Five-Port Optical Router Based on Microring Switches for Photonic Networks-on-Chip

Ruiqiang Ji, Jiang Xu, and Lin Yang, *Member*, *IEEE*

***Abstract*— We demonstrate a five-port optical router that is suitable for large-scale photonic networks-on-chip. The optical router is designed to passively route the optical signal travelling in one direction and actively route the optical signal making a turn. In the case that an XY dimension-order routing is used, the passive routing feature guarantees that the maximum power consumption to route the data through the network is a constant that is independent of the network size. The fabricated device has an efficient footprint of $\sim$ 460 × 1000 μm^2. The routing functionality of the device is verified by using a 12.5-Gbit/s optical signal. The capability of multiwavlength routing for the optical router is also explored and discussed.**

***Index Terms*— Multiprocessor interconnection networks, optical resonators, optical switches, wavelength division multiplexing.**

I. Introduction

CHIP multiprocessor (CMP) is becoming a major trend for high-performance processors, because it can significantly improve the performance of computing systems. Not only the performance of single processor but also the communication efficiency among different processors, determines the total performance of the CMP. As the CMP applications demand more on-chip and off-chip communications, electronic networks-on-chip (NoC) is becoming the bottleneck of the performance of CMP due to the limited bandwidth, higher power consumption and longer latency of metallic interconnects [1]–[3]. Fortunately, the novel development of integrated optics makes it available to construct photonic NoC, which can offer larger bandwidth and lower latency with lower power consumption [4]–[6].

Optical router is one of the most essential components for photonic NoC, and several on-chip optical routers have been reported [7]–[12]. These optical routers organize multiple switching elements according to different topologies. The switching elements generally adopt microring resonators (MRRs) or Mach-Zehnder interferometers, while the more important work is the topology design for the optical router. Previously we have demonstrated two optical routers based on MRRs [10], [11]. Here, we present a new five-port optical router employing a different topology that has been optimized for large-scale mesh and torus networks. Compared with the previously reported in [11], the optical router is designed to passively route the optical signal travelling in one direction. The passive routing property guarantees that the maximum power consumption to guide the signal through a mesh network is a constant independent of the network size while using XY dimension-order routing [13]. In addition, the optical router has fewer waveguide crossings by employing more parallel coupled MRRs. In the design, the optical router adopts MRRs with larger radius, which means smaller FSR and leads to more channels available in a certain wavelength range. The optical router is expected to have lower power consumption, lower insertion loss and higher throughput.

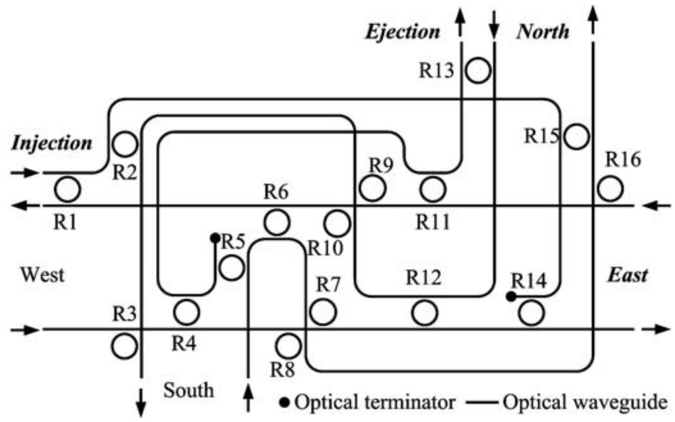

Fig. 1. Schematic of the five-port nonblocking optical router based on MRRs.

II. Topology of The Optical Router

Five-port optical routers are required to implement 2-D mesh and torus networks. As shown in Fig. 1, the optical router has five bidirectional ports including *East*, *South*, *West*, *North* and *Local* ports. The *Local* port (*Injection*/*Ejection*) is connected with a tile and other four ports are connected with four neighboring nodes in the network [11]. The optical router comprises six waveguides, sixteen MRRs and two waveguide terminators. Through topological optimization, the number of waveguide crossings is reduced to be twelve. The MRRs have the same radii, thus the optical router can switch not only a

Manuscript received August 14, 2012; revised December 20, 2012; accepted January 23, 2013. Date of publication January 29, 2013; date of current version February 15, 2013. This work was supported in part by the National Natural Science Foundation of China under Grant 60977037 and in part by the National High Technology Research and Development Program of China under Grant 2012AA012202.

R. Ji and L. Yang are with the State Key Laboratory on Integrated Optoelectronics and Optoelectronic System Laboratory, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China (e-mail: jiruiqiang@semi.ac.cn; lyang@semi.ac.cn).

J. Xu is with the Department of Electronic and Computer Engineering, The Hong Kong University of Science and Technology, Kowloon, Hong Kong (e-mail: jiang.xu@ust.hk).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2013.2243427

TABLE I
TWENTY OPTICAL LINKS OF THE FIVE-PORT OPTICAL ROUTER

		Input ports				
		East	*South*	*West*	*North*	*Injection*
Output ports	*East*	-	R7	None	R12	R14
	South	R9	-	R3	None	R2
	West	None	R6	-	R10	R1
	North	R16	None	R8	-	R15
	Ejection	R11	R5	R4	R13	-

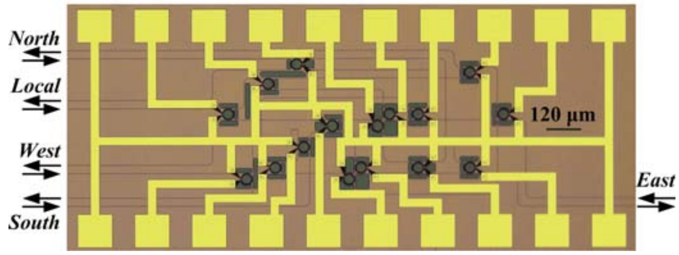

Fig. 2. Microscope image of the fabricated optical router.

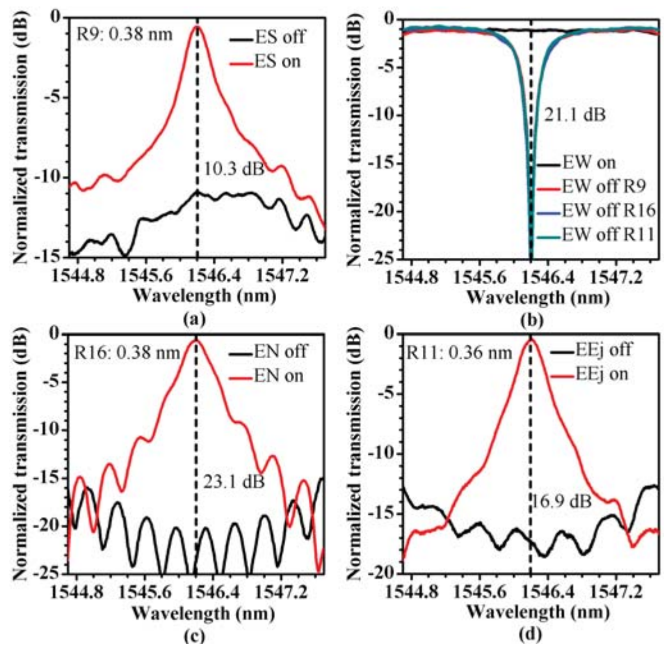

Fig. 3. Extinction ratios of the optical links from *East Input port to*: (a) *South*, (b) *West*, (c) *North*, and (d) *Local Output* ports (denoted as ES, EW, EN, and EEj, respectively).

single wavelength but also a wavelength set with the channel spacing equaling to the free spectral range (FSR) of the MRR [14], [15]. The terminators are used to reduce the reflection of the residual optical signal at the ends of the waveguides connected with *Ejection* and *Injection* ports. The optical router is strictly non-blocking, which maximizes network usability and throughput. The non-blocking architecture guarantees any optical link from any input port to any output port except for U turn. As shown in Table 1, there are twenty input-output paths, and each of them is either established by a specific resonant MRR (denoted as "Rn") or connected by an optical waveguide (denoted as "None").

The optical router is designed after considering dimension order routing that is often used in mesh and torus networks. Because all MRRs have the same designed radius, and a detuned wavelength is selected to be the working wavelength, the optical router will passively route the optical signal in one dimension. In other words, the transmission of the optical signal between *East* and *West* ports, as well as between *South* and *North* ports, requires no MRR being powered up. Only one MRR is active when the optical signal needs to make a turn in the optical router. Only two or three MRRs are required to be active to maintain the optical link connecting any two tiles when XY routing algorithm is used by the network. Thus, the maximum power consumption to maintain the communication between any two tiles is a constant, which is independent of the network size. The property of the optical router makes it suitable for the application in the large-scale 2-D network. In practice the identically designed MRRs have a resonance wavelength shift (> 1 nm) due to the imperfect fabrication. Thermal tuning used in the experiment of this letter is the most common solution [10], [11], but it conflicts with the above mentioned passive routing property. Another approach to solve this problem is to locally trim the resonances of the MRRs. Fortunately, several post-fabrication trimming methods have been demonstrated [16]–[18].

III. FABRICATION AND EXPERIMENTS

The optical router is fabricated on an 8-inch SOI wafer with 220-nm-thick top Si layer and 2-μm-thick buried dioxide layer. The waveguides are formed by 248-nm deep ultraviolet photolithography and inductively coupled plasma etching. Then, a 1500-nm-thick silica layer is deposited by plasma enhanced chemical vapor deposition (PECVD). After the separation layer is formed, a 200-nm-thick TiN is sputtered and Ω-shaped heaters are etched. Then, a 300-nm-thick silica layer is deposited using PECVD. After etching contact holes, 1-μm-thick aluminum layer is deposited and etched to form wires and the test pads. The rib waveguides are used to form the MRRs and bus waveguides, which have width of 425 nm, height of 220 nm and slab thickness of 70 nm. Such waveguides only support the fundamental TE-like mode. All MRRs have the same radii of 20 μm and have two symmetric gaps of 250 nm. The efficient footprint of the optical router is ~460 × 1000 μm^2, which can be reduced further when electro-optical switching elements are used. As shown in Fig. 2, the placement of ports is specially designed to make it easy to characterize the optical links between *East* port and other four ports. In this letter, the fundamental building block of the optical router is MRR. Here, first-order MRR is adopted for the proof-of-concept. In the future, high-order MRRs, such as parallel-coupled [19]–[20] and series-coupled [21]–[23] MRRs, can be employed to achieve a flat passband and a high out-of-band rejection ratio.

The transmission spectra of the optical router are tested using a broadband source and an optical spectrum analyzer. The static response spectra for the four optical links from *East Input* port to other four output ports in the OFF and ON states are shown in Fig. 3. The working wavelength

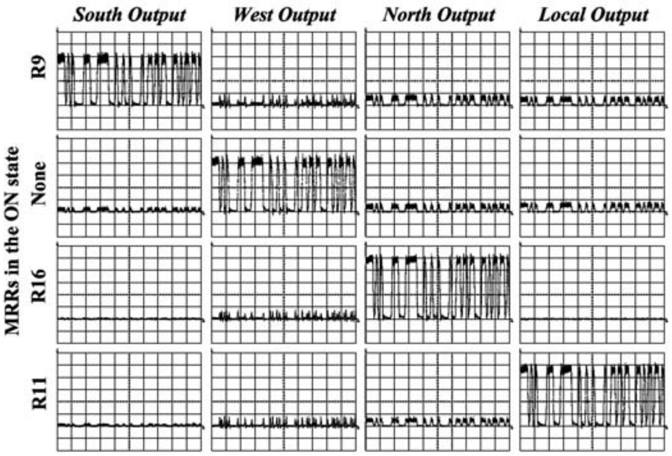

Fig. 4. Verification of the routing functionality for the optical router. Single-channel 12.5-Gb/s optical signal injected from *East Input* port is directed to other four output ports. Light at the wavelength of 1546.2 nm is encoded by a $2^{15}-1$ PRBS pattern. The transverse and vertical scale are 500 ps/div and 500 μW/div, respectively.

(i.e. on-state wavelength) is chosen to be 1546.20 nm. The extinction ratios are larger than 10.3 dB for all four tested optical links at the working wavelength. The resonances have the 3-dB bandwidths of larger than 0.36 nm (~45 GHz), which guarantees the transmission of data at 12.5 Gbit/s with negligible distortion and enhances the tolerance of on-chip temperature fluctuations. The MRRs have a FSR of ~4.8 nm and the tuning efficiency of ~52.75 mW/FSR. The rib waveguide has the linear propagation loss of < 3 dB/cm, and the elliptic crossing has insertion loss of ~ 0.5dB/crossing. The drop loss is ~1 dB and the through loss can be negligible for MRRs in our device. As shown in Fig. 3(a), R9 has a relatively large crosstalk (~−10 dB), which is probably induced by the grating effect between R9 and R10 and can be reduced by optimizing the layout design.

The routing functionality of the optical router is demonstrated by transmitting single-channel 12.5-Gbit/s optical signal. A Mach-Zehnder optical modulator is used to externally modulate the continuous wave with the wavelength of 1546.20 nm. The optical signal is injected into *East Input* port through a lensed fiber and then respectively directed to *South*, *West*, *North* and *Local Output* ports. The ejected optical signal from the output port is amplified by an erbium-doped fiber amplifier (EDFA). Then a tunable optical filter is used to reduce the noise induced by the EDFA. Finally, the optical signal is sent to a digital communication analyzer (Agilent 86100A). Fig. 4 shows the waveforms of the signals at the destination output ports and the crosstalk at other output ports for the four routing configurations. It is found that the crosstalk of different output ports is related to the order in which the MRRs arrange. As shown in Fig. 1, the optical signal injected from *East Input* port sequentially passes through R16, R11 and R9 (see Fig. 1). As a result, *North Output* port, corresponding to R16, suffers worse crosstalk than other output ports. The crosstalk could also be reduced by using high-order MRRs as building blocks of the optical router.

MRR can be used as a comb switch in WDM application due to its periodic filtering characteristics [14]. The WDM

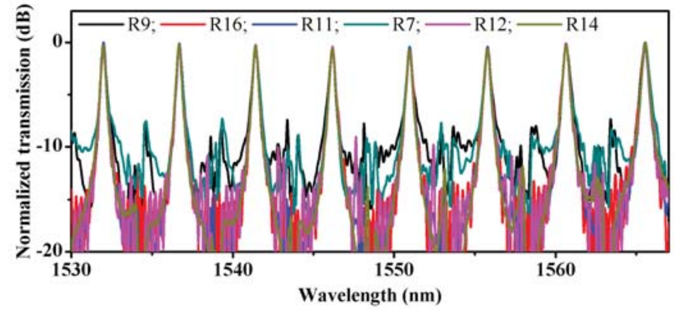

Fig. 5. Drop transmissions for MRRs R9, R16, R11, R7, R12, and R14.

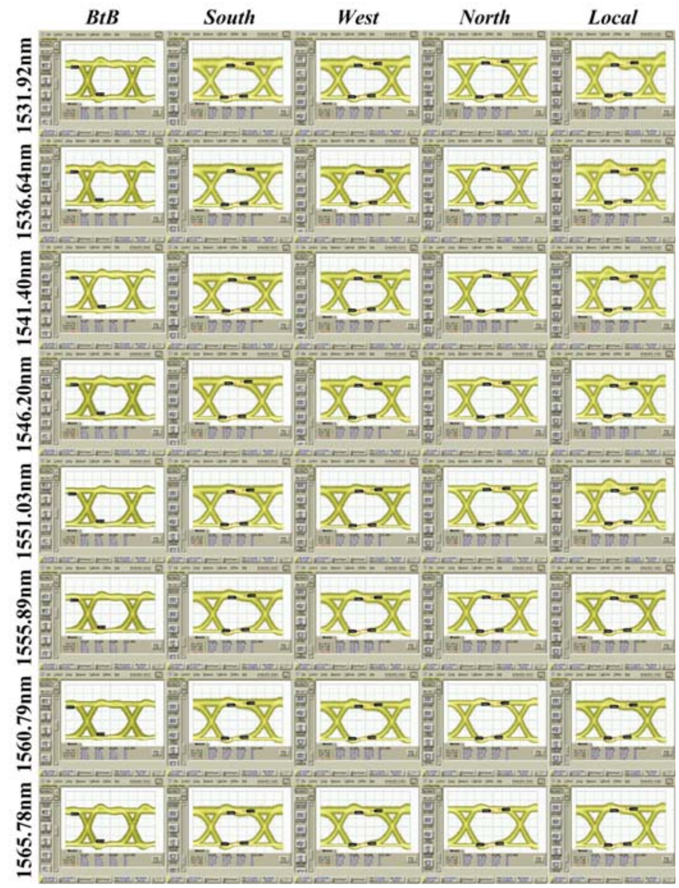

Fig. 6. Back-to-back (BtB) eye diagrams and eye diagrams of the optical signals at the *South*, *West*, *North*, and *Ejection Output* ports, which are from East Input. Eight 12.5-Gb/s wavelength channels are used, which are encoded by $2^{31}-1$ PRBS pattern.

technology can increase the aggregate bandwidth of optical NoC without changing the routing algorithm or increasing the extra electrical power consumption. As for WDM application all MRRs must have the uniform performance especially channel spacing, considering that the optical router contains up to sixteen MRRs. As shown in Fig. 5, for all six measurable MRRs, although the adjacent channel spacing is slowly increases for these channels due to the dispersion of silicon waveguide, fortunately the resonances with the same order for different MRRs can match well. For MRR with a radius of 20 μm the FSR is ~4.8 nm, and in C band there are eight available operation wavelengths, including 1531.92, 1536.64, 1541.40, 1546.20, 1551.03, 1555.89, 1560.79 and 1565.78 nm. The experiments are carried out by scanning the wavelength using a tunable laser in the experimental setup above mentioned. As shown in Fig. 6, the open eye diagrams indicate that the device enables distortion-free transmission for high-speed data.

IV. Conclusion

We present a five-port optical router that is suitable for the application in the large-scale 2-D network. The optical router is designed under considering the routing algorithm in photonic NoC. Due to its passive routing feature in one direction, the architecture requires at most three MRRs to be active to connect any two tiles while using XY routing algorithm, which is independent of the network size. The optical router is fabricated on SOI using CMOS technology. The efficient footprint of the optical router is $\sim 460 \times 1000\ \mu m^2$. The routing functionality of the optical router is demonstrated by the transmission of a 12.5-Gbit/s optical signal. The capability of multiwavelength routing for the optical router is also demonstrated by scanning eight wavelength channels.

References

[1] S. Kumar, *et al.*, "A network on chip architecture and design methodology," in *Proc. IEEE Comput. Soc. Annu. Symp. VLSI*, Aug. 2002, pp. 117–124.

[2] M. Haurylau, *et al.*, "On-chip optical interconnect roadmap: Challenges and critical directions," *IEEE J. Sel. Topics Quantum Electron.*, vol. 12, no. 6, pp. 1699–1705, Nov./Dec. 2006.

[3] D. A. B. Miller, "Device requirements for optical interconnects to silicon chips," *Proc. IEEE*, vol. 97, no. 7, pp. 1166–1185, Jun. 2009.

[4] R. Beausoleil, P. Kuekes, G. Snider, S. Wang, and R. Williams, "Nanoelectronic and nanophotonic interconnect," *Proc. IEEE*, vol. 96, no. 2, pp. 230–247, Feb. 2008.

[5] A. W. Poon, X. Luo, F. Xu, and H. Chen, "Cascaded microresonator-based matrix switch for silicon on-chip optical interconnection," *Proc. IEEE*, vol. 97, no. 7, pp. 1216–1238, Jul. 2009.

[6] B. G. Lee, A. Biberman, J. Chan, and K. Bergman, "High-performance modulators and switches for silicon photonic networks-on-chip," *IEEE J. Sel. Topics Quantum Electron.*, vol. 16, no. 1, pp. 6–22, Jan./Feb. 2010.

[7] N. Sherwood-Droz, *et al.*, "Optical 4×4 hitless silicon router for optical networks-on-chip (NoC)," *Opt. Express*, vol. 16, no. 20, pp. 15915–15922, Sep. 2008.

[8] A. Kazmierczak, *et al.*, "Highly integrated optical 4×4 crossbar in silicon-on-insulator technology," *J. Lightw. Technol.*, vol. 27, no. 16, pp. 3317–3323, Aug. 15, 2009.

[9] M. Yang, *et al.*, "Non-blocking 4×4 electro-optic silicon switch for on-chip photonic networks," *Opt. Express*, vol. 19, no. 1, pp. 47–54, Jan. 2011.

[10] R. Ji, *et al.*, "Microring-resonator-based four-port optical router for photonic networks-on-chip," *Opt. Express*, vol. 19, no. 20, pp. 18945–18955, Sep. 2011.

[11] R. Ji, *et al.*, "Five-port optical router for photonic networks-on-chip," *Opt. Express*, vol. 19, no. 21, pp. 20258–20268, Oct. 2011.

[12] T. Hu, *et al.*, "Wavelength-selective 4 × 4 nonblocking silicon optical router for networks-on-chip," *Opt. Lett.*, vol. 36, no. 23, pp. 4710–4712, Dec. 2011.

[13] H. X. Gu, K. H. Mo, J. Xu, and W. Zhang, "A low-power low-cost optical router for optical networks-on-chip in multiprocessor systems-on-chip," in *Proc. IEEE Comput. Soc. Annu. Symp. VLSI*, May 2009, pp. 19–24.

[14] B. G. Lee, A. Biberman, P. Dong, M. Lipson, and K. Bergman, "All-optical comb switch for multiwavelength message routing in silicon photonic networks," *IEEE Photon. Technol. Lett.*, vol. 20, no. 10, pp. 767–769, May 15, 2008.

[15] A. Biberman, B. G. Lee, N. Sherwood-Droz, M. Lipson, and K. Bergman, "Broadband operation of nanophotonic router for silicon photonic networks-on-chip," *IEEE Photon. Technol. Lett.*, vol. 22, no. 12, pp. 926–928, Jun. 15, 2010.

[16] J. Schrauwen, D. Van Thourhout, and R. Baets, "Trimming of silicon ring resonator by electron beam induced compaction and strain," *Opt. Express*, vol. 16, no. 6, pp. 3738–3743, Mar. 2008.

[17] Y. Shen, I. B. Divliansky, D. N. Basov, and S. Mookherjea, "Electric-field-driven nano-oxidation trimming of silicon microrings and interferometers," *Opt. Lett.*, vol. 36, no. 14, pp. 2668–2670, Jul. 2011.

[18] A. Canciamilla, *et al.*, "Photo-induced trimming of chalcogenide-assisted silicon waveguides," *Opt. Express*, vol. 20, pp. 15807–15817, Jul. 2012.

[19] L. Y. M. Tobing, P. Dumon, R. Baets, and M. K. Chin, "Box-like filter response based on complementary photonic bandgaps in two-dimensional microresonator arrays," *Opt. Lett.*, vol. 33, no. 21, pp. 2512–2514, Nov. 2008.

[20] A. Melloni, "Synthesis of a parallel-coupled ring-resonator filler," *Opt. Lett.*, vol. 26, no. 12, pp. 917–919, Jun. 2001.

[21] Q. Li, S. Yegnanarayanan, M. Soltani, P. Alipour, and A. Adibi, "A temperature-insensitive third-order coupled-resonator filter for on-chip Terabit/s optical interconnects," *IEEE Photon. Technol. Lett.*, vol. 22, no. 23, pp. 1768–1770, Dec. 1, 2010.

[22] H. L. R. Lira, S. Manipatruni, and M. Lipson, "Broadband hitless silicon electro-optic switch for on-chip optical networks," *Opt. Express*, vol. 17, no. 25, pp. 22271–22280, Dec. 2009.

[23] P. Dong, *et al.*, "GHz-bandwidth optical filters based on high-order silicon ring resonators," *Opt. Express*, vol. 18, no. 23, pp. 23784–23789, Nov. 2010.