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Loss reduction of silica-based 8 × 8 optical matrix switch by optimizing waveguide crossings using WFM method

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Abstract: We designed waveguide crossings using the wavefront matching method to reduce the excess loss of a silica-based optical 8 × 8 matrix switch. We fabricated the switches using silica-based planar lightwave circuit (PLC) technology and confirmed that the excess loss of our designed waveguide crossings was lower than that of conventional crossings by 0.3 dB. The average insertion loss of the fabricated switch including fiber-coupling loss was 1.7 dB, which is the lowest value yet reported for a PLC-based switch. The designed waveguide crossings are practically useful for improving the performance of PLC switches with a large number of crossings.

Keywords: optical switch, planar lightwave circuit, waveguide crossings

Classification: Photonics devices, circuits, and systems

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1 Introduction

To cope with the rapid growth in Internet traffic, optical networks have to be more flexible and economical. Transparent networks using reconfigurable optical add/drop multiplexing and optical cross connect architectures are promising solutions because they do not require OEO conversion. Space-division optical switches are indispensable components in such networks. Various kinds of optical switches have been demonstrated using several materials and mechanisms [1, 2, 3]. Thermo-optic silica-waveguide switches based on planar lightwave circuit (PLC) technology have many advantages such as simple drive control, long-term stability, and mass-producibility. 8 × 8 and 16 × 16 PLC matrix switches have already been developed and achieved good levels of performance [4, 5]. These switches have switch units with a double gate configuration composed of two Mach-Zehnder interferometers (MZIs) for a high extinction ratio. For instance, an 8 × 8 matrix switch fabricated with 0.75% refractive index difference waveguides, which has 8 switch units (16 MZIs), exhibited a low insertion loss of 3.5 dB and a high extinction ratio of 53 dB [4]. As the use of these switches has spread, their device size and insertion loss are of increasing concern. To reduce the chip size of matrix switches, Watanabe *et al.* proposed a compact MZI arrangement [6]. And, the chip size of an 8 × 8 matrix switch fabricated with this compact MZI arrangement is half the previously reported value. In addition, the insertion loss is 1 dB lower owing as a result of the total waveguide length being halved. The remaining loss of the 8 × 8 matrix switches consists of waveguide propagation loss, optical fiber coupling loss and the excess losses of the 3-dB couplers and waveguide crossings. In this letter, we describe waveguide crossings optimized by using the wavefront matching (WFM) method in order to reduce the excess loss at crossings. We fabricated and examined an 8 × 8 matrix switch with optimized crossings. We obtained a very low insertion loss of 1.7 dB, which is the lowest value yet reported.

2 Waveguide crossings design

Figure 1 shows an 8 × 8 matrix switch topology and a switch unit layout. The switch unit consists of two asymmetrical MZIs with thermo-optic phase

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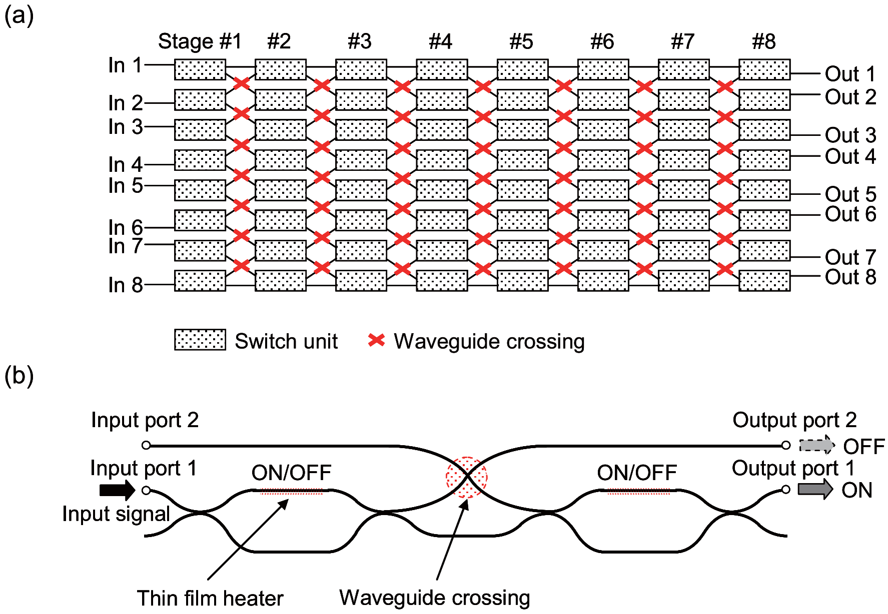

Fig. 1. (a) Matrix switch topology and (b) switch unit layout

shifters in order to provide low crosstalk, and a waveguide crossing connects these MZIs. The switch units are also connected by the crossings as shown in Fig. 1 (a). Any path passes through 14 crossings from the input port to the output port. Therefore, to reduce the loss of the matrix switches, we must reduce the crossing loss even if only slightly. Reducing the crossing loss is particularly important for larger scale matrix switches, because the crossing number is proportional to the switch unit number.

To reduce the excess loss of the crossings, we optimized their waveguide shape with the WFM method, which enables us to synthesize an optimum waveguide pattern from the desired characteristics [7]. The principle of the WFM method can be summarized as follows: Assuming a lossless and reciprocal waveguide, the coupling efficiency between the output light field ($\phi(x, z_{\mathrm{out}})$) from the waveguide and the desired output light field ($\psi(x, z_{\mathrm{out}})$), $<\phi(x, z_{\mathrm{out}})\psi^*(x, z_{\mathrm{out}})>$, is equal to that between the forward-propagating input field and the backward-propagating desired output field, $<\phi(x, z)\psi^*(x, z)>$, at any position z, where $<>$ and an asterisk denote the overlap integral as regards x and a complex conjugate, respectively. Therefore, if we modify the waveguide pattern at z to match the wavefronts of $\phi(x, z)$ and $\psi^*(x, z)$, the coupling efficiency, $<\phi(x, z_{\mathrm{out}})\psi^*(x, z_{\mathrm{out}})>$, is necessarily improved. In concrete terms, we can improve the coupling efficiency, which corresponds to a loss reduction, by employing the waveguide pattern change determined by $\mathrm{Im}[\phi(x, z)\psi^*(x, z)]$. (See [8] for a detailed explanation.) Fig. 2 (a) shows the waveguide pattern of the conventional crossing of an 8×8 matrix switch. The waveguide width was $7\,\mu$m, and the crossing angle was about 40°. Fig. 2 (b) shows the waveguide pattern of a crossing optimized by using the WFM method. As shown in Fig. 2 (b), our designed crossing has an aperiodically modulated core width. In the WFM calculation, we set the fundamental

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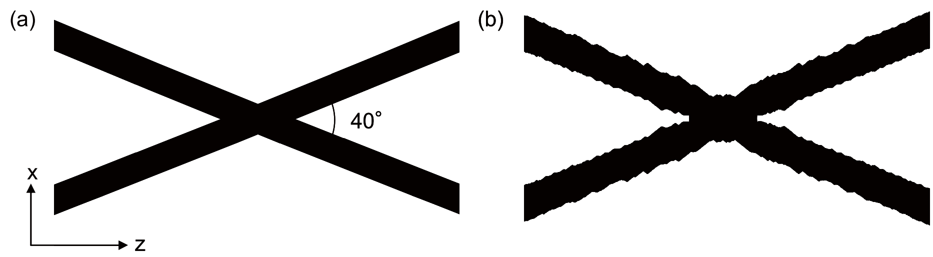

Fig. 2. Waveguide pattern of (a) conventional crossing (b) our designed crossing

mode of the access waveguide at $\phi(x, z_{\text{in}})$ and $\psi(x, z_{\text{out}})$. The excess losses of both crossings were calculated using the beam propagation method (BPM). The calculated excess loss of the conventional and designed crossings were 0.05 and 0.025 dB/point, respectively, at a wavelength of 1550 nm. Although the loss reduction effect of a single crossing was only 0.025 dB, the total loss reduction was expected to be about 0.35 dB because the input light passes through 14 crossings in an 8×8 matrix switch. Of course, this loss reduction of the switch realized by using our designed crossings becomes more significant for larger scale matrix switches. In this study, we demonstrated the effectiveness of our designed crossing by applying it to an 8×8 matrix switch.

3 Experimental results

We fabricated the 8×8 matrix switches incorporating our designed waveguide crossings using silica-based PLC technology. The refractive index difference was 0.75%, and the core layer was 6 μm thick. The minimum bending radius was 5 mm. Thin film heaters, which operate as phase shifters based on the thermo-optic effect, and power supply lines were patterned on the overcladding layer. To achieve low power consumption, we formed heat-insulating grooves along the MZI arms to heat the waveguide core efficiently. The chip size was 106 mm $\times$ 15 mm, and 6 chips were arranged on a 6-inch wafer. We fabricated switches with conventional crossings on the same wafer for comparison.

We measured the characteristics of the switches using non-polarized light. Fig. 3 (a) shows the ON-state losses of the switches with conventional crossings and our designed crossings for all 64 possible paths from the input port to the output port. The measured ON-state loss includes a waveguide fiber (dispersion-shifted-fiber) coupling loss of 0.3 dB. The average insertion loss of the switch with our designed crossings was 1.7 dB, and the minimum and maximum losses were 1.5 and 1.9 dB, respectively. Compared with the average insertion loss of the switch with conventional crossings, the excess loss of our designed crossings was 0.3 dB lower than that of conventional crossings. This loss reduction agrees well with the BPM simulation result. The wavelength-dependent loss of the switch with our designed crossings was less than 0.16 dB, which was equal to that of the switch with the conventional

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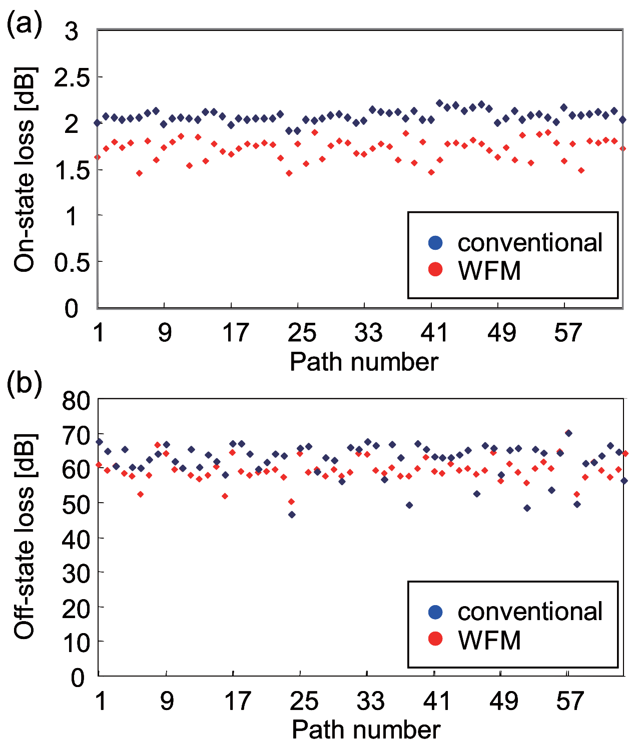

Fig. 3. Optical characteristics of fabricated 8 × 8 switches (a) ON-state loss (b) OFF-state loss

crossings, over the C-band. Fig. 3 (b) shows the OFF-state losses of the switches. For the fabricated switch with our designed crossings, the OFF-state losses ranged from 50.3 to 70.2 dB, with an average value of 59.5 dB. The extinction ratio, namely the difference between the ON-state and OFF-state losses, was over 48 dB. The average electrical switching power was 0.21 W per MZI, and the total power consumption was 3.4 W. We successfully demonstrated that our designed crossings contributed to reducing the matrix switch loss with no degradation in the extinction ratio or electrical power consumption.

4 Conclusion

We designed low-loss waveguide crossings with the WFM method to reduce the excess loss of PLC switches. We fabricated 8 × 8 matrix switches with optimized crossings using silica-based PLC technology. The fabricated switch exhibits an average insertion loss of 1.7 dB and an extinction ratio higher than 48 dB, and we confirmed the practical effectiveness of our designed crossings. We believe that our designed crossings will greatly reduce the loss of larger scale matrix switches.

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