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H-Tree-Type Optical Clock Signal Distribution Circuit Using a Si Photonic Wire Waveguide

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We fabricated an ultra small H-tree-type optical signal distribution circuit on a silicon-on-insulator substrate. We used a micron-size bent-waveguide-type optical branch in a Si photonic wire waveguide and observed clear light output from eight output ports for laser light of 1.5 μm wavelength. The fluctuation of distributed light intensity was 2–5 dB. It was caused by a nonuniform branching ratio, and can be reduced by improving asymmetric corner shapes of each branch. [DOI: 10.1143/JJAP.41.L1461]

KEYWORDS: integrated optics, photonic circuit, optical waveguide, branch, photonic wire, SOI, FDTD

The clock skew will be a serious problem in the next-generation high-speed VLSI circuit. The clock signal distribution by an intra chip optical interconnection is a key solution to this problem. The free-space interconnection by diffractive optical elements has a simple configuration, but requires a small diffraction angle of the distributed light beam to obtain a high diffraction efficiency. Therefore, it is difficult to install into a VLSI chip of square centimeter area and millimeter thickness. On the other hand, the interconnection by an optical waveguide can be completely integrated, if an ultra small waveguide is realized, which produces high-density optical wirings and low-loss small branches for signal distribution. Here, let us consider an H-tree circuit, as shown in Fig. 1. It distributes a signal to all output ports via waveguides of the same length. Assuming that there are 128 ports inside a 10 mm^2 area, a branch much smaller than the area occupied by each distribution section (< 1 mm^2) is essential. From the input port to one output port, light successively passes through seven branches and an approximately 15-mm-long waveguide. Let us denote the excess loss at a branch to be A [dB] and the propagation loss of the waveguide to be B [dB/mm]. The incident light suffers $3 \times 7 + 7A + 15B$ [dB] loss before reaching the output port. Providing that the incident power is 10 mW and the output power required is of 10 μW order, A must be of 0.1 dB order and B of 0.1 dB/mm order. Of course, all the wirings should be in the singlemode for stable branching characteristics.

Such an H-tree circuit has not been realized yet, except for a large prototype composed of a polymer waveguide with millimeter-size branches and bends.[1)] For the drastic miniaturization of this circuit, the photonic wire waveguide on a silicon-on-insulator (SOI) substrate[2–5)] is effective. An ultra high relative refractive index difference of more than 40% between the Si core (index $n = 3.5$) and the SiO$_2$ ($n = 1.45$) or air ($n = 1.0$) cladding achieves strong optical confinement and flexible wirings. Previously, we fabricated a singlemode waveguide with a 0.5 μm $\times$ 0.32 μm rectangular cross section. We measured a propagation loss of ~ 10 dB/mm and a bend loss of ~ 0.2 dB at a bend radius of 2.5 μm at a wavelength $\lambda = 1.55$ μm.[4)] We also proposed a bent-waveguide-type branch,[5)] as shown in Fig. 1, whose dimensions are less than 6 μm $\times$ 6 μm. We theoretically calculated an excess loss of less than 0.2 dB and 0.5 : 0.5 branching ratio, which is insensitive to the position of the input waveguide relative to a central axis of the branch. In addition, we experimentally demonstrated an excess loss of 0.3 dB. This is much lower than those reported for reflection-type and resonant-type small branches.[6,7)] It is attributed to its simple structure, a small wavelength dependence and a large fabrication tolerance. Based on these results, we aimed at demonstrating an ultra small H-tree circuit by using this branch. In this letter, we describe the fabrication and optical distribution characteristics of this circuit, and discuss two intensity fluctuations caused by the Fabry-Perot resonance and a nonuniform branching ratio.

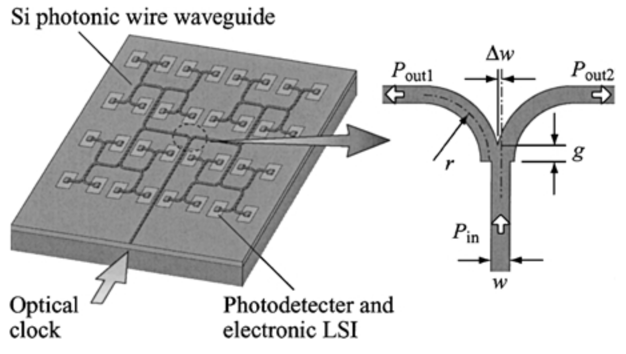

Fig. 1. Schematic of H-tree-type optical clock signal distribution circuit composed of Si photonic wire waveguide. Magnified figure shows the schematic of bent-waveguide-type branch.

We designed a 35 μm $\times$ 25 μm circuit composed of a 0.5-μm-wide waveguide and eight output ports. It included a total of seven branches, so that light successively passed through three branches between the input port and one output port. The bend radius of the branches was 2.75 μm, which completely suppressed the bend loss. The length of the slab region[5)] at the center of the branch was designed to be 0.8 μm. The theoretical calculation showed that this length causes an excess loss of 0.5 dB, which is slightly larger than its minimum of 0.2 dB. However, this length ensures a stable 0.5 : 0.5 branching ratio even against the position shift of the input waveguide in the branch.[5)] Each of the two branches was connected by a straight waveguide of 5 μm length. Each output port was terminated by a straight waveguide of 3 μm length. The fabrication process is the same as that reported previously.[4)] We used a unibond-type SOI wafer (SOI TEC Inc.), which had an SiO$_2$ layer of 1.0 μm thickness and a top Si layer of 0.32 μm thickness. For the pattern drawing, we used field-emission-type electron beam (EB) writer ELS-7300 (Elionix Inc.). For the formation of Si channels, we used CF$_4$/Xe inductively coupled plasma etching. An important issue in this process is the fine lithography of complex patterns including straight and bent waveguides. A standard vector scanning EB exposure and a continuous dot exposure were used for straight and round patterns, respectively. However, these patterns were sometimes disconnected. To avoid this, we prepared a 1.0 to 1.5-μm-long overlap region between them.

We formed the cleaved end facet of the input waveguide, and focused transverse electric (TE)- or transverse magnetic (TM)-polarized 1 mW laser light to a spot diameter of 1 μm on this facet. We observed light output from the top of the sample using a vidicon camera and measured the output intensity using an optical power meter through a lens system. Figure 2 shows a scanning electron micrograph of the fabricated circuit and the near field pattern of light output for TM-polarized light at $\lambda = 1.55\,\mu$m. Clear outputs are observed from the eight ports without any irregular scattering at the branches. Figure 3 shows transmission spectra. Here, the intensity level includes a calculated coupling loss of 6 dB at the input end, experimental waveguide losses of 1.2 dB and 1.6 dB for TE and TM polarizations, respectively, an experimental total excess loss of 2 dB at the branches and a calculated reflection loss of 3 dB at the output end. On the other hand, it excludes the loss in the optical setup and the intensity attenuation by power distribution of 9 dB. The intensity fluctuation of 7–8 dB is primarily caused by the Fabry-Perot resonance either between input and output ends of waveguides, between a waveguide end and a branch or between two branches. The typical wavelength space of the resonance is 15 nm. This corresponds to a resonator length of 16 μm, when a group velocity index is assumed to be 4.5.[4] This length is the same as that between the second branch and an output end. This indicates that the branches in vertical directions have some imperfections, while the branches in horizontal directions are almost perfect. This Fabry-Perot resonance is not a serious problem, since it is easily removed by some structural modifications. We experimentally observed that it was completely suppressed by tapered ends of waveguides. Except for this resonance, there still remain intensity fluctuations among eight ports of ~ 5 dB for TE polarization and ~ 2 dB for TM polarization, which must be due to an unstable branching ratio. The inset of Fig. 4 shows the magnified view of a fabricated branch. Let us denote the shift of the input waveguide from the center axis of the branch as Δw. The normalized shift $\Delta w/w$ was measured to be 0–9% in the branches. The length of the slab region g was 0.71–0.75 μm. Moreover, the

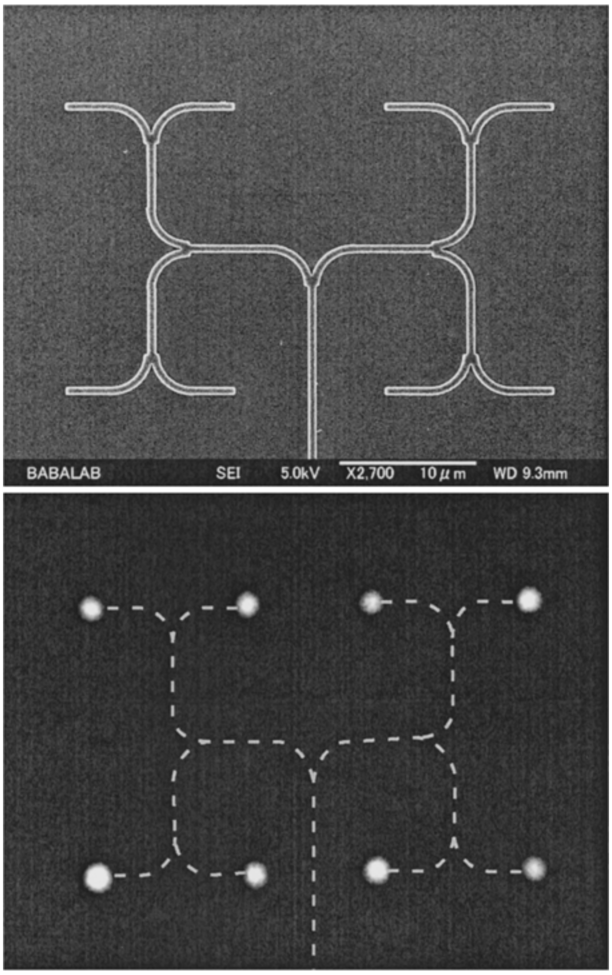

Fig. 2. Top view of H-tree circuit and corresponding near field pattern of light output for TM-polarized light at $\lambda = 1.55\,\mu$m. Dashed curves are added for better understanding of waveguide position.

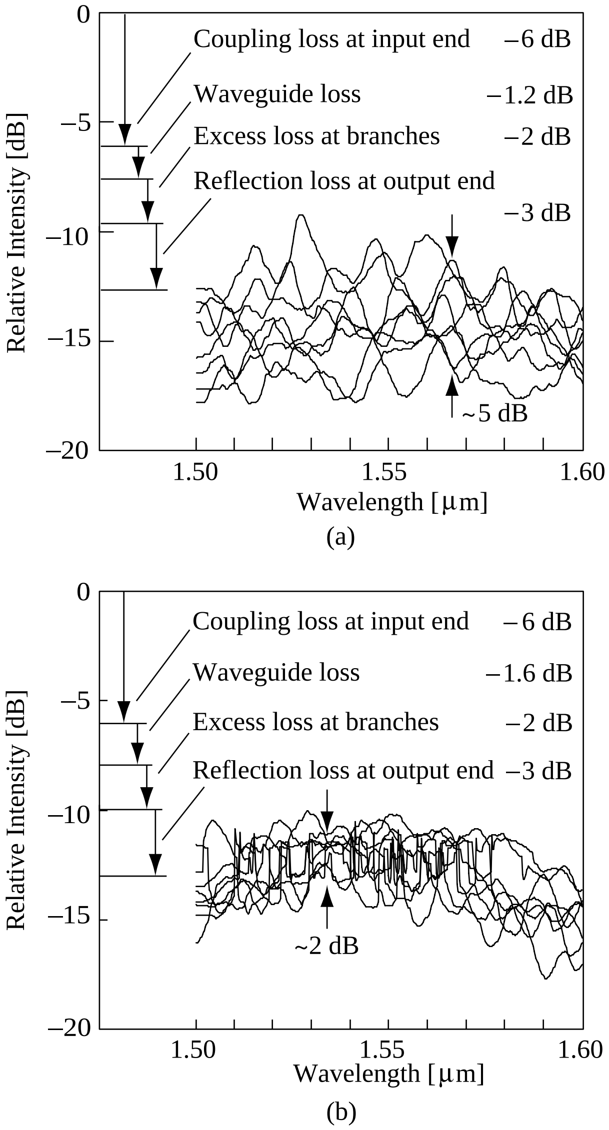

Fig. 3. Measured transmission spectra for eight ports. (a) TE polarization. (b) TM polarization. Fast oscillation seen in one output port in (b) is not due to the waveguide but to the unstable condition of the optical power meter.

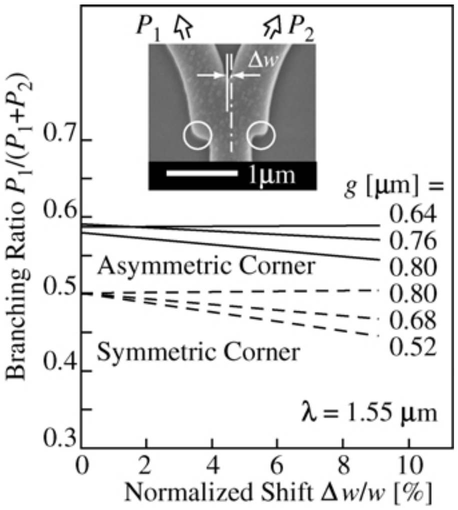

Fig. 4. Magnified top view of fabricated branch, and branching ratio calculated with normalized shift $\Delta w/w$. The top view shows a shift Δw of the input waveguide against the center axis of the branch and asymmetric corner shape of the slab region, which is indicated by white circles. The calculation method is the same as that described in ref. 5. Solid and dashed curves indicate asymmetric and symmetric corners, respectively.

corner shape of the slab region was asymmetric. The left corner of the slab region was round and its position was shifted by ∼80 nm from the right corner. Figure 4 also shows the branching ratio calculated with $\Delta w/w$. Imperfections in Δw and g only give a total intensity fluctuation of less than 0.5 dB without the asymmetric corner. This value dose not agree with the experimental value. On the other hand, the branching ratio is 0.58 : 0.42 with the asymmetric corner. This ratio yields a total fluctuation of ∼3 dB, which almost agrees with the experimental value. This asymmetric corner shape seems to be caused by anisotropic scanning in the EB exposure.

In addition to this intensity fluctuation, other remaining problems of this study are a large waveguide loss of 10 dB/mm order and a large coupling loss of ∼6 dB at the input end. The origin of the waveguide loss is light scattering caused by the process roughness at waveguide sidewalls.[3,4] Therefore, it can be reduced by simple technical improvements as already demonstrated in other reports. For example, 0.08 dB/mm was achieved in a thin-film channel by an additional oxidation process[8] and 0.6 dB/mm was achieved in a square channel by optimized EB exposure.[9] The coupling loss can also be reduced using a spot size converter[9] or a grating coupler.[10] Thus, the H-tree circuit discussed here is expected to become a practical and useful tool by the integration of photodetectors sensitive to 1.5 μm wavelength.[11]

In conclusion, we fabricated an H-tree optical distribution circuit within an area of 35 μm × 25 μm by combining low-loss branches in Si photonic wire waveguides, and successfully demonstrated clear light output from eight ports. The transmission spectra showed an intensity fluctuation of 2–5 dB among output ports, except for the oscillation by the Fabry-Perot resonance. This is primarily caused by the asymmetric corner shape of the branch, and will be reduced by controlling the scanning in the EB exposure process.

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