NPFONoC: A Low-loss, Non-blocking, Scalable Passive Optical Interconnect Network-on-Chip Architecture

Junyong Deng *, Haoyue Wu *, Rui Shan *, Yiwen Fu *, Xinchuang Liu *and Ping Wang*
*Xi'an University of Posts & Telecommunications, Xi'an, China
E-mail: why1484132896@163.com Tel: +86-29-13609253237

***Abstract*— With the increase of inter-core communication requirements for large-scale processors, optical interconnection on-chip is an important means of multi-core processor communication. At present, high-blocking, large delay, and high insertion loss is the bottleneck of large-scale processor inter-core communication. This paper proposes a non-blocking, low-loss, scalable passive optical interconnection network-on-chip structure (NPFONoC). In this structure, the 2*2 optical switch unit network-on-chip is designed by wavelength division multiplexing technology and passive optical interconnect micro-ring resonator self-resonance characteristics, it is easily expanded into 16*16, 32*32, 64*64 optical networks structure and achieve non-blocking communication simultaneously. The number of waveguides and micro-ring resonators in the optical interconnection on-chip structure are important parameters affecting the insertion loss of the network structure. In the 16*16 optical interconnection network structure, NPFONoC has great advantage in the number of micro-rings compared with the λ-route, GWOR, Crossbar and new topology structure, with reduction rate of 90.9%, 90.9%, 75%, and 20% respectively. By detecting the performance parameters of the 8*8 optical interconnection network structure on the OMNET++ platform, the results show that the average insertion loss of NPFONoC is smaller than λ-route, GWOR, Crossbar and Mesh structures by 11.6%, 3%, 16.7%, 4.8%.**

Keywords: Network On-chip, Non-block, Passive optical interconnection, WDM, Scalable

I. INTRODUCTION

With the development of multi-core processors, optical interconnection network-on-chip has become an important communication structure. Optical interconnect structure has higher bandwidth, lower transmission delay and lower energy loss than electrical interconnect structure. At present, photonic elements and transistors of integrated chips have been achieved and optical communication of chips is realized by using photonic devices on chip[1].

In a large-scale inter-core communication network, inter-core communication will have a communication bottleneck with high blocking, large delay, and high insertion loss. An inter-core non-blocking and easily expandable optical interconnect network structure is a hot spot of interconnection on-chip to meet the requirements of large-scale inter-core communication. Passive optical interconnect network is an important transmission method for on-chip optical interconnects. Wavelength division multiplexing[2][3] technology achieves non-blocking[4] and scalability of optical interconnection network-on-chip by implementing wavelength synthesis and splitting. Passive optical interconnect networks on-chip have higher bandwidth, lower transmission delays, and lower energy losses[5][6]. For small-scale circuits, the traditional electrical interconnection method and optical interconnection on-chip have small difference in communication performance between cores. However, with the further development of technology, the demand for technology is becoming more and more advanced. The electrical interconnection method is the bottleneck of multi-core processor performance improvement, and it has large power consumption, limited bandwidth and long access delay time[7]. Therefore, the communication between larger and more complex circuits is more strict with the requirements for transmission speed, bandwidth, loss and non-blocking between cores.

A non-blocking passive optical interconnect network-on-chip proposed in this paper can solve the problem of transmission speed, bandwidth and loss in communication between large-scale circuits. The contribution of this paper can be describe this follows:

(1) This paper proposes a low-loss, non-blocking, scalable passive optical interconnect network structure. A 2*2 non-blocking optical network switch structure easily extends to 4*4, 8*8, 16*16 optical network structure. The wavelength division multiplexing technology of passive optical interconnects synthesizes and decomposes wavelengths, by controlling the micro-ring resonators to resonate different wavelengths to achieve larger inter-core non-blocking communication.

(2) Micro-ring resonator, wavelength, and waveguide are important components in optical interconnect network architectures. Under the premise of satisfying the inter-core communication function, how to reduce the number of micro-ring resonators is one of the key technologies to improve the performance of the entire network structure. The number of micro-ring resonators in the optical interconnect network of this paper has great advantages compared with λ-route, GWOR, Crossbar and new topology structure.

(3) Reducing the insertion loss is one of the key technologies to improve the performance of the optical interconnect network. The passive optical interconnect network structure designed in this paper has great advantages over λ-route, GWOR, Crossbar and Mesh structures.

This paper first introduces the 2*2 basic optical switch structure. On this basis, 4*4, 8*8, 16*16 passive optical interconnect structures are designed. Subsequently, the working principle and wavelength distribution of a specific optical network structure are introduced. Finally, by comparing with other optical network structures, the optical interconnect structure proposed in this paper is more advantageous in micro-ring resonator number, insert loss and energy loss.

II. OPTICAL INTERCONNECT STRUCTURE

A. Micro-ring resonator optical switch structure

Considering Micro-ring resonators are the key components of the optical interconnect network-on-chip. They are mainly responsible for the coupling, transmission, steering and filtering of optical signals. Different optical interconnection networks on-chip are constructed using different micro-ring resonator structures. Micro-ring resonators have different transmission modes for corresponding specific wavelengths, and micro-ring resonators can be divided into two types, active and passive. Active micro-ring resonators use heat, voltage, etc. to configure the micro-ring resonator to achieve transmission of signals corresponding to specific wavelengths. The resonant wavelength of a passive micro-ring resonator is different from that of its active. Its transmission to a specific wavelength is determined by its own device structure and the radius of the micro-ring.

Fig. 1 shows the structure of a conventional micro-ring resonator. λ_r is the resonant wavelength of the micro-ring resonator. When the transmission wavelengths λ_i and λ_r in the horizontal direction are the same, the resonance condition of the micro-ring resonator is satisfied, so that the transmission direction is obtained. Change 90 degrees, transmitted from the vertical below, this process is the drop process of the micro-ring resonator; when the wavelengths λ_i and λ_r of the input port are not equal, the optical signal continues to propagate along the input direction, which is the micro-ring resonator transmission process. Transmission of different wavelengths can be achieved by configuring the wavelength of the passive optical interconnect network structure or by using different types of micro-ring resonators. The conventional micro-ring resonator can only transmit signals of one type of wavelength at a time. Therefore, in circuit-switched or large-scale optical network communication, the fewer the number of micro-ring resonators, the problem of large power consumption on the chip will be solved.

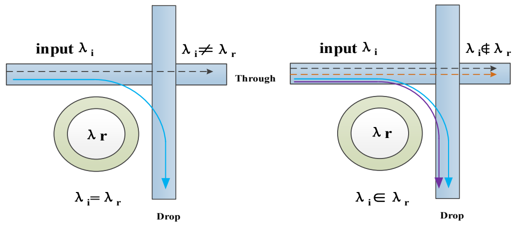


Fig. 1 Conventional micro-ring resonator and multi-resonance wavelength micro-ring resonator structure

With As shown in Fig. 2, the micro-ring resonator switch structure, Cross represents the micro-ring without resonance state data transmission mode, in this case, the I_0 transmission path destination is O_1, the I_1 transmission path destination is O_0; the Bar state is the wavelength transmitted at this time. It is consistent with the resonant wavelength of the micro-ring resonator. At this time, the I_0 transmission path is turned 270 degrees to O_0 at the micro-ring resonator, and the I_1 transmission path destination is O_1. The transmission path is selected by different input wavelengths and different resonance wavelengths of the micro-ring resonator.

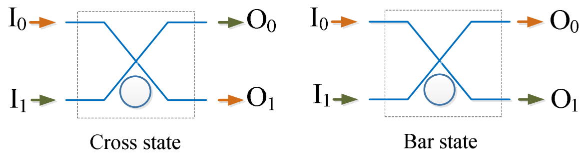
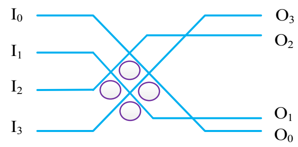


Fig. 2 Micro-ring resonator switch structure

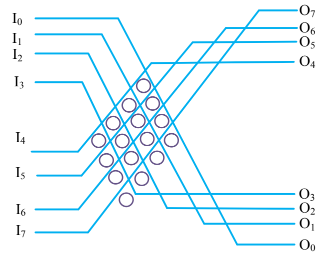
B. Passive optical network structure

By analyzing optical signal exchange processes such as basic 2×2 optical switching units, the micro-ring resonators in the passive optical interconnect structure can resonate with different wavelengths, so different wavelength inputs can achieve different communication paths by controlling the micro-ring resonators. At the resonant wavelength, optical communication between multiple cores can be achieved.

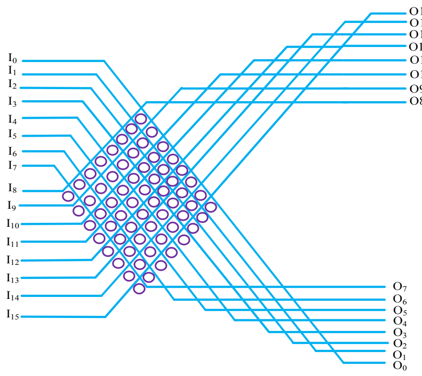
According to the micro-ring resonator switch structure of Fig. 2, the optical interconnect network structure of 4*4, 8*8, 16*16 is designed in this paper, as shown in (a), (b) and (c) of Fig. 3 below.



(a) 4*4 optical interconnect switch structure



(b) 8*8 optical interconnect switch structure



(c) 16*16 optical interconnect switch structure

Fig. 3 Optical interconnect switch structure

C. *Optical link layer structure*

For a structure with a node number N, N electro-optical conversion units and N photoelectric conversion units are required for transmitting and receiving the request signal. At the same time, a 2-level exchange switch is required. For the mutual communication between 16 PEs, this structure cannot communicate internally with PE8 and PE9 at the design level, but there can be local memory on the array processor for internal receiving and transmitting functions, and other inter-PE communication and internal communication can be It is implemented. The mutual communication of the original design of 16 PEs has been achieved. The resonant wavelength of the micro-ring resonator can be controlled by the control of the wavelength to achieve the transmission direction, and the resonant wavelength and the unsatisfied resonant wavelength have their own specific transmission paths.

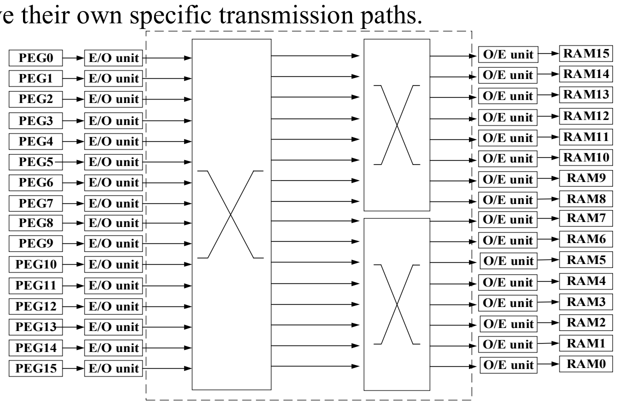


Fig. 4 Optical link layer structure

In an interconnected network with 16 nodes, a total of 16 photoelectric conversion units and 16 electro-optical conversion units are required, as shown in Fig. 4. In a storage access process, a two-stage optical switch is required to implement the connection between the request signal and the corresponding destination memory. The inter-cluster communication optical interconnection network of 16 PEs as shown in the figure is realized by a two-stage optical switch, wherein the first-stage switching switch is composed of one 16-port switching unit, and the second-stage switching switch is composed of two eight-switches. The port switching unit is constructed.

The sixteen-port switching unit of the first-stage switching switch is composed of 16 micro-ring resonators and 16 optical waveguides, and the resonant wavelength of each micro-ring resonator is λ_0, λ_1, λ_2, λ_3, λ_4, λ_5, λ_6, λ_7, the main function is to receive the optical request signals from the 16 processing element clusters for the first level of switching.

The eight-port switching unit of the second-stage switching switch is composed of eight micro-ring resonators and eight optical waveguides, and the resonant wavelength of each micro-ring resonator is λ_8, λ_9, λ_{10}, λ_{11}, λ_{12}, λ_{13}, λ_{14}, λ_{15}. The main function is to receive the first-level exchanged optical request signal for the second-level exchange.

The optical link layer structure is composed of a total of five parts. The 16 processing element clusters transmit the target storage unit of the communication that they need. At this time, it is an electrical signal. In order to achieve the function of transmission speed block, small loss and excellent performance, the electro-optic is used. The converter converts the electrical signal into an optical signal for transmission into the link transmission structure for communication. Then these optical signals arrive at the optical switch, that is, the designed optical network structure, to realize mutual communication between 16 PEs according to the network structure, and after the optical signal is transmitted at the output port, the photoelectric converter converts the optical signal into electrical signal transmission. Going out, finally these transmitted electrical signals are transmitted to the corresponding storage unit, thereby realizing the transmission of the entire signal to the destination PE.

III. Optical Network Communication Process

Before the optical interconnection network-on-chip makes a request, all information in response to the configuration package needs to be transmitted at the electrical configuration layer and then transmitted to the optical transmission network. At this time, the micro-ring resonator can perform communication wavelength configuration according to the requirements of each resonant wavelength. After the wavelength configuration is completed, each processing unit will send a response request signal for storing access through the photoelectric conversion device, and the request signal is coupled to the corresponding allocated wavelength, which is a transmission process of non-blocking parallel access between 16 PEs through the NPFONoC structure. Table 1 is the algorithm for wavelength assignment.

To describe the request signal transmission process in more detail, all We Chat resonators in the NPFONoC structure are numbered. The two red lines in Fig. 5 indicate the case where PEG3 access RAM 6 and PEG 10 access RAM 6, respectively. When PEG3 wants to access bank6, it can be obtained through the table-wavelength distribution display. By the resonant wavelength of λ6 distributed by the micro-ring, it can be rotated by 270 degrees to achieve the change of the propagation path, thus achieving PEG3 to RAM6 access, such as The red path above shows the figure. PEG10 to RAM6 access, when PEG10 transmits a set of wavelengths of λ_0, λ_1, λ_2, λ_3, λ_4, λ_5, λ_6, λ_7, as shown by the red path below in Fig. 5, according to the wavelength assignment of Table 2, λ_5 is encountered When the resonance wavelength is uniform, a 90-degree rotation occurs, and the transmission path change has been reached, thereby realizing the transmission to the RAM 6.

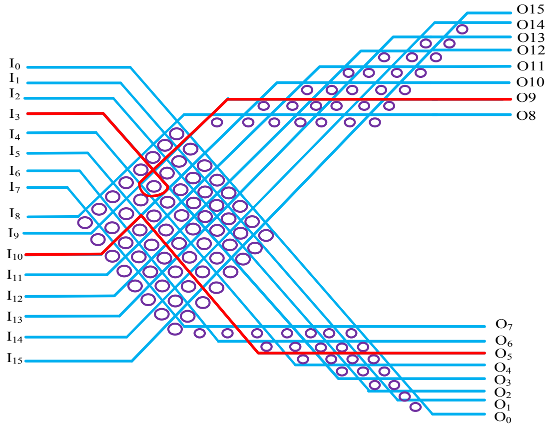


Fig. 5 Communication process

Table 1 The algorithm of 16*16 optical router design

Procedure wavelengths distribution
Input: total number of port(i) ,wavelengths(j),Optical switch(k)
output: MR rotational transmission angle

```
begin
if k=1
  for j=0 to 7
    if i=0 to 7
      if The input wavelength is consistent with the MR resonant wavelength
      then rotate 270 degrees through the micro-ring resonator transmission direction
      else transmitting along the waveguide
    if i=8 to 15
      if The input wavelength is consistent with the MR resonant wavelength
      then rotate 90 degrees through the micro-ring resonator transmission direction
      else transmitting along the waveguide
if k=2
  for j=8 to 15
    for i=0 to 15
      if The input wavelength is consistent with the MR resonant wavelength
      then rotate 270 degrees through the micro-ring resonator transmission direction
      else transmitting along the waveguide
end
```

In the passive optical interconnect on-chip structure, a wavelength assignment method is designed such that each communication is connected to the specified carrier wavelength through 16 input ports and 16 output ports, and can be accessed through parallel access without blocking. Table 2 shows the wavelength allocation scheme.

IV. Network Performance Analysis

A. Number of micro-ring resonators

Position Micro-ring resonators have many advantages in optical interconnect network structures. Their low energy loss, good wavelength selection and small footprint have been achieved through resonance. Therefore, micro-ring resonators are widely used in optical switching switches and optical wavelength routing structures in optical interconnection networks on-chip [7-9]. In the NPFONoC structure, the micro-ring resonator is to perform the wavelength screening of the light to realize the difference of the transmission path under different conditions of resonance, thereby realizing the function of the optical switch of the micro-ring resonator.

In an optical interconnect network-on-chip structure, the number of micro-ring resonators is an important parameter to measure network performance. Table 3 shows the number of 2*2, 4*4, 8*8, 16*16, 32*32, 64*64 network structure micro-ring resonators and waveguides used.

Table 3 Different sizes of micro-rings and wavelengths

Network size	MRs	Wavelengths
2*2	1	2
4*4	4	4
8*8	16	8
16*16	64	16
32*32	256	32
64*64	1024	64

Table 2 Optical interconnection 16*16 wavelength allocation scheme

	O_0	O_1	O_2	O_3	O_4	O_5	O_6	O_7	O_8	O_9	O_{10}	O_{11}	O_{12}	O_{13}	O_{14}	O_{15}
I_0	λ_{15}	λ_{14}	λ_{13}	λ_{12}	λ_{11}	λ_{10}	λ_9	λ_8	λ_0	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7
I_1	λ_{14}	λ_{15}	λ_8	λ_{13}	λ_{12}	λ_{11}	λ_{10}	λ_9	λ_7	λ_0	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6
I_2	λ_{14}	λ_8	λ_{15}	λ_9	λ_{13}	λ_{12}	λ_{11}	λ_{10}	λ_6	λ_7	λ_0	λ_1	λ_2	λ_3	λ_4	λ_5
I_3	λ_{14}	λ_8	λ_9	λ_{15}	λ_{10}	λ_{13}	λ_{12}	λ_{11}	λ_5	λ_6	λ_7	λ_0	λ_1	λ_2	λ_3	λ_4
I_4	λ_{14}	λ_8	λ_9	λ_{10}	λ_{15}	λ_{11}	λ_{13}	λ_{12}	λ_4	λ_5	λ_6	λ_7	λ_0	λ_1	λ_2	λ_3
I_5	λ_{14}	λ_8	λ_9	λ_{10}	λ_{11}	λ_{15}	λ_{12}	λ_{13}	λ_3	λ_4	λ_5	λ_6	λ_7	λ_0	λ_1	λ_2
I_6	λ_{14}	λ_8	λ_9	λ_{10}	λ_{11}	λ_{12}	λ_{13}	λ_{15}	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_0	λ_1
I_7	λ_{14}	λ_8	λ_9	λ_{10}	λ_{11}	λ_{12}	λ_{15}	-	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_0
I_8	λ_0	λ_7	λ_6	λ_5	λ_4	λ_3	λ_2	λ_1	-	λ_{14}	λ_{12}	λ_{11}	λ_{10}	λ_9	λ_8	λ_{15}
I_9	λ_1	λ_0	λ_7	λ_6	λ_5	λ_4	λ_3	λ_2	λ_{14}	λ_{13}	λ_{12}	λ_{11}	λ_{10}	λ_9	λ_8	λ_{15}
I_{10}	λ_2	λ_1	λ_0	λ_7	λ_6	λ_5	λ_4	λ_3	λ_{13}	λ_{12}	λ_{14}	λ_{11}	λ_{10}	λ_9	λ_8	λ_{15}
I_{11}	λ_3	λ_2	λ_1	λ_0	λ_7	λ_6	λ_5	λ_4	λ_{12}	λ_{13}	λ_{11}	λ_{14}	λ_{10}	λ_9	λ_8	λ_{15}
I_{12}	λ_4	λ_3	λ_2	λ_1	λ_0	λ_7	λ_6	λ_5	λ_{11}	λ_{12}	λ_{13}	λ_{10}	λ_{14}	λ_9	λ_8	λ_{15}
I_{13}	λ_5	λ_4	λ_3	λ_2	λ_1	λ_0	λ_7	λ_6	λ_{10}	λ_{11}	λ_{12}	λ_{13}	λ_9	λ_{14}	λ_8	λ_{15}
I_{14}	λ_6	λ_5	λ_4	λ_3	λ_2	λ_1	λ_0	λ_7	λ_9	λ_{10}	λ_{11}	λ_{12}	λ_{13}	λ_8	λ_{14}	λ_{15}
I_{15}	λ_7	λ_6	λ_5	λ_4	λ_3	λ_2	λ_1	λ_0	λ_8	λ_9	λ_{10}	λ_{11}	λ_{12}	λ_{13}	λ_{15}	λ_{14}

B. Insertion loss

The used of the number of micro-ring resonators and the number of wavelengths, and the insertion loss are all important parameters that affect the performance of the optical interconnect network-on-chip.

The following is the calculation formula for insertion loss:

$$IL = \sum IL_{bend} + \sum IL_{cross} + \sum IL_{drop} + \sum IL_{through} \quad (1)$$

Where IL is the insertion loss and IL_{bend} is the waveguide bending loss. IL_{cross} represents the loss of a straight line through the waveguide, IL_{drop} represents the loss at the resonance of the micro-ring resonator, and $IL_{through}$ is the loss through the micro-ring. These parameters [14] in the formula are shown in Table 4.

Table 4 Optical signal parameter

Parameters	Value	Unit
MR drop	1.5	dB
MR throuth	0.01	dB
Waveguid crossing	0.05	dB
Waveguid bend	0.013	dB/90°
Laser efficiency	30	%
Modulator	5	mW
Demodulator	0.3	mW

The micro-ring resonator, waveguide and wavelength are three important parameters in the optical interconnect network structure, which is one of the key factors affecting the performance of the optical network structure loss. Therefore, the number of micro-ring resonators is the key factor affecting the loss. In the NPFONoC structure, the number of micro-ring resonators is small compared to other structures. This makes it possible to greatly reduce the loss caused by the micro-ring resonator. On the other hand, in the NPFONoC structure, there is only a two-stage switching structure, so that the waveguide bending becomes smaller in terms of energy loss, so the overall performance of this structure is superior to other structures.

For the sake of comparison, based on the 16*16 optical interconnect network structure on chip designed in this paper, the comparison of insertion loss using different network structures base on 8*8 optical interconnect network is shown in Table 5 as below.

Table 5 Insertion loss results under different structures

Insertion loss	λ-router	GWOR	Crossbar	New topology	Mesh	NPF ONoC
maximum	1.99	2.21	2.44	1.5	3.1	3.13
Minimum	-	-	-	0.73	0.725	0.39
average	1.81	1.65	1.92	1.1	1.68	1.6

C. Performance comparison

As shown in Fig. 6 below, Fig. 7 shows the optical interconnect network and the λ-router [10], GWOR [11], Crossbar [12], and new topology [13] respectively. The number comparison is compared with the number of wavelengths used.

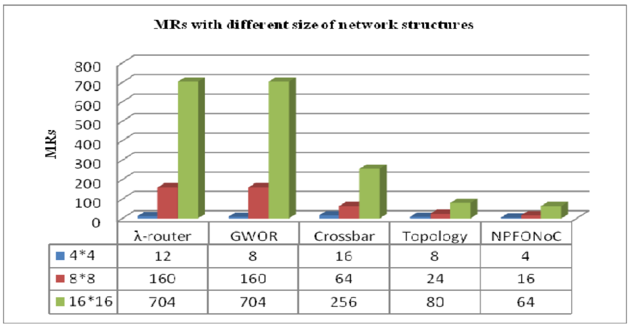


Fig. 6 Comparison of the number of micro-ring resonators

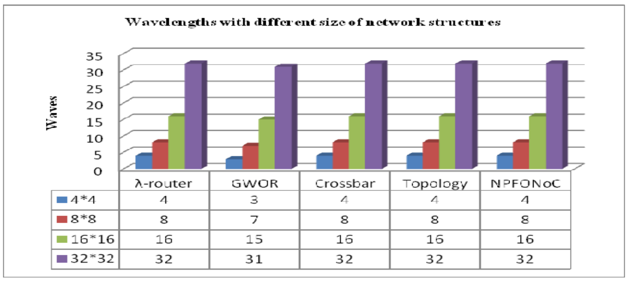


Fig. 7 Comparison of wavelengths

Analysis of the above results that the number of micro-ring resonators used of NPFONoc structure is reduced by 90.9%, 90.9%, 75% and 20% compared to λ-route, GWOR, Crossbar and new topological optical network structures based on the 16*16 optical interconnect network structure on chip, which makes the overall optical network structure insertion loss have certain advantages.

V. Conclusion

In this paper, a non-blocking, low loss, Scalable optical interconnect network structure of a two-stage optical switch on-chip is designed. The advantage of this structure is that it uses fewer micro-ring resonators to achieve the same inter-processor communication than the λ-route, GWOR, Crossbar and new topology structure, which makes the overall optical interconnect network structure insertion loss a great advantage. The results show that (1) in the 16*16 optical network, the micro-ring resonator reduction rate is 90.9%, 90.9%, 75%, and 20% compared with λ-route, GWOR, Crossbar and new topology structure; (2) by testing on the OMNET++ optical simulation platform, in the 8*8 optical interconnection network, NPFONoC insertion loss reduction rate is 11.6%, 3%, 16.7%, 4.8% compared with λ-route, GWOR, Crossbar and Mesh structures.

Acknowledgment

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