RoR: A low insertion loss design of rearrangeable hybrid photonic-plasmonic 6 × 6 non-blocking router for ONoCs

Muhammad Rehan Yahya(1), Ning Wu(2), Gaizhen Yan(1,2), Fen Ge(1), and Tanveer Ahmed(1)

Abstract Optical networks on chip (ONoC) delivers a promising alternative to meet growing needs of higher bandwidth and low power consumption in manycore processors. Optical routers are the key element in ONoCs that significantly affect the performance of overall network. In this letter, we propose a rearrangeable non-blocking 6 × 6 router (RoR) constructed with 2 × 2 hybrid photonic-plasmonic switching (HPPS) elements. Router architectures with 15 HPPS elements and an optimized design using reduced HPPS elements are presented and analyzed. In optimized form, proposed design consumes only 12 HPPS elements which results in low insertion loss and crosstalk noise in comparison to the un-optimized architecture. We observe up to 50% reduction in switching elements count in comparison to other router architecture of same radix.

Keywords: optical networks on chip (ONoC), non-blocking router, silicon photonics, optical router

Classification: Integrated optoelectronics

1. Introduction

Optical on-chip interconnects have materialized as a practical substitute to the conventional electrical interconnects. Compatibility of optical interconnects with CMOS technology make them highly suitable to deploy as on-chip interconnects [1, 2]. Optical networks on chip (ONoC) exploits the feature of wavelength division multiplexing (WDM) to deliver reduced communication latency, high communication throughput and lower power consumption [3, 4, 5, 6]. An optical router is an essential component of ONoC responsible for data transfer among different cores in manycore processors [7].

Several optical router architectures are proposed and demonstrated in literature. Different 5-port optical router designs are presented and fabricated for optical NoC topologies [8, 9, 10, 11, 12, 13]. However, 5-port routers don’t support cluster Mesh or 3D NoC topologies. Therefore, 6-port routers are suitable in cluster Mesh and 3D NoCs, where additional port is utilized for extra core in cluster Mesh network while this additional port can be employed for vertical link in case of 3D NoC [14, 15]. Several architectures and methods are proposed to build non-blocking optical routers/switches with minimum number of optical switching elements [16, 17, 18, 19]. Recently, a method to reduce the number of optical switching elements by replacing them with waveguide crossings is proposed in [20]. Multiple non-blocking optical switch architectures and their topological impact on the scalability of optical switches are discussed in [21, 22]. Different kinds of networks are proposed i.e. blocking, strictly non-blocking, rearrangeable non-blocking, repackable and wide sense non-blocking [23]. When all inputs-outputs permutations of optical router can be rearranged such that all information is transmitted at the same time, the condition is called rearrangeable non-blocking (RNB) [24].

Most of the optical router architectures construction schemes are based on mirroring resonators (MMR) and Mach-Zehnder interferometer (MZI) basic switching elements. MMR based architectures suffers with intrinsic property of thermal sensitivity due to inherent imperfections and consumes larger footprint. To overcome this problem a new 2 × 2 basic switching element called hybrid photonic-plasmonic (HPPS) is proposed and utilized with reduced footprint and fast switching capabilities in comparison to MMR and MZI [25, 26, 27, 28]. Using HPPS in optical routers as a basic switching element has shown promising capacities of reduced footprint of 8.9 μm × 1.4 μm and fast switching of 5.1 ps [25]. In this letter, we proposed a new rearrangeable non-blocking optical switch design with 15 and 12 HPPS elements respectively. Our router architecture holds the RNB property where all inputs-outputs can transfer all the information in parallel. Detailed architecture and comprehensive analysis on insertion loss (IL) is also furnished in this letter. Our major contributions in this letter are:

1) Design of low insertion loss 6 × 6 rearrangeable non-blocking router using 15/12 HPPS elements.
2) Optimization yield reduction of up to 50% in switching elements in comparison to other 6 × 6 router architectures.
3) Low insertion loss and crosstalk noise is also observed as a result of optimized 6 × 6 architecture.

2. 6 × 6 router architecture using HPPS elements

Proposed 6 × 6 router architecture consists of 15 HPPS elements using 6 waveguides having 8 crossings. We chose HPPS element as a basic switching unit to construct RoR. HPPS consists of two waveguides with one switching...
element as shown in Fig. 1a. Using bias voltage, states of the switch can be switched between Cross and Bar states [25]. Using a control unit, states of HPPS switch are controlled by bias voltage that changes carrier concentration of indextunable active (ITO) layer [28]. When the bias voltage is applied, optical signal passes through same waveguide and input signal is transmitted from \( I_1 \) to \( O_1 \) and \( I_2 \) to \( O_2 \) defined by ‘Bar’ state as shown in Fig. 1b. If no bias voltage is applied, the optical signal changes it waveguide to other side and signal is transmitted from one input to other output from \( I_1 \) to \( O_2 \) and \( I_2 \) to \( O_1 \) and defined by ‘Cross’ state as shown in Fig. 1c.

![Fig. 1. (a) 2 x 2 HPPS Element (b) HPPS in Bar state with applied voltage (c) HPPS in Cross state with no voltage applied.](image)

RoR consists of 15 basic 2 x 2 HPPS elements as shown in Fig. 2, having \(^{215} \) possible switching states, however some of these states are redundant. In order to hold rearrangeable non-blocking property, distinct states should be \( 6! = 720 \) states. The proposed RoR fully conforms to above mentioned condition and can route 720 routing combinations using 15 HPPS elements.

![Fig. 2. RoR with 15 HPPS elements.](image)

In order to reduce HPPS element count we apply optimization, where some switching elements are replaced with straight waveguides and certain inputs and outputs are reorganized while maintaining the non-blocking feature i.e. 720 routing states available. Optimized RoR (oRoR) is shown in Fig. 3 with 12 HPPS where \( H_1, H_14 \) and \( H_15 \) are eliminated. We reorganize respective inputs and outputs to retain the same functionality of the optical router. This reduction in switching elements reduces the insertion loss and power consumption which improves the overall performance of NoC and achieves a more compact footprint of the oRoR.

For validation of non-blockingness of RoR/oRoR, we performed MATLAB simulations for 720 routing states. Since, there exists 720 distinct routing states, where each routing state is the combination of six input-output routing paths that can transmit data in parallel. However, for simulations and analysis, we select 6-routing represented as R1, R2, ... R6 states, which covers all input-output routing paths, while other routing states are different combinations of selected routing states mentioned in Table I. All 6 routing states can be used employing HPPS elements Bar/Cross combinations, where \( I_1 \to O_1 \) is represented as ‘i/j’ e.g. \( I_1 \to O_2 \) is denoted as ‘12’. The Cross state of HPPS element \( H_a \) is represented as ‘1’ while Bar state is represented as ‘0’ for switching combination. We have shown the best and worst case switching combinations of HPPS elements. Best case implies switching combination with minimum number of HPPS elements in Bar state, however, worst case yields maximum HPPS elements in Bar states.

![Fig. 3. oRoR with 12 HPPS elements.](image)

| Routing State | Best/Worst | Switching Combination RoR \((H_1,H_2...H_6)\) | Switching Combination oRoR \((H_1,H_2...H_12)\) |
|---------------|------------|--------------------------------|----------------------------------|
| (R1)          | Best       | 111111001011111111           | 111110011111111111           |
| 11,22,33,44,55,66  | 00000000000000000 | 000000010000100001110 | 00000000000000000111001001 |
| (R2)          | Best       | 000110011101111111           | 000110011111111111           |
| 12,23,34,45,56,61  | 00000000000000000 | 000000010000100001110 | 00000000000000000111001001 |
| (R3)          | Best       | 001001011101111111           | 011011011111111111           |
| 13,24,35,46,51,62  | 00000000101111111 | 000000010000100001110 | 00000000000000000111001001 |
| (R4)          | Best       | 111111111111111111           | 111111111111111111           |
| 14,25,36,41,52,63  | 00000000101111111 | 000000010000100001110 | 00000000000000000111001001 |
| (R5)          | Best       | 001001101101111111           | 001001101111111111           |
| 15,26,31,42,53,64  | 00000000101111111 | 000000010000100001110 | 00000000000000000111001001 |
| (R6)          | Best       | 001001101101111111           | 001001101111111111           |
| 16,21,32,43,54,65  | 00000000101111111 | 000000010000100001110 | 00000000000000000111001001 |

### 3. Comparisons, results and analysis

In this section, we evaluate the effect of insertion loss and crosstalk noise for the proposed 6 x 6 optical router. We have also presented the comparison of RoR/oRoR with other 6-port optical router/switch architectures.

#### 3.1 Insertion loss of RoR/oRoR

Higher insertion loss in optical router can contribute to degraded performance of ONCs. Insertion loss of RoR/oRoR is calculated using Eq. (1).

\[
IL_T = \sum IL_B + \sum IL_C + \sum IL_X + \sum IL_b
\]  

(1)

Where \( IL_T \) is total insertion loss and calculated as sum of losses due to HPPS in Bar/Cross states denoted as \( IL_B/IL_C \) respectively, while \( IL_X \) represents losses due to waveguide crossings and \( IL_b \) denotes losses occurred due to waveguide bends. To analyze the impact of insertion loss on
proposed router architecture following parameters are used, i.e. 2.1 dB for $IL_B$ and 0.4 dB for $IL_C$ [25], 0.04 dB for $IL_X$ [29] and 0.005 for $IL_b$ [30]. Using loss parameters, we calculate the worst (i.e. Maximum loss) and average case insertion losses of all 6 routing states based on HPPS switching combinations listed in Table I. Worst case insertion loss is the maximum insertion loss for optical router which determines the transmission budget of optical router. While average insertion loss is the arithmetic mean calculated from each path for every routing state considering best and worst cases.

We have observed that oRoR with minimized number of HPPS elements shows better performance for both best and worst cases. Maximum worst case insertion loss of 31.9 dB and 20.5 dB is observed for RoR and oRoR respectively, in case of R1 routing state for worst switching combination. For the best case switching combination, maximum insertion loss of 16.6 dB for RoR while 15.4 dB for oRoR in R2 and R6 routing states is observed. Detailed results of maximum insertion loss for worst and best switching combinations are shown in Fig. 4.

Reduction of almost 31% and 16% in maximum insertion loss for worst and best switching combinations respectively in oRoR architecture is observed in Fig. 4. For average insertion loss, up to 18% and 42% reduction for oRoR in comparison to RoR is observed for best and worst case respectively as shown in Fig. 5. Minimum best case average insertion loss of 1.74 dB is observed for routing state R4 in oRoR architecture, while worst case average loss of 11.7 dB is not for routing state R1 in case of RoR. Reduction in count of HPPS elements significantly reduce average insertion loss of proposed router architecture.

In addition, per path maximum loss for worst and best case in all routing states is also calculated and shown in Fig. 6. For the worst case in RoR, maximum loss of 14.88 dB, 11.08 dB, 9.37 dB, 13.18 dB, 9.38 dB and 11.08 dB in R1, R2, R3, R4, R5 and R6 routing states is observed. Similarly, for oRoR 8.96 dB, 11.08 dB, 5.18 dB, 8.98 dB, 6.7 dB and 7.28 dB of maximum loss for R1, R2, R3, R4, R5 and R6 routing states is observed. We have also presented the maximum and minimum insertion loss for individual paths in RoR and oRoR, in best case 7.5 dB and 7.1 dB respectively for R6 state is noticed, while minimum value of 2.09 dB and 1.29 dB respectively for R4 is reported as shown in Fig. 7. Likewise, per path maximum worst case insertion loss of 14.88 dB for RoR is observed in case of R1, while 11.08 dB maximum loss in worst case of oRoR for R2 is noted. Lastly, minimum worst case loss of 3.3 dB for RoR and 2.99 dB for oRoR in R2 routing state is also shown in Fig. 7.

Simulation results of insertion loss show that oRoR with 12 HPPS elements has overall reduced maximum, average and per path insertion loss in comparison to RoR.

3.2 Crosstalk noise of RoR/oRoR
Crosstalk is an intrinsic feature of optical on-chip interconnections. HPPS element can be characterized by insertion loss (IL), crosstalk noise (CN) and extinction ratio (ER) in Bar and Cross states. Insertion loss in Bar and Cross states is represented as $IL_B$ and $IL_C$ respectively, crosstalk noise in Bar and cross state is denoted as $CN_B$ and $CN_C$ and extinction ratio is characterized as $ER_B$ and $ER_C$ respectively [32]. Extinction ratio is defined as the ratio of chosen port’s output power to the undesired output.
port for Bar and Cross states. Chosen port is the output from which light is expected to be propagate, while undesired output port is when light is anticipated to transmit to other port [25]. Extinction ratio of HPPS element in Bar state is 24.2 dB while 9.3 dB in Cross state. To compute the crosstalk noise of proposed RoR/oRoR, we rely on above mentioned performance parameters provided for ER and IL for HPPS element in [25]. Crosstalk noise in Bar or Cross state is determined by relationship between extinction ratio and insertion loss which can be expressed using Eq. (2) and Eq. (3).

\[ CN_B = \frac{IL_C}{IL_B \cdot ER_C} \]  
\[ CN_C = \frac{IL_B}{IL_C \cdot ER_B} \]  

To calculate the total crosstalk noise (CN) of proposed design, we use the following Eq. (4).

\[ CN_T = \sum CN_B + \sum CN_C \]  

Where \( CN_T \) is total crosstalk noise of optical router and calculated as the sum of \( CN_B \) and \( CN_C \), where \( CN_B \) and \( CN_C \) are crosstalk noise of HPPS elements in Bar and Cross states respectively. Worst case crosstalk noise is calculated by first identifying maximum number of HPPS elements in Cross states, which determine the worst case crosstalk noise of optical router. Switching combinations mentioned in Table I as best combinations, where maximum switching elements are in Cross state are considered as worst case for crosstalk noise. Simulation results of crosstalk noise are shown in Fig. 8. The worst case CN of 3.25 dB for RoR, while 2.6 dB maximum crosstalk noise for oRoR in routing state R4 is observed. Overall, oRoR shows better performance having lower values of CN for all routing stages in comparison to RoR. Reduction in HPPS elements and number of stages, lead to lower crosstalk in oRoR architecture that alleviate the impact of crosstalk noise in overall router architecture.

### 3.3 Comparisons of optical routers

In addition to insertion loss and crosstalk analysis, we have compared the hardware cost of proposed router in terms of number of switching elements and waveguide crossings with different 6 × 6 router architecture listed in Table II.

From Table II it can be seen that some 6 × 6 routers have no crossings, however number of switching elements is higher which is main contributor in insertion loss and power consumption of ONOcs. In comparison to the other 6 × 6 optical routers our proposed oRoR architecture consumes least number of switching elements with lesser waveguide crossings. As compared to six port router in [15] which also consists of 12 switching elements, oRoR possesses lesser waveguide crossings. Maximum of 50% reduction in switching elements count is observed for the proposed oRoR architecture in comparison to [16, 17].

### 4. Conclusion

In this letter, we proposed a 6-port rearrangeable non-blocking router architectures with 15 and 12 HPPS elements. Maximum, average and per path insertion loss for both RoR/oRoR for different routing states under best and worst case are calculated and analyzed. In addition, impact of maximum crosstalk noise on both router architectures is also evaluated and analyzed. In comparison to the state of the art router architectures, proposed design has an advantage of reduced switching elements count that can lead to compact footprint with HPPS allowing fast switching of 5.1 ps for each switch. In future, we aim to employ proposed router architecture in 3D Mesh topology to explore the effect of router design on overall performance of 3D ONOc.

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