Research article

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Six-port optical switch for cluster-mesh photonic network-on-chip

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Abstract: Photonic network-on-chip for high-performance multi-core processors has attracted substantial interest in recent years as it offers a systematic method to meet the demand of large bandwidth, low latency and low power dissipation. In this paper we demonstrate a non-blocking six-port optical switch for cluster-mesh photonic network-on-chip. The architecture is constructed by substituting three optical switching units of typical Spanke-Benes network to optical waveguide crossings. Compared with Spanke-Benes network, the number of optical switching units is reduced by 20%, while the connectivity of routing path is maintained. By this way the footprint and power consumption can be reduced at the expense of sacrificing the network latency performance in some cases. The device is realized by 12 thermally tuned silicon Mach-Zehnder optical switching units. Its theoretical spectral responses are evaluated by establishing a numerical model. The experimental spectral responses are also characterized, which indicates that the optical signal-to-noise ratios of the optical switch are larger than 13.5 dB in the wavelength range from 1525 nm to 1565 nm. Data transmission experiment with the data rate of 32 Gbps is implemented for each optical link.

Keywords: optical interconnect; optical switches; wavelength-division multiplexing; silicon photonics.

1 Introduction

With more processor cores integrated on a chip, larger bandwidths are required to establish the communication among them. Traditional electrical interconnection becomes a bottleneck for improving the performance of a multiple-core processor due to its limited bandwidth, high power consumption and long latency. For example, electrical interconnections become bandwidth limited beyond 10 GHz because of RC delay, frequency-dependent loss, the skin effect and the dielectric loss. The effects of reflection and crosstalk are also challenging problems [1, 2]. Optical interconnection is considered as a candidate to overcome the limitations of its electrical counterpart [3, 4].

A series of optical devices are required to construct the optical interconnection between two processor cores, such as lasers [5], modulators [6], multiplexers and demultiplexers [7] and detectors [8]. Such a point-to-point optical interconnection is the simplest communication mode. However, for a multiple-core processor, each processor core is required to communicate with other processor cores to share the heavy computing task. An electro-optic system that offers the optical interconnection between two cores has been reported [9]. Furthermore, for the interconnection among more cores, the work is usually implemented by an optical switch, which is located at each node of photonic network-on-chip (NoC) and utilized to connect the local processor core with its neighboring nodes.

To save the limited chip area and improve the utilization of precious network resources, two processor cores can be placed in one tile and share the same cache and router. It is implemented in the well-known Single-Chip Cloud Computer and the Xeon Phi processors manufactured by Intel Corporation [10]. This two-core-per-tile based mesh architecture is called “cluster-mesh”, which achieves a good tradeoff between the performance and manufacturability.

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Optical switches for photonic NoC have received much attention in recent years [11–30]. Widespread utilization of mesh NoC in commercial products leads to extensive research on five-port optical switch [11], which is used to connect the processor core and other four nodes on the north, south, east and west directions. To deploy cluster-mesh architecture, six-port optical switch is required. The added port is used to connect the second core. Some six-port router architectures have been reported [15–17].

In this paper, we propose a six-port optical switch based on Spanke-Benes architecture, which includes twelve 2×2 optical switching units. The number of optical switching units is decreased by 20% compared with the Spanke-Benes architecture, which means that the footprint and power consumption of the optical switch can be reduced at the expense of sacrificing the network performance in some cases. We also demonstrate a six-port optical switch based on thermally tuned silicon Mach-Zehnder optical switching units. Its theoretical spectral responses are evaluated by establishing a numerical model. The experimental spectral responses of the fabricated device are characterized, and its optical signal-to-noise ratios (SNRs) are larger than 13.5 dB in the wavelength range from 1525 nm to 1565 nm. Data transmission experiment at a rate of 32 Gbps is implemented for each optical link.

2 Architecture and its numerical simulation

2.1 Architecture of the optical switch

A six-port optical switch based on typical Spanke-Benes architecture has fifteen 2×2 optical switching units, as shown in Figure 1A. One 2×2 optical switching unit has two states (i.e. “cross” and “bar” states), so the number of possible switching configurations of this architecture is $2^{15} = 32,768$, while for a non-blocking six-port optical switch, the number of non-repeated routing states is factorial $(6) = 720$. Each routing state is constituted by six routing paths connecting six input and output ports, which can transfer information in parallel. The optical switching unit is an active component, which will consume power, and its insertion loss is larger than those of the passive components such as waveguide and waveguide crossing. Reducing the number of the used optical switching units and maintaining the connectivity of the routing path are very useful as less used optical switching units mean that the architecture is more compact and more power-efficient. Note that this reduction will affect the network performance as the path options for some routing paths are reduced. It is suitable for some applications in which the latency requirements are not

Figure 1: Rectangles represent the optical switching units. Both (A) and (B) have identical connectivity.

(A) Architecture of six-port optical switch based on typical Spanke-Benes architecture and (B) architecture of the optimized six-port optical switch.

so sensitive. To ensure the routing path connectivity, the total number of routing states should be factorial (N). Otherwise, the optical switch will become blocked.

For the architecture in Figure 1A, if we exhaust all the combinations of the optical switching units, we will get 32,768 switching states; while most of them are repetitive, the non-repetitive number is 720, which is equal to its number of routing states.

To facilitate the optimization process, we reduce the number of optical switching units one by one and substitute them by waveguide crossings or waveguides and then count the number of routing states again; if the number is reduced, the substitution is canceled. Finally, the number of optical switching units is reduced to 12, while the number of routing states will still remain 720. The optimized architecture is shown in Figure 1B; the 12 optical switching units are denoted as $S_1, S_2, \dots, S_{12}$.

2.2 Numerical simulation

First we give the transfer matrix expressions of the optical switching unit and waveguide crossing. An optical switching unit has two input ports, In_1 and In_2 , and two output ports, Out_1 and Out_2 . When the optical switching unit is in the “cross” state, two incident lights are guided from its input ports In_1 and In_2 to its output ports Out_2 and Out_1 . When the optical switching unit is in the “bar” state, two incident lights are guided from its input ports In_1 and In_2 to its output ports Out_1 and Out_2 .

The M-Z optical switching unit can be divided into three parts: the front 2×2 multimode interference (MMI) coupler, the two arms and the back 2×2 MMI coupler. The transfer matrix of the front and back 2×2 MMI coupler can be expressed as

$$T_{\text{coupler}} = \begin{pmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{pmatrix}, \quad (1)$$

where $t_{ik} = a_{ik} e^{j(\varphi_{ik} + \delta\varphi_{ik})}$ and $j = \sqrt{-1}$ [31, 32]. φ_{ik} is the relative phase shift of the image at output port k for input port i ,

$$\begin{aligned} \varphi_{11} = \varphi_{22} &= -7\pi/16 \\ \varphi_{12} = \varphi_{21} &= \pi/16. \end{aligned} \quad (2)$$

$\delta\varphi_{ik}$ is the relative phase deviation of the image at output port k for input port i . a_{ik} is the real field amplitude transfer coefficient from input port i to output port k . Two arms of the optical switch can be described by the diagonal 2×2 transfer matrix as

$$T_{\text{ARM}} = \begin{pmatrix} A_1 e^{j(\theta_1 + \delta\theta_1)} & 0 \\ 0 & A_2 e^{j(\theta_2 + \delta\theta_2)} \end{pmatrix}. \quad (3)$$

A_1 and A_2 are the loss coefficients of arm 1 and arm 2, respectively, and can be expressed as

$$A_i = \exp(-\alpha L_i), \quad (4)$$

where α is the propagation loss of the waveguide. Based on the data from experiment, we assume $\alpha = 2.5$ dB/cm.

L_i is the length of arm i , and θ_i is the phase shift through arm i and can be expressed as

$$\theta_i = 2\pi n_{\text{eff}}^i(\lambda) L_i / \lambda, \quad (5)$$

where λ is the wavelength of light in the vacuum and n_{eff}^i is the effective refractive index of arm i . $\delta\theta_i$ is the phase shift deviation due to imperfect fabrication. The total transfer matrix of the M-Z optical switching unit is then given by

$$T_{2 \times 2} = T_{\text{coupler}}^{\text{back}} \cdot T_{\text{ARM}} \cdot T_{\text{coupler}}^{\text{front}}. \quad (6)$$

The output optical field distributions of the M-Z optical switching unit are expressed by the following matrix equation:

$$\begin{pmatrix} E_1^{\text{out}} \\ E_2^{\text{out}} \end{pmatrix} = T_{2 \times 2} \cdot \begin{pmatrix} E_1^{\text{in}} \\ E_2^{\text{in}} \end{pmatrix}. \quad (7)$$

For simplicity, the transfer matrix of an optical switching unit is expressed by

$$T_{2 \times 2} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix}. \quad (8)$$

Similarly, the matrix expression of a waveguide crossing (or an ideal optical switching unit in the “cross” state) and waveguide (or an ideal optical switching unit in the “bar” state) can be expressed by

$$T_{\text{crossing}} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$T_{\text{bar}} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad (9)$$

As shown in Figure 1B, the architecture of the six-port optical switch can be divided into six columns; each column consists of optical switching units, straight waveguides or waveguide crossings and can be expressed by the transfer matrix M_i ($i = 1, 2, \dots, 6$). M_i is a partitioned matrix,

$$M_i = \begin{pmatrix} T^{B/C} & 0 & \cdots & 0 & 0 \\ 0 & T^{B/C} & 0 & \vdots & \vdots \\ \vdots & 0 & \ddots & 0 & 0 \\ 0 & \vdots & 0 & T^{B/C} & 0 \\ 0 & 0 & \cdots & 0 & T^{B/C} \end{pmatrix} \quad (10)$$

where

$$\begin{cases} T^{B/C} = T_{\text{cross}}, & \text{optical switching unit is in the "cross" state} \\ T^{B/C} = T_{\text{bar}}, & \text{optical switching unit is in the "bar" state} \end{cases}$$

In detail, we show the transfer matrix M_1 as an example:

$$M_1 = \begin{pmatrix} T(1)_{11} & T(1)_{12} & 0 & 0 & 0 & 0 \\ T(1)_{21} & T(1)_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & T(2)_{11} & T(2)_{12} & 0 & 0 \\ 0 & 0 & T(2)_{21} & T(2)_{22} & 0 & 0 \\ 0 & 0 & 0 & 0 & T(3)_{11} & T(3)_{12} \\ 0 & 0 & 0 & 0 & T(3)_{21} & T(3)_{22} \end{pmatrix}, \quad (11)$$

The input and output optical fields have the following relation:

$$E^{\text{out}} = M_6 \cdot M_5 \cdot M_4 \cdot M_3 \cdot M_2 \cdot M_1 \cdot E^{\text{in}} = M \cdot E^{\text{in}}, \quad (12)$$

where M is the transfer matrix of the six-port optical switch.

In the following simulation, the propagation loss of the MMI coupler is 0.25 dB, which is achieved by three-dimensional finite-difference time-domain simulation. The two phase shifters are 200 μm each in length, and the propagation loss of the silicon rib waveguide (structural parameters can be found in Section III) for the two phase shifters is 2.5 dB/cm. The power splitting ratio imbalance of the MMI coupler is caused by fabrication imperfection. In simulation we set the splitting ratio as a random distribution within the range of 49%–51%, which is achieved from the extinction ratio of optical switching unit in experiment.

To study the spectral responses of the six-port optical switch, we focus on its five routing states which cover its 30 optical links (no U turn routing) to constitute an independent analysis scenario. Other reconfigurable routing paths from the same input ports to the same output ports are just the combination of the constituent parts of these specific routing paths. Table 1 shows the states of the 12 optical switching units and the established 30 optical links in the selected five routing states of the six-port optical switch.

In each routing state, the optical signals are guided from six input ports to six output ports. Although the optical signal from a specific input port is aimed to be guided to a specific output port, it is unavoidable that a tiny part of the optical signal is leaked to the other five output ports and becomes the noises to the five output ports. In actual application, the light beams injected from the six input ports are incoherent with each other, so the total noise of one specific optical link is the sum of the noise from the other five input ports individually. In order to maintain consistency with the experiment, the light beams of different input ports are considered as incoherent in simulation. Figure 2 shows the calculated transmission spectra of the optical switch in its five routing states.

The propagation loss of the optical signal links fluctuates from 3.4 dB to 5.6 dB, which mainly depends on the number of on-line optical switching units. More on-line optical switching units means larger propagation loss. For each optical link, the signal comes from a specific input port and the noises come from the other five input ports. The five noises have different weights on the optical crosstalk of the optical link depending on the number of on-line optical switching units, power leakage and the length of the routing path. Some periodic intensity fringes can be observed in the transmission spectra of some crosstalk optical links. As the extinction ratio of each optical switching unit is finite, there exists non-ideal light leaking from each switching unit. For a specific optical link, there may exist more than one noise beams due to the leakage. When these beams have comparable power levels, the

Table 1: States of the 12 switching units in selected five routing states of the six-port optical switch which cover its 30 optical links.

RS	Optical links	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}
1	$I_1 \rightarrow O_2, I_2 \rightarrow O_3, I_3 \rightarrow O_4, I_4 \rightarrow O_5, I_5 \rightarrow O_6, I_6 \rightarrow O_1$	B	B	C	B	B	C	C	B	C	B	B	B
2	$I_1 \rightarrow O_3, I_2 \rightarrow O_4, I_3 \rightarrow O_5, I_4 \rightarrow O_6, I_5 \rightarrow O_1, I_6 \rightarrow O_2$	B	B	B	C	C	C	C	B	C	C	C	B
3	$I_1 \rightarrow O_4, I_2 \rightarrow O_5, I_3 \rightarrow O_6, I_4 \rightarrow O_1, I_5 \rightarrow O_2, I_6 \rightarrow O_3$	B	C	C	C	C	C	C	C	B	C	B	B
4	$I_1 \rightarrow O_5, I_2 \rightarrow O_6, I_3 \rightarrow O_1, I_4 \rightarrow O_2, I_5 \rightarrow O_3, I_6 \rightarrow O_4$	B	B	B	B	C	C	C	C	B	C	C	C
5	$I_1 \rightarrow O_6, I_2 \rightarrow O_1, I_3 \rightarrow O_2, I_4 \rightarrow O_3, I_5 \rightarrow O_4, I_6 \rightarrow O_5$	C	C	B	B	C	C	B	B	B	C	B	C

RS, Routing state; B, in the "bar" state; C, in the "cross" state.

Figure 2: Simulated spectral responses in the selected five routing states (OSNR, optical signal-to-noise ratio; RS, routing state).

interferences among them will cause these oscillations. Such a multiple-beam interference characteristic is the inherent property of the optical switch with a reconfigurable non-blocking architecture and may deteriorate the optical crosstalk of the optical switch in specific optical links. Improving the extinction ratio of the optical switching units can degrade its negative effect. The optical switch has optical SNRs of 18.5 dB to 37.2 dB for different optical links in different routing states. For different optical links, the number of on-line optical switching units is different. And the unexpected leakage from the optical switching units are different. These factors cause the differences in optical SNRs.

3 Fabrication and experimental results

3.1 Parameter design of the optical switch

Silicon rib waveguide with 400 nm width, 220 nm height and 70 nm slab thickness is utilized to construct the optical switch, which only supports quasi-transverse electric fundamental mode. Each optical switching unit consists of two 2×2 MMI couplers and two modulation arms. We adopt the 2×2 MMI coupler with paired interference mechanism to realize the power splitting and combining

since it has a better performance in power splitting imbalance [31]. We optimize the 2×2 MMI coupler by three-dimensional finite-difference time-domain method. The calculated propagation loss of the MMI coupler is 0.25 dB. The length of each arm of the optical switching unit is 240 μm , with 200 μm covered by micro-heater. The optical switch is actuated by thermo-optic effect of silicon. A silicon inverse taper covered by an air-bridge silicon dioxide intermediate transition waveguide is used to reduce the coupling loss between the silicon waveguide and the normal single-mode fiber [33, 34], which is about 3 dB/facet.

3.2 Fabrication of the optical switch

We utilize the silicon photonics foundry of Institute of Microelectronics in Singapore for device fabrication. The 8-inch silicon-on-insulator wafer with a 220 nm top silicon layer and a 2 μm buried silica layer is adopted to fabricate the device. Silicon rib waveguides are formed by 248-nm deep ultraviolet photolithography and inductively coupled plasma etching. A 1.5 μm silica layer is deposited on the silicon waveguide as an isolated layer by plasma-enhanced chemical vapor deposition (PECVD) in order to avoid the optical absorption by the following metal layer. A 200 nm TiN layer with high resistivity is deposited and etched to form the heaters with a width of 2 μm . Via holes

Figure 3: Microscope image of the fabricated optical switch.

are etched after depositing a 300-nm-thick silica layer by PECVD. A 1.5 μm Al layer with low resistivity is deposited and etched to form the electrical traces. A microscope image of the fabricated device is shown in Figure 3, which is $\sim 1300 \mu\text{m} \times 700 \mu\text{m}$ in footprint.

3.3 Experimental spectral responses of the optical switch

Amplified spontaneous emission source and optical spectra analyzer (OSA) are utilized to characterize the spectral responses of the optical switch, and voltage

sources are used to tune the switching states of the optical switching units. To characterize the propagation loss and optical SNR of the optical switch, 12 voltage sources are employed to tune the states of the 12 optical switching units. Figure 4 shows the spectral responses of the optical switch in the routing states shown in Table 1.

From one by one comparison, we find that the tendency of the optical SNRs and measured transmission spectra of the signal and the main noises are similar to the simulated ones. The optical SNR of the optical links is mainly determined by the transmission spectra of the signal and sum of noises, which fluctuate from 13.5 dB to 18.6 dB. Unexpected leakage from optical switching units causes the deterioration of the SNRs. Moreover, the measured transmission spectra of the noises are different from the simulated ones, which are relatively flat and are considered to be mainly from the background noise of the OSA as the signals meet its limitation. Moreover, the different transmission loss from the interconnecting wires lead to the intensity differences of beams, which influence the efficiency of interferences.

3.4 Data transmission of the optical switch

In order to verify the routing property of the optical switch, high-speed data transmission experiment is performed for

Figure 4: Static spectral responses of the optical switch in the selected five routing states (OSNR, optical signal-to-noise ratio; RS, routing state).

Figure 5: Eye diagrams for the 30 optical links of the six-port optical switch at the wavelength of 1550 nm.

its 30 optical links. An external LiNbO_3 optical modulator is used to modulate the continuous-wave light at the wavelength of 1550 nm, which is generated by a tunable laser. A pseudorandom binary bit sequence with the pattern length of $2^{31}-1$ and the data rate of 32 Gbps is generated by a pulse pattern generator and then is applied to the LiNbO_3 optical modulator. The polarization of the optical signal is controlled by a polarization controller. The optical signal is coupled into and out of the device by two single-mode fibers (SMF-28) and then fed into a digital communication analyzer (Agilent DCA 86100D) with a photodetector for eye diagram observation.

Figure 5 shows the measured eye diagrams for the 30 optical links of the optical switch. The extinction ratios of the eye diagrams for the data transmission through the 30 optical links fluctuate from 16.4 dB to 17.7 dB, which approach the extinction ratio of the back-to-back eye diagram (18.2 dB). Clear and open eye diagrams verify the routing functionality of the optical switch. It should be noted that the eye diagrams are achieved by launching light into one input port. The actual eye diagram will be probably deteriorated as the optical crosstalk among different optical links affects the quality of signal. And the actual extinction ratio of the eye diagram will be a little less than the measured one.

Wavelength-division multiplexing (WDM) technology is widely used to increase the communication capacity of

the optical NoC without changing the routing algorithm and consuming extra power. Mach-Zehnder optical switch with two balanced arms have large optical bandwidths due to its symmetric interference architecture. As shown in Figure 4, the optical bandwidth of the switch covers 1525 nm to 1565 nm, which enables the switch supporting WDM data transmission in the whole wavelength range. We choose 50 wavelengths with 100 GHz channel spacing for eye diagrams characterization. The optical link $I_5 \rightarrow O_6$ in routing state 1 with a moderate optical SNR is chosen to

Figure 6: WDM transmission of the optical link $I_5 \rightarrow O_6$ of the six-port optical switch.

Table 2: Power consumptions of each optical switching unit.

	S_1	S_2	S_3	S_4	S_5	S_6
$P_{\text{Cross}}/\text{mW}$	30.7	20.8	17.3	36.0	25.2	0.4
P_{Bar}/mW	10.1	0	38.9	14.5	3.4	23.5
	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}
$P_{\text{Cross}}/\text{mW}$	8.3	34.7	33.3	21.9	29.4	19.2
P_{Bar}/mW	30.7	12.4	12.0	1.6	9.0	0

perform the WDM data transmission. The mean extinction ratio with the standard deviation is 17.1 ± 0.3 dB (Figure 6).

Due to the fabrication imperfection, the initial phase differences between the two arms are different for different optical switching units, so the corresponding driving voltages and power consumptions are also different. The power consumptions of all optical switching units are listed in Table 2. By this table we can calculate the power consumption of any routing state. Within all routing states, the largest power consumption is 344.3 mW. It is achieved when all optical switching units are set at the state with higher power consumption; the established optical paths are $I_1 \rightarrow O_1$, $I_2 \rightarrow O_3$, $I_3 \rightarrow O_4$, $I_4 \rightarrow O_5$, $I_5 \rightarrow O_6$ and $I_6 \rightarrow O_2$. The lowest power consumption is 89 mW. It is achieved when all optical switching units are set at the state with lower power consumption; the established optical paths are $I_1 \rightarrow O_5$, $I_2 \rightarrow O_1$, $I_3 \rightarrow O_4$, $I_4 \rightarrow O_3$, $I_5 \rightarrow O_6$ and $I_6 \rightarrow O_2$. To reduce the power consumption of the optical switch, air trench can be implemented to improve the heat efficiency [35, 36]. A 10 kHz square-wave electrical signal is applied to each optical switching unit to measure its response time. Figure 7 shows the dynamic response of the optical switching unit, whose 10%–90% rising time and 90%–10% falling time are 11 μs and 16 μs , respectively. The responses of all optical switching units are around these values. The response speed of each optical link is decided by each optical switching unit that it comes through. More specifically, the response speed is decided by the slowest

Figure 7: Dynamic response of the optical switching unit.

optical switching unit. Relatively low switching speed limits the actual application of the optical switch. Higher switching speed is expected by utilizing an electro-optic tuning mechanism in the future [25].

4 Conclusion

In summary, we demonstrate a non-blocking six-port optical switch on silicon photonics platform, which is composed of 12 thermally tuned M-Z optical switching units. A numerical simulation method is given to evaluate its theoretical spectral responses. The performance of the fabricated device is characterized. The optical SNRs of 30 optical links of the optical switch are larger than 13.5 dB in the wavelength range from 1525 nm to 1565 nm.

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