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SOI-based Si/SiO$_2$ high-mesa waveguides for a compact infrared sensing system

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High-mesa waveguides have been fabricated for a compact infrared sensing system, as they have a benefit of having optical evanescent field outside of their solid waveguides and thus this contributes to the sensing of gas or liquid in a compact area. Fabricated semiconductor on insulator (SOI)-based Si/SiO$_2$ high-mesa waveguides, by using neutral loop discharge (NLD) plasma etching technique, showed extremely low propagation loss compared to those fabricated by using conventional reactive ion etching (RIE) technique. Moreover, we also demonstrate actual sensing for liquid methanol. By using 6 mm SOI-based Si/SiO$_2$ high-mesa waveguide with waveguide width of 0.7 μm, we could successfully obtain sufficient infrared absorption for the first time, therefore, this proved that the proposed waveguide had an optical field outside of the waveguide.

Key words: *optical waveguide, SOI, Si/SiO$_2$, high-mesa waveguide, breath-sensing, NLD plasma etching, low loss, infrared absorption, optical field*

1. Introduction

Handy health-check system has been desired for daily health-care recently. We focus on breath-contents as disease-markers, because human breath contains various diagnostic information[1)], with less detecting stress to human-body. For the development of such that breath-sensing[2, 3)] and others with easy-use, we have researched on compact sensing system by using photonic integrated circuits with telecom-band infrared spectroscopy. Especially, we have researched on compact gas or liquid-cell consisting from optical waveguides[4)] instead of using conventional free-space light propagation. By using the above mentioned compact gas or liquid-cell (we call this as waveguide-cell), it can be possible to realize very compact gas or liquid-cell[4)] compared to regular one.

One critical issue for such that waveguide-cell is the way how to introduce gas or liquid toward the propagating light into the waveguide. This is because a regular optical waveguide[5)] is consisted from solid material, which prevents gas or liquid penetration into light propagating region.

For realizing gas or liquid penetration into at least a part of propagating light, we have proposed to utilize high-mesa waveguide structure[4)]. High-Δ waveguide, such as (semiconductor on insulator) SOI-based Si/SiO$_2$ high-mesa waveguide, also contributes to realize compact sensing cell because this allows μm-order very small radius of curvature at bending waveguide[6)]. Based on the characteristics, we can design several meter long waveguide in very compact chip size[4)]. However, this kind of high-Δ waveguide may have a problem of having too much propagation loss[6)]. This is critical for sensing of gas since huge amount of loss prevent proper sensing of infrared absorption. For this reason, we have exploited neutral loop discharge (NLD) plasma etching technology[7)] for realizing extremely low loss SOI-based Si/SiO$_2$ high-mesa waveguide[8)]. NLD can realize highly dense plasma with low etching pressure, which contributes to relatively low etching-damage with high mask-selectivity. As a result, low propagation loss of 0.3 dB/cm at waveguide width of 2.5 μm has been achieved. Moreover, we also demonstrate actual sensing by using the single high mesa waveguide for the first time.

In this paper, the concept of our waveguide-cell is discussed in chapter 2. Then

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in chapter 3, we discuss about the above mentioned NLD technology, following with the actual results of low loss SOI-based Si/SiO$_2$ high mesa waveguides. In chapter 4, we demonstrate the sensing ability of the SOI-based Si/SiO$_2$ high mesa waveguide. In this work, we used liquid material to confirm its optical profile which must exist with a certain portion out of the waveguide.

2. Concept of waveguide-cell

A schematic concept of future waveguide-cell is shown in Fig. 1 (a). Based on an optical waveguide technology, it has a potential of integrating meter-long or even much longer path length, which realizes ppm-order small portion of gas sensing, in a very limited area. This is because the radius of curvature at the bending waveguide can be very small, especially in case of using high-Δ waveguide including high-mesa waveguide (a few μm order in the radius of curvature[6]). Based on the characteristics, we can design several meter length waveguide in very compact chip size. For instance, totally 5 m-long waveguide can be integrated in approximately 1 cm^2 area in case we design 5 μm for the radius of curvature[4].

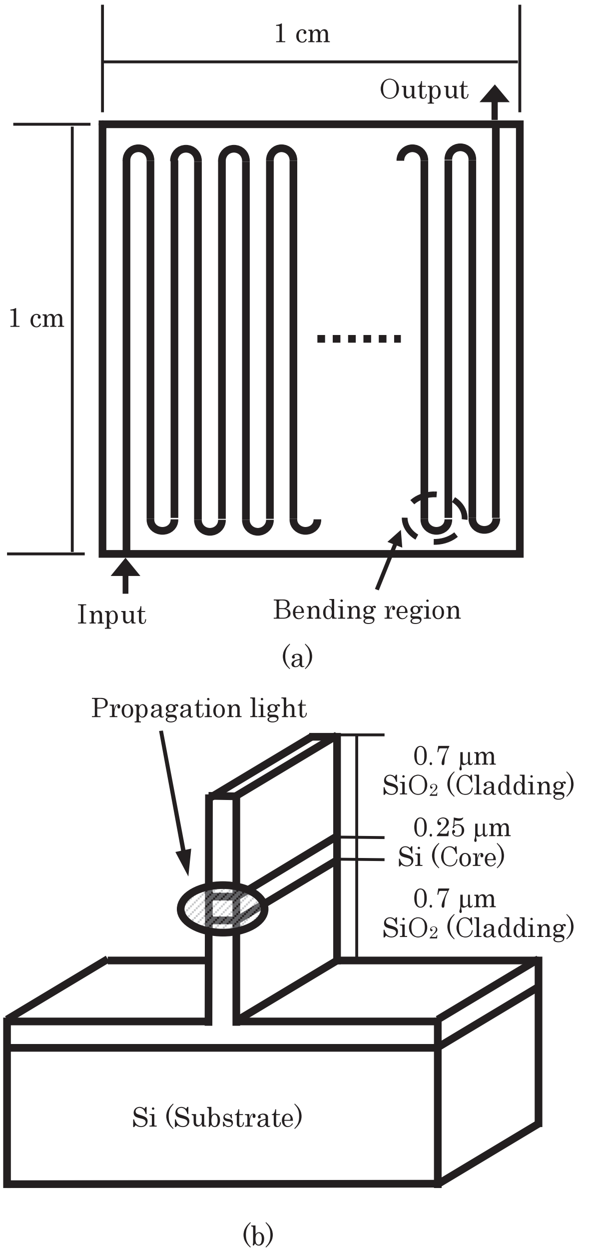


Fig.1 Schematics of waveguide-cell.

(a) Integrated waveguide structure.

(b) Perspective view of SOI-based Si/SiO$_2$ high-mesa waveguide.

As we mentioned in chapter 1, one critical issue is the way how to introduce a small fraction gas (or liquid) toward the propagating light into the waveguide. This is because that normally the optical field of propagating light in regular optical waveguides, such as buried-hetero or rib waveguide, is mainly profiled into solid material as an evanescent optical field.

On the other hand, in case of using SOI-based Si/SiO$_2$ high-mesa waveguide (see Fig. 1 (b)), a part of optical field is profiled out of the solid material. Figure 2 shows an example of an optical field in SOI-based Si/SiO$_2$ high-mesa waveguide (waveguide width w = 0.7 μm), calculated by using finite element method (FEM)[9]. As can be seen in this figure, approximately 5 % of its optical field is profiled out of the waveguide. This optical filed profile out of the waveguide, we called this as optical confinement Γ_{air}, can contribute to infrared absorption when gas or liquid is filled outside of the waveguide.

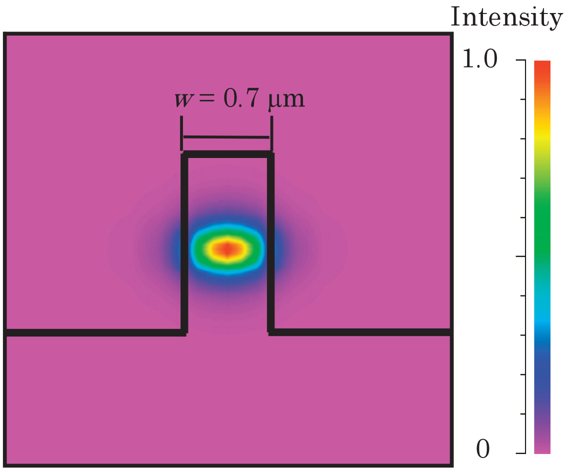


Fig.2 Optical profile of the designed waveguide.

3. Waveguide fabrication

3.1 NLD plasma etching

One critical issue for such that SOI-based Si/SiO$_2$ high-mesa waveguide is a propagation loss, that may prevent high sensitivity as is discussed in chapter 1. For this reason, we have tried to realize low propagation loss waveguides by using NLD plasma etching[10]. The configuration of NLD plasma etching system, shown in Fig. 3, is similar to those of conventional inductively coupled plasma (ICP) etching one[11, 12]. The difference is that the NLD one has "magnetic neutral loop", which contributes to high plasma density and low electron temperature with low etching pressure compared to ICP one. Such NLD plasma, which has those characteristics, is therefore suitable for the implementation of low loss optical waveguide as it is expected to offer low plasma damage with high selectivity against etching-mask.

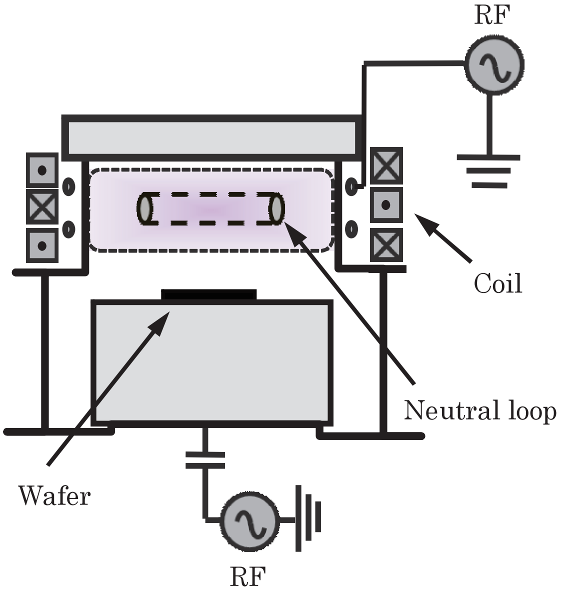


Fig.3 NLD plasma etching system.

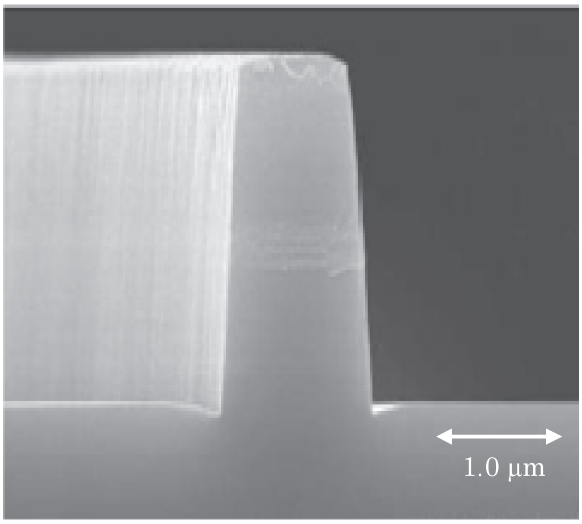


Fig.4 Cross section of fabricated SOI-based high-mesa waveguide.

3. 2 Low propagation loss waveguides

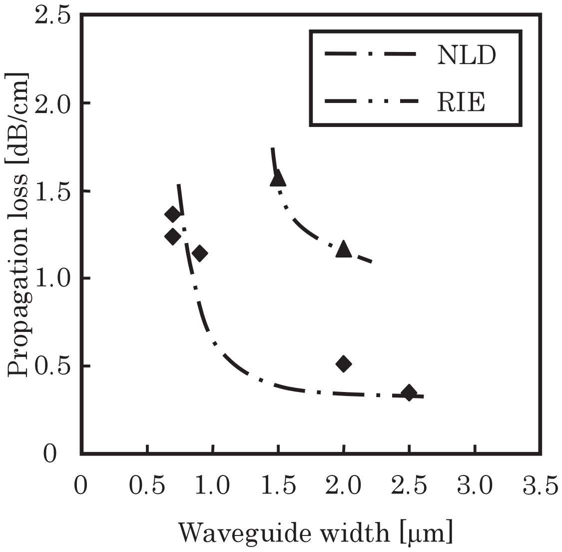
We have fabricated SOI-based Si/SiO$_2$ high-mesa waveguides by using the above explained NLD plasma etching technique. The fabricated waveguide structures have waveguide-width varying from 0.7 to 2.5 μm. The thickness of Si core was set to be 0.25 μm. On top of the Si core, 0.7 μm thick SiO$_2$ film was deposited by using regular thermal chemical vapor deposition method. The etching condition of high-mesa waveguide is shown in Tab. 1. As can be seen in this table, we used different and thus proper etching condition for each Si and SiO$_2$ layers to obtain vertical and smooth side-wall.

Figure 4 shows the cross section of the fabricated SOI-based Si/SiO$_2$ high-mesa waveguide. As is shown in this figure, vertical side-wall was obtained with relatively less roughness at the etched side-wall. This implies that the fabricated optical waveguide has relatively low scattering loss, caused by the side-wall roughness, as well as low plasma damage which may cause absorption loss in the light-guiding region. Figure 5 (a) shows the measured propagation loss. We used a regular distributed-feedback laser diodes which emits at λ = 1550 nm with TE mode for the loss

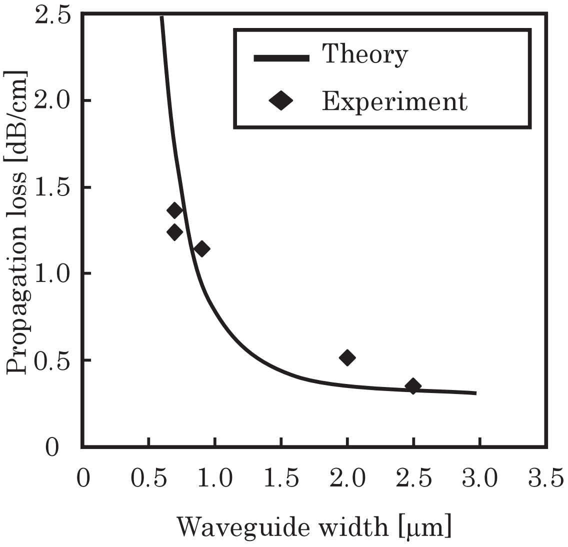
Tab.1 Etching condition of high-mesa waveguide.

	Upper SiO$_2$ cladding	Si core	Lower SiO$_2$ cladding
Etching gas	C_3F_8, Ar	C_3F_8, SF_6	C_3F_8, Ar
Pressure [Pa]	0.67	0.80	0.67
Bias Power [W]	400	100	400
Etching time [sec]	110	60	100

evaluation. The propagation loss was evaluated by using fabry-perot resonance technique[13]. For comparison, the measured propagation loss of the same SOI-based Si/SiO$_2$ high-mesa waveguide, fabricated by using conventional (and thus commonly used) reactive ion etching (RIE) technique, is also shown in this figure. As can be seen in this figure, significant loss reduction by using NLD has been achieved compared to the results by using RIE. Especially, extremely low propagation loss of 0.3 dB/cm has been achieved at the waveguide width of 2.5 μm.



(a)



(b)

Fig.5 Propagation loss.
(a) Experimental results.
(b) Curve-fitting result(7).

To discuss about the above obtained results, we analyzed the obtained loss by using curve-fitting regarding waveguide-width dependency of the scattering loss[14] (see Fig. 5 (b)). We assumed a side-wall roughness of 3 nm and a certain offset to fit to the above obtained results. From this analysis, we estimated that the propagation loss of 0.3 dB/cm (2.5 μm width) was caused by the scattering loss of 0.05 dB/cm, which corresponded to the 3 nm side-wall roughness, and the others of 0.25 dB/cm including plasma damage and material absorption. Further loss reduction is expected when we suppress the above side-wall roughness, and the optimization of the etching-conditions.

4. Sensing by using SOI-based Si/SiO$_2$ high-mesa waveguides

4.1 Waveguide-cell structure

Figure 6 shows an actually implemented SOI-based high-mesa waveguide-cell for liquid sensing purpose. Especially, as the absorption of liquid chemical is high against near infrared light in general, compared to the case of sensing the other volatile gas material, it is expected to achieve easily the proof of the optical field profile partly existing out of the waveguide, with using only several mm straight waveguide. Outside of the waveguide, with certain etched-down area, is surrounded with un-etched region, which prevents liquid leakage from the waveguide-cell. We used waveguide width of 0.7 μm single high-mesa structure (Si core thickness of 0.2 μm) for this liquid sensing waveguide-cell. The expected Γ_{air} of the waveguide was estimated to be 4.8 % (See Fig. 7). The length of this waveguide cell was set to be 6 mm, which may be sufficient for infrared absorption against liquid chemicals.

4.2 Liquid sensing

To demonstrate the sensing capability of the SOI-based high mesa waveguide, we filled the waveguide-cell by using liquid chemical. Especially this time we used liquid methanol to demonstrate its sensing capability as it is known that liquid methanol absorbs infrared light around 1550 nm telecom-band wavelength light[15]. To obtain infrared absorption without any internal interference effect in absorption spectroscopy, we used super-luminescent light emitting diode (SLED) as a light source (center wavelength: 1550 nm, TE-mode). We used hemispherical lensed fiber to couple an incident light of the SLED into this very narrow width (0.7 μm) waveguide. Figure 8 shows the near field pattern (NFP) at the waveguide facet after the fiber-coupling. As is shown in this figure, we could confirm proper light coupling into the waveguide.

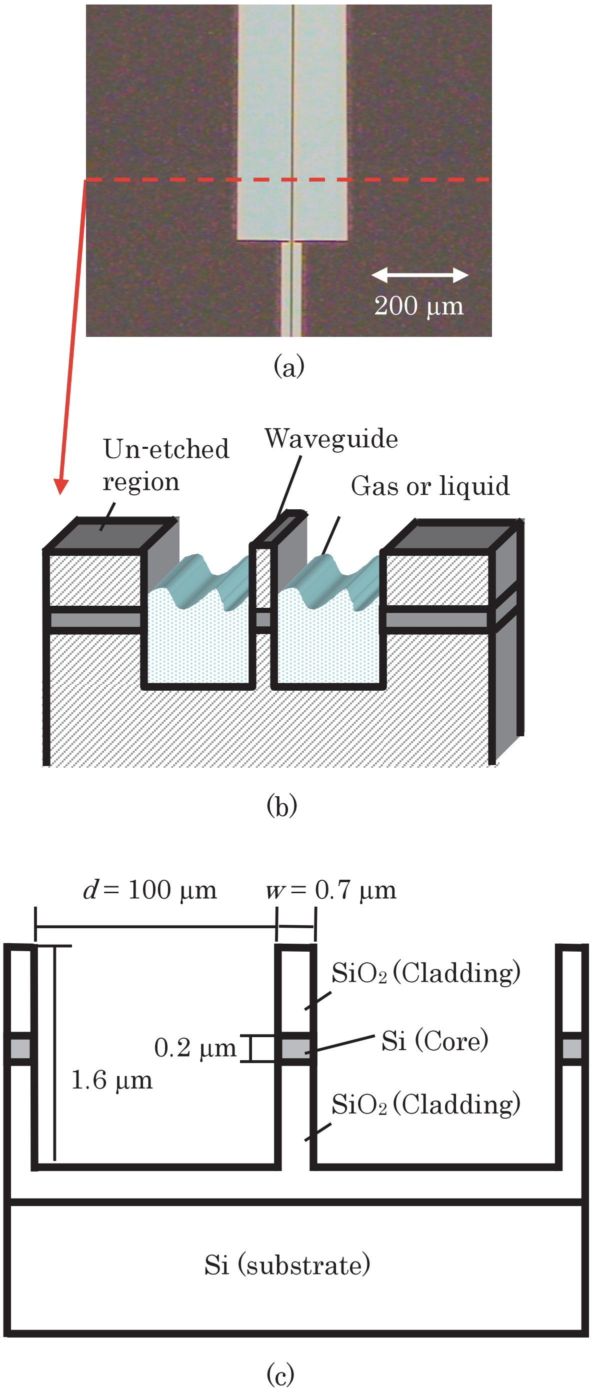


Fig.6 SOI-based Si/SiO$_2$ high mesa waveguide-cell for liquid sensing purpose.

(a) Implemented waveguide-cell.

(b) Cross section.

(c) Layer structure.

Figure 9 (a) shows the results of infrared absorption by using the SOI-based Si/SiO$_2$ high mesa waveguide. The waveguide was full-filled with methanol. Sufficient infrared absorption, compared to the case without methanol, has been achieved successfully. This demonstrates that the evanescent optical field of the SOI-based Si/SiO$_2$ high-mesa waveguide, which profiles out of the waveguide, contributes to obtain sufficient infrared absorption against liquid methanol. The obtained absorption coefficient was estimated to be 6 dB/cm. We could also confirm that the propagation loss of the fabricated SOI-based Si/SiO$_2$ high-mesa waveguide, already discussed in chapter 3, was low enough to

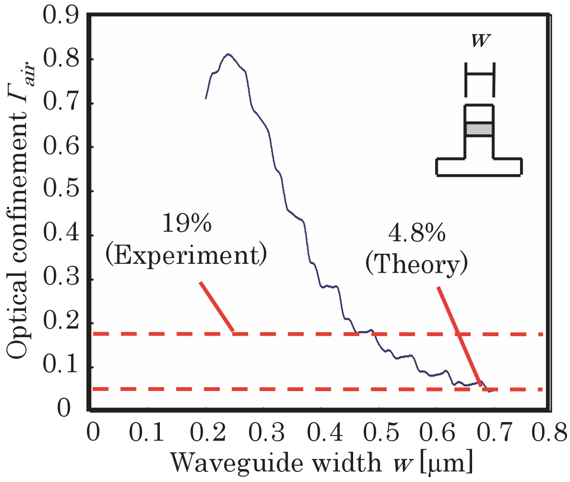


Fig.7 Calculated optical confinement out of the waveguide.

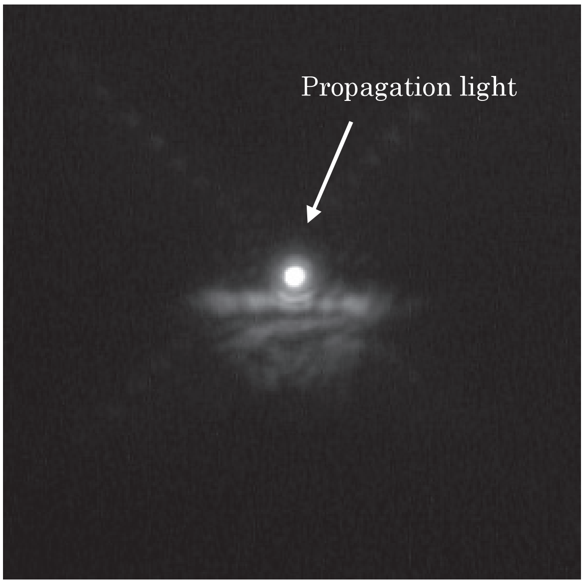


Fig.8 The near field pattern (NFP) at the waveguide facet.

measure this infrared absorption spectroscopy.

For comparison, we also measured infrared absorption of liquid methanol, filled in a regular glass-cell, with direct light injection. Figure 9 (b) shows the results of infrared absorption with direct light injection. The obtained absorption coefficient was estimated to be 30 dB/cm.

By comparing the above obtained absorption coefficients, we could roughly evaluate the actual portion of optical field profile out of the SOI-based Si/SiO$_2$ high mesa waveguide. Table 2 shows the results. As can be seen in the table, the estimated Γ_{air}, which is an optical field confinement out of the waveguide, was 19 %, which was higher than the calculated one. The difference might be due to the refractive index difference between experiment and design, as well as there was a possibility that unguided light might also contribute to the infrared absorption.

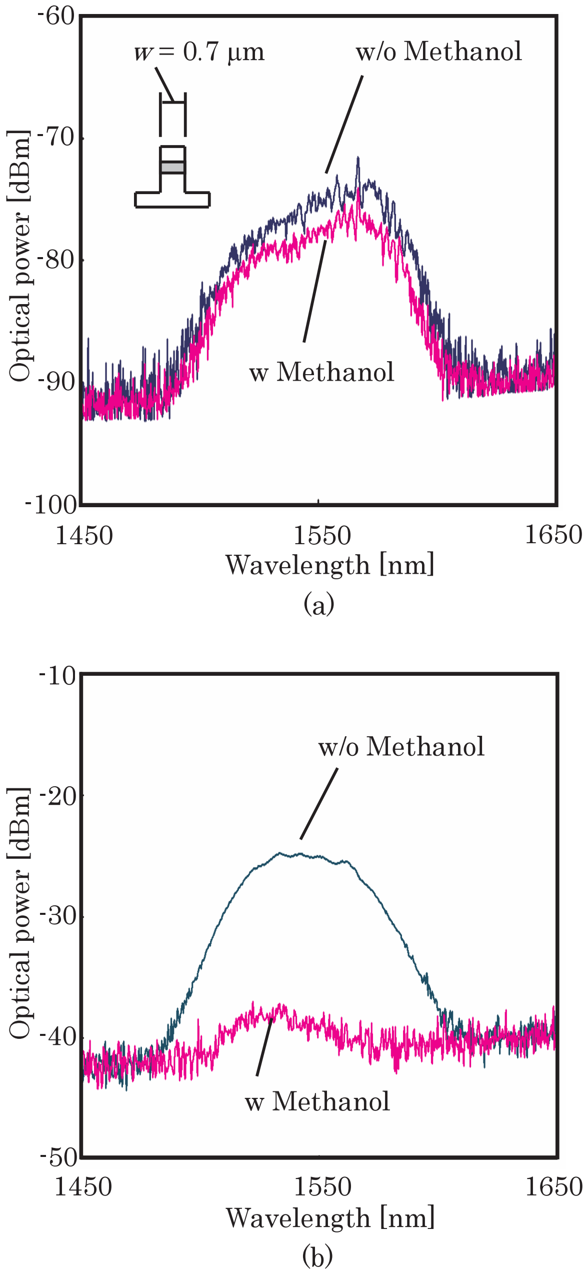


Fig.9 Results of infrared absorption in case of liquid methanol.

(a) Single high-mesa waveguide.

(b) Glass cell.

We have already proposed a double high-mesa structure[4] to enhance the optical field confinement Γ_{air} significantly up to approximately 90 %[16], therefore, to implement this double high-mesa structure with using the above discussed SOI-based Si/SiO$_2$ high-mesa waveguide will contribute to realize more highly sensitive optical waveguide-cell in the future.

Tab.2 Infrared absorption in case of liquid methanol (wavelength λ = 1550 nm).

	Glass cell	Optical waveguide
Absorbance [dB]	12.0	3.4
Length [µm]	4.0	6.0
Absorption coefficient [dB/cm]	30	5.7
Optical confinement Γ_{air}	---	0.19

5. Summary

SOI-based Si/SiO$_2$ high-mesa waveguide was fabricated by using NLD plasma etching. Significant propagation loss reduction has been achieved compared to those by using conventional RIE. Especially, low propagation loss of 0.3 dB/cm has been achieved at the waveguide width of 2.5 µm. Further loss reduction is expected in the future by the improvement of scattering, etching-conditions and others.

Moreover, we could demonstrate actual infrared absorption by using this SOI-based Si/SiO$_2$ high-mesa waveguide structure.

We hope and believe that this concept will contribute to realize compact and highly sensitive waveguide-cell in the future. Especially, we have already proposed a double high-mesa structure[4] to enhance the optical field confinement Γ_{air} significantly up to approximately 90 %[16], therefore, to implement this double high-mesa structure with using this low loss SOI-based Si/SiO_2 high-mesa waveguide will contribute to realize more highly sensitive optical waveguide-cell in the future.

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References

1) N. Marczin, and S. A. Kharitonov, “Disease markers in exhaled breath”, Marcel Dekker, Inc. (2003)
2) M. Mürtz, “Breath diagnostics using laser spectroscopy”, Optics & Photonics News, Vol. 16, No. 1, pp. 30-35 (2005)
3) G. V. Basum, H. Dahnke, D. Halmer, P. Hering, and M. Mürtz, “Online recording of ethane traces in human breath via infrared laser spectroscopy”, Journal of Applied Physiology, Vol. 95, pp. 2583-2590 (2003)
4) S. Yano, K. Kameyama, K. Kuwahara, and K. Hamamoto, “Double high mesa quasi hollow waveguide cell for compact breath-sensing system via infrared spectroscopy”, IEIEC Technical Report, OPE 2006-96, pp. 27-31 (2006)
5) K. Okamoto, “Fundamentals of optical waveguides”, Academic Press (2000)
6) T. Tsuchizawa, K. Yamada, H. Fukuda, T. Watanabe, J. Takahashi, M. Takahashi, T. Shoji, E. Tamechika, S. Itabashi, and H. Morita, “Microphotonics devices based on silicon microfabrication technology”, IEEE Journal of Selected Topics in Quantum Electronics, Vol. 11, No. 1, pp. 232-239 (2005)
7) T. Uchida, “Application of radio-frequency discharged plasma produced in closed magnetic neutral line for plasma processing”, Japan Journal of Applied Physics, Vol. 33, Part 2, No. 1A, pp. L43-L44 (1994)
8) S. Yano, K. Kameyama, and K. Hamamoto, “Low loss SOI-based high-mesa waveguides fabricated using neutral loop discharge (NLD) plasma etching for compact breath-sensing system”, Conference Proceedings of Integrated Photonics and Nanophotonics Research and Applications, No. 215, IWA7, Salt Lake, USA (2007)
9) M. V. K. Chari, and P. P. Silvester, “Finite elements in electrical and magnetic field problems”, John Wily & Sons (1980)
10) Y. Morikawa, W. Chen, T. Hayashi, and T. Uchida, “Investigation of surface reactions in neutral loop discharge plasma for high-aspect-ratio SiO_2 etching”, Japanese Journal of Physics, Vol. 42, No. 3, pp. 1429-1434 (2003)
11) J. Etrillard, P. Ossart, G. Patriarche, M. Juhel, J. F. Bresse, and C. Daguet, “Anisotropic etching of InP with low sidewall and surface induced damage in inductively coupled plasma etching using $SiCl_4$”, Journal of Vacuum Science & Technology A, Vol. 15, No. 3, pp. 626-632 (1997)
12) K. Hamamoto, E. Gini, and H. Melchior, “Low internal loss InP/InGaAsP laser diodes fabricated using inductively coupled plasma etching”, Conference Proceedings of 13th International Conference on Indium Phosphide and Related Materials, WP-02, pp. 136-139, Nara, Japan (2001)
13) R. Regener, and W. Sohler, “Loss in low-finesse Ti:$LiNbO_3$ optical waveguide resonators”, Applied Physics B, Vol. 36, No. 3, pp. 143-147 (1985)
14) F. P. Payne, and J. P. R. Lacey, “A theoretical analysis of scattering loss from planar optical waveguides”, Optical and Quantum Electronics, Vol. 26, No. 10, pp. 977-986 (1994)
15) P. Roychoudhury, R. O’Kennedy, B. McNeil, and L. M. Harvey, “Multiplexing fibre optic near infrared (NIR) spectroscopy as an emerging technology to monitor industrial bioprocesses”, Analytica Chimica Acta, Vol. 590, pp. 110-117 (2007)
16) K. Kameyama, Y. Matsunaga, and K. Hamamoto, “Propagation loss reduction and sensitivity improvement of SOI-based high-mesa waveguide for compact breath-sensing system”, IEICE Technical Report, OPE 2007-112, pp. 81-85 (2007)