Silicon photonics based 1 × 2 wavelength selective switch using fold-back arrayed-waveguide gratings

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Abstract: We report on a novel design of a wavelength selective switch (WSS) using silicon photonics technology. It comprises of 1 × 4 interleavers, arrayed-waveguide gratings (AWGs) connected to fold-back waveguides, and 1 × 2 optical Mach-Zehnder interferometer switches. In the proposed WSS, fold-back waveguides enable the AWGs to be used for both demultiplexing and multiplexing. Therefore the WSS has less waveguide crossings than a conventional configuration. Moreover, a 20-channel, 200-GHz spacing, 1 × 2 fold-back type WSS was fabricated on 5 mm × 10 mm SOI chip using CMOS technology.

Keywords: silicon photonics, optical switch, optical communication, arrayed waveguide grating, waveguide crossing, wavelength selective switch

Classification: Optical systems

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1 Introduction

A wavelength selective switch (WSS) is an optical device, with which light signals can be sent to multiple output ports selected depending on wavelength. The architecture of a reconfigurable optical add/drop multiplexer (ROADM) at a network node is required to have high functionality, i.e., colorlessness, directionlessness and contentionlessness (CDC), and this functional architecture can be made available using WSSs [1].

A $1 \times N$ WSS comprises one demultiplexer, a switching array and $N$ multiplexers. There are two main types of WSS that have been reported; WSSs using free space optics [2, 3] and WSSs using optical waveguides [4, 5]. Waveguide type WSSs are integrated on silica chip. In particular silicon waveguide type WSSs can be compact because dense integration can be obtained. They can also be low cost, since fabrication can be done using a CMOS process.

However, conventional waveguide type WSSs [4] have many waveguide crossings, which cause transmission loss, loss variation and crosstalk. The number of waveguide crossings increases in proportion to the number of channels and the number of ports, this puts a limitation on the number of ports and channels of waveguide type WSSs. We have reported on the design and fabrication of a WSS in a silicon optical circuit with a reduced number of crossings [6, 7, 8, 9, 10].

In this paper, we present our proposal for $1 \times 2$ WSS using fold back type [11] AWGs. This configuration includes less waveguide crossings than a conventional
WSS since it uses fold back waveguides connected to the AWGs that enables the AWGs to be used for both demultiplexing and multiplexing. Our WSS design was fabricated on an SOI wafer using CMOS technology. We briefly introduced design of a 200-GHz-spacing, 20-channel, 1 × 2 WSS using fold back type AWGs in the previous conference paper [10]. The detailed design and the measured switching characteristics of the WSS are described in the present paper.

2 Configuration of 1 × 2 fold-back type WSS

The configuration and operation of a 1 × 2 fold-back type WSS with N channels is shown in Fig. 1. The fold-back type WSS has one 1 × M interleaver for the input, M AWGs, N 1 × 2 Mach-Zehnder interferometer (MZI) switches, and two M × 1 interleavers for the output. Each AWG is connected to N/M MZI type switches through fold-back waveguides, and is used for both demultiplexing and multiplexing.

The wavelength division multiplex (WDM) signals at the input is separated into M wavelength groups by the 1 × M interleaver and these wavelength groups are demultiplexed by the AWGs into the N channels. Each channel has a 1 × 2 MZI switch, which sends the signals back through the AWG via fold back waveguides. The multiplexed wavelength groups pass through either from waveguide a or b in the AWGs. Finally, the signal is output via Output #1 or Output #2 after being combined at the M × 1 interleavers.

In this configuration, there are some waveguide crossings between the AWGs and the output interleavers. The number of waveguide crossings increases according to the number of AWGs or wavelength groups, not the number of channels, so that the maximum number of waveguide crossings per path can be M − 1. For our fabricated 1 × 2 WSS, the number of channels, N, was 20 and the number of wavelength groups, M, was 4. The maximum number of crossings is 3, as we describe later. It should be noted that the loss variation among the switching paths can be significantly reduced with the smaller number of crossings compared to the conventional WSS [4].

3 Design of 200-GHz-spacing, 20-channel, 1 × 2 fold-back WSS

The mask layout of the 200-GHz-spacing, 20-channel, 1 × 2 fold-back type WSS is shown in Fig. 2. There are one 1 × 4 interleaver for the input, two 4 × 1 inter-
leavers for the output, and four AWGs, each of which is connected to five $1 \times 2$ MZI switches via fold-back waveguides. In this design, the maximum number of waveguide crossings per path is 7; there are 3 structurally unavoidable crossings and 4 crossings with monitor waveguides for the input interleaver.

3.1 Design of $1 \times 4$ interleaver

The design of the interleavers for the input and output is the same. It is a 3-stage configuration comprising seven $1 \times 2$ interleavers. The free spectral range (FSR) of the first stage $1 \times 2$ interleaver is 400 GHz and those of the second and third stages are 800 GHz. The first stage interleaver separates the WDM signals into odd and even wavelength groups and the ones at the second stage demultiplex these into 4 wavelength groups. The third stage interleavers are the same design as those at the second stage and are used for reducing crosstalk. The differences in the arm lengths of the interleavers at 1st stage ($\Delta L_1$), for odd group ($\Delta L_2$), and for even group ($\Delta L_3$) at 2nd and 3rd stages, are 195.20 µm, 97.46 µm, and 97.60 µm, respectively. Thermo-optic phase shifters are put on each arm to compensate for the phase error.

3.2 Design of the fold-back-type AWG and MZI switch

The configuration of the fold-back type AWG with $1 \times 2$ MZI switches is shown in Fig. 3. The AWGs are connected to channel waveguides and the fold-back waveguides of the MZI switches at the edge of the 2nd slab waveguide. Each MZI switch has an input waveguide and two output fold back waveguides as shown in Fig. 3.
The light returning through fold-back waveguide a is passed to Output #1 via waveguide a.

Table I shows the design parameters of the fold-back type AWG. The center wavelength, channel spacing, and free spectral range of the AWG are 1.55 µm, 800 GHz, and 6.02 THz, respectively. The 1 × 2 MZI switches have TiN heaters on both arms employing the thermo-optic effect in silicon. The length of the heater is 200 µm and its resistance is 469 Ω.

| Parameter                        | Value   |
|----------------------------------|---------|
| Center wavelength                | 1.55 µm |
| Channel spacing                  | 800 GHz |
| Free spectral range              | 6.02 THz|
| Number of arrayed waveguides     | 90      |
| Diffraction order                | 23      |
| Length of slab waveguide         | 249.147 µm |
| Spacing between channel waveguides| 9.0 µm  |
| Spacing between channel waveguide and fold back waveguide | 3.4 µm |

4 Switching characteristics of the WSS

4.1 Experimental result

A photograph of a 1 × 2 fold-back type WSS is shown in Fig. 4. The 5 mm × 10 mm chips were fabricated on a 12” SOI wafer using a CMOS pilot line at AIST. Switching was done by controlling the current applied to the TiN heaters on the MZI switches. The heaters on the interleavers for the input and output were used for finely tuning the position of the spectral fringe of the first stage to those of the second and the third stages.

Fig. 4. Photograph of 1 × 2 fold-back type WSS

The transmittance of the fabricated 1 × 2 fold back type WSS when wavelength group #2 was switched to the outputs are shown in Fig. 5. Channel 6 was not available because of a heater breakdown. Table II shows the transmittances of Output #1 and Output #2 when each channel was switched to Output #1 and Output #2. The transmittances in Table II are average values of 6% of the channel spacing around the channel wavelength, and don’t include the coupling loss between the fiber and the chip. As shown in the table, the average transmittances in the off and on states for Output #1 are −46.4 dB and −44.0 dB, respectively, and those for Output #2 are −42.8 dB and −39.1 dB, respectively. Thus, the extinction ratios for Output #1 and Output #2 are 2.4 dB and 3.7 dB, respectively. The power
consumed by the interleavers was 373 mW. The average powers required to switch the signal to Output #1 and to Output #2 were 12.9 mW and 5.4 mW, respectively.

4.2 Discussion
Switching operation of the fabricated $1 \times 2$ fold-back type WSS was confirmed and the average extinction ratio of 3.3 dB was obtained by controlling the current.

![Fig. 5.](image)

(a) Transmittance to Output #1 when channel 4, 8, 12, 16, and 20 were selected (red curve), and when no channels were selected (blue curve).

(b) Transmittance to Output #2 when channel 4, 8, 12, 16, and 20 were selected. (red curve), and when no channels were selected (blue curve).

### Table II. Transmittances of Output #1 and Output #2 when each channel was switched to Output #1 and Output #2.

| Channel number (group number) | Transmittance to Output #1 | Transmittance to Output #2 |
|------------------------------|-----------------------------|----------------------------|
|                              | Switched to Output #2 [dB]  | Switched to Output #1 [dB]  | Extinction ratio [dB]  | Switched to Output #2 [dB]  | Extinction ratio [dB]  |
| 1 (#3)                       | −48.4                       | −42.6                       | 5.8                     | −49.9                       | −40.0                       | 9.9                     |
| 2 (#4)                       | −45.0                       | −41.7                       | 3.3                     | −40.8                       | −36.2                       | 4.6                     |
| 3 (#1)                       | −56.3                       | −53.3                       | 3.0                     | −51.8                       | −46.1                       | 5.7                     |
| 4 (#2)                       | −47.0                       | −43.8                       | 3.2                     | −46.6                       | −40.4                       | 6.2                     |
| 5 (#3)                       | −45.2                       | −43.8                       | 1.4                     | −42.9                       | −38.7                       | 4.2                     |
| 6 (#4)                       | -                           | -                           | -                       | -                           | -                           | -                       |
| 7 (#1)                       | −56.2                       | −51.8                       | 4.4                     | −50.9                       | −43.6                       | 7.3                     |
| 8 (#2)                       | −47.7                       | −43.8                       | 3.9                     | −45.5                       | −39.6                       | 5.9                     |
| 9 (#3)                       | −42.5                       | −42.0                       | 0.5                     | −41.4                       | −38.8                       | 2.6                     |
| 10 (#4)                      | −44.9                       | −42.7                       | 2.2                     | −39.0                       | −36.8                       | 2.2                     |
| 11 (#1)                      | −56.0                       | −52.7                       | 3.3                     | −50.3                       | −43.6                       | 6.7                     |
| 12 (#2)                      | −48.7                       | −43.0                       | 5.7                     | −44.6                       | −39.1                       | 5.5                     |
| 13 (#3)                      | −44.3                       | −41.4                       | 2.9                     | −41.2                       | −37.7                       | 3.5                     |
| 14 (#4)                      | −43.7                       | −43.4                       | 0.3                     | −39.0                       | −38.0                       | 1.0                     |
| 15 (#1)                      | −56.4                       | −51.5                       | 4.9                     | −48.3                       | −42.2                       | 6.1                     |
| 16 (#2)                      | −45.6                       | −44.7                       | 0.9                     | −41.8                       | −38.5                       | 3.3                     |
| 17 (#3)                      | −44.5                       | −42.8                       | 1.7                     | −42.7                       | −38.9                       | 3.8                     |
| 18 (#4)                      | −45.2                       | −43.5                       | 1.7                     | −40.7                       | −38.4                       | 2.3                     |
| 19 (#1)                      | −54.1                       | −50.9                       | 3.2                     | −44.7                       | −41.6                       | 3.1                     |
| 20 (#2)                      | −44.2                       | −42.1                       | 2.1                     | −41.0                       | −37.2                       | 3.8                     |
| Average                      | −46.4                       | −44.0                       | 2.4                     | −42.8                       | −39.1                       | 3.7                     |
injected to the TiN heaters on the MZI switches. However, there were large differences between the transmittances of the different wavelength groups, and the loss in the ON state was still large, especially for wavelength group #1, which was sent to channels 3, 7, 11, 15, and 19. This is due to problems with multiplexing and demultiplexing by the interleavers. Some TiN heaters for interleavers were burnt due to overcurrent and the phase errors were not compensated successfully.

The transmission losses were very large; however, they can be reduced sufficiently by optimizing the design and fabrication processes. For example, much larger scale, $32 \times 32$ silicon wire optical switch fabricated by the same CMOS pilot line at AIST achieved the transmission loss of 6.4 dB, although any transmission path included 32 MZI switches and 31 waveguide crossings [12]. Table III shows loss of each element on the test chip, fabricated simultaneously with the $1 \times 2$ fold back type WSS. The estimated losses, when the design and the fabrication processes are optimized, are also shown in Table III for reference. The large loss of the AWG is mainly due to the coupling loss at the joint of the slab waveguide and the waveguide array. It can be reduced by improving the SiO$_2$ deposition process for cladding and adopting the rib structure between them. The simulated transmission loss of the optimized AWG was 1.54 dB. The other major loss was due to the loss of multimode interference (MMI) couplers in interleavers and MZI switches. The loss of MZI switch with optimized structure was only 0.13 dB [12]. The $1 \times 4$ interleaver had a three-stage configuration; therefore, the loss was estimated to be 0.39 dB. The loss at the crossing can also be lowered by using the optimized structure to 0.024 dB [12]. The total loss of 40.4 dB may be reduced to 4.2 dB with such improvements.

| Element of WSS                       | Loss value (test chip) | Loss value (optimized) |
|--------------------------------------|------------------------|------------------------|
| $1 \times 4$ interleaver for input   | 2.9 dB                 | 0.39 dB                |
| AWG (demultiplexing)                 | 11.3 dB                | 1.54 dB                |
| $1 \times 2$ MZI switch              | 3.8 dB                 | 0.13 dB                |
| AWG (multiplexing)                   | 11.3 dB                | 1.54 dB                |
| $1 \times 4$ interleaver for output  | 4.7 dB                 | 0.39 dB                |
| Seven waveguide crossings            | 6.4 dB                 | 0.17 dB                |
| Total                                | 40.4 dB                | 4.2 dB                 |

5 Conclusions

We designed a $1 \times 2$ fold-back type WSS with 20 channels and 200 GHz-spacing, aiming at least number of waveguide crossings. Fabrication of the WSS was done on an SOI wafer using CMOS technology. The switching performance was confirmed by controlling the current applied to heaters on the MZI switches. The average extinction ratio was 3.3 dB, and the average power required to switch individual channels to Output #1 and Output #2 were 12.9 mW and 5.4 mW, respectively.

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