Journal of Advances in Computer Research
Quarterly pISSN: 2345-606x eISSN: 2345-6078
Sari Branch, Islamic Azad University, Sari, I.R.Iran
(Vol. 7, No. 3, August 2016), Pages: 47-53
www.jacr.iausari.ac.ir

Five-Port Optical Router Design Based on Mach–Zehnder Switches for Photonic Networks-on-Chip

Elham Yaghoubi✉, Midia Reshadi
Department of Computer, Science and Research branch, Islamic Azad University, Tehran, Iran
e.yaghoubi@srbiau.ac.ir; reshadi@srbiau.ac.ir

Received: 2015/09/13; Accepted: 2016/02/18

Abstract

We design and simulate a five-port optical router, which is composed of twenty Mach-Zehnder-based switching elements and twelve waveguide crossings for use in integrated photonic interconnection networks. We simulated and analyzed the operation of the proposed optical router from the aspects of insertion loss,power budget, Q-factor and the minimum bit error ratio by use of OptiSystem simulator. The simulation results show that twenty possible input/output routing paths of the five-port optical router are verified at a data transmission rate of 20 Gbps for all input-output channels.

Keywords: *Five-Port Optical Router, Mach-Zehnder Interferometer Switch, On-Chip Optical Interconnects, Optical Design, Photonic Network on Chip*

1. Introduction

Photonic Networks-on-Chip (NoC) is a potential solution for increasing the communication bandwidth, lowering the latency with reducing the power consumption in high performance chip multiprocessors (CMPs) [1-3]. Moreover, significant advances in silicon photonics compatible with complementary metal-oxide-semiconductor (CMOS) technology have made the photonic NoC an ideal candidate for on- and off-chip communications [4-6].

Optical router is one of the essential components for photonic NoC; that is the ability to connect the local processing core with other remote processing cores of photonic NoC. An optical router is also responsible for selecting paths between the input and output ports on the network. Recently, several silicon optical routers based on microring resonator (MRR) or Mach–Zehnder interferometer (MZI) have been reported [7-13]. Many five-port optical routers have been proposed [7-10, 12], however, the most of these schemes were based on MRRs, and only very few of them were designed using MZI-based switches. Previously we have reported two six- and seven-port optical routers based cascaded Mach-Zehnder interferometers (MZIs) [13]. Here, we proposed a new five-port optical router based on MZIs that can be used in photonic NoCs.

The MZI-based switches are preferable for optical router design due to their high – speed routing for data stream with nanosecond switching time [14-16], while the switching speed of MRR-based switches is microsecond; Furthermore, using MZI-based switches for optical router design, the number of switching elements and waveguide crossings needed are reduced and the router performance is improved in cases of crosstalk, bandwidth and power consumption in contrast with the MRR-based switches.

Our proposed five-port optical router is composed of twenty MZI switches and twelve waveguide crossing; in which, the number of them is fewer in comparison with [10]. The simulation results show that 20 possible I/O paths were successfully verified with high-speed 20 Gbps data transmission for all input-output channels of our five-port optical router.

This paper is organized as follows. Section 2 reviews the MZI switch operation in detail. In section 3, we firstly introduces new optical non-blocking five-port router for photonic NoC, Secondly, we analyze the performance of our proposed router by using OptiSystem simulator. The conclusions of this work are given in the last section.

2. Mach-Zehnder Interferometer switch

Figure 1 shows a schematic of the MZI switch, including two arm waveguides and two 3-dB couplers which are placed at the input and output arms. The MZI operates with relative phase shift variations between the two arms caused by a change in length of one of the arms. The MZI optical switch routes the optical signals at input port 1 or port 2 to the two output ports; so that operates in two status called "bar" and "cross" with nanosecond switching time, as mentioned in introduction section [14-16]; this means that if the optical signal at port 1 passes to port 4 and the optical signal at port 2 passes to port 3, the MZI switch is on the "cross" status; and if the optical signal at port 1 passes to port 3 and the optical signal at port 2 passes to port 4, then it is on the "bar" status. Recently, the MZI switches with fast switching speed, lower power consumption, lower loss and crosstalk and small size have been reported and fabricated, so that they are capable of using in photonic NoC [14-18]. We use the reported MZI switch in Ref. [18] for five-port optical router design.

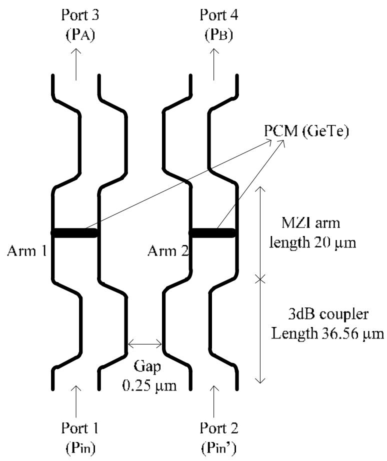

Figure 1. The schematic of the reported MZI switch in Ref. [18].

As shown in Figure 1, the size of the MZI switch, the lengths of the arms and 3-dB coupler are about 93 × 1.7 μm2, 20 and 36.56 μm, respectively. Also, the gap of the directional coupler is 0.25 μm. In this switch, GeTe layer is used as the PCM on both arms of MZI in such that the MZI is switched between "cross" and "bar" status with amorphous GeTe and crystalline GeTe, respectively. The thickness of the GeTe layer is 20 nm. The insertion loss in "bar" status is higher than that in "cross" status due to absorption loss in crystalline state is more than that in the amorphous state. The insertion loss of this switch in "cross" and "bar" status was 0.5 and 3.45 dB, respectively, which was calculated by the following equations [18]:

$$\text{Insertion Loss (cross state)} = -10\log_{10}\frac{p_{B,cross}}{p_{in}} \quad (1)$$

$$\text{Insertion Loss (bar state)} = -10\log_{10}\frac{p_{A,bar}}{p_{in}} \quad (2)$$

Where P_{in} represents the input power, $P_{B,cross}$ and $P_{A,bar}$ are the output powers from port B and A in the "cross" and "bar" statuses, respectively.

3. Design of non-blocking five-port optical router and simulation result

In this section, we introduce and simulate a new MZI-based five-port optical router. Our proposed router can be used to for implementing different architectures of photonic NoC. Figure 2 shows the schematic layout of the proposed five-port optical router based on cascaded MZIs, which consist of twenty MZI switches and twelve waveguide crossing. As shown in Figure 2, the ports of the optical router are labeled as north (N), south (S), east (E),west (W) and Center (C). Table 1 illustrates the twenty possible physical input-output paths of the optical router. As U-turn is not allowed, the diagonal entries of this table are blank.

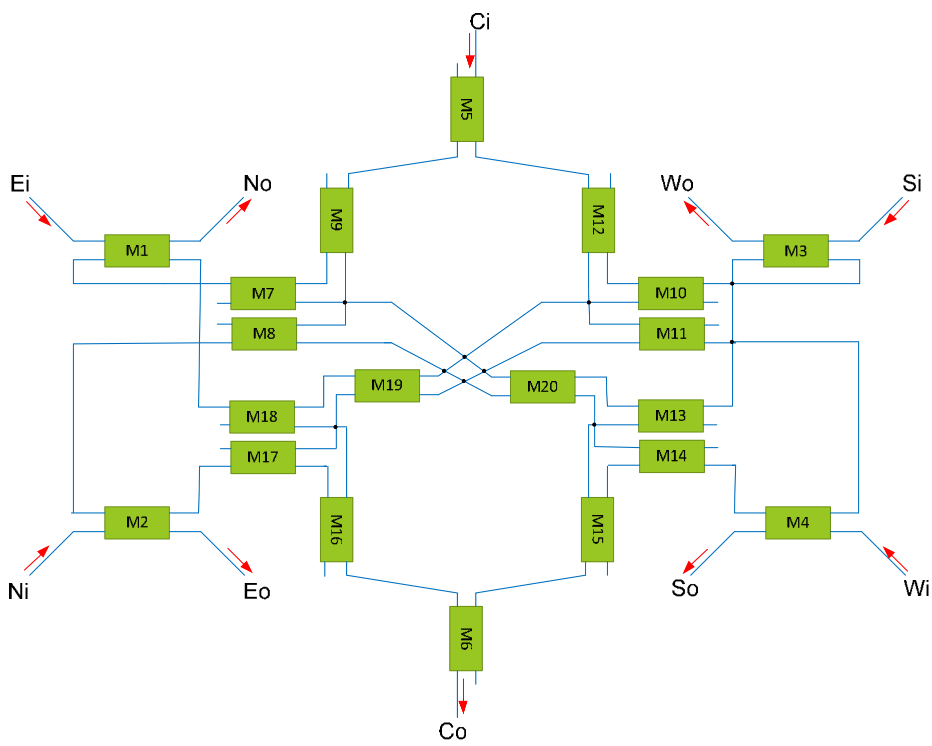

Figure 2. The schematic of the non-blocking five-port optical router with twenty MZI-based switching elements (M1-M20) and twelve waveguide crossing.

Table 1. Routing paths of the five-port router.

	Ei	Ni	Ci	Si	Wi
Eo	-	M2	M5,M9,M8,M2	M3,M13,M20,M8,M2	M4,M14,M20,M8,M2
No	M1	-	M5,M9,M7,M1	M3,M13,M20,M7,M1	M4,M14,M20,M7,M1
Co	M1,M18,M16,M6	M2,M17,M16,M6	-	M3,M13,M15,M6	M4,M14,M15,M6
So	M1,M18,M19,M11,M4	M2,M17,M19,M11,M4	M5,M12,M11,M4	-	M4
Wo	M1,M18,M19,M10,M3	M2,M17,M19,M10,M3	M5,M12,M10,M3	M3	-

Our optical router comprises fewer switching elements and waveguide crossings compared to the previously reported five-port optical routers based on MRR switching elements or even MZI switching elements. Reduction of the number of switching elements can offer the advantages in the aspects of power consumption and device area; also, the reduction in insertion loss and crosstalk comes in the reduction of the number of waveguide crossings in router design; so, the our optical router is suitable for use in photonic NoC.

We used OptiSystem simulator for verifying the functionality of the five-port optical router; so that the minimum bit error ratio (BER) and Q-factor metrics are achieved by analyzing the eye diagrams using a non-return-to-zero optical data pattern consisting of a 20 Gbps at the wavelength of 1550 nm for each input/output path of optical router. The Q-factor is a quality parameter for a measure of the eye opening; while the BER is the most ultimate quality determinant in optical communications [19]. The simulation of five-port optical router comprises an externally modulated laser source in the input port which is driven by a 20 Gbps optical signal. At the output port, the optical signal passed through a PIN photo detector and low pass filter, and then was sent to a digital communication analyzer in order to observe the eye diagrams and waveforms. From the measured transmission waveform, the minimum BER and Q-factor metrics can be calculated; so that, the obtained values have been recorded in Table 2; in addition, the insertion loss in each input/output path of five-port optical router is shown in this table.

The simulation results of five-port optical router show that, the amounts of Q-factor and BER in the worst case are 6.79797 and 5.3053e-012, respectively; and also, in the best case are 6.91855 and 2.28138e-012 respectively. Also, we calculated the optical power budget parameter for our proposed optical router. For optical power budget calculation, we used data provided by the Perl Corporation for the minimum transmitting power and the minimum receiving sensitivity parameters, which these values have been reported as -15 and -38 dBm, respectively; so the initial optical power budget parameter is equal to 23 dBm; while the correct calculation of the minimum optical power budget is achieved with considering the loss of light power during transmission from cables, connectors, switches, etc; so the power budget parameter can be calculated and is equal to 14.6 dBm in the worst case for our five-port optical router. Therefore, our router has great potential for application in optical interconnection, especially in photonic NoC. On the other hand, the switching module has -34 dB crosstalk for the wavelength range of 1.5 to 1.6 µm; while it has a worst case crosstalk of −10.3 dB for a wavelength range of 80 nm. However, there are some algorithms that can reduce optical crosstalk to the point where it can be ignored [20]; so we consider the more analyses of the routing states of the proposed optical router in aspects of the crosstalk level of each state and improve the crosstalk with reported algorithms in [20], and evaluate the extinction ratio parameter for future work.

Table 2. Optical analysis results of proposed MZI-based five-port optical router.

Path	Path IL (dB)	Max. Q factor	Min. BER
Ei →No	3.45	6.9124	2.38253e-012
Ei →Co	7.9	6.82158	4.5021e-012
Ei →So	8.4	6.79797	5.3053e-012
Ei →Wo	8.4	6.79797	5.3053e-012
Ni →Eo	3.45	6.9124	2.38253e-012
Ni →Co	7.9	6.82158	4.5021e-012
Ni →So	8.4	6.79797	5.3053e-012
Ni →Wo	2.5	6.91855	2.28138e-012
Ci →Eo	4.95	6.89679	2.65945e-012
Ci →No	4.95	6.89679	2.65945e-012
Ci →So	7.9	6.82158	4.5021e-012
Ci →Wo	7.9	6.82158	4.5021e-012
Si →Eo	8.4	6.79797	5.3053e-012
Si →No	8.4	6.79797	5.3053e-012
Si →Co	4.95	6.89679	2.65945e-012
Si →Wo	3.45	6.9124	2.38253e-012
Wi →Eo	8.4	6.79797	5.3053e-012
Wi →No	2.5	6.91855	2.28138e-012
Wi →Co	4.95	6.89679	2.65945e-012
Wi →So	3.45	6.9124	2.38253e-012

The eye diagrams for all 20 possible routing paths at input wavelength of 1550 nm are shown in figure 3. All open eye diagrams indicating data transmission of the 20 Gbps through the five-port optical router. As shown in the figure 5, an increased noise level observes (i.e. Si to No, Ei to Wo, etc.) in some of the eyes. This occurs due to additional insertion loss incurred by passing through five MZI switching elements in these specific input/output paths.

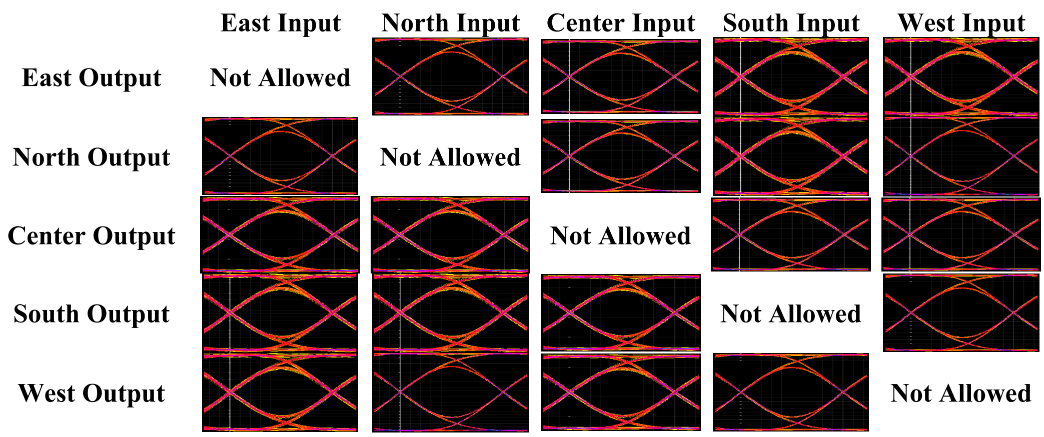

Figure 3. Eye diagrams for the 20 possible routing paths through the five-port optical router, using 20 Gbps optical data at a wavelength of 1550 nm.

Since waveguide crossings can establish crosstalk and additional loss in router, reduction of their number can offer the benefits in router's performance; also, the reduction of the number of switching elements means the lower size of the router. Therefore, the design of the router should be done with at least the number of switching elements and waveguide crossings. The proposed five-port optical router has twenty switching elements and twelve waveguide crossings which in compared with the five-port optical routers reported previously in [10], our proposed router consists of less number of waveguide crossings and switching elements. A comparison of the number of switching elements and waveguide crossings of existing routers and our proposed router is shown in table 3.

Table 3. The number of switching elements and waveguide crossings in different routers.

Optical router	$N_{switching\ element}$	$N_{waveguide\ crossing}$
Our MZI-based five-port	20	12
MZI-based Five-port in [12]	15	15
MRR-based five-port in [10]	25	25

4. Conclusion

We have designed and simulated a MZI-based non-blocking five-port optical router for optical NoCs. In our design we used twenty MZI switches and twelve waveguide crossing; therefore, our router has fewer waveguide crossings and switching elements compared to the existing five-port optical routers based on MRRs or MZIs; that improve the router's performance in the aspects of the device area and lower insertion loss and lower crosstalk. The results show the successful transmission of 20 Gbps optical signals for each desired port of the 20 possible physical links. Finally, our four-port optical router has potential applicable for use in the on-chip optical Interconnects.

References

[1] Beausoleil, R. G. et al., "Nanoelectronic and Nanophotonic Interconnect," Proc. IEEE, Vol.96, No.2, pp. 230–247, 2008.

[2] Miller, D. A. B., "Device requirements for optical interconnects to silicon chips," Proc. IEEE, Vol.97, No.7, pp.1166–1185, 2009.

[3] Shacham, A.; Bergman, K.; Carloni, L. P., "Photonic networks-onchip for future generations of chip multiprocessors," IEEE Trans. On Computers, Vol.57, No.9, pp.1246–1260, 2008.

[4] Batten, C. et al., "Building many core processor-to-DRAM networks with monolithic silicon photonics," in 16th IEEE Symp. on high performance interconnects, HOTI '08, Stanford, California, pp.21– 30, 2008.

[5] Bogaerts, W. et al., "Nanophotonic waveguides in silicon-on-insulator fabricated with CMOS technology," Lightw. Technol., Vol.23, No.1, pp.401–412, 2005.

[6] Zhiping Zhou; Zhijuan Tu; Bing Yin; Wei Tan; Li Yu; Huaxiang Yi and Xingjun Wang, "Development trends in silicon photonics," Chin. Opt. Lett., Vol.11, No.1, pp.012501, 2013.

[7] Rui, M. et al., "A universal method for constructing N-port nonblocking optical router for photonic networks-on-chip," Lightw. Technol., Vol.30, No.23, pp.3736–3741, 2012.

[8] Xianfang, T. et al., "On a scalable, non-blocking optical router for photonic networks-on-chip designs," Photonics Optoelectron, Vol.1, No.4, pp.16–18, 2011.

[9] Xianfang, T. et al., "A generic optical router design for photonic network-on-chips," Lightw. Technol., Vol.30, No.3, pp.368–376, 2012.

[10] A. W. Poon, F. Xu, & X. Luo., "Cascaded active silicon microresonator array cross-connect circuits for WDM networks-on-chip," IEEE, Vol.52, No.3, 689812-689812, 2008.

[11] Yang, M. et al., "Non-blocking 4x4 electro-optic silicon switch for on-chip photonic networks," Opt. Express, Vol.19, No.1, pp.47–54, 2011.

[12] Li, X. et al., "Mach-Zehnder-based five-port silicon router for optical interconnects," Opt. Lett., Vol.38, No.10, pp.1703–1705, 2013.

[13] Yaghoubi, E.; reshadi, M.; hosseinzadeh, M., "Mach-Zehnder-based optical router design for photonic networks on chip," Opt. Eng., Vol.54, No.3, pp.035102, 2015.

[14] Van Campenhout ,J. et al., "Low-power, 2 × 2 silicon electro-optic switch with 110-nm bandwidth for broadband reconfigurable optical networks," Opt. Express, Vol.17, No.26, pp.24020–24029, 2009.

[15] Green, W. M. J.; Rooks, M. J.; Sekaric, L.; Vlasov, Y. A., "Ultra-compact, low RF power, 10 Gb/s silicon Mach-Zehnder modulator," Opt. Express, Vol.15, No.25, pp.17106–17113, 2007.

[16] Xing, J.; Li, Z.; Zhou, P.; Gong, Y.; Yu, Y.; Tan, M.; Yu, J., "Compact silicon-on-insulator-based 2 × 2 Mach–Zehnder interferometer electro-optic switch with low crosstalk," Chin. Opt. Lett., Vol.13, No.6, pp.061301, 2015.

[17] Van Campenhout, J.; Green, W.; Vlasov, Y., "Design of a digital, ultra-broadband electro-optic switch for reconfigurable optical networks-on-chip," Opt. Express, Vol.17, No.26, pp.23793–23808, 2009.

[18] Jain, P.; Tanaka, D.; Tsuda, H., "Mach Zehnder interferometer optical switch using phase-change material," Photonics Switch, Vol.1, N0.3, pp.1–3, 2012.

[19] Freude, W.; et al., "Quality metrics for optical signals: eye diagram, Q-factor, OSNR, EVM and BER," Transparent Opt. Netw., Vol.1, No.4, pp.2–5, 2012.

[20] Othman , M.; Mohd Auzar, T. D. S. R., Chap. 9 in "The Development of Crosstalk-Free Scheduling Algorithms for Routing in Optical Multistage Interconnection Networks," InTech, Malaysia, 2010.