Crosstalk Noise Analysis and Optimization in 5 × 5 Hitless Silicon-Based Optical Router for Optical Networks-on-Chip (ONoC)

Yiyuan Xie, Jiang Xu, Jianguo Zhang, Zhengmao Wu, and Guangqiong Xia

***Abstract*—Crosstalk noise is an intrinsic characteristic of photonic devices used by optical router which is used in optical networks-on-chip. It also adds a new dimension to the design of the optical router based on the photonic devices. We analyzed crosstalk noise at device level and router level. Based on the detailed analysis, we proposed a general analytical model to study the transmission loss, crosstalk noise, optical signal-to-noise ratio (OSNR), and bit error ratio in the 5 × 5 hitless optical router. For the first time, this paper used the crossing angles of 60° or 120° instead of the conventional 90° crossing angle to design the optical router. It is obtained that by using this method OSNR is improved by about 10 dB.**

***Index Terms*—Integrated optics, optical crosstalk, optical fiber communication, photonic switching systems.**

I. INTRODUCTION

OPTICAL communication based on silicon-on-insulator (SOI) platform and integration are two attractive solutions for current and projected limitations in inter- or intra-chip communication. The introduction of photonics in the on chip global interconnect structures for multiprocessor system-on-chip can potentially leverage the unique advantages of optical communication and capitalize on the capacity, transparency, and fundamentally low energy consumption that have made photonics ubiquitous in long-haul transmission systems [1]–[3]. SOI is envisaged to be one of the most promising platforms for enabling high-density integration of optical devices. The high refractive index contrast allows tightly confined waveguides with a submicrometer core. In addition, the compatibility of SOI technology with the complementary metal–oxide–semiconductor processes developed by the microelectronics industry may significantly decrease device costs.

A key element in SOI communication system is the ability to silicon-based optical router, i.e., the ability to dynamically select the destination for an input source on the network. Various techniques for silicon-based optical router have been proposed and thoroughly explained in previous literatures by several groups in the last few years. These techniques can be divided into two main types of optical networks-on-chip (ONoC) routing techniques which are passive and active routings. Passive routing is typically performed by routing signals based on their wavelengths [4]–[7]. The problem with this scheme is that it requires as many light sources as the network has distinct paths. This leads to some problems in scaling due to the necessary physical space and power consumption required by each light source. Active routing usually uses single wavelength and uses electronic signal to control the status of the router to realize optical data signal routing. Droz *et al.* introduced an ONoC in which its router is an optical 4 × 4 hitless silicon router [8]. Cianchetti *et al.* proposed a hybrid electrical/optical network based on a low latency optical crossbar [9]. Pan *et al.* proposed a hybrid optical network based on a crossbar [10]. Joshi *et al.* offered an optical NoC with the nodes connected in a mesh topology using global crossbar [11], where optical interconnect is used for the high-throughput traffic and electrical interconnect is used for local and fast switching. Gu *et al.* provided an optical 5 × 5 hitless silicon-based optical router whose name is Cygus [12]. Finally, an optical 5 × 5 silicon-based optical router (Crux) which is used in mesh-based ONoC is proposed by Xie *et al.* [13]. However, the active routing network is typically suffered from contention problems since multiple signals cannot overlap on the same optical wire.

In the aforementioned optical router, crossing and microresonator are used in all of them. They are utilized as the basic building block in all optical routers that are used with ONoC. This is due to their small size, CMOS-compatible, and some other advantages. A major shortcoming of the crossing and microresonator-based switching is crosstalk which is the effect of the undesirable coupling between the two waveguides of the basic elements used in the optical router. A small portion of the signal power will be directed to the undesired output channel; therefore, the performance of the optical router will be considerably affected by the crosstalk.

In the design of an optical router, it is essential to be able to predict the deterioration of the information signals experienced due to the optical noise introduced by the basic elements. Crosstalk noise analysis is one of the necessary and important research areas for the optical router design. Crosstalk adds a

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Y. Xie, Z. Wu, and G. Xia are with the School of Physics, Southwest University, Chongqing 400715, China (e-mail: xieyiyuan1000@hotmail.com; zmwu@swu.edu.cn; gqxia@swu.edu.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).

J. Zhang is with the Department of Electrical Computer and Communications Engineering, London South Bank University, London, SE1 0AA, U.K. (e-mail: Jian-guo-zhang@126.com).

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new dimension to the design of an optical router. In this paper, we will focus on this subject. In our best acknowledgment, the crosstalk analyze model is first proposed. From analysis of the crosstalk, this paper used the crossing angles of 60° or 120° instead of the conventional 90° crossing angle to optimize the optical router.

II. OPTICAL ROUTER ARCHITECTURE

Optical routers whose function is to establish and maintain the optical paths from sources to destinations for optical signals are the necessary and key components to build many types of ONoCs. The physical limitations imposed by integration necessitate a compact and low loss design while maintaining the maximum level of functionality for application in photonic on-chip interconnection network architectures. These requirements are very important in ONoC, but the minimal crosstalk noise is the most important requirement since the basic function of the ONoC is faultlessly information transmitting.

In an optical router, two types of basic elements are used including the microresonators and waveguides. They form three basic optical devices: waveguide crossing [see Fig. 1(a)], parallel switching [see Fig. 1(b) and (c)] and crossing switching [see Fig. 1(d) and (e)]. The SOI waveguide consists of a 205 nm thick silicon layer placed on top of a 3 μm thick silica layer. A waveguide width of 500 nm has been chosen to achieve single-mode transmission for TE polarization. A bend radius of 5 μm was also previously designed and selected to achieve negligible bend losses. The radius of the ring resonator based on SOI technology is 5 μm. The rectangular cross section of both ring and waveguide is roughly 500 nm wide and 250 nm high. The microresonators have a certain resonance frequency, derived from material and structural properties. The passive switching element can be in one of these possible states.

1) OFF state: The wavelength λ_S on which the optical signal is modulated is different from the resonant frequency of the microring λ_{off}. The input optical signal with wavelength λ_{S} will propagate from the input port to the through port when the microresonator is power OFF [see Fig. 1(b) and (d)].
2) ON state: The switch is turned ON by the injection of electrical current which is injected into p-n contacts surrounding the rings or the metal-plate-based thermal heating which is used to change the temperature; the resonance frequency λ_{on} of the microring shifts so that the light ($\lambda_{\text{S}} = \lambda_{\text{on}}$), now on resonance, is coupled into the rings and directed to the drop port, thus causing a switching action [see Fig. 1(c) and (e)]. In this paper, switching is achieved through resonance modulation by carrier injection into the ring.

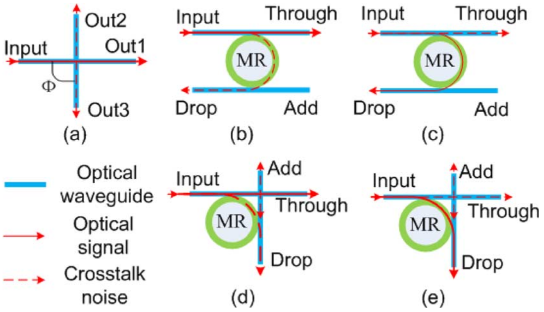

Fig. 1. Basic optical switching elements. (a) Waveguide crossing. (b) Parallel switching element in OFF state. (c) Parallel switching element in ON state. (d) Crossing switching element in OFF state. (e) Crossing switching element in ON state.

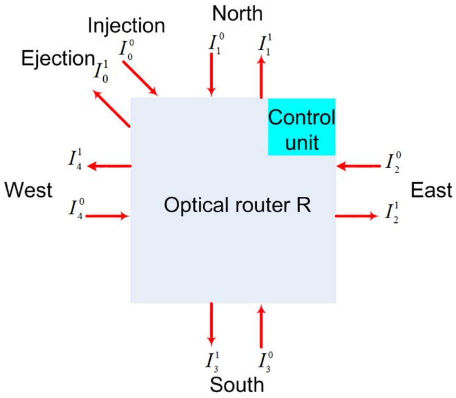

Fig. 2. General model of a 5 × 5 nonblocking optical router.

We can use the basic optical elements to design many optical routers with different structures. Fig. 2 shows the general model of a 5 × 5 nonblocking optical router. The optical router consists of two subsystems, the first one is switching fabric which is built from the basic elements as shown in Fig. 1 and the second one is the control unit which uses electrical signals to configure the switching fabric according to the routing requirements of each packet. $I_i^j = I_i^0$ for input port and $I_i^j = I_i^1$ for output port, where $i = 0, 1, 2, 3,$ and 4 for injection, north, east, south, and west port, respectively. In the general model, the optical router architecture can be described as a list of the basic switching devices, waveguide crossings, and their connection. According to the general model, we can easily explore the crosstalk noise, insertion loss, and optical signal-to-noise ratio (OSNR) of arbitrary optical router architectures.

Similar to the structure of the general model, many 5 × 5 nonblocking optical routers have been proposed for ONoC in the last few years. Beausoleil *et al.* offered a 5 × 5 nonblocking optical router named optical crossbar [14] which is shown in Fig. 3(a). Gu *et al.* proposed a 5 × 5 nonblocking optical router named Cygnus [12] which is shown in Fig. 3(b). Although all of mentioned routers can establish and maintain optical paths from sources to destinations for optical signals which carry payload data, a major shortcoming of the optical routers is crosstalk which is the effect of the undesirable coupling between the two waveguides of the basic elements used in the optical router. For reducing the crosstalk noise, in this paper, we use the crossing angles of 60° or 120° instead of the conventional 90° crossing angle to optimize the optical routers which are shown in Fig. 3(c) and (d).

We can reduce full-connected crossbar, as some turns are not required, since the U turns that are from one direction to itself is not allowed. U-turn function is not implemented because routing and flow control algorithms normally avoid it. In these optical routers, the microresonators in the switching fabric are identical, and have the same OFF state and ON state resonance wavelengths, λ_{off} and λ_{on}. The light with the wavelength λ_{on} is

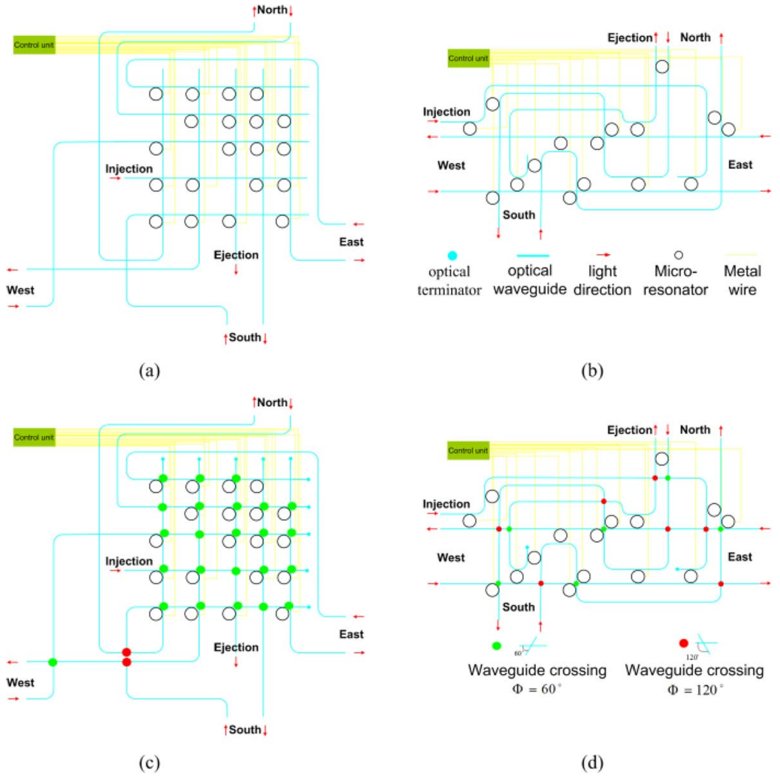

Fig. 3. 5 × 5 hitless optical routers (a) Optical crossbar router. (b) Cygnus router. (c) Optimized crossbar router. (d) Optimized Cygnus router.

used to transmit optical data signal. The routers have five bidirectional ports, including injection/ejection, east, south, west, and north. The injection/ejection port is used as the input/output port which connects a functional core to optical router through an optical/electronic interface. When the optical signal travels in one dimension, the optimized Cygnus becomes passive router in which none of the microresonator is used. Different from other optical routers, the optimized Cygnus takes the advantage of the crossing angles of 60° or 120° instead of the conventional 90° crossing angle and the parallel switch element to reducing the crosstalk noise. Especially, the two waveguides for the injection/ejection port only use the parallel switching elements. As we will see in the following section, comparing with the crossbar and Cygnus, the crosstalk noise of the optimized Cygnus is very small.

III. TRANSMISSION LOSS, CROSSTALK NOISE, OSNR, AND BIT ERROR RATIO (BER) ANALYSIS

Crosstalk is an intrinsic characteristic of the basic devices as shown in Fig. 1. It is caused by the undesirable coupling among optical signals when they pass microresonators and waveguide crossings. Crosstalk which is a small portion of the power of one signal is directed to another optical signal and becomes noise. Since the imperfect resonant cavity cannot prevent all the resonant modes that are excited from the input port from decaying into Out2 and Out3, there will be crosstalk noise on the undesired output ports, if we suppose P_I is the power of the input optical signal.

For waveguide crossing, the output power in Out1, Out2, and Out3 ports as a function of the input optical power which can be expressed as

$$\begin{aligned} P_{O1} &= L_C P_I \\ P_{O2} &= K_{11} P_I \\ P_{O3} &= K_{12} P_I \end{aligned} \tag{1}$$

where L_C is the power loss per crossing, $P_{O1}, P_{O2}, \text{and} P_{O3}$ are the output power in Out1, Out2, and Out3 ports, respectively, and K_{11} and K_{12} are crosstalk coefficients per crossing. When the cross angle is 90°, $K_{11} = K_{12}$.

For the parallel switching element, when it is in OFF state, the output power can be shown in this way

$$\begin{aligned} P_T &= L_{P1} P_I \\ P_D &= K_2 P_I. \end{aligned} \tag{2}$$

For the parallel switching element, when it is in ON state, the output power can be illustrated as

$$\begin{aligned} P_D &= L_{P2} P_I \\ P_T &= K_3 P_I. \end{aligned} \tag{3}$$

For the cross switching element, when it is in OFF state, the output power can be calculated by

$$\begin{aligned} P_T &= L_{C1} P_I \\ P_D &= \left(K_2 + L_{P1}^2 K_{12}\right) P_I \\ P_A &= K_{11} L_{P1} P_I. \end{aligned} \tag{4}$$

For the cross switching element, when it is in ON state, the output power can be expressed as

$$\begin{aligned} P_D &= L_{C2} P_I \\ P_T &= L_C K_3 P_I \\ P_A &= K_{11} K_3 P_I \end{aligned} \tag{5}$$

where P_I is the input power, P_T, P_D, and P_A are the output powers in through, drop, and add ports, respectively, L_{P1} is the power loss, and K_2 is the crosstalk coefficient per the parallel switching element which is in OFF state. Similarly, L_{P2} and K_3 are the power loss and crosstalk coefficient when the parallel switching element is in ON state. L_{C1} is the power loss and K_1 is the crosstalk coefficient of the crossing switch element which is in OFF state. It can be seen that the crosstalk coefficient of the crossing switch in OFF state is similar with the crossing. L_{C2} is the power loss per crossing switching element in ON state. When crossing switching element is in ON state, its crosstalk model is the same as the parallel switching element in ON state.

In the general model of the optical router, $P_{i,j}$ is defined as the optical power outputted by the *j*th port caused by the optical power injected into the *i*th port in router *R*. It can be calculated by (6), where P_i^0 is the optical power injected into the input of the *i*th port of router *R*

$$P_{i,j} = P_i^0 L_{i,j}, i, j \in \{0, \dots, 4\}. \tag{6}$$

In (6), $L_{i,j}$ is defined as the insertion loss from the ith port to the jth port in router *R*.

We defined $N_{i,j}$ as the crosstalk noise added to the optical signal traveling from the ith port to the jth port in router *R*

$$\begin{aligned} N_{i,j} = P_0^0 K_{i,j,0} + P_1^0 K_{i,j,1} + P_2^0 K_{i,j,2} + P_3^0 K_{i,j,3} \\ + P_4^0 K_{i,j,4} i, j \in \{0, \dots, 4\}. \end{aligned} \tag{7}$$

In (7), $K_{i,j,m}$ is defined as the coefficient for the crosstalk noise introduced by P_m^0 onto the optical signal traveling from the ith port to the jth port in router R.

OSNR is defined as the ratio of a signal power to the noise power corrupting the signal, and can be calculated by

$$\text{SNR}_{i,j} = \frac{P_{i,j}}{N_{i,j}}. \tag{8}$$

In an ONoC, the optical non-return-to-zero format is used. In other words, the ONoC is an ON–OFF keying (OOK) system. From communication principle, the BER and the OSNR equations of the OOK system is [15]

$$P_e = \frac{1}{2} e^{-\text{SNR}/4}. \tag{9}$$

IV. SIMULATIONS AND ANALYSIS

We developed a parameter analyzer for optical routers based on the general model. The parameter analyzer can explore the crosstalk noise, insertion loss, and OSNR of arbitrary optical router architectures. Based on the parameter analyzer, we analyzed the insertion loss, the crosstalk noise, OSNR, and BER from numerical simulation. Although crosstalk and transmission losses which are reported in [16] and [17] are very small, these crossings require accuracy fabrication. In optical router for ONoC, there are a large number of crossings that have the same structure. In this paper, we use the direct crossing, because the approach is much simple, compact, robust against fabrication inaccuracies, and not bandwidth-limited [18]. The loss and crosstalk coefficient parameters of the basic elements that are used in optical router are shown in Tables I and II [18]–[21].

TABLE I
LOSS PARAMETERS LIST

L_C	L_B	L_{P1}	L_{P2}	L_{C1}	L_{C2}
-1.6dB/60°, -1.5dB/90° -1.6dB/120°	-0.005dB/90°	-0.005dB	-0.5dB	-0.125dB	-0.5dB

TABLE II
CROSSTALK COEFFICIENTS LIST

Crossing with 60°	K_{11}	K_{12}	K_2	K_3
	-17dB	-20dB	-45dB	-25dB
Crossing with 90°	K_{11}	K_{12}	K_2	K_3
	-10dB	-10dB	-45dB	-25dB
Crossing with 120°	K_{11}	K_{12}	K_2	K_3
	-20dB	-18dB	-45dB	-25dB

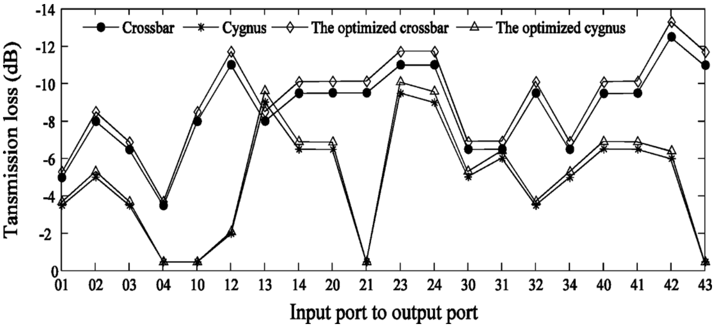

Fig. 4. Transmission loss of each signal path.

Optical power loss of the optical router decides the size and the feasibility of an ONoC as well as the transmittance optical power which must guarantee the power of receive signal to be greater than the detector sensitivity. In our analysis, four major sources of optical insertion losses are considered which are shown in Table I, such as: waveguide crossing insertion loss L_{C}, bending loss L_{B}, passing microresonator loss (L_{P1} and L_{C1}), and microresonator insertion loss (L_{P2} and L_{C2}). Their values are also shown in Table I. Based on Table I and the, we can easily calculate the port to port loss (see Fig. 4).

From Fig. 4, we can understand that the different input–output pairs of an optical router have different losses. All of losses of input–output pairs of the optimized Cygnus are more than the Cygnus. The same rule can be found in the crossbar. The reason is that using the crossing angles of 60° instead of the conventional 90° crossing angle. Comparing the optimized router to the traditional router, the insertion

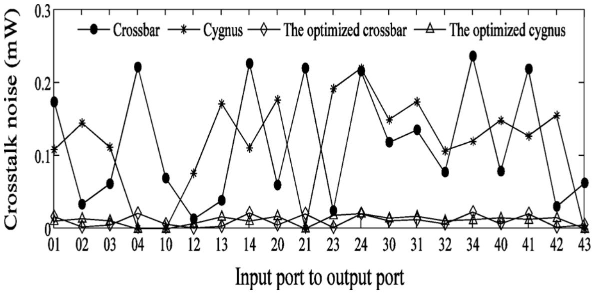

Fig. 5. Maximum crosstalk noise of each signal path.

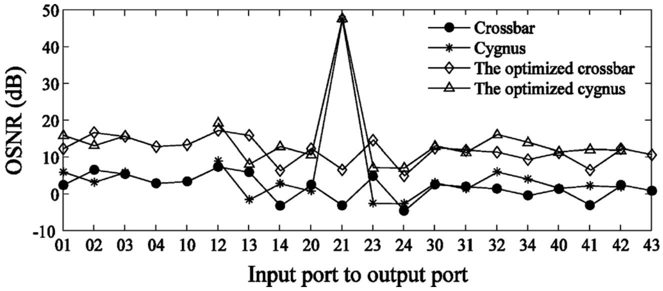

Fig. 6. Minimum OSNR of each signal path.

loss of the optimized router is more than the insertion loss of a traditional router about 0.4 dB. In the optimized crossbar, the maximum loss of an input–output pair is -13.34 dB and the minimum loss is -3.52 dB. These are, respectively, corresponding to west–east pair and injection–west pair. In the optimized Cygnus, the maximum loss of an input–output pair (east–south pair) is -10.12 dB and the minimum loss (injection–west, north–ejection, and west–south pairs) is -0.5 dB. The result shows that the insertion loss of Cygnus and the optimized Cygnus is less than crossbar and the optimized crossbar. Based on our analysis, we can find that the lower number of crossings is used, and the lower insertion loss is obtained. By the way, we need to point out that the insertion losses of input–output pairs vary widely; this problem may result in some problems in a real application. To solve this problem, we need to redesign a new optical router with new structure and improve the nanostructure fabrication technology. Fig. 5 shows the maximum crosstalk noise at each output port when the optical power at each input port is 1 mW. Because $K_{\mathrm{i}}\ (i = 1, 2, 3)$ is a very small number, we can suppose $K_iK_j \approx 0 i, j \in \{1, 2, 3\}$. This supposition will be used in all of analysis in this paper.

Using the crosstalk analyzer, we analyzed the maximum crosstalk noise of the different input port and output port pairs. The different input–output pairs of an optical router have different maximum crosstalk noise because the different paths of an optical router have various number of basic elements. Based on the expression (7) and Fig. 5, it is obtained that the maximum crosstalk noise of injection–west, north–ejection and west–south pairs is zero in the Cygnus and the optimized Cygnus router. All of the maximum crosstalk noise at output port in the optimized crossbar and the optimized Cygnus is less than or equal to the crossbar and Cygnus. The reason is that using the crossing angles of 60° or 120° instead of the conventional 90° crossing angle to design the optical router. Comparing the optimized router to the traditional router, the crosstalk noise of the optimized router is less than the crosstalk noise of the traditional router about 10 dB.

Based on (8), Figs. 4 and 5, the minimum OSNR at each input–output pair can be calculated. The minimum OSNR of the optimized router and the traditional router is shown in Fig. 6. Since the maximum crosstalk noise of injection–west, north–ejection, and west–south pairs is zero at Cygnus and the optimized Cygnus, the OSNR of these output ports is infinity which cannot be shown in Fig. 6.

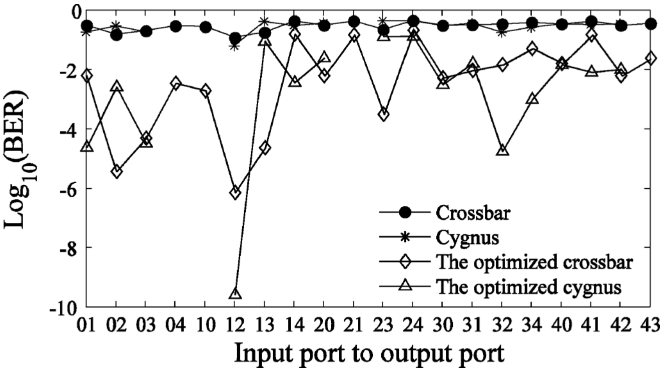

Fig. 7. BER of each signal path.

Fig. 6 shows the minimum OSNR of each input port and output port combination. The average minimum OSNR of crossbar is 2.01 dB, while the average minimum OSNR of the optimized crossbar is 11.8 dB. On average, the minimum OSNR of the optimized crossbar is 9.8 dB better compared with crossbar. The same rule can be found in Cygnus and the optimized Cygnus. The optimized router has significantly better OSNR than the traditional router. Since the optimized router is using waveguide crossing with optimized angle, the minimum OSNR of the optimized router is more significant than the traditional router. The ONoCs based on the optimized router will have higher OSNR compared with the ONoCs based on the traditional router.

By substituting (8) into (9), the maximum BER can be obtained, as shown in Fig. 7. Since the maximum crosstalk noise of injection–west, north–ejection and west–south pairs is zero at Cygnus and the optimized Cygnus, the maximum BER of these output ports is zero which cannot be shown in Fig. 7.

Fig. 7 shows the maximum BER of signal which passes through the different input–output pairs of the optimized router and the traditional router. BER increases exponentially as OSNR decreases. Because the OSNR of the optimized router is significantly less than the traditional router, the maximum BER of the optimized router is less than the traditional router. The maximum BER of crossbar is ranged from $10^{-0.34}$ to $10^{-0.91}$ and the average maximum BER of crossbar is $10^{-0.52}$, while the maximum BER of crossbar is ranged from $10^{-6.12}$ to $10^{-0.64}$ and the average maximum BER of crossbar is about 10^{-3}. On average, the maximum BER of crossbar is nearly 300 times the maximum BER of the optimized crossbar. From

Fig. 7, the same rule can be obtained in Cygnus and the optimized Cygnus. On average, the maximum BER of Cygnus is nearly 400 times the maximum BER of the optimized crossbar.

V. CONCLUSION

Silicon waveguide crossings and silicon optical switching elements are the basic devices in ONoC. The crosstalk is an intrinsic characteristic of the basic devices which must be reduced in building a robust ONoC. Although crosstalk noise is very small at device level, it has a significant impact on the BER of ONoCs. For the first time, the general model of optical routers is built. Based on the model, we analyzed crosstalk noise, OSNR, and BER of optical routers. A crosstalk analyzer for optical routers is developed. To relieve the crosstalk issue, we proposed a novel method which is using the crossing angles of 60° or 120° instead of the conventional 90° crossing angle to design the optical router. The optimized routers have significantly better OSNR and BER performance than the traditional router.

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Author biographies not included at author request due to space constraints.