let us obtain very-high-density integrated devices at low cost.

### 4. Flexible direct laser-written waveguide

A method of writing waveguides directly in glass using a femtosecond laser was first proposed in 1996 [4]. We have recently utilized this approach to fabricate optical circuits. The femtosecond pulses can increase the refractive index to about  $10^{-2}$ . Since this occurs only at the focal point, by scanning the focal point, we can fabricate an optical circuit with a flexible layout design.

A PLC waveguide is fabricated with a planar core layer, so it is difficult to make a three-dimensional (3D) waveguide. However, the laser direct-writing waveguide fabrication method lets us fabricate a waveguide whose direction and shape can be readily controlled. Therefore, this approach has the potential to make high-density 3D circuits. In addition, we can make new functional devices by adding a new laser-written waveguide to a PLC.

Although the laser-written waveguide fabrication technique is effective for achieving flexible designs, it takes a long time to make a complex optical circuit. An effective solution is to fabricate a circuit using a combination of the laser-written and conventional

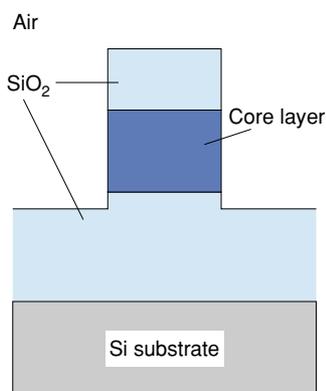


Fig. 4. Deep-ridge waveguide.

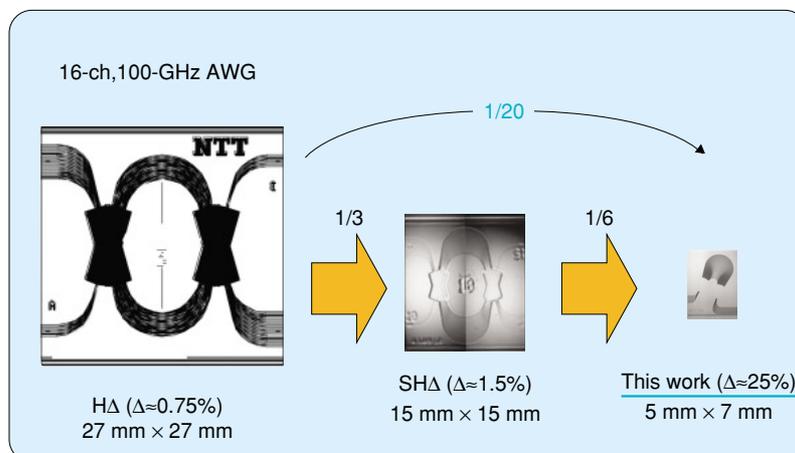


Fig. 5. Compact AWG and comparison with conventional AWG chip.

PLC waveguide fabrication techniques. We can expect to make a new waveguide circuit that offers high functionality, which can be changed at will.

It is more difficult to write a waveguide in PLC glass than in bulk glass because the PLC glass contains a dopant required for waveguide fabrication. When a femtosecond optical pulse is tightly focused on the glass film, optical damage can easily be induced and this makes it difficult to obtain a low-loss waveguide. **Figure 6** shows our new laser writing method for forming a low-loss waveguide in a PLC. With this approach, we write a narrow waveguide and overlap it several times to generate a nearly rectangular core shape.

In addition, we can connect a separate PLC waveguide to this laser-written waveguide [5]. Schematic views of waveguide interconnection achieved using a laser-written waveguide are shown in **Fig. 7**. This figure shows the junction of a PLC waveguide and a laser-written waveguide. The two waveguides are

well connected without any waveguide offset. The junction- and polarization-dependent losses of the junction are very small. This technique expands the potential for creating flexible optical circuits.

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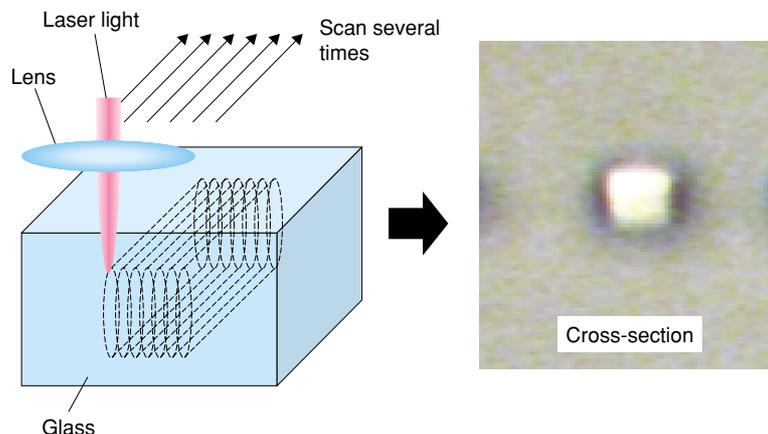


Fig. 6. Waveguide writing method for PLC.

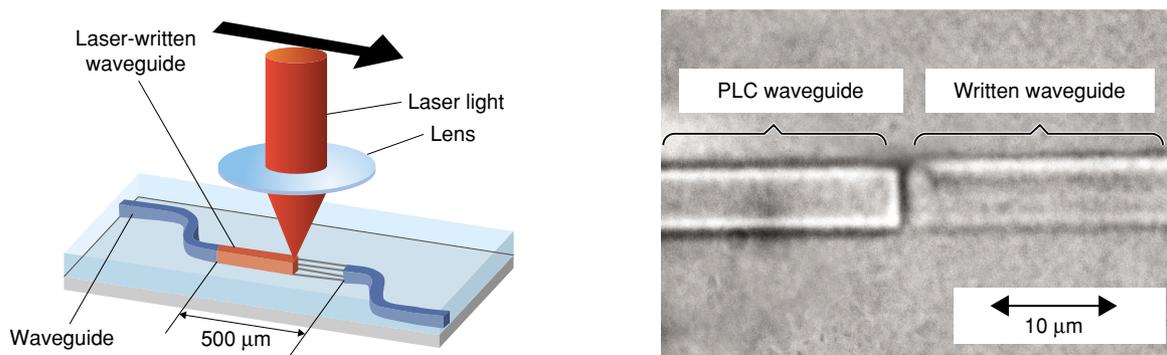


Fig. 7. Waveguide interconnection using waveguide written with a femtosecond laser.


**Masaki Kohtoku**

Senior Research Engineer, Hyper-photonic Component Laboratory, NTT Photonics Laboratories.

He received the B.E. and M.E. degrees in physical electronics from Tokyo Institute of Technology, Tokyo in 1989 and 1991, respectively. He is now engaged in research on semiconductor and silica-based waveguide devices. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan and the Japan Society of Applied Physics (JSAP).


**Yusuke Nasu**

Research Engineer, Hyper-photonic Component Laboratory, NTT Photonics Laboratories.

He received the B.E. degree in electrical engineering and the M.E. degree in electronic engineering from the University of Tokyo, Tokyo in 2000 and 2002, respectively. In 2002, he joined NTT Photonics Laboratories, Atsugi, Japan. Since then, he has been engaged in research on silica-based planar lightwave circuits for optical communication systems. He is a member of IEICE and JSAP.


**Toshimi Kominato**

Senior Research Engineer, Hyper-photonic Component Laboratory, NTT Photonics Laboratories.

He received the B.E. and M.E. degrees in electrical engineering from Tokyo University of Agriculture and Technology, Tokyo in 1985 and 1987, respectively. In 1987, he joined NTT Ibaraki Electrical Communication Laboratories, Ibaraki, Japan, and he has been engaged in research on optical waveguide devices. He is a member of IEICE and JSAP.


**Tomohiro Shibata**

Senior Research Engineer, Hyper-photonic Component Laboratory, NTT Photonics Laboratories.

He received the B.S. degree in physics, the M.E. degree in applied physics, and the Ph.D. degree in crystalline materials science from Nagoya University, Nagoya, Aichi in 1983, 1985, and 1995, respectively. In 1985, he joined NTT Laboratories, where he engaged in research on the epitaxial growth of thin-film semiconductors utilizing ECR plasma technology. He is now engaged in the fabrication of silica-based PLCs. He is a member of IEICE and JSAP.