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Brief Communication

Mach–Zehnder Interferometers Composed of μ-Bends and μ-Branches in a Si Photonic Wire Waveguide

Fumiaki OHNO, Tatsuhiko FUKAZAWA and Toshihiko BABA

Department of Electrical and Computer Engineering, Yokohama National University, 79-5 Tokiwadai, Hodogaya-ku, Yokohama 240-8501, Japan

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We fabricated compact Mach–Zehnder interferometers consisting of μ-branches and/or μ-couplers in a Si photonic wire waveguide. Clear interference spectra with a maximum extinction ratio of more than 20 dB and an alternating light output between two output ports were observed. A high diffraction order of 300 was also demonstrated within a small foot space of $30 \times 20\,\mu\text{m}^2$. [DOI: 10.1143/JJAP.44.5322]

KEYWORDS: Si photonics, integrated optics, optical circuit, optical waveguide, Mach–Zehnder interferometer, photonic wire, SOI

A Si photonic wire waveguide[1–8] on a silicon-on-insulator (SOI) substrate realizes micron bends (μ-bends) and branches (μ-branches) by a large relative index difference Δ of more than 40% between the core and claddings. In these years, the propagation loss of this waveguide and the coupling loss to the single-mode fiber have been rapidly reduced to sufficiently low levels.[4,5] Therefore, the issue of interest is moving toward the demonstration of functional devices such as ring resonators,[6] lattice filters,[7] and arrayed waveguide gratings.[8] However, there are no reports on a Mach–Zehnder interferometer (MZI), although it is one of the most basic waveguide devices. In this paper, we discuss compact MZIs consisting of μ-bends and μ-branches and/or μ-couplers. We demonstrate not only the simple one-input and one-output (1×1) type but also two-output (1×2 and 2×2) types suitable for the wavelength dropping function. We also demonstrate a high diffraction order of 300 within a small device foot space by a flexible layout of the waveguide.

The fabrication process was the same as those reported previously.[8] We prepared SOI wafer with SiO_2 layer ($1.0\,\mu$m thickness) and a Si layer ($0.32\,\mu$m). For this wafer, we fabricated the waveguide using *e*-beam lithography and inductively coupled plasma etching. The waveguide width was typically $0.4\,\mu$m, which satisfied the single-mode condition at a wavelength λ of $1.55\,\mu$m. First, we present the 1×1 MZI consisting of a couple of μ-branches. As the μ-branch, we employed the bend-waveguide-type branch,[2,3] in which the ends of two bend waveguides (radius $r = 3\,\mu$m) were in contact with each other and connected to the input waveguide. The path difference ΔL between the branched waveguides was changed in the range of 17–103 μm. These values correspond to diffraction orders N ($= n_g \Delta L/\lambda$) of 50–300 for $\lambda = 1.55\,\mu$m and a group index $n_g = 4.5$.[1] The fabricated device with $\Delta L = 17\,\mu$m and $N = 50$ is shown in Fig. 1(a). Due to sharp bends, the device only occupies a foot space of $21 \times 13\,\mu\text{m}^2$. Figure 1(a) also shows the transmission spectrum measured by inserting tunable laser light. Here, the vertical axis is normalized by the light output from the simple straight waveguide fabricated simultaneously. The spectrum clearly exhibits the slow oscillation by the interference. Corresponding to $N = 50$ and $n_g = 4.5$, the interval of oscillating peaks is nearly 35 nm. The maximum extinction ratio is 20.5 dB. It is thought as a very good result, because the extinction of light in this device is obtained by the radiation loss at the confluent portion, which is not so robust against the process-induced asymmetry. Therefore, the result is evidence of good splitting and confluent characteristics of the two μ-branches and a small propagation loss in the branched waveguides. Fine peaks in the spectrum were caused by the Fabry–Perot resonance inside the device. The peak interval is fluctuating but roughly 1.5 nm. This suggests that the Fabry–Perot cavity is constructed by end facets of the input and output waveguides with a total length of nearly 150 μm. The fluctuation in the

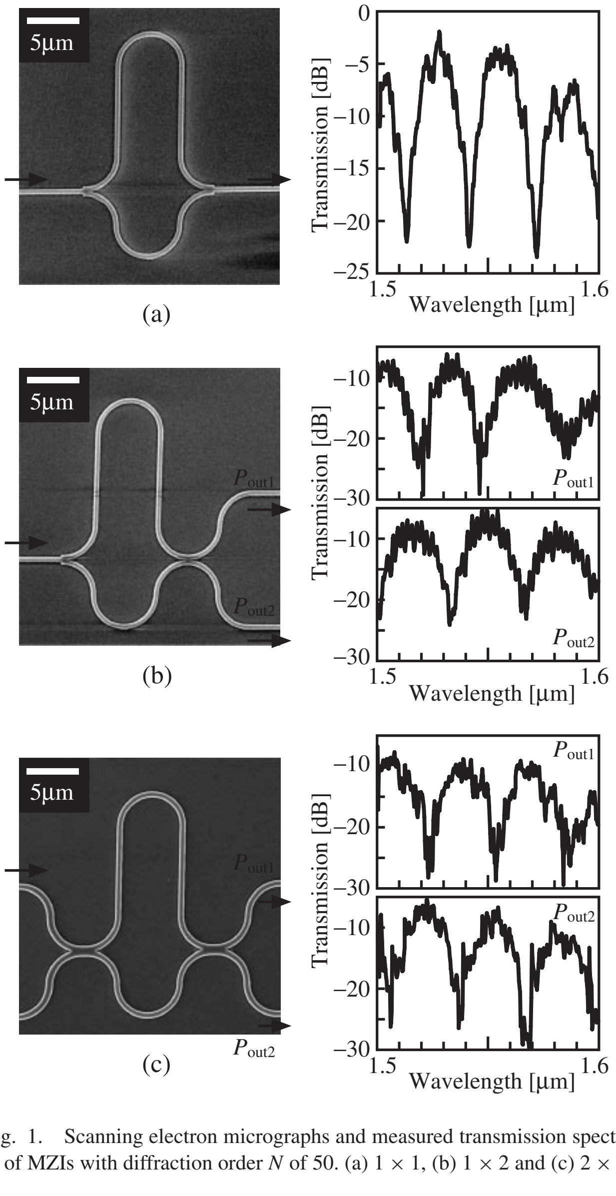

Fig. 1. Scanning electron micrographs and measured transmission spectra of MZIs with diffraction order N of 50. (a) 1×1, (b) 1×2 and (c) 2×2.

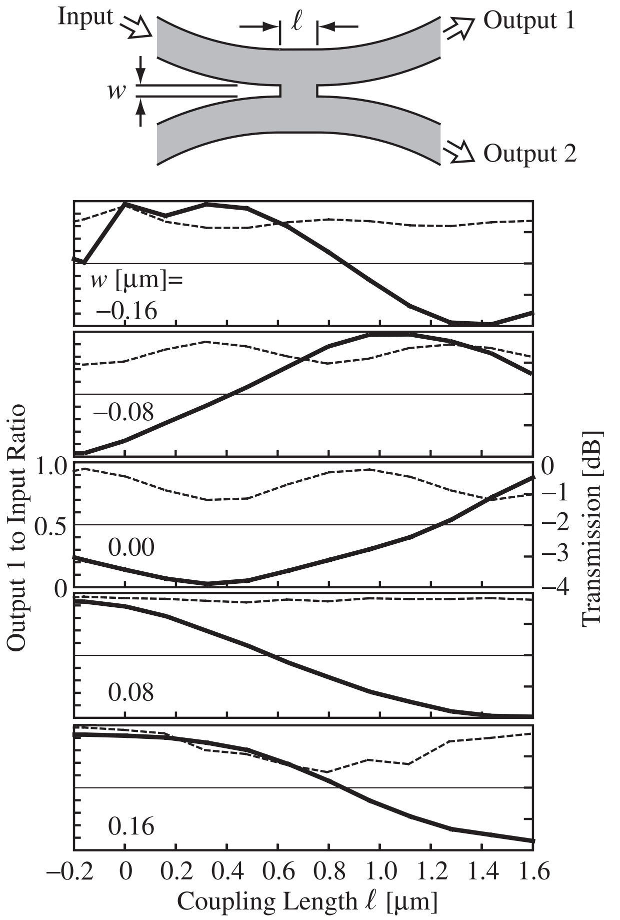

Fig. 2. Calculation model of bend-waveguide-type coupler, and its branching ratio (thick solid line) and insertion loss (thin dotted line) calculated by three-dimensional finite-difference time-domain method.

peak interval must be induced by different path lengths.

Next, we present the 1×2 and 2×2 MZIs with 3-dB couplers. The waveguide width and bend radius are the same as those in the 1×1 MZI. As the 3-dB coupler, a directional coupler is sometimes used. However, the directional coupler based on the Si photonic wire waveguide only tolerates errors in waveguide width and interwaveguide spacing of less than 10 nm for the equal branching ratio. In this study, we considered a simple and compact bend-waveguide-type coupler. Figure 2 shows the model of the coupler and the branching ratio and insertion loss calculated with the coupling length ℓ at $\lambda = 1.55\,\mu$m. Here, the interwaveguide distance w is taken as a parameter. The equal branching ratio and a loss of less than 0.3 dB are given by $w = 0.08\,\mu$m and $\ell = 0.56\,\mu$m. Figures 1(b) and 1(c) show the fabricated 1×2 and 2×2 MZIs including the coupler. Here, ΔL and N are the same as those in the 1×1 MZI. The measured spectra clearly show alternating characteristics for two output ports. The maximum extinction ratios of the 1×2 and 2×2 MZIs are as large as 23 and 22 dB, respectively. In the 2×2 MZI, however, the extinction ratio for the output power P_{out1} (straight output) is nearly 5 dB lower than P_{out2} (cross output). Let us assume different branching ratios $R : (1 - R)$ for the couplers. In addition, let us consider an excess loss of 0.03–0.17 dB in a longer waveguide, which is expected from a typical propagation loss of 2–10 dB/mm in this experiment. Then, the different extinction ratios for the straight output and cross output can be explained by $R = 0.66$–0.67 and 0.48–0.47 for the first and second couplers, respectively. The error from the equal branching ratio may be caused by a slight change in the distance w of less than 100 nm, as understood from Fig. 2.

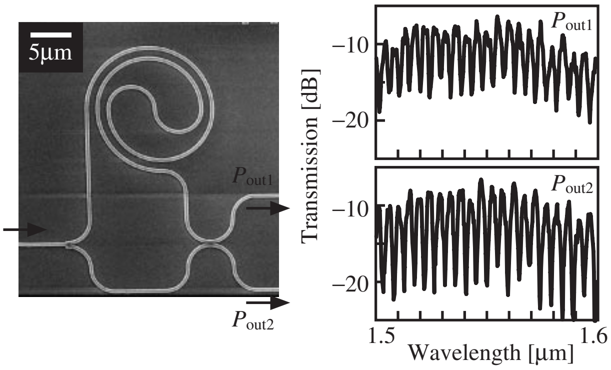

Fig. 3. Scanning electron micrograph and measured transmission spectrum of MZI with $N = 300$.

Figure 3 shows a device with a diffraction order N of 300. The longer branched waveguide of 103 μm length is spirally rolled, keeping a minimum bend radius of 3 μm and an interwaveguide spacing of 1 μm. This allows a small foot space of $\sim 30 \times 20\,\mu\mathrm{m}^2$. The peak interval is 2.5 nm, which corresponds to $N = 300$ and $n_{\mathrm{g}} = 4.5$. In this device, the maximum extinction ratio for P_{out2} is reduced to 14 dB. It is explained similarly by different branching ratios and a larger excess loss. The lower extinction ratio for P_{out1} is due to the same reason as mentioned above.

In conclusion, we fabricated compact MZIs consisting of μ-branches and/or μ-couplers in a Si photonic wire waveguide. We observed clear interference spectra with a maximum extinction ratio of more than 20 dB and peak intervals of 35–2.5 nm well corresponding to diffraction orders of 50–300. Such compact MZIs are applicable to functional devices such as modulators, switches, lattice filters, and so on.

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