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Short Note

Low Loss Intersection of Si Photonic Wire Waveguides

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We fabricated a low loss elliptical intersection of Si photonic wire waveguides on a silicon-on-insulator substrate. An insertion loss of less than 0.1 dB was achieved at a wavelength of 1.55 μm. The experimental loss characteristic closely agreed with the theoretical one. We also used this intersection as a suspension of an air-bridge-type waveguide and evaluated a low loss characteristic similar to that mentioned above. [DOI: 10.1143/JJAP.43.646]

KEYWORDS: Si photonics, integrated optics, optical circuit, optical waveguide, intersection, photonic wire, SOI

Flexible optical wirings are important for dense and compact optical circuits. The Si photonic wire waveguide[1–5] has a high-index Si channel core and low-index SiO_2 and air claddings. It allows μm-order radius bend suitable for dense optical wirings due to a large relative index difference Δ of over 40% between the core and claddings. Recently, a study on the combination of this waveguide and the photonic crystal (PC) waveguide[6] has been actively pursued for the purpose of producing functional devices and circuits.[7–9)]

In a conventional optical circuit, intersections are not frequently used since they cause loss and crosstalk. However, an optical wiring pattern that avoids intersections makes the circuit significantly large and consequently increases the total waveguide loss. Therefore, a low loss and low crosstalk intersection is an important fundamental component in dense and compact optical circuits. In addition, a series of intersections are useful as mechanical suspensions of the air-bridge-type waveguide, when they are integrated with an air-bridge-type PC waveguide. Thus far, a resonant-type intersection has been theoretically studied for the Si photonic wire waveguide.[10] An insertion loss of < 0.2 dB was calculated by the two-dimensional (2-D) finite-difference time-domain (FDTD) method. However, the transmission band calculated was as narrow as $\sim$10 nm at a wavelength λ of approximately 1.55 μm. On the other hand, a small crosstalk was theoretically calculated for an intersection with mode expanders in standard low-Δ waveguides.[11] This type of intersection has a broader transmission band than that of the resonant-type. In this study, we designed the mode-expander-type intersection for the Si photonic wire waveguide and experimentally demonstrated a low loss.

First, we calculated the loss characteristic of a standard intersection without mode expanders by the 3-D FDTD method. As incident light, $\lambda = 1.55$ μm and the transverse-electric-like polarization were assumed. Indexes of the Si core, lower SiO_2 and upper air claddings were 3.46, 1.44, and 1.0, respectively. The thickness and width of the Si core were 0.32 μm and 0.44 μm, respectively. These parameters satisfy the singlemode condition. In the standard intersection, the insertion loss and the crosstalk increase as the crossing waveguide becomes wider. Figure 1(a) shows the mode profile when the width of the crossing waveguide is equal to that of the input waveguide. The insertion loss and crosstalk were estimated to be 1.4 dB and -9.2 dB, respectively. (In this paper, the crosstalk is determined for one crossing waveguide.) Next, we investigated the mode-expander-type intersection. It is known that the mode can be expanded without any excitation of higher order modes in a parabolic shape mode expander.[12] Since an expanded mode has a narrow angular spectrum, the crosstalk is significantly suppressed. In this study, we employed an elliptical instead of parabolic shape for the mode expansion and shrinkage, since the elliptical shape is much easier to form in the experiment. As the first step of this study, we placed one elliptical region along the direction of the input waveguide. The calculated mode profile is shown in Fig. 1(b). Light smoothly expands and shrinks in the elliptical region, and passes through the intersection with no irregular scattering and crosstalk. The insertion loss and crosstalk were estimated to be < 0.1 dB and < -30 dB, respectively, at $\lambda = 1.51$–1.57 μm for an elliptical region with short and long axes of 1.5 μm and 7.2 μm, respectively. We also calculated the four fold symmetric intersection using two elliptical regions, as shown in Fig. 1(c). The insertion loss was estimated to be 0.4 dB for short and long axes of 1.6 μm and 10.4 μm, respectively.

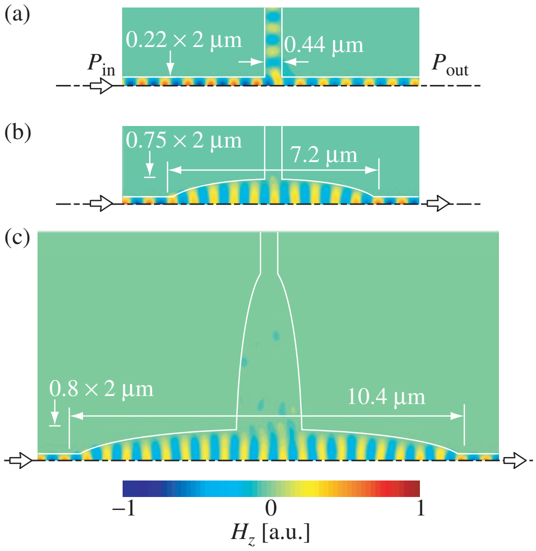
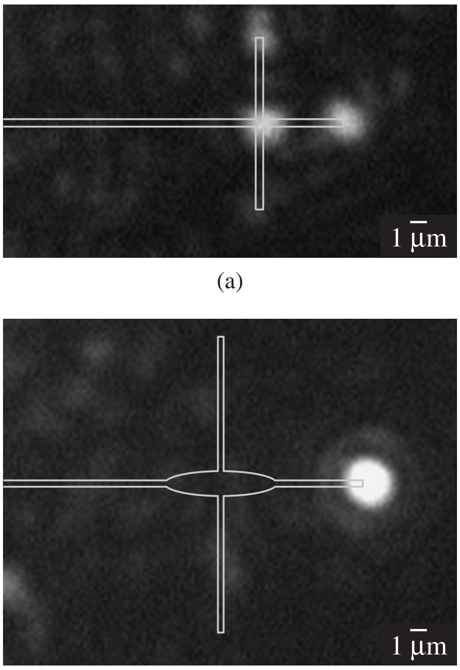


Fig. 1. Magnetic field profiles of transverse-electric-like mode at $\lambda = 1.55$ μm, which were calculated by the 3-D FDTD method. Since the profiles are symmetric against waveguide axis, only half of them are shown. (a) Standard intersection. (b) Elliptical intersection with short and long axes of 1.5 μm and 7.2 μm, respectively. (c) Four fold symmetric elliptical intersection with short and long axes of 1.6 μm and 10.4 μm, respectively.

The fabrication process of the Si photonic wire waveguide with the SiO_2 lower cladding (SOI-type) was the same as that described in ref. 2. We also fabricated the air-bridge-



(a)

(b)

Fig. 2. Near field patterns of light at $\lambda = 1.55\,\mu\text{m}$. (a) Standard intersection. (b) Elliptical intersection.

type waveguide, where the SiO_2 lower cladding was removed by HF wet etching. The crossing waveguide, which was used as a suspension of the air-bridge-type, was $5\,\mu\text{m}$ in length on each side. The width of the fabricated Si core was $0.45\,\mu\text{m}$. Figure 2 shows near field patterns at $\lambda = 1.55\,\mu\text{m}$ for the standard and elliptical intersections of the SOI-type waveguide. For the standard intersection, irregular light scattering and crosstalk were observed. On the other hand, they were negligibly observed for the elliptical intersection. We estimated the insertion loss of one intersection by measuring the ratio of output intensity from a waveguide with a series of intersections to that from a simple straight waveguide. Figure 3 shows measured loss for various long axes a of the elliptical region. Here, the short axis was fixed at $1.5\,\mu\text{m}$. The marked increase in theoretical loss at $a \sim 2\,\mu\text{m}$ arises from the circular shape of the elliptical region, in which some resonance occurs. Experimental plots for the SOI-type agreed well with the theoretical line calculated by the 3-D FDTD method. For the air-bridge-type, as shown in the inset of the same figure, values similar to those for the SOI-type waveguide were obtained. For $a = 7.2\,\mu\text{m}$, the average loss and crosstalk were evaluated to be $< 0.1\,\text{dB}$ and $< -25\,\text{dB}$, respectively. (These values were mostly determined from the background noise level.) For the four fold symmetric elliptical intersection, the loss was evaluated to be 1.2 dB. For this type of intersection, more careful optimizations of the structure, *e.g.*, a balance between the long and short axes, may be necessary.

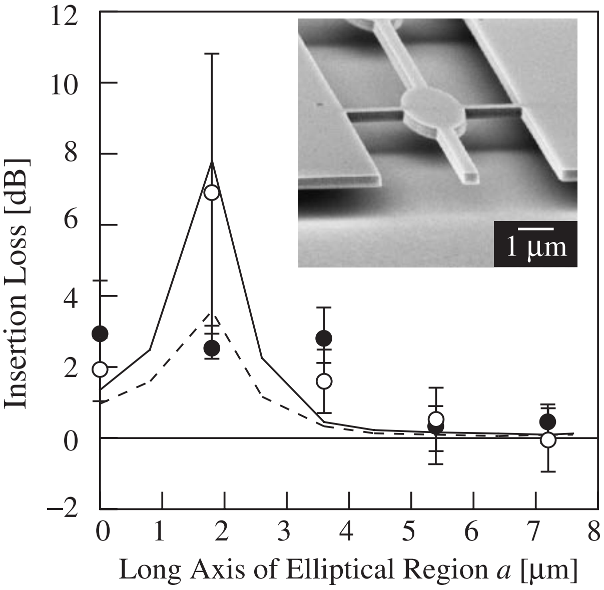


Fig. 3. Insertion loss as a function of the long axis of the elliptical region. Solid and dashed curves denote the theoretical result by the 3-D FDTD method, and open and closed plots denote experimental results for SOI-type and air-bridge-type waveguides, respectively.

In conclusion, we demonstrated $< 0.1\,\text{dB}$ loss for the elliptical intersection of Si photonic wire waveguides theoretically and experimentally. This type of intersection is useful for both flexible optical wirings and suspensions of air-bridge-type waveguides.

1) K. K. Lee, D. R. Lim, H.-C. Luan, A. Agarwal, J. Foresi and L. C. Kimerling: Appl. Phys. Lett. **77** (2000) 1617.
2) A. Sakai, G. Hara and T. Baba: Jpn. J. Appl. Phys. **40** (2001) L383.
3) A. Sakai, T. Fukazawa and T. Baba: IEICE Trans. Electron. **E85-C** (2002) 1033.
4) T. Fukazawa, A. Sakai and T. Baba: Jpn. J. Appl. Phys. **41** (2002) L1461.
5) T. Shoji, T. Tsuchizawa, T. Watanabe, K. Yamada and H. Morita: Electron. Lett. **38** (2002) 1669.
6) T. Baba, N. Fukaya and J. Yonekura: Electron. Lett. **35** (1999) 654.
7) A. Mekis and J. D. Joannopoulos: J. Lightwave Technol. **19** (2001) 861.
8) E. Miyai, M. Okano, M. Mochizuki and S. Noda: Appl. Phys. Lett. **81** (2002) 3729.
9) H. Yamada, M. Tokushima and M. Shirane: Proc. SPIE **4870** (2002) 357.
10) C. Manolatou, S. G. Johonson, S. Fan, P. R. Villeneuve, H. A. Haus and J. D. Joannopoulos: J. Lightwave Technol. **17** (1999) 1682.
11) T. Kato and Y. Kokubun: Proc. Spring Meet. IEICE, 2002, C-3-851.
12) W. K. Burns, A. F. Milton and A. B. Lee: Appl. Phys. Lett. **30** (1977) 28.