

Development of Low Loss Ultra-High Δ ZrO₂-SiO₂ PLC for Next Generation Compact and High-Density Integrated Devices

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SUMMARY For next generation planar lightwave circuit (PLC) devices, high function and high-density integration are required as well as downsizing and cost reduction. To realize these needs, high refractive index difference between a core and a clad (Δ) is required. To use PLC for practical applications, silica-based PLC is one of the most attractive candidate. However, degradation of the optical properties and productivity occur when Δ of the core becomes high. Thus, Δ of most of the conventional PLC with GeO₂-SiO₂ core is designed less than 2.5%. In this paper, we report a silica-based ultra-high Δ PLC with ZrO₂-SiO₂ core. 5.5%- Δ ZrO₂-SiO₂ PLC has been realized with low propagation loss and basic characteristics has been confirmed. Potential of chip size reduction of the ZrO₂-SiO₂ PLC is shown.

key words: *integrated optics, MMI coupler, optical communication, optical device, planar lightwave circuit*

1. Introduction

For next generation planar lightwave circuit (PLC) devices, high function and high-density integration are required as well as downsizing and cost reduction. To realize these features, in general, high refractive index difference between a core and a clad (Δ) is required. Various devices employing core design with high Δ have already been reported, such as silica glass PLC, SiON, InP, and Si based waveguides [1]–[5]. However, high Δ waveguides generally cause degradation both optical performance and productivity. Especially, low propagation loss and low coupling loss to single mode fibers (SMF) are necessary for practical applications, and productivity is also important. All these technologies have advantages and disadvantages. The InP waveguide is smaller than the silica PLC, and the Si wire waveguide is the smallest platform among these materials, and these materials are advantageous for high-density integration. However, high propagation loss and connection loss to SMF become problem. On the other hand, the silica PLC has various advantages such as extremely low propagation loss, low connection loss to SMF, and established productivity. To take these advantages into account, the silica PLC is the most promising material if downsizing of the chip is realized.

In this paper, we report development of the silica-based high Δ PLC to realize downsizing of the chip. Ultra-high Δ PLC is realized by employing ZrO₂ as a dopant of the core, and the chip size is reduced drastically. We discuss

feasibility of the ZrO₂-SiO₂ PLC to use next generation PLC devices though fine characteristics of the PLC.

2. Design of Ultra-High Δ PLC

A PLC has the structure where light transmits the core embedded to the inside of the clad deposited on a Si substrate. To confine the light in the core, refractive index of the core (n_{core}) needs to be designed higher than that of the clad (n_{clad}), and the light is confined in the core by reflection at the boundary between the core and the clad. Since a chip size of the PLC is mainly determined by a minimum bending radius (r_{min}) of the waveguide, it is effective to reduce r_{min} . In order to make r_{min} small, it is necessary to confine the light strongly in the core by raising Δ . Therefore, it is necessary to raise Δ to reduce chip size.

In the conventional PLC, GeO₂ is doped to the core to raise the n_{core} higher than n_{clad} . In order to realize higher n_{core} , it is necessary to increase concentration of GeO₂. However, if the concentration of GeO₂ is increased, degradation of the optical performance and productivity of the PLC occur [1]. Thus, Δ of the most of the conventional PLC is designed less than 2.5%.

2.1 Required Δ for next generation PLC

Target Δ of the next generation PLC to realize downsizing of the chip and high-density integration is investigated. Relationships between r_{min} of the waveguide and Δ are calculated by beam propagation method (BPM). In this simulation, propagation loss of the waveguide with 90-degree bending is calculated. A bending radius (r) and Δ of the waveguide are given as variable numbers. When r is larger than the critical value, propagation loss is not increased by changing r . On the contrary, when the r becomes smaller than the critical value, propagation loss is increased as r becomes small. We defined r_{min} as r where propagation loss is increased by 0.01 dB. Figure 1 shows calculated r_{min} for each Δ . In general, Δ of the conventional PLC is designed about 1.5% or less to use practically. In this case, r_{min} becomes about 1500 μm to 2000 μm . When Δ is designed 2.5%, chip size is reduced to one-quarter of the conventional PLC. On the other hand, to satisfy the demands for the next generation high performance PLC devices, the target r_{min} needs to be set to 500 μm or less comparable as semiconductor waveguides [6] such as the InP waveguide.

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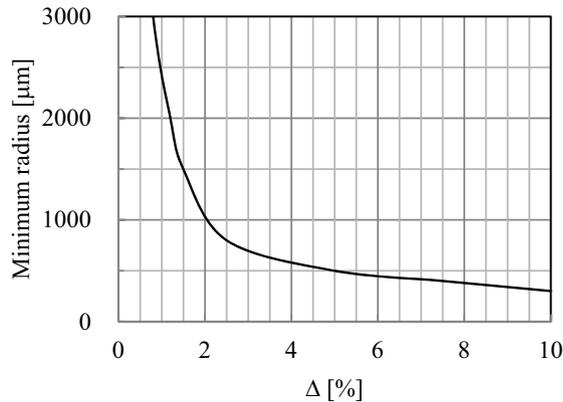


Fig. 1 Calculated minimum bending radius for various Δ .

However, since 5% or more Δ which exceeds maximum Δ of the GeO_2 - SiO_2 PLC is necessary to realize r_{\min} of 500 μm , changing dopant is necessary.

2.2 Material of dopant for ultra-high Δ PLC

A new dopant of SiO_2 glass to realize an ultra-high Δ PLC is investigated. At first, materials which have n higher than that of GeO_2 and lower thermal expansion coefficient are listed as candidates. Table 1 shows the characteristics of materials for the dopant [7], [8]. Since these materials are used as a dopant for SiO_2 glass, it is important for the dopant to have high affinity to SiO_2 .

Among these materials, ZrO_2 and HfO_2 have high affinity to SiO_2 . In comparison of ZrO_2 and HfO_2 , ZrO_2 has higher n , and raw material of Zr has advantages in terms of the low cost, large amount of deposits, and availability [9]. Then ZrO_2 is selected as the dopant for the ultra-high Δ PLC. In the case of the ZrO_2 doped glass, α_{glass} becomes equal to α_{Si} when Δ is about 15%. Thus, high Δ ZrO_2 doped glass is theoretically possible.

3. Fabrication Process of ZrO_2 - SiO_2 PLC

ZrO_2 doped ultra-high Δ PLC was actually designed and fabricated. Fabrication process of the ZrO_2 - SiO_2 PLC is following. ZrO_2 doped glass was formed by sputtering technique on an under clad deposited on a Si substrate. After the glass deposition, ZrO_2 doped glass was annealed over 1000 degree Celsius to remove defects generated in the deposition process. Next, waveguide pattern was formed by photolithography and dry etching. Finally the waveguide was embedded in an over clad. In the fabrication process of the ZrO_2 - SiO_2 PLC, we optimized annealing condition and dry etching process to reduce propagation loss of the ZrO_2 - SiO_2 PLC.

3.1 Annealing process

During the core deposition process, oxygen defects were generated in the glass, and the propagation loss became high due to its absorption. The oxygen defects were removed by

Table 1 Characteristics of Metallic Oxide Listed as Dopant for Ultra-High Δ PLC.

	Reflective index	$\alpha \times 10^{-6}$	Affinity to SiO_2
TiO_2	2.45	9.0	Poor
Ta_2O_5	2.20	5.0	Poor
Nb_2O_5	2.31	2.0	Poor
ZrO_2	2.17	8.0	Good
HfO_2	2.02	6.5	Good
GeO_2	1.70	12.0	Good
SiO_2	1.45	—	—

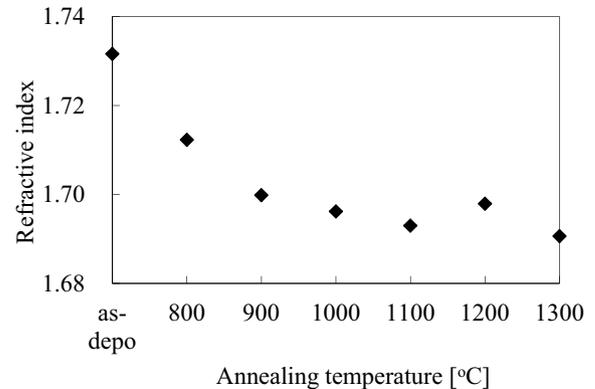


Fig. 2 Reflective index of ZrO_2 - SiO_2 glass for annealing temperature.

annealing treatment in oxygen ambient. Refractive index (n) of the glass depends on the interaction of light and the electron which constitutes glass. When the glass is considered to be an aggregate of ions, n is given by following equation based on Lorentz-Lorenz equation:

$$\frac{n^2 - 1}{n^2 + 2} = \frac{4\pi}{3} \sum_j N_j a_j \quad (1)$$

Where a_j is polarizability of ions, N_j is number of molecules. From equation (1), n becomes high when the glass consists of ions with high polarizability. Since the polarizability of O^{2-} is large among ions which constitute the glass, n of the glass with oxygen defects becomes high.

Figure 2 shows the relationships between annealing temperature and n of the ZrO_2 - SiO_2 glass measured by prism coupling method. n becomes low when annealing temperature becomes high, and n is stabilized by annealing at the temperature of 1000 degree Celsius or more. This result indicates that oxygen defects were removed by annealing with sufficiently high temperature. It is confirmed that oxygen defects are removable by annealing treatment with annealing temperature of over 1000 degree Celsius. However, crystallization of Zr is expected by exposing to the high temperature, and propagation loss will be increased by this effect. To clarify the effect of crystallization, An X-ray diffraction (XRD) spectrum of the ZrO_2 - SiO_2 glass was measured. Figure 3 shows the measured XRD spectra. From this result, crystallized material was deposited when the annealing temperature became high. The deposited grain was found to be ZrO_2 by spectrum identification. The mean size of the grain was calculated by Scherrer equation written as

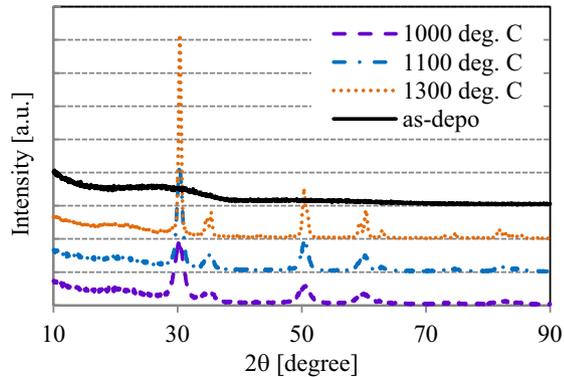


Fig. 3 X-ray diffraction spectrum of ZrO₂-SiO₂ glass related to annealing temperature.

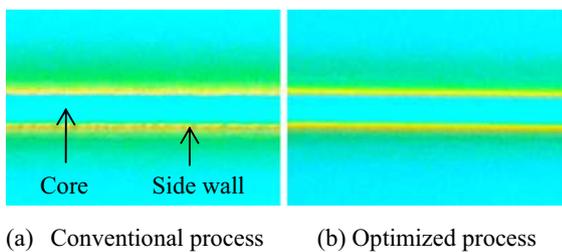


Fig. 4 Picture of the core of ZrO₂-SiO₂ PLC formed by dry etching.

equation (2):

$$\tau = \frac{K\lambda}{\beta \cos \theta} \quad (2)$$

Where τ is the mean value of the grain size, K is a dimensionless shape factor, λ is the X-ray wavelength, β is the line broadening at half the maximum intensity (FWHM), θ is the Bragg angle. Calculated grain sizes at the annealing temperature of 1000, 1100, 1300 degree Celsius were 1.2, 2.0, 4.4 nm, respectively. The Grain size became larger as the annealing temperature became high. However, these grain sizes were far smaller than wavelength of the light used for optical communication.

3.2 Dry etching

Surface roughness of the core will cause scattering of the light and an increase of propagation loss. Figure 4 shows pictures of the core of the ZrO₂-SiO₂ PLC after dry etching process. In the fabrication process of the PLC, waveguide patterns are formed by photolithography and dry etching after glass deposition of an under clad and a core. As compared with GeO₂ which is used as a dopant of the conventional PLC, ZrO₂ has high steam pressure of reaction products generated in the plasma etching process using halogen system gas as reactive gas [10]. Furthermore, for strong Zr-O coupling [10], ZrO₂ is etching material with difficulty. For these reasons, roughness of the sidewall of the ZrO₂ doped core was generated during the dry etching process with the same process conditions as the conventional PLC. Figure 4 (a) shows the core of the ZrO₂-SiO₂ PLC formed by dry etching with conventional process. The fabrication

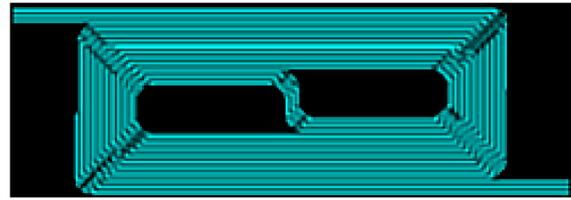


Fig. 5 Spiral circuit for propagation loss measurement.

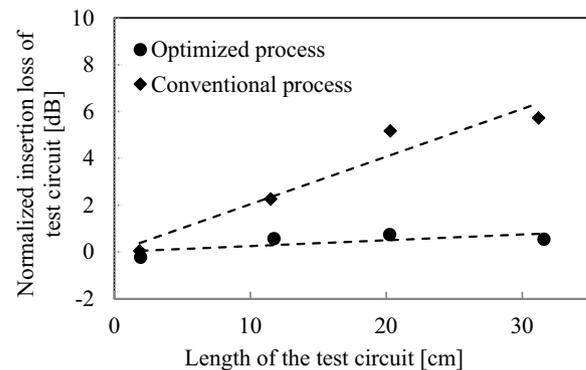


Fig. 6 Normalized insertion loss of the test circuit with various circuit length. Rate of increase of the insertion loss to circuit length is calculated as propagation loss.

process of the ZrO₂-SiO₂ PLC was optimized to reduce the roughness of the sidewall of the core. Figure 4 (b) shows the core of the ZrO₂-SiO₂ PLC formed by optimized process. From this result, roughness of the sidewall was reduced drastically, and scattering of the light was expected to be suppressed.

3.3 Propagation loss measurement

The propagation loss of the fabricated ZrO₂-SiO₂ PLC was measured. A spiral circuit shown in Fig. 5 was used for the measurement. Insertion loss of the spiral circuit with different circuit length was measured, and the rate of increase of the insertion loss to circuit length was calculated as a propagation loss of the PLC. Fig 6 shows the calculated propagation loss of the ZrO₂-SiO₂ PLC. First, ZrO₂-SiO₂ glass of 5.5%- Δ was deposited on the under clad, and annealing treatment was performed at the temperature of over 1000 degree Celsius. The size of the circuits using 5.5%- Δ core was set to $3 \times 3 \mu\text{m}$. When the spiral circuits were formed by the same process as the conventional PLC, measured propagation loss was 0.2 dB/cm. The propagation loss of the ZrO₂-SiO₂ PLC is about one-tenth of that of the InP waveguide [4], and low propagation loss was achieved among waveguides consisting of high Δ material by the effective glass deposition and the annealing process. However, the propagation loss was still higher than that of the conventional PLC. Then, the propagation loss of the circuit formed by the optimized fabrication process was measured. As a result, the propagation loss was successfully decreased to 0.02 dB/cm. Influence of the roughness of the sidewall of the core was clarified, and effect of the optimized fabrication

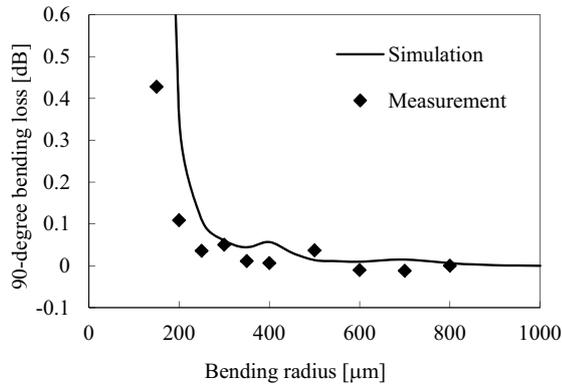


Fig. 7 Bending loss of the test circuit with various bending radius.

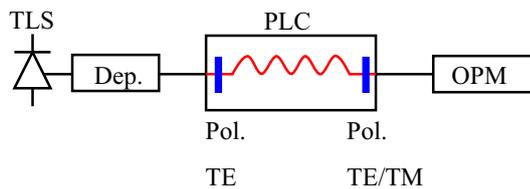


Fig. 8 Setup for PER measurement.

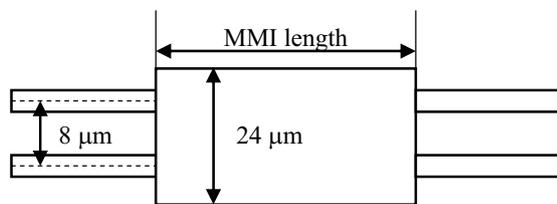


Fig. 9 Schematic diagram of fabricated MMI coupler.

process was confirmed. The low propagation loss comparable as the conventional PLC was successfully achieved in the 5.5%- Δ ZrO_2 - SiO_2 PLC.

4. Basic Optical Characteristics of ZrO_2 - SiO_2 PLC

The Low loss 5.5%- Δ ZrO_2 - SiO_2 PLC was realized by design and investigation of the dopant for high Δ silica glass shown in the Section II and the optimized fabrication process shown in the Section III. Basic optical characteristics of the ZrO_2 - SiO_2 PLC required for various optical devices are evaluated.

4.1 Minimum bending radius

A r_{\min} of the fabricated ZrO_2 - SiO_2 PLC was measured. Test circuits which comprised straight waveguide and bending waveguide with different bending radii were used for the measurement. Figure 7 shows 90-degree bending loss with different bending radii. This result indicated that r_{\min} of the ZrO_2 - SiO_2 PLC was 300 μm . This result shows that r_{\min} of the ZrO_2 - SiO_2 PLC was one-fifth or less as compared with that of the conventional PLC, and reduction of the chip size of the ZrO_2 - SiO_2 PLC was expected. This result agrees well with the result of the simulation shown as the solid line in

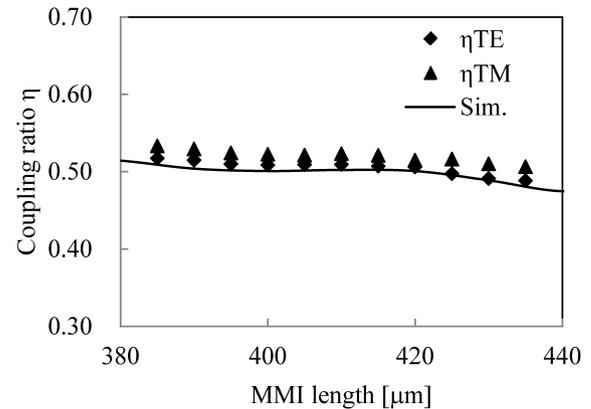


Fig. 10 Coupling ratio of MMI coupler for MMI length.

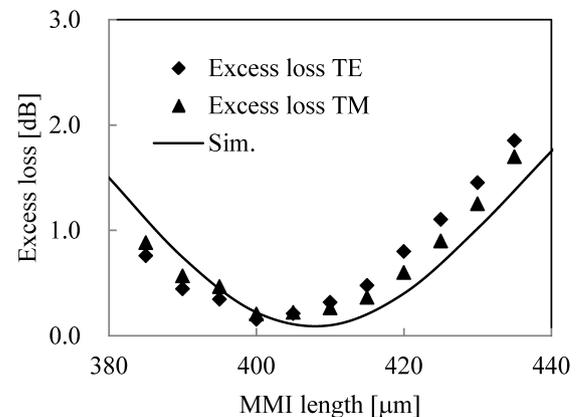


Fig. 11 Excess loss of MMI coupler for MMI length.

Fig. 7. From these results, we confirmed that the ZrO_2 - SiO_2 PLC was fabricated properly as designed.

4.2 Polarization extinction ratio

Polarization extinction ratio (PER) of the ZrO_2 - SiO_2 PLC was measured. Figure 8 shows a setup for the PER measurement. A tunable laser source (TLS) was used for the light source, and wavelength was set to 1550 nm. After pass through a depolarizer (Dep.), the light was launched into the PLC sandwiched between two polarizers. Intensity of the output light from the PLC was observed by an optical power meter (OPM). The polarizer (Pol.) which allowed to transmit transverse-electric (TE) wave was set to the input side of the PLC, and TE and transverse-magnetic (TM) Pol. were used for the output side. The PLC with the wavy circuit same as the one used in the r_{\min} measurement was used for the measurement. In the PLC, the TE Pol. launched a TE polarized light into the test circuit. If the light remains TE polarized, the light is shut off by the TM polarizer placed on the output side of the circuit, and then the high PER will be observed. The measured PER was 29 dB, and fine polarization maintaining characteristics was confirmed.

4.3 MMI coupler

In order to evaluate basic performance of the ZrO₂-SiO₂ PLC, we designed and fabricated a MMI coupler. The schematic diagram of the designed MMI coupler was shown in Fig. 9. Pitch of input and output waveguide and width of the MMI were set to 8 μ m and 24 μ m, respectively. Figure 10 shows relationships between MMI length and coupling ratio of the fabricated MMI coupler, and excess loss for the MMI length was shown in Fig. 11. In Fig. 10 and Fig. 11, plots show measured values for the input light with TE and TM polarization, and solid lines show calculated values. The measured values agreed well with the simulation. Low excess loss of 0.2 dB and coupling ratio of 0.5 were achieved as designed. Coupling loss between the fabricated ZrO₂-SiO₂ PLC and SMF was about 2.7 dB/facet with simple horizontal taper. Reduction of the coupling loss is expected by optimized interface such as a spot-size converter.

5. Conclusion

For the downsizing of the chip and high density integration required for the next generation PLC devices, compact silica-based PLC has been realized. The silica glass based 5.5%- Δ PLC is realized by employing ZrO₂ which has high refractive index and low thermal expansion coefficient as a dopant. The chip size of the fabricated 5.5%- Δ ZrO₂-SiO₂ PLC is reduced drastically to one twenty-fifth as compared with the conventional PLC due to its r_{\min} of 300 μ m.

The fabricated 5.5%- Δ ZrO₂-SiO₂ PLC has low propagation loss of 0.02 dB/cm, and PER of 29 dB. Fine characteristics of the MMI coupler are confirmed.

From these results, we confirmed that the ZrO₂-SiO₂ PLC is one of the most promising candidates for the next generation PLC devices.

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