Jpn. J. Appl. Phys. Vol. 40 (2001) pp. L383–L385
Part 2, No. 4B, 15 April 2001

Propagation Characteristics of Ultrahigh-Δ Optical Waveguide on Silicon-on-Insulator Substrate

Atsushi SAKAI, Go HARA and Toshihiko BABA
Division of Electrical and Computer Engineering, Yokohama National University, 79-5 Tokiwadai, Hodogaya-ku, Yokohama 240-8501, Japan

(Received January 22, 2001; accepted for publication February 19, 2001)

A submicron rectangular waveguide with a relative refractive index difference Δ of 45% was fabricated on a silicon-on-insulator substrate, and its propagation characteristics were evaluated using the Fabry-Perot resonance method. The propagation loss was of the order of $10\,\mathrm{cm}^{-1}$, and was dominated by light scattering at rough interfaces. However, a large modal effective index of more than 4.5 and a low bend loss of less than 1 dB at a 0.5-μm-radius bend were also observed. These results suggest the potential of an ultrasmall and high-density lightwave circuit, which accepts the relatively large propagation loss.

KEYWORDS: SOI, optical waveguide, integrated photonics, lightwave circuit

An optical waveguide with strong optical confinement allows dense and sophisticated optical wiring in lightwave circuits. Photonic crystal waveguides[1,2] are attracting considerable attention for this reason. On the other hand, a waveguide with a high relative refractive index difference $\Delta \equiv (n_1^2 - n_2^2)/2n_1^2$ between the core (index n_1) and claddings (index n_2) is another candidate for achieving the same degree of strong optical confinement, although its principle is highly conventional. For this purpose, a commercially available silicon-on-insulator (SOI) substrate is a promising platform. It provides a crystal-quality high-index ($n_1 \sim 3.5$) Si film on low-index ($n_2 \sim 1.45$) SiO_2, which can be used for both electronic circuits and waveguides at optical fiber communication wavelengths. Thus far, rib-type waveguides on SOI substrates with a low propagation loss of $0.1\,\mathrm{cm}^{-1}$ order have been demonstrated.[3,4] However, the bend radius was of mm order due to the essentially weak optical confinement of this type of structure. For an optical confinement strong enough to realize micron-size bends, the Si core must be completely etched down and exposed to low-index claddings. Such a waveguide with a rectangular Si core has also been reported.[5] For such a high-Δ waveguide, however, the scattering loss at rough sidewalls dominates the propagation loss.[6] The relation between the scattering loss and the waveguide structure which satisfies the single-mode condition is an important issue to be investigated for further advance of this type of waveguide. In this study, we fabricated such SOI rectangular waveguides, employing electron beam (EB) lithography and inductively coupled plasma (ICP) etching to reduce the sidewall roughness. We measured the propagation loss and the effective index (sometimes called the group index) of the guided mode using the Fabry-Perot resonance method. We also fabricated and evaluated a sharp bend, which is a key component for the miniaturization of lightwave circuits.

The SOI substrate used in this study had a 0.32-μm-thick p-Si layer bonded on a 1-μm-thick SiO_2 layer. The fluctuation in the Si thickness was less than 20 nm inside a $7 \times 7\,\mathrm{mm}^2$ cleaved piece. Since the resistivity of the Si layer was relatively high (14 Ω·cm), the free carrier absorption loss of light was negligible compared with the scattering loss at rough sidewalls as described below. For the EB lithography, a high-resolution positive resist, ZEP 520, Nippon Zeon, Inc., was used. After the liftoff process to transfer the pattern to a metal mask, the Si layer was completely etched down into a rectangular shape by ICP etching with CF_4 and Xe gases. In the measurement, transverse electric (TE) polarized light of $\lambda \sim 1.55\,\mu$m from a tunable laser diode was focused on the cleaved end of the waveguide. The top view of a 1-μm-wide waveguide and a near-field pattern (NFP) of light are shown in Fig. 1. According to the 3-dimensional finite difference time domain (FDTD) simulation, waveguide widths of $0.23\,\mu$m and $0.51\,\mu$m result in cut off conditions of the TE-like polarized 0th- and 1st-order modes at $\lambda = 1.55\,\mu$m. The circular light spot observed in Fig. 1 indicates the quasi-single-mode propagation caused by the scattering loss discrimination of higher-order modes.

For the Fabry-Perot resonance method, we formed two cleaved facets as input and output ends of the waveguide. For a constant power of the input light, the light output was detected directly by a sharpened single-mode fiber. The transmission spectrum was measured with changing λ, as shown in Fig. 2. The propagation loss coefficient α and the effective index n_{eff} are given by

$$\alpha = -\frac{1}{L}\ln\left(\frac{1}{R}\cdot\frac{\sqrt{I_{\max}/I_{\min}}-1}{\sqrt{I_{\max}/I_{\min}}+1}\right) \tag{1}$$

$$n_{\mathrm{eff}} = \frac{\lambda^2}{2L\,\Delta\lambda} = n_{\mathrm{eq}} - \lambda\frac{\partial n_{\mathrm{eq}}}{\partial\lambda}, \tag{2}$$

where L is the waveguide length, R is the facet modal reflectivity, $I_{\max}$ and $I_{\min}$ are the peak and bottom intensities of each resonance, respectively, $\Delta\lambda$ is the space between neighboring

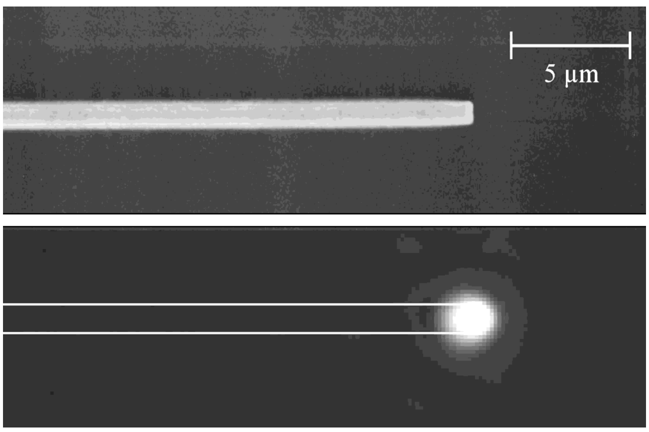

Fig. 1. Scanning electron micrograph (upper) of waveguide top and NFP of TE-like polarized light output at $\lambda = 1.55\,\mu$m with white lines drawn for better understanding (lower).

resonance peaks and n_{eq} is the equivalent index of the guided mode defined as the propagation constant divided by the wave number. Compared with the conventional cut back method,[6] this method yields a more precise evaluation of such high-Δ waveguides, since the ratio I_{max}/I_{min} is independent of the coupling condition of the input and output light. The reflectivity R was assumed to be 42%, which was calculated by the FDTD method. In this experiment, we prepared samples A and B with different channel widths. Average propagation losses for these samples are $35-50\,\text{cm}^{-1}$ ($152-217$ dB/cm) and $12-42\,\text{cm}^{-1}$ ($52-182$ dB/cm), respectively, as shown in the inset of Fig. 2. The difference between these samples is in the roughness amplitude σ of sidewalls, i.e., ~70 nm and ~20 nm in samples A and B, respectively. In general, the scattering loss in a single-mode waveguide with rough interfaces is proportional to σ^2.[7] The qualitative agreement between this expected result and the experimental result indicates that the propagation loss is dominated by the scattering loss. Theoretically, the scattering loss is also proportional to $\Delta^{2.5}$.[7] The waveguide in this study has the maximum Δ of 45% between Si and air, nearly 150 times the typical value, <0.5%, of silica-based waveguides. Considering this large difference in Δ and the typical propagation loss of $0.01\,\text{cm}^{-1}$ order in silica waveguides, we can conclude that the loss evaluated in this study is $1-2$ orders of magnitude lower than the expected value. This is clearly attributed to the low roughness obtained by the use of EB lithography and ICP etching. The loss will be further reduced to nearly $1\,\text{cm}^{-1}$, if the sidewall roughness can be reduced to less than 5 nm. Such a low roughness seems to be feasible, considering that $\sigma < 10$ nm has already been achieved for III-V compounds through the optimization of etching conditions.[8] However, a loss of less than $0.1\,\text{cm}^{-1}$ cannot be expected without sidewall of atomic-level smoothness which is not possible with the present technology. We should instead discuss the miniaturization of lightwave circuits, which accept a relatively large loss.

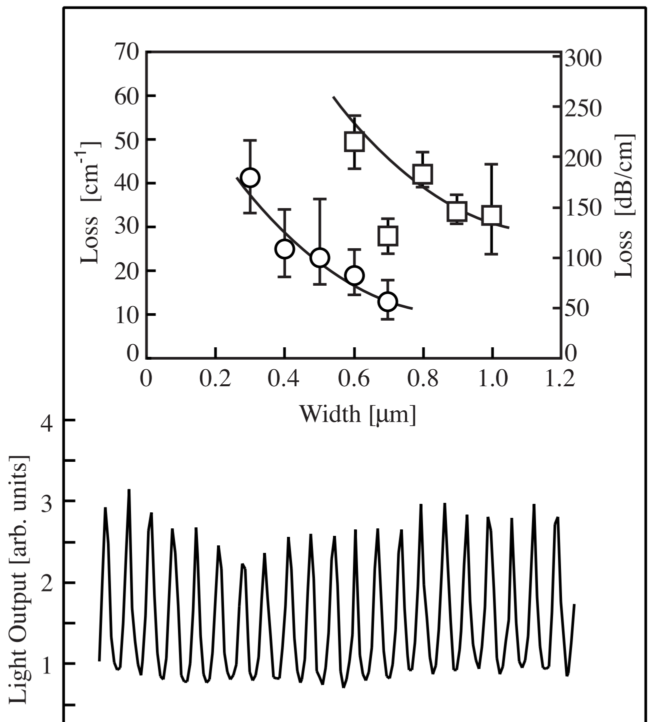

Fig. 2. Transmission spectrum of TE-like polarized light in a 283-μm-long and 0.7-μm-wide waveguide, and propagation loss evaluated for various channel widths. Squares and circles denote samples A and B, respectively.

Figure 3 shows dispersion curves of the 0th-order mode for a channel width of 0.50 μm, which is calculated by the FDTD method. Due to the large Δ and corresponding large change in n_{eq}, the second term in eq. (2), representing the structural dispersion, becomes extraordinarily large. Due to this effect, n_{eff} can be larger than the material index of Si. From the measured resonance shown in Fig. 2 and eq. (2), n_{eff} of the fabricated waveguide is evaluated to be $4.3-4.6$. This almost agrees with the theoretical curve. This large value cannot be caused by the material dispersion, since $\lambda = 1.55\,\mu$m is fully separated from the electric band edge, 1.1 μm, of Si. This large n_{eff} indicates a low group velocity, which enhances the interaction of the waveguide and the guided light. This is one of the reasons for the large scattering loss. However, it is also effective for shortening functional devices.

One of the most attractive properties of high-Δ waveguides is the low-loss sharp bend. We fabricated such bends simultaneously with the straight waveguides. The top view of a 1-μm-wide waveguide with a 90-degree bend and NFP of light output at $\lambda = 1.55\,\mu$m are shown in Fig. 4. The quasi-single mode was observed for the same reason as mentioned above.

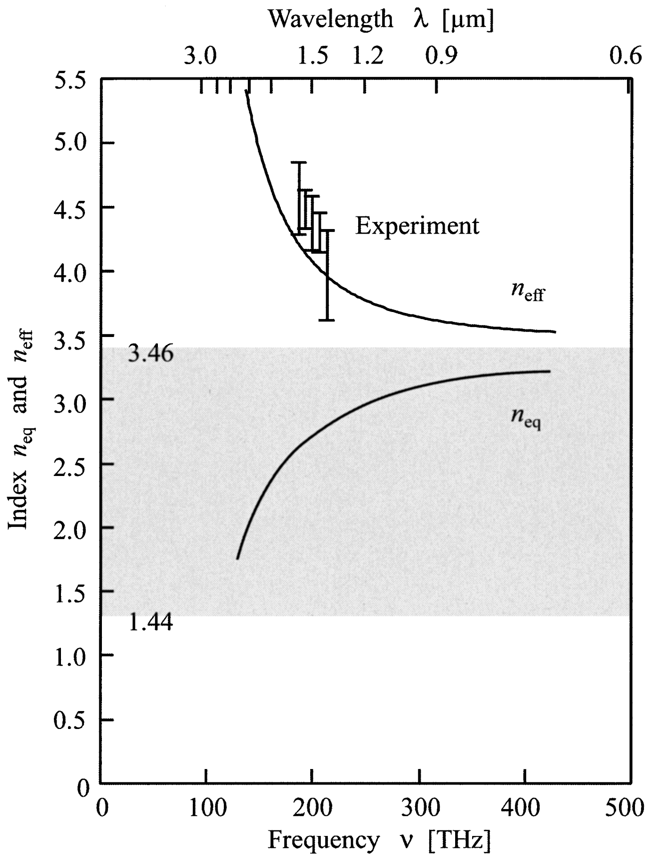

Fig. 3. Calculated dispersion characteristics of equivalent index n_{eq} and effective index n_{eff} of the TE-like polarized 0th-order mode. Thickness and width of Si channel are assumed to be 0.32 μm and 0.5 μm, respectively. Experimental result of n_{eff} for the same structural waveguide is also plotted.

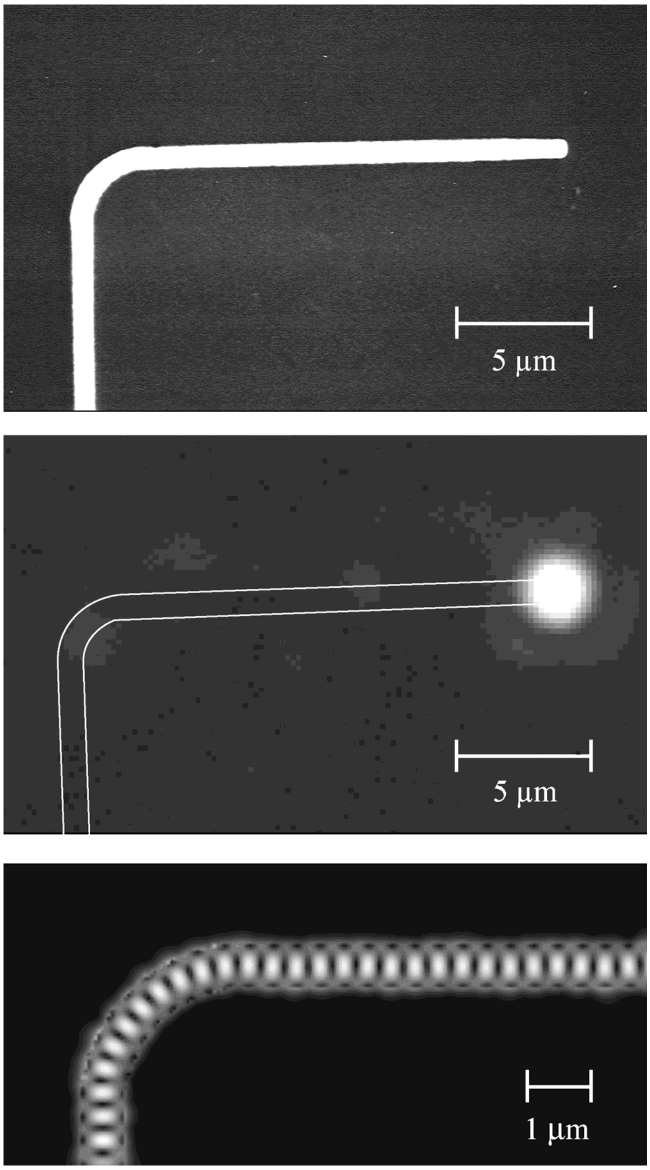

Fig. 4. Top view of a 1-μm-wide waveguide with a 90-degree bend (upper), NFP of TE-like polarized light at $\lambda = 1.55\,\mu$m (middle), and 3D-FDTD-simulated electric field distribution in 0.5-μm-wide waveguide (lower).

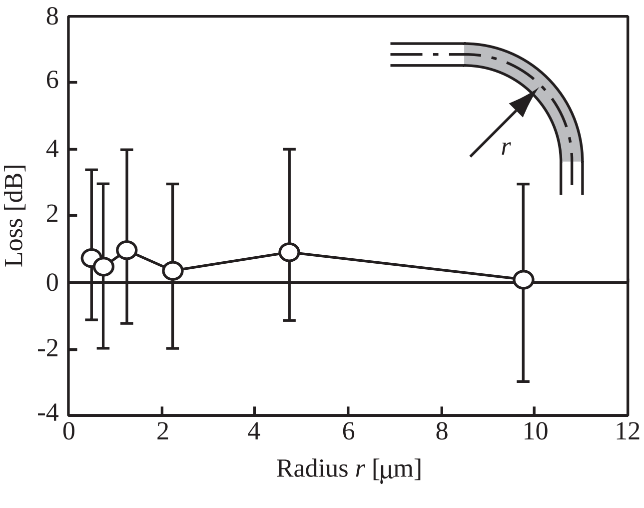

Fig. 5. Bend loss in 0.5-μm-wide waveguide at $\lambda = 1.55\,\mu$m.

The light radiation at the bend is negligible compared with the output light intensity, even though the bend radius measured from the waveguide center is as small as 2 μm. We also simulated the in-plane electric field distribution in a 0.5-μm-wide waveguide with such a bend, as shown in Fig. 4, which also shows that the radiation at the bend is negligible. Figure 5 shows 90-degree-bend loss specified by measuring the total loss of bent waveguides and subtracting the propagation loss in straight waveguides. The channel width was 0.5 μm. The average bend loss is less than 1 dB even though the radius is as small as 0.5 μm. Due to the ~20% fluctuation of the Fabry-Perot resonance, as shown in Fig. 2, the bend loss includes ±3 dB error. Considering this error, the maximum loss could be over 4 dB. However, the NFP and simulated field profile in Fig. 4 indicate a much smaller value.

In conclusion, we demonstrated rectangular waveguides on an SOI substrate with an ultrahigh-Δ and submicron-size Si core. The sidewall roughness was suppressed to less than 20 nm by the use of EB lithography and ICP etching. However the propagation loss was of 10 cm^{-1} order and dominated by the scattering loss at interfaces. We should discuss a compact lightwave circuit which accepts at least 1 cm^{-1} loss. From this point of view, the large effective index of more than 4 and low loss of less than 1 dB at the 0.5-μm-radius bend, which were obtained in this study, are very attractive. The bend radius of 0.5 μm is smaller than that in a silica-based waveguide by a factor of 200 − 500. When considering that the size and the flexibility of the lightwave circuit are strongly restricted by a large bend radius, the small bend radius demonstrated in this study suggests the high potential of such a fully compact circuit.

1) A. Mekis, J. C. Chen, I. Kurand, S. Fan, P. R. Villeneuve and J. D. Joannopoulos: Phys. Rev. Lett. **77** (1996) 3787.
2) T. Baba, N. Fukaya and J. Yonekura: Electron. Lett. **35** (1999) 654.
3) J. Schmidtchen, A. Splett, B. Schuppert and K. Petermann: Electron. Lett. **27** (1991) 1486.
4) A. G. Rickman and G. T. Reed: IEE Proc. Optoelectron. **141** (1994) 391.
5) J. S. Foresi, P. R. Villeneuve, J. Ferrera, E. R. Thoen, G. Steinmeyer, S. Fan, J. D. Joannopoulos, L. C. Kimerling, H. I. Smith and E. P. Ippen: Nature **390** (1997) 143.
6) K. K. Lee, D. R. Lim, H.-C. Luan, A. Agarwal, J. Foresi and L. C. Kimerling: Appl. Phys. Lett. **77** (2000) 1617.
7) Y. Suematsu and K. Furuya: Oyo Butsuri **42** (1973) 938 [in Japanese].
8) M. Fujita, A. Sakai and T. Baba: IEEE J. Sel. Topics Quantum Electron. **5** (1999) 673.