LETTER

Waffle: A New Photonic Plasmonic Router for Optical Network on Chip

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SUMMARY Optical interconnect is a promising candidate for network on chip. As the key element in the network on chip, the routers greatly affect the performance of the whole system. In this letter, we proposed a new router architecture, Waffle, based on compact 2×2 hybrid photonic-plasmonic switching elements. Also, an optimized architecture, Waffle-XY, was designed for the network employed XY routing algorithm. Both Waffle and Waffle-XY are strictly non-blocking architectures and can be employed in the popular mesh-like networks. Theoretical analysis illustrated that Waffle and Waffle-XY possessed a better performance compared with several representative routers.

key words: *optical interconnect, router, network on chip*

1. Introduction

Taking the superiorities of optical interconnect, Optical Network on Chip (ONoC) has been illustrated as a promising solution compared with metallic interconnection for giga-scale multiprocessor system on chip (MPSoC) owing to its large channel capacity, high data transfer rate and radically low energy consumption [1]. As an essential element in ONoC, optical router [2] possesses the basic function of directing the optical signals.

However, the majority of optical routers that have been proposed are based on micro resonators. The micro resonators can be switched between on and off states enabling the routers to guiding optical signals via heating [3] or adding bias voltage [4] to change the resonating wavelengths. Both two operating methods have certain drawbacks. The approach of adding bias voltage cannot provide broad variation in wavelength to deal with the limitation of fabrication and utilizing heater will reduce the switching speed from picoseconds to microseconds [3], [4]. Moreover, the micro resonators are thermal sensitive, which may spoil the performance and reliability of ONoC [5].

To avoid the intrinsic imperfections of micro resonators, Sun *et al.* proposed a new optical non-resonate switch element, namely hybrid photonic-plasmonic switch (HPPS) [6], which also supports broadband communication for WDM application. Appling this switch into optical routers will fundamentally improve the performance of ONoC. In this letter, we proposed Waffle, the 5×5 photonic router with hybrid photonic-plasmonic switch for optical network on chip. Some optimizations were done for networks using XY routing algorithms and the architectures were evaluated.

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2. Waffle Router

2.1 Router Architecture

The router architecture is named as Waffle (Fig. 1(a)) because of its appearance's similarity with Waffle pancake and this router is based on hybrid photonic-plasmonic switch. As shown in Fig. 1(b), the switch has three components, including two bus waveguides and one switching material. Through controlling the bias voltage added on the index-tunable active layer (ITO layer) with a control unit, the carrier concentration in the ITO layer will be changed and the switch will be shifted between the CROSS state and the BAR state. If the bias voltage equals to 0, the switch will be in CROSS state. In this state, optical signals will travel through the switching material to the waveguides on the other side. When suitable bias voltage is added, the switch will be in BAR state and the optical signals will travel from one input port to the output port on the same waveguide.

Waffle has 25 switching elements lied in 5×5 array and 18 waveguides. Each of the five ports, North, South, West, East and Local respectively, includes one input port and one output port. The switching elements are numbered from 1 to 25 as shown in Fig. 1(a). If the sequence number of the switch element is odd, it will be in the northeast direction, or it will be in the northwest direction. In this way, the internal paths will only be vertical or horizontal, which makes the router space-saving and symmetrical. Additionally, ten

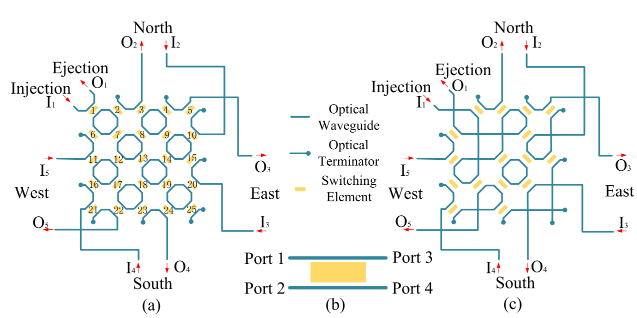

Fig. 1 (a) Waffle optical router architecture. (b) Hybrid photonic-plasmonic switch. (c) Waffle-XY optical router architecture

ports are separated to four sides of the router rather than gathering the input ports and output ports to the West and South, so that the number of waveguide crossing will be reduced.

Taking a birds-eyes view of the router's architecture, all the 25 switch elements and waveguides compose 10 internal paths, i.e. 5 input paths and 5 output paths. Each input path has 5 crossings with 5 output paths separately. Each crossing has one switch element to control the direction of optical signals. There are only two waveguide crossings in the whole architecture, i.e. from port 4 and port 5 and from port 8 and port 9. The communication between arbitrary input ports and output ports will only need one switching element in BAR state, which contributes to save the communication energy cost.

XY routing algorithm is a popular routing algorithm for 2D mesh-like topologies because of its live lock and deadlock freedom as well as its simplicity [7]. XY routing algorithm requires each packet to be sent along the horizontal axis of the topology first until it reaches the destination column. Then, the packet will propagate along the vertical axis to the destination node. Turns from Y dimension to X dimension are forbidden. Therefore, the router architecture can be further simplified. The switching elements at certain positions are eliminated and replaced with crossings, leading to an optimized architecture, Waffle-XY, as illustrated in Fig. 1(c).

2.2 Operation Rules and Non-Blocking Feature Analysis

Waffle is a strict non-blocking router architecture. When one input port is communicating with another output port, the connection will take two internal paths, one belongs to the input port and the other belongs to the output port. The switching element at the crossing of the two optical paths needs to be in the BAR state and the other switches along the two optical paths will be in the CROSS state. The operation rule of routing the signals is illustrated in Table 1. Assume that an optical signal is injected through input port I_m and sent to output port O_n.

An informal proof is given for the non-blocking character of this structure. First thing needs to be illustrated is that two independent communication connections (i.e. $I_m \rightarrow O_n$ and $I_{m'} \rightarrow O_{n'}$ where m ≠ m' and n ≠ n') do not share any internal path. According to the operating principle, it can be observed that each internal path corresponds to one port and each possible communication connection is made up by one unique combination of two optical paths connected to the input port and output port respectively. Therefore, any two independent communication links will not utilize the same internal path. Besides, as each combination of optical path possesses a unique crossing, the optical switch will be in BAR state will not interfere with other independent connections. Hence, Waffle is non-blocking.

For the Waffle-XY structure, the operating rules and non-blocking feature are still valid because the optimization does not change the position of internal path and critical switching elements.

Table 1 Operation principle

Internal Paths	HPPS State	Switching Element Number
I_m to O_n	CROSS	$\begin{cases} m+(i-1)\times 5 & (i \in \{1,2,3,4,5\}, i \neq n) \\ j+(n-1)\times 5 & (j \in \{1,2,3,4,5\}, j \neq m) \end{cases}$
	BAR	$m+(n-1)\times 5$

3. Analysis and Comparison

3.1 Insertion Loss Analysis

Insertion loss is an essential performance indicator for the optical routers. Higher losses will influence the power consumption and also limit the scalability of the optical network. The insertion loss (L) is expressed in decibel (dB). As illustrated in Eq. (1), it is calculated through summing up the losses introduced by components along the optical path, where bend represents for optical waveguide bends, crossing represents for optical waveguide crossings, BAR and CROSS represent for the loss of HPPS in two different states. Each of these parameters is assumed to be 0.005 dB [8], 0.04 dB [9], 0.4 dB and 2.1 dB [6] respectively.

$$L_{insert} = \sum L_{bend} + \sum L_{crossing} + \sum L_{BAR} + \sum L_{CROSS} \quad (1)$$

The results are shown in Fig. 2, in which the loss of each possible optical link is represented as a point in the graph and the values are marked near the corresponding points in the unit of decibel. The loss of each internal path is mainly determined by the number of CROSS-state HPPS it contains. In the Waffle router structure, the worst case is happened at the internal path from input port 4 to output port 3, where the optical signal will travel through eight CROSS-state HPPS and one BAR-state, resulting 5.49dB loss. Additionally, the average loss is the arithmetic mean of the loss values of every possible optical link. In the Waffle structure, the average loss is 3.7902dB.

Due to reduction of the switching elements, the losses of different internal paths have been cut down in various degree in the Waffle-XY. The average loss is 3.239 dB, which

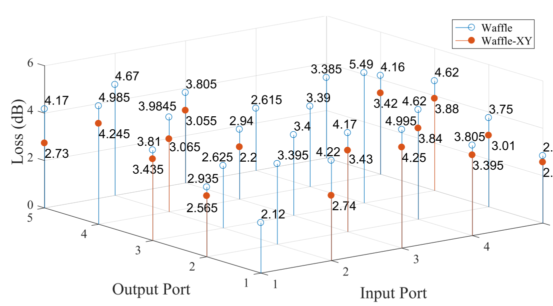

Fig. 2 Insertion loss of Waffle and Waffle-XY

Table 2 Comparison result

Project	A. Poon et al. [10]	H. Jia et al. [11]	X. Li et al. [12]	E. Y. et al. [13]	S. Sun et al. [6]	This Work General/XY
Switching Element	MMR	MMR	MZI	MZI	HPPS	HPPS
Element Number	25	8	10	20	8	25/16
Average Loss (dB)	0.57	16.5	2.4	6.0	2.5	3.79/3.239
Maximum Loss (dB)	1	18.3	9.6	8.4	3.2	5.49/4.245
Area (μm^2)	-	4.8×10^5	9.6×10^5	-	200	8.4×10^3
Switching Time (ps)	2×10^7	2×10^7	$10^6/10^3$*	-	100	100
Mesh-Network Compatible	Yes	No	No	No	No	Yes

* This device supports both thermal (slow) and electrical (fast) turning.

is approximately 15% lower than general Waffle structure. And the worst case is the connection between I_1 and O_4, nearly 23% smaller than that of ordinary Waffle router and yielding 4.245 dB.

3.2 Comparison among Different Routers

In this section, some popular 5×5 routers based on different switching elements, micro-ring resonator (MMR), Mach-Zehnder interferometer (MZI) and hybrid photonic-plasmonic switch, will be discussed.

The HPPS possesses the advantages of fast switching time (5.1 ps) and the compact size (8.9 μm ×1.4 μm), which is smaller than MMR and MZI. These features contribute to the Waffle's better comprehensive performance. Additionally, the Waffle structure makes up the drawbacks of the structure proposed in [6], which is incompatible with mesh or tours network.

The details for comparison of these routers are summarized in Table 2.

4. Conclusion

In this letter, we proposed Waffle, a five-port non-blocking router based on a new switching element called hybrid photonic-plasmonic switch, and customized this structure for XY routing algorithm. The insertion loss was analyzed, and the comparison of different routers shows the new routers possess better comprehensive performance. In our future work, we will further optimize the routers with HPPS and analyze their performances in network level.

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