Recent Advances in Large-scale Optical Switches Based on Silicon Photonics

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Abstract: We review our recent results in multi-port strictly non-blocking silicon photonics switches. Challenges for polarization and wavelength insensitive operations are discussed. These results indicate the Si-photonics switch is suitable for the data center network applications.

1. Introduction

The recent spreading of the on-demand movie, cloud-based services, and teleworking are accelerating the increase of data flow within the data centers. The data center consists of a lot of servers connected with optical fiber links and network switches. Hence, a high throughput network switch is one of the most important functions. To catch up with the throughput demand, the bandwidth of the switch ASIC in the network switch is expanding at a rate of doubling in two years and reaching 25.6 Tb/s [1]. This bandwidth expansion is accompanied by the increase of electric power consumption, and which becomes a bottleneck for further expansion of the bandwidth. As one of the solutions to the bottleneck, optical switches are expected to play an important role. One of the reasons is that the power consumption of the optical switches does not depend on the symbol rate of the transmitting signals. By utilizing this characteristic, some network systems exploiting the optical switches were demonstrated [2-4].

To realize the optical switch, a silicon photonics platform is one of the suitable options because it enables fast (micro to nanoseconds) switching, large-scale integration with high uniformity, and mass production. Previously, we reported on a low fiber-to-fiber insertion loss (average 10.8 dB) 32 input ports × 32 output ports silicon photonics switch [5]. The 32 × 32 switch consisted of 2 × 2 Mach-Zehnder (MZ) switches with thermooptic phase shifter and adiabatic intersections, and its switch topology was path-independent insertion loss (PILOSS) [6]. By using the switch, we demonstrated a full-loaded operation of 0.29 pJ/bit wall-plug efficiency and 81.9 Tb/s throughputs [7]. This switch, however, operates for transverse-electric (TE) polarization and has narrow bandwidth (3.5 nm for -20 dB crosstalk). Hence, our next challenges are polarization and wavelength insensitive operations. About the polarization insensitivity, we think that polarization diversity is a realistic option [8]. As a preliminary demonstration, we composed the polarization diversity 8 × 8 switch by preparing the two sets of optical switches and their control electronics [9]. Recently, we demonstrated single-chip integration of the polarization-diversity 8 × 8 switch [10]. About the wavelength insensitivity, the double-MZ element switch is suitable for the PILOSS topology [11]. We demonstrated ~90 nm bandwidth for -30 dB crosstalk bandwidth [10].

In this paper, we review our recent progress for polarization and wavelength insensitive operation of silicon photonics switches. Especially, we focus on polarization diversity 32 × 32 switch with non-duplicated diversity scheme and polarization-diversity double MZ 8 × 8 switch.

2. Nonduplicate Polarization-Insensitive 32 × 32 Switch

In general, the polarization-diversity scheme requires two identical switch matrices to deal with the two orthogonal polarization components. This becomes an obstacle for a large-scale optical switch because the number of electrodes and control electronics, and the footprint of the switch matrix becomes twice. As one solution for the obstacle, we proposed the non-duplicated polarization-diversity scheme based on bidirectional use of the PILOSS topology [12]. Figure 1(a) shows the 32 × 32 switch chip fabricated with AIST's pilot line. The edge couplers were aligned on the left side of the chip, then connected to the polarization splitter/rotators (PSRs). As shown in Fig.1(b), the switch chip was composed of two layers: Si underpass with element switches, and SiN overpass waveguides. To transfer the propagating light between the two layers, we used a vertical directional coupling. The SiN overpass waveguides were used to simplify the connection between the output of PSR and the right-side input ports of the switch matrix.

We measured fiber-to-fiber insertion loss and polarization-dependent loss (PDL) of sampled 32 paths. The average and minimum insertion losses in a wavelength of 1.55 μm were 35 dB and 27 dB, respectively. The largest part of the insertion loss came from a propagation loss of the SiN waveguide. If we designed the switch for O or L band operation, the improvement of the insertion loss would be expected. Figure 1(c) shows the measured PDL of the sampled 32 paths. The PDL in 75% of measured paths was less than 3 dB. The PDL can be improved by optimizing the element devices. The differential group delay (DGD) was 1.7 ps, which was obtained by propagating short optical pulses while adjusting input polarization shown in Fig.1(d). This value is low enough for signal transmission, such as 50 Gbaud. These results indicate that the polarization-insensitive operation in the large-scale optical switch is feasible.

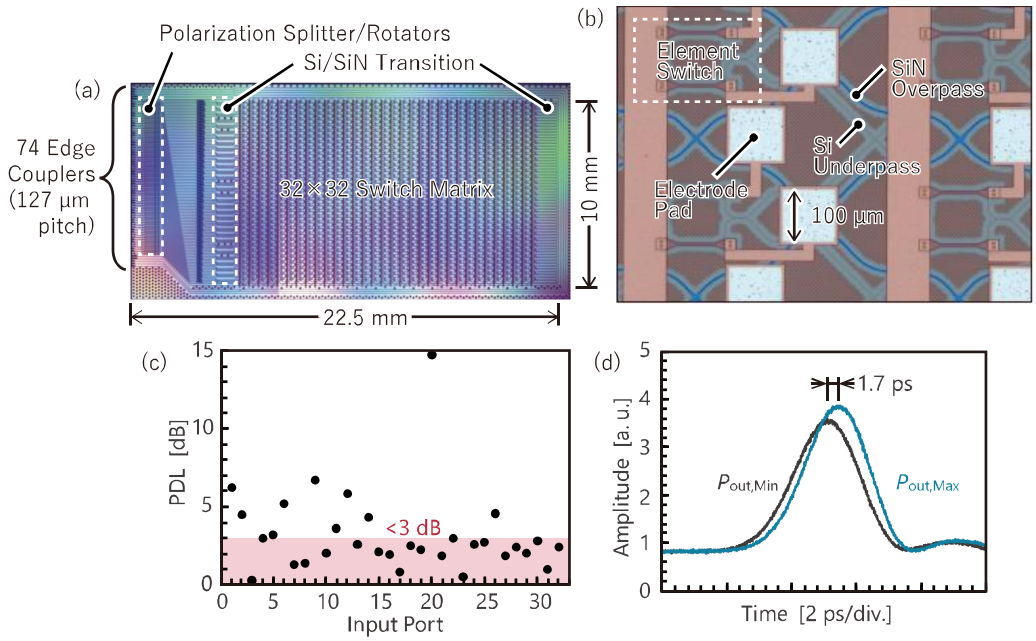

Fig. 1. (a) Fabricated non-duplicated polarization-diversity 32 × 32 switch chip. (b) Magnified image of the element switches and SiN overpass waveguides. (c) Measured polarization dependent loss. (d) Optical pulses propagated path from input port 23 to output port 23' while adjusting input polarization.

3. Polarization and Wavelength Insensitive 8 × 8 Switch

In a scale of 8 × 8 ports, we demonstrated polarization and wavelength insensitive operation [10]. For polarization insensitivity, we used two switch matrices which were nested to simplify and equalize the optical paths. For wavelength insensitivity, we used a double-MZ switch [11], which consisted of two cascaded MZ switches and an intersection. The 8 × 8 switch chip was fabricated by using AIST's CMOS pilot line. The diced chip was flip-chip bonded onto a ceramic interposer, then the fiber array was attached and fixed with glue. Finally, the interposer was inserted into a socket on a printed circuit board with control electronics which was composed of two FPGAs, as shown in Fig.2(a). The whole size of the switch was 13.5 cm × 9 cm, which is comparable with a smartphone.

We measured the fiber-to-fiber insertion losses of all 64 paths. The average and minimum insertion losses were 11.9 and 11.0 dB, respectively. The largest portion of the insertion loss was fiber/chip coupling (~5 dB). The coupling loss can be reduced by optimizing the edge coupler. The crosstalk spectrum in the worst case is shown in Fig.2(b). The crosstalk was less than -30 dB in a wavelength range of ≈90 nm. The PDLs of all paths were less than 0.4 dB in a wavelength range of 1520 – 1600 nm as shown in Fig.2(c). The DGD was less than 1.8 ps at a wavelength range of 1520 – 1600 nm (Fig.2(d)). These low PDL, DGD, and crosstalk in a wide wavelength range indicate that the silicon photonics switch is one of the most promising candidates for the high-speed photonics switch in a data center or high-performance computing applications.

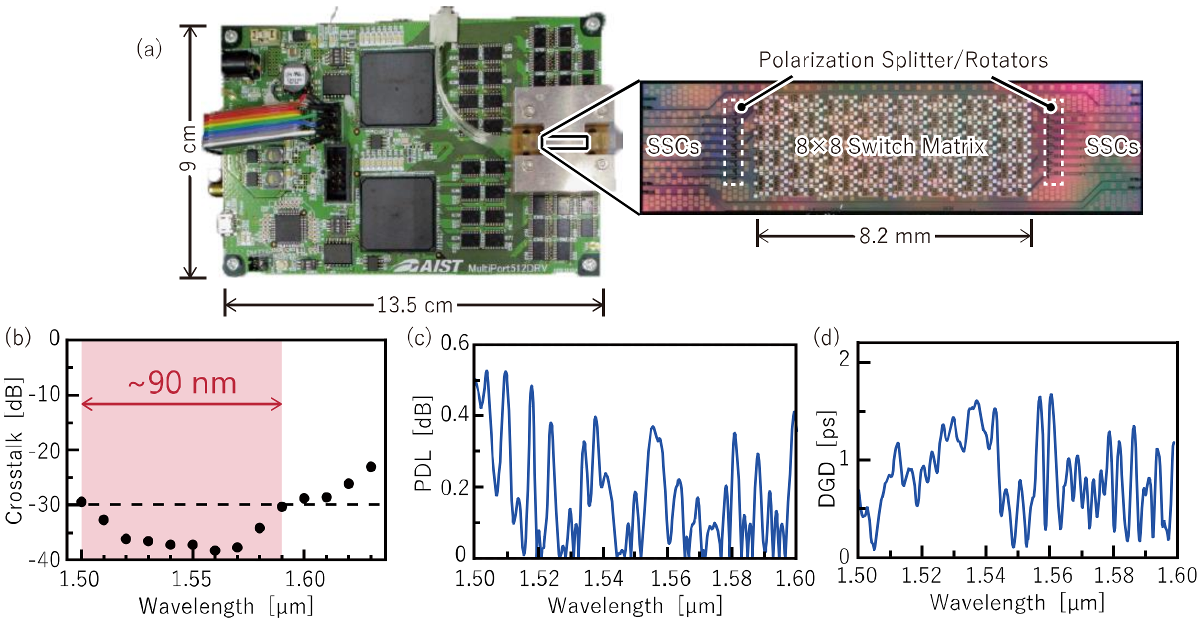

Fig. 2. (a) Polarization-diversity double Mach-Zehnder 8 × 8 switch assembled on printed circuit board. (b) Measured crosstalk spectrum. (c) Measured polarization dependent loss spectrum of path from input port 7 to output port 6. (d) Measured differential group delay spectrum of path 7 to 6'.

4. Discussion

To realize optical switch acceptable for practical applications, it is important to achieve the polarization and wavelength insensitivity simultaneously. Although the port scale is 8 × 8, we achieved that as described above [10]. Hence, our next target is the expansion of the port count, such as 32 × 32. The largest obstacle is the fan-out of electrodes. If we expand the port count from 8 × 8 to 32 × 32 simply, we must handle more than 8,000 electrodes. We need some technology that can reduce the number of electrodes, such as integration with control electronics. Additionally, the operating wavelength of the switches described above is C and L band. Considering the applications to the data centers in near future, O-band operation is preferable. We confirmed that the O-band operation is possible by optimizing the design parameters [13].

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