Design and system implementation of a configurable optical interconnection network

Bowen Yang* and Junyong Deng†, Jiaying Luo†, Yu Feng†
*Xi'an University of Posts and Telecommunications, Xi'an, China
E-mail:yangbowen@xupt.edu.cn Tel: +86-13991226699
†Xi'an University of Posts and Telecommunications, Xi'an, China
E-mail: djy@xupt.edu.cn Tel: +86-18192964908
E-mail: jiayingluo22@163.com Tel: +86-15029922078
E-mail: xupttdh@163.com Tel: +86-15029050365

***Abstract*— With the development of silicon photonics and wavelength division multiplexing, the advantages of on-chip optical interconnection, such as low loss, low delay and high bandwidth, can make up for the disadvantages of electrical interconnection. However, with the increase of network scale and complexity, a series of problems, such as communication congestion, low utilization rate of microring resonator and increase of insertion loss, appear in optical interconnection network. The traditional optical interconnection network structure is relatively fixed and cannot meet the needs of reconfigurable array processors. Therefore, this paper designs a configurable, non-blocking, scalable, low loss optical interconnection network structure ReLONEONoC. Depending on the array size, electrical interconnection is used within clusters, and optical communication is used for mass data transmission between clusters. Finally, the simulation and verification model of optical link is built by Waveshaper 500A/SP configurable optical device, and the coupling screening effect of microring resonator is simulated to verify the functional correctness of optical link. The prototype system of ReLONEONoC was designed by combining Waveshaper and UltraScale + VU440 development platform. Statistical results show that optical communication between clusters improves both delay and loss.**

***Index Terms*— configurable; On-chip optical interconnection; Passive optical interconnection; Optical router**

I. INTRODUCTION

With the development of CMOS (complex metal oxide semiconductor) technology and the rapid development of multi-core processor, the network integration on chip is increasing and network communication is blocked.The storage wall problem of traditional electrical interconnection is getting worse and worse, and the problems of energy consumption, time delay and signal crosstalk are becoming increasingly prominent.

A new technology of optical network on silicon has emerged.[1] The advantages of high bandwidth and low loss, on-chip optical interconnect chip becomes the development direction of global interconnection of multi-core processor systems in the future. In 2015, IBM designed and manufactured an optoelectronic hybrid microprocessor chip mitics, which combines the advantages of photons and electronics, and uses optical and electrical methods for signal transmission[2]on a same chip. This marks the beginning of the chip level optoelectronic system, which is of great significance for changing existing processing chip architecture and realizing a chip system with stronger computing power. The on-chip optical devices can be used to communicate with other chips through optical signals.

Although the development of silicon on chip photonic technology brings higher bandwidth, lower delay and lower loss[3]for multi-core processor. Due to the limitation of on-chip optical devices, the scalability of the existing optical interconnection network is poor. In order to adapt to the development trend of increasing processor scale, a reconfigurable optical interconnection network structure[4]for large-scale array processors is needed. With the increase of the scale of multi-core processor, the density of optical interconnection network is gradually increasing, which leads to the emergence of new problems[5-14], including: how to ensure the strict non blocking communication of optical network structure in high-density optical network structure; How to reduce the number of exponentially increasing microring resonators and improve the utilization of microring resonators and waveguides; How to reduce the unnecessary insertion loss in optical network; How to reduce the crosstalk of optical signal in the transmission process; How to solve these new problems has become a new research direction in optical interconnection network structure. At the same time, in order to better adapt to high-density network, the scalability of optical interconnection network structure also needs to be paid attention to.

II. DESIGN OF THE STRUCTURE

The development of network on chip brings higher bandwidth, lower delay and power consumption to the development of multi-core processors, and solves the communication bottleneck[15]in the electrical interconnection mode. However, with the increase of processor scale, the traditional 4-port and 5-port can not meet the current network density requirement[16]. With the expansion of optical interconnection network, there are some problems such as communication congestion, low utilization of microring resonator. In this paper, we propose a reconfigurable optical interconnection network structure named ReLONEONoC for 4096 PE arrays. This chapter introduces the overall design of reconfigurable optical interconnection network structure and the design of key components and conversion units, including the detailed wavelength configuration and path selection control in WDM state. Finally, the design of network structure is simulated and verified. The simulation results of OMNeT++ show that the utilization ratio of microring resonators is improved and the number of microring resonators is reduced by more than 41.67%; The insertion loss is reduced by more than 27.05%; In the area cost aspect also has certain superiority, the area expense reduces more than 10%. Moreover, the biggest characteristic of the ReLONEONoC structure is that it is simple and easy to expand, and has better adaptability for the future high-density network requirements.

A. The Overall structure

ReLONEONoC supports the communication between any two clusters, and has flexible scalability. As shown in Figure 1, the ReLONEONoC consists of three parts, in which L1 is 4096 processing elements, which mainly completes the electrical transmission of data within the cluster; The second layer L2 is the first layer of optical routing, which mainly makes a preliminary screening and classification of optical information; The top layer L3 is composed of 16 sub routers, mainly for the secondary accurate routing of optical information after the first screening of the first layer optical router. As an optical interconnection network structure for array processor, the traditional electrical interconnection is used in the part with small amount of data transmission in the underlying cluster, which can better play the advantages of flexible and simple electrical interconnection; In the part with large amount of data transmission between clusters, optical interconnection transmission is used to better play the advantages of high bandwidth and low loss.

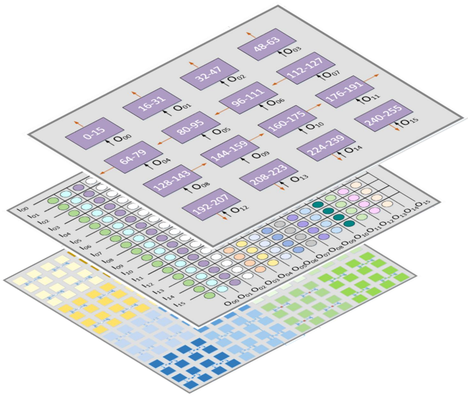

Fig.1 overall structure of optical interconnection network.

In Fig.1, the electrical interconnection layer consists of 4096 PE units, each of which is a processing unit cluster. There are 256 clusters in 4096 processing units. As shown in Fig.2, a photoelectric conversion unit is connected to the PE33 of each cluster to facilitate the conversion between optical signals and electrical signals.In a cluster, all signals are transmitted in the form of electrical signals, and the signals in a cluster are also transmitted by electrical signals. When one cluster needs to access another cluster, the electrical signal is converted into optical signal by the photoelectric conversion unit in the cluster, and the converted optical signal will transmit multiple optical signals in the same waveguide through the wavelength division multiplexer. The optical information processed by WDM technology is transmitted to the first layer L2 of the optical network layer through the waveguide.

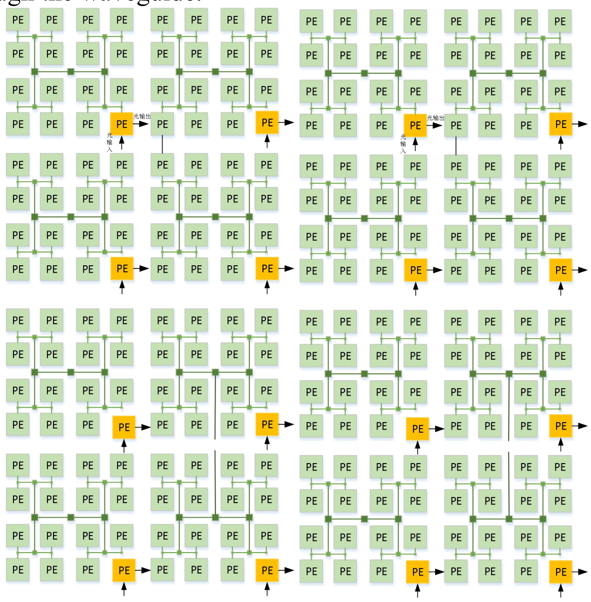

Fig.2 connection of 16 clusters and optical router.

The L2 layer consists of 256 microring resonator groups, which are divided into 16 types, and each microring resonator group has 16. The same kind of microring resonator group can couple the wavelengths in the same wavelength range.As shown in Fig.1, 16 different color circles represent 16 microring resonator groups with different resonant wavelength ranges. The same microring resonator group can couple the wavelengths in the same range from different ports to the same outlet. The resonant wavelength range of each microring resonator group is 16 wavelengths. In this way, L2 layer can couple the converted optical information of L1 layer to 16 different output ports through different wavelengths. The 16 output ports of L2 are respectively connected with the input ports of 16 sub routers of L3 layer.

As the second layer of optical network, L3 layer is mainly responsible for the secondary accurate routing of optical signals, as shown in Fig.3, the optical signal is first screened by the microring resonator group of L2 layer, the optical signal with wavelength of 1-16 is screened by the ring resonator group of L2 layer, and the optical signal of wavelength 1-16 will be output from the output port o (M20), and the screened signal will be transmitted to the first sub router of L3 layer through the waveguide, and the optical signal of the sub router will be routed to the target port according to the wavelength assignment table, The output optical signal is transmitted to the target cluster after WDM, and then converted into corresponding electrical signal by photoelectric conversion unit, and then transmitted to the cluster. The 16 output ports of L2 layer correspond to 16 subrouters of L3 layer one by one. The wavelength range that each sub router can resonate is the output wavelength range of each corresponding output port.

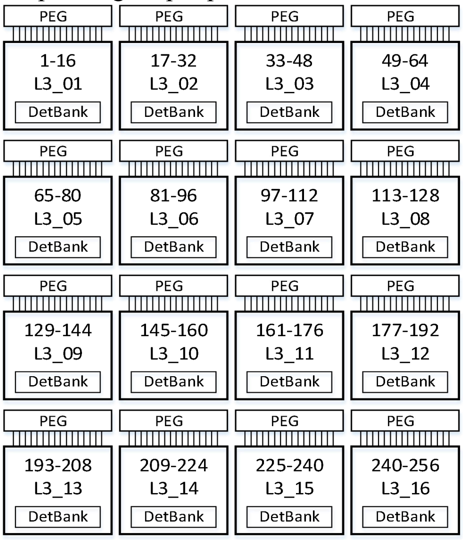

Fig.3 overall structure of optical interconnection network.

As the second layer of optical network, L3 layer is mainly responsible for the secondary accurate routing of optical signals, as shown in Fig.3, the optical signal is first screened by the microring resonator group of L2 layer, the optical signal with wavelength of 1-16 is screened by the ring resonator group of L2 layer, and the optical signal of wavelength 1-16 will be output from the output port o (M20), and the screened signal will be transmitted to the first sub router of L3 layer through the waveguide, and the optical signal of the sub router will be routed to the target port according to the wavelength assignment table, The output optical signal is transmitted to the target cluster after WDM, and then converted into corresponding electrical signal by photoelectric conversion unit, and then transmitted to the cluster. The 16 output ports of L2 layer correspond to 16 subrouters of L3 layer one by one. The wavelength range that each sub router can resonate is the output wavelength range of each corresponding output port.

B. Interface design of wavelength forwarding unit

Each PE33 is connected with a photoelectric conversion unit. When the PE33 outputs the signal, the electrical signal is converted into optical signal by the photoelectric conversion unit, and then the converted optical signal is transmitted to the first level top-level optical router through the optical waveguide. The transmission units of the top-level router and the sub router are shown in Fig.4. The output port of each top-level router contains 16 kinds of optical signals. The forwarding unit needs to couple and forward each group of optical signals from the output port of each top-level optical router to each corresponding sub router. In the secondary accurate routing of wavelength, the sub router will route a group of optical signals input by the top-level router to each port. The output port of the sub router outputs the optical signal after routing to the corresponding photoelectric conversion unit of PE33, and then converts the optical signal into electrical signal, which is sent into a cluster by PE33 for data transmission within the cluster.

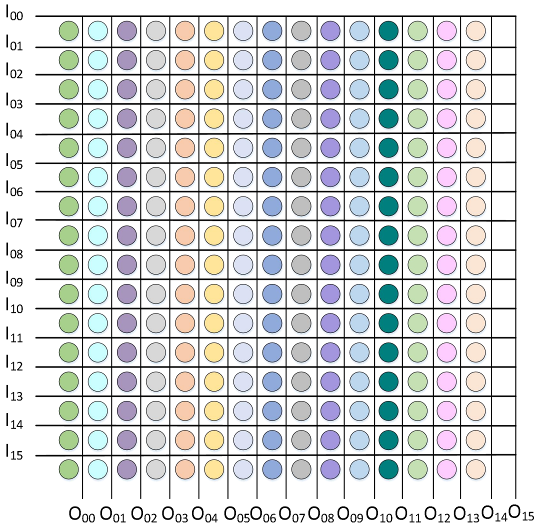

Fig.4 top level router forwarding unit

As shown in Fig.4, the conversion unit includes 16 horizontal waveguides, 16 vertical waveguides and 16 × 16 microring resonators. The resonant wavelengths of each microring resonator group are the same. Each vertical waveguide and 16 horizontal waveguides form 16 cross points, and 16 microring resonator groups are placed on the 16 intersection points of vertical waveguide and horizontal waveguide. In this way, a set of wavelengths of each port of the top router can be forwarded to the 16 input ports of each subrouter.

Wavelength division multiplexing (WDM) technology can transmit multiple wavelength optical signals on the same waveguide. Each microring resonator group can make the wavelength within the resonance range resonate and turn. When the resonance range of the optical signal transmitted on the waveguide is different from that of the resonant group, the optical signal will continue to transmit along the original direction without changing the current transmission direction. Until the transmitted optical signal resonates with the microring resonator group, otherwise it will be transmitted in the original direction until it is output from the output port.

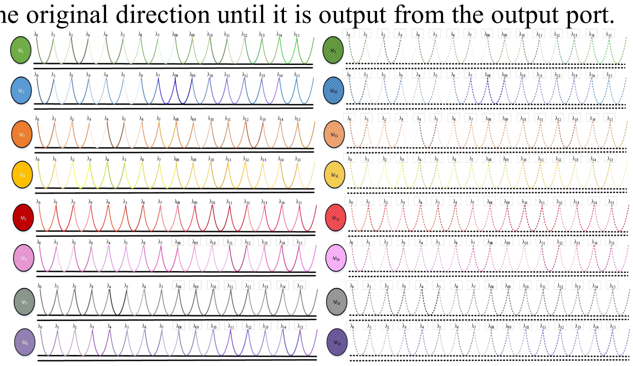

Fig.5 16 kinds of microring resonator group

The scale of 4096 array processor needs 16 kinds of bandwidth microring resonators. The resonant wavelength groups are M1, M2, M3, M4, M5, M6, M7, M8, M9, M10, M11, M12, M13, M14, M15, M16. The relation of the wavelength λi corresponding to the 16 groups of bandwidth resonant microloops, the relationship oiis shown in Fig.5: the resonant wavelength range of each microring resonator group is different. The resonance wavelength of the group M1 includes, $\lambda_0,\lambda_1,\lambda_2...\lambda_{13},\lambda_{14},\lambda_{15}$; Resonance wavelength group M2 resonance wavelength includes $\lambda_{16},\lambda_{17},\lambda_{18}...\lambda_{29},\lambda_{30},\lambda_{31}$; The resonant wavelength range of M3 is λ_{32}~λ_{47}, the resonant wavelength range of M4 is λ_{48}~λ_{63}, and so on, the resonant wavelength range of M16 is λ_{241}~λ_{255}.

C. Design of optical router LONE

As the basic unit of optical interconnection network structure, optical switch has two basic states, cross state and bar state[17]. As shown in Fig.6, the cross state of the microring resonator indicates that no resonance occurs in the microring resonator, and the optical signal is transmitted along the direction of the waveguide. The transmission address[18]of the optical signal is controlled by changing the transmission direction of the optical signal at the target wavelength. Then the optical signal is used to route the target address.

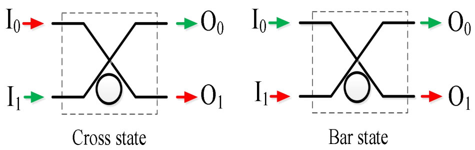

Fig.6 Diagram of resonator 6 resonator

The passive network structure does not change the resonant state of the microring resonator by adding voltage or heating. Its resonance state to the wavelength mainly depends on the structure of the device and the radius of the microring[19]. By analyzing the optical signal exchange process of basic 2×2 optical switch, the microring resonator in passive optical interconnection structure can be configured with different wavelengths corresponding to resonance. Therefore, the switching function can be completed by configuring the resonant wavelength and input wavelength of the microring resonator to realize the communication of different paths. According to the characteristics of the microring resonator in the passive optical interconnection network, the parallel non blocking optical communication between multiple cores can be realized.

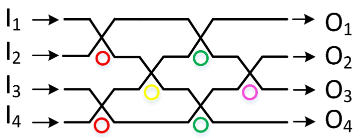

Figure 7 4×4 non blocking optical switch

4×4 switch is the basic element in various photonic topologies[20]. In a design performance of 4×4 switch, several factors need to be considered. The first is to minimize the number of microrings needed to minimize the insertion loss requirements of the design. Based on the basic optical switch structure, this paper designed a 4-ports optical router structure, as shown in Fig.7. The 4-ports optical router consists of 6 microring resonators and 4 waveguides. The wavelength coming in from the input port can change the transmission direction through different microring resonators, and then route to the target port. For example, if the input wavelength from I_1 is to be routed to the target port O_1, only the input wavelength is the same as the resonant wavelength of the yellow microring; If routing to port O_2, only the input wavelength is the same as the resonant wavelength of the green microring; If routing to the target port O_3, the input wavelength should be the same as the resonant wavelength of the red microring; If it is necessary to route to the O_4 of the port, only the input wavelength needs to be different from the resonant wavelength of other microring resonators, then the input wavelength does not change and is transmitted to port O_4 along the waveguide.

Wavelength division multiplexing (WDM) technology allows multiple independent signals to be transmitted in parallel in an optical waveguide. In the design of this paper, the non blocking function is realized by assigning MR with appropriate resonant wavelength to appropriate intersection points. Therefore, each pair of input and output ports can set the path according to a certain wavelength.In this way, this article can easily change LONE from a 4×4 optical router expanded to an 16×16 optical router.

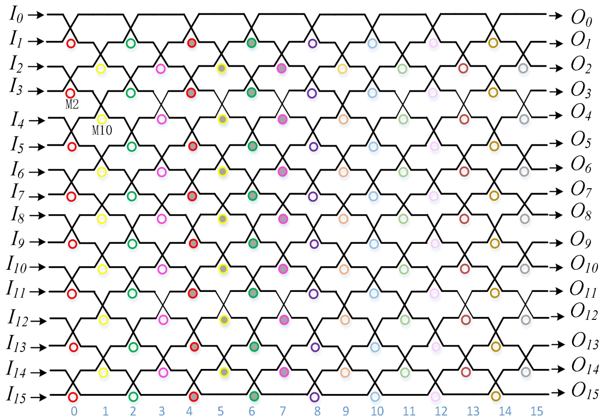

Fig.8 16 port optical router structure

As shown in Fig.8, the 16 port router LONE proposed in this paper can realize non blocking communication. The same microring resonator can be reused to realize 90 ° and 270 ° steering of the same microring resonator. For example, when the I_2 port and O_{12} port communicating, the microring resonator M2 starts to couple the optical signal input from the I_2 port. The signal is output from the output port O_{12} after turning 270 ° . The other 14 microring resonators along the way do not resonate and are in the off state. Similarly, when the I_5 port and O_{13} port communicating, the microring resonator (M10) starts to couple the optical signal input from the I_5 port, so that the optical signal turns 90 ° and outputs from the output port O_{13}. The other 14 microring resonators along the way do not produce resonance and are in the off state.

Through reasonable wavelength assignment, the communication between 16 ports is completed by specific wavelength. The 16-port LONE optical router uses 16 wavelengths to complete data exchange. When 16 output ports are accessed from the same input port, the wavelengths will not be duplicated. At the same time, when 16 input ports access the same output port, the 16 wavelengths will not repeat, causing communication congestion. 16 kinds of resonators with 16 kinds of resonators have been realized.

Fig.9 shows the modeling process of a 16-port optical router. The data sent by the processor is a group of 16. The processor sends the generated data to an electro-optic conversion module to convert the original electrical signal into an optical signal. The converted optical signal is sent to the optical router module luo16, the int numports of the optical router is 16, and the wavelength interval of WDM is 0.1. The 16-port optical router uses 120 microring resonators, 16 input ports and 16 output ports. Each microring resonator has two input ports and two output ports. The vertin vertical port and horizin horizontal port are respectively used. According to the design of topology, the input port is connected by waveguide bending in the vertin port of microring.

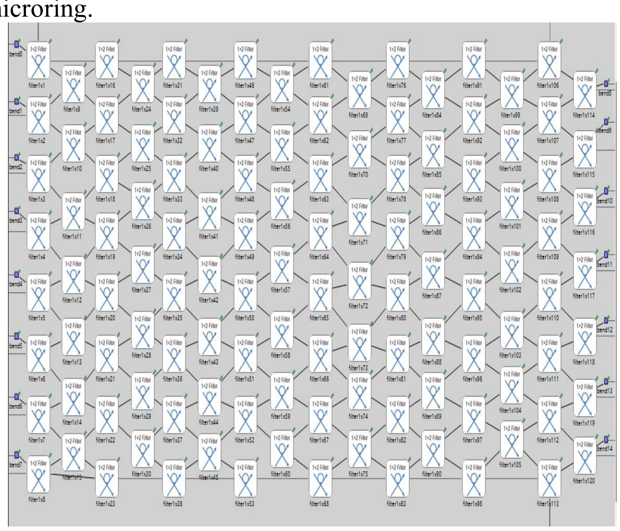

Fig.9 16 port optical router model

III. Verification and Performance

A. ReLONEONoC modeling

As shown in Fig.10, the left part is the top-level optical router. Through the wavelength ratio of the top-level optical router, it can be clearly known that the output port of each top-level router will conduct an initial range screening on the optical signal. After filtering out the optical signal, the optical signal will be sent to the sub router meeting the range for detailed secondary routing screening. The optical signal is routed to the appropriate position through the resonance of the micro ring resonator. A 16-port top-level router represents a 16 wavelengths range with a width of 16, that is, the corresponding sixteen 16-port sub router.The output port of each top-level router is the input port of a sub router.

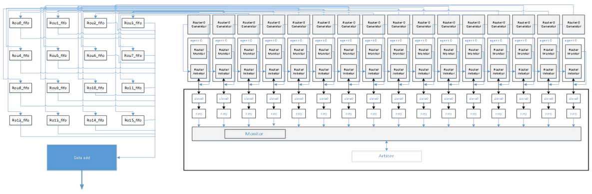

Fig.10 schematic diagram of two-stage router connection in optical interconnection layer

Fig.11 shows the verification scheme of the ReLONEONoC network, which consists of four parts: prplane, phplane, conv1 and conv2. Prplane completes the message generation and communication request sending, and conv1 performs electro-optical conversion of the data output from the processor layer. Phplane completes the data optical transmission, in which the phplane module contains two parts, the top_16 at the top layer routes the light signal firstly.The routing light signal is routed a second time by the 16 ports light router LONE. After the routing of the optical signal through conv2, the output data of the optical layer is photoelectric converted. The converted signal is then transmitted to prplane.

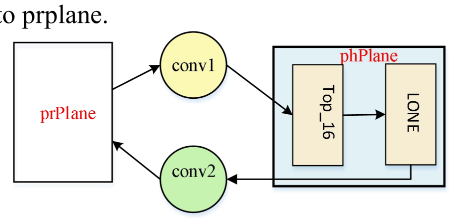

Fig.11 network verification case of reLONEonoc

Firstly, the processor layer generates different request signals according to different applications. The request signal is converted into the corresponding optical signal by the conversion module conv1. Then, the conv1 module transmits the optical signal to the optical network layer. The optical network layer uses the electrical control unit of the optical router to judge the access address and get the corresponding output port. The electric control unit configures the corresponding micro ring resonator switch state according to the port information, and sends the information to the optical switch unit to complete the transmission path establishment of the optical network layer. The optical signal is transmitted along a predetermined optical link and output from the corresponding port. Finally, the optical signal is transmitted from the optical network layer to conv2, which converts the signal to the processor layer and completes the communication process.

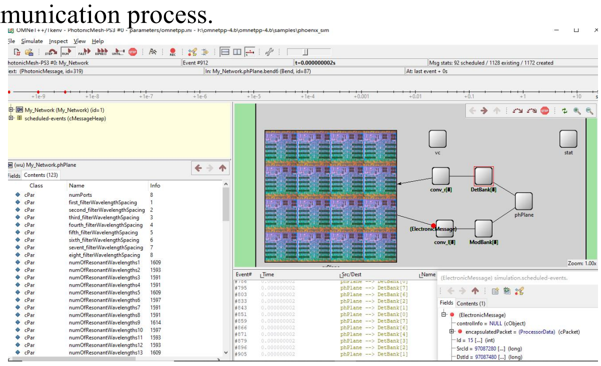

Fig.12 network simulation process of ReLONEONoC

Fig.14 shows the network simulation interface of ReLONEONoC, in which the red dot movement process simulates the signal communication process. The whole process of data communication from the processor layer to the conversion module, from the conversion module to the optical network layer, from the optical network layer to the conversion module, and from the conversion module to the processor layer. The optical modulator is demodulated to the optical network layer and optical modulator in turn. Finally, the photoelectric conversion unit receives the optical signal and transmits the converted electrical signal to the corresponding node of the processor layer to complete the optical transmission process of a group of data.

B. Performance analysis of reLONEonoc

For 4096 PEs array processor, the optical network structure (ReLONEONoC) includes 17 16-port optical routers, 16 forwarding units and 256 photoelectric conversion units. The number of microrings in the ReLONEONoC is counted. A total of 2040 microring resonators are used in the optical routers, and 256 microring resonators are used in forwarding units. In order to solve the problem of increasing insertion loss caused by the excessive number of microring resonators in the expansion process of the existing passive optical network on chip, the waveguide bending is used to replace the waveguide crossing to reduce the overall insertion loss. Because of the reconfigurability of network scale, different array sizes have different sizes. The number of microring resonators and waveguides used are also different. The specific results are shown in Table 1 it can be clearly seen from the table that with the gradual expansion of the scale of the underlying PE array, the scale of the corresponding optical network structure is also increasing, the number of microring resonators consumed and the type of waveguide are increasing synchronously.

Table 1 resource cost of optical network structure corresponding to different scale network structure.

Scale of underlying PE array	Optical network scale	MRs	Wavelengths
64	4×4	6	4
128	8×8	28	8
256	16×16	120	16
512	One 2×2 Two 16×16	243	33
1024	Four 16×16 One 4×four	490	68
2048	Eight 16×16 One 8×8	996	136
4096	17 16×16	2296	272

The comparison results are shown in Fig.13. The number of microring resonators used by ReLONEONoC is significantly less than that of other on-chip optical interconnection network structures, and other passive on-chip optical interconnection architectures almost need the same number of microring resonators. Compared with the λ-Router and LMRONoC ,the router has significantly reduced the number of microrings by 94% and 52%.

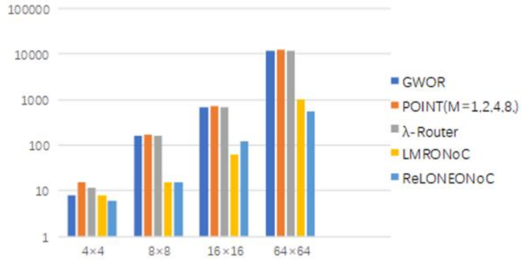

Fig.13 number of Microrings with different structures

As a reconfigurable optical interconnection structure, the size of the optical interconnection network structure can be configured according to the whole scale of the bottom layer. With the synchronous expansion of the scale of the bottom array and the optical interconnection network, the number of waveguides required in the whole network is increasing.

Whether in electrical interconnection or optical interconnection network, area overhead is an important index parameter to measure the performance of network structure. Fig.14 shows the comparison results of area consumption between 16-port optical router ReLONEONoC and other optical router structures of the same size. With the increase of network size, the number of waveguides with different structures increases, as shown in Fig.15. Table 2 shows the comparison results of the number of wavelengths used for different scale network on chip structures.

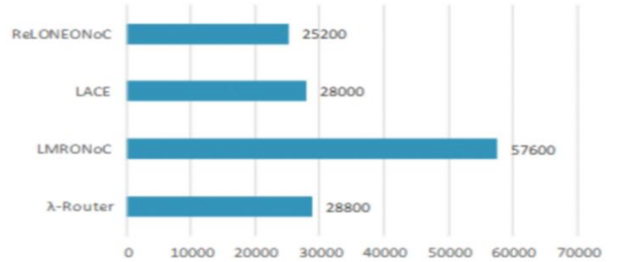

Fig.14 16×Comparison of area cost of 16 scale network structure

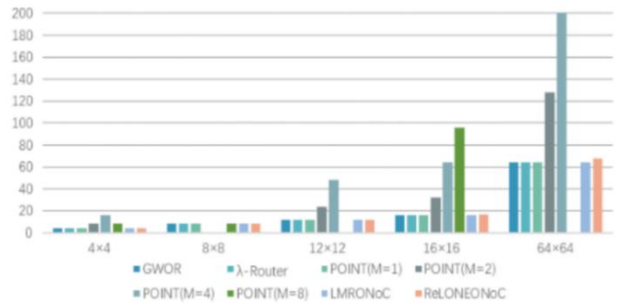

Fig.15 number of waveguides used under different network sizes

Table 2 number of wavelengths used by systems with different network sizes

	4×4	8×8	12×12	16×16	64×64
GWOR	4	8	12	16	64
λ-Router	3	7	11	15	63
POINT(M=1)	4	8	12	16	64
POINT(M=2)	2	4	6	8	62
POINT(M=4)	1	2	3	4	16
POINT(M=8)	-	1	-	2	8
LMRONoC	2	-	-	4	8
ReLONEONoC	4	8	12	16	64

Power consumption is another key factor in the design of on-chip optical interconnection. The number of microring resonators, the transmission mode of microring resonators, the number of waveguides and the transmission mode of waveguide all affect the insertion loss of the whole optical interconnection network. The insertion loss is derived from the following formula 1[22], and PLoss, Signalrepresents the insertion loss from the source node to the target node. The specific calculation is as follows:

$$P_{Loss,Signal} = P_{MR,DP} \times N_D + P_{MR,TP} \times N_T + P_B \times N_B + P_W \times L_L + P_{IL,WC} \times N_{WC} + P_{CR} \quad 1)$$

N_D and N_T represent the number of microring resonators through which optical signals in the drop and through states pass, respectively; N_B represents the number of bent waveguides; L_l represents the longest optical link length. For each row and column, the length is about 4.5mm in the optical network layer; $N_{IL,WC}$ refers to the number of cross waveguides in optical interconnection network. Table 3 shows the insertion loss parameters of each optical device in the optical interconnection network.

Table 3 optical insertion loss and energy parameters[19]

Parameter	Implication	Value
$P_{MR,DP}$	Drop-port insertion loss (BMR)	1.3 dB
$P_{MR,TP}$	Through-port insertion loss	0.01 dB
P_B	Waveguide bending loss	0.005 dB
P_W	Waveguide propagation loss	0.5 dB/cm
$P_{IL,WC}$	Waveguide crossing insertion loss	0.12 dB
P_{CR}	Coupling loss	0.6 dB

Loss is one of the key factors affecting the performance of optical networks. According to the simulation results of neomt, the results are shown in Fig.18. The maximum insertion loss of 16×16 ReLONEONoC is only 1.39db, and the minimum insertion loss is 0.99db, which is obviously better than other optical interconnection network structures of the same scale.

Fig. 18 comparison of insertion loss of ReLONEONoC

Table 4 shows the crosstalk and signal-to-noise ratio (SNR) of each part of the ReLONEONoC.Crosstalk mainly comes from two parts: the electrical signal crosstalk caused by modulator and demodulator and the optical signal crosstalk caused by microring resonator. The maximum crosstalk of electrical signal is 31.5312 (dB), the maximum crosstalk of optical signal is 15.7656 (dB), and the crosstalk of electrical signal is twice that of optical signal. Compared with the data in Table 4, the crosstalk in optical network mainly comes from the crosstalk of electrical signals. The simulation scale of this paper is larger than 8×8, the average power of optical signal is less than that of crosstalk noise, resulting in a negative value.

Table 4 crosstalk and SNR of each part of (ReLONEONoC)

	Count	Min	Avg	Max
Electrical SNR	1024	-52.8278	-35.7909	31.5312
Noise Power	1024	-16.5306	17.1945	25.6632
Optical SNR	1024	-26.4139	-17.8955	15.7656
Signal Power(dBm)	1024	-0.77019	-0.70092	-0.3675

IV. CONCLUSIONS

In this paper, we design a reconfigurable passive optical interconnection networks with 4096 PE arrays. This paper introduces the overall structure design of the ReLONEONoC, which can realize the all-optical communication of 256 clusters. Through the reasonable allocation of 256 wavelengths, the communication between 256 clusters can be realized without blocking. A 16-port non blocking optical router, LONE, is designed according to the communication requirements of ReLONEONoC. The structure is optimized by using relatively few microring resonators. On the OMNeT++ optical network simulation platform, the performance analysis of the ReLONEONoC and the optical router LONE is carried out. Finally, complete the optical signal routing on FPGA, and realize the optical module on FPGA to realize the data transmission from electrical interconnection layer to optical interconnection layer.

ACKNOWLEDGMENT

This work is supported by the National Natural Science Foundation of China (No. 61834005,61802304, 61772417).

REFERENCES

[1] Adao R M R, Alves T L, Maibohm C, et al. Two-photon polymerization simulation and fabrication of 3D microprinted suspended waveguides for on-chip optical interconnects[J]. Optics Express, 2022, 30(6): 9623-9642.

[2] Sun C, Wade M T, Lee Y, et al. Single-chip microprocessor that communicates directly using light[J]. Nature, 2015, 528(7583): 534-538.

[3] Werner S, Navaridas J, Luján M. Designing low-power, low-latency networks-on-chip by optimally combining electrical and optical links[C]//2017 IEEE International Symposium on High Performance Computer Architecture (HPCA). IEEE, 2017: 265-276.

[4] Yahya M R, Wu N, Fang Z, et al. A low insertion loss 5× 5 optical router for mesh photonic network-on-chip topology[C]//2019 IEEE conference on sustainable utilization and development in engineering and technologies (CSUDET). IEEE, 2019: 164-169.

[5] Sherwood-Droz N, Wang H, Chen L, et al. Optical 4×4 hitless silicon router for optical networks-on-chip (NoC)[J]. Optics express, 2008, 16(20): 15915-15922.

[6] Gu H, Chen K, Yang Y, et al. MRONoC: A low latency and energy efficient on chip optical interconnect architecture[J]. IEEE Photonics Journal, 2017, 9(1): 1-12

[7] Yang Y, Chen K, Gu H, et al. TAONoC: A regular passive optical network-on-chip architecture based on comb switches[J]. IEEE Transactions on Very Large Scale Integration (VLSI) Systems, 2018, 27(4): 954-963.
[8] Poon A W, Luo X, Xu F, et al. Cascaded microresonator-based matrix switch for silicon on-chip optical interconnection[J]. Proceedings of the IEEE, 2009, 97(7): 1216-1238.
[9] Gu H, Mo K H, Xu J, et al. A Low-power Low-cost Optical Router for Optical Networks-on-Chip in Multiprocessor Systems-on-Chip[C]// IEEE Computer Society Symposium on Vlsi. IEEE Computer Society, 2009:19-24.
[10] Min R, Ji R, Chen Q, et al. A Universal Method for Constructing N-Port Nonblocking Optical Router for Photonic Networks-On-Chip[J]. Journal of Lightwave Technology, 2012, 30(23):3736-3741.
[11] Tan X, Yang M, Zhang L, et al. On a scalable, non-blocking optical router for photonic networks-on-chip designs[C]//2011 Symposium on Photonics and Optoelectronics (SOPO). IEEE, 2011: 1-4.
[12] Ji R, Yang L, Zhang L, et al. Five-port optical router for photonic networks-on-chip[J]. Optics express, 2011, 19(21): 20258-20268.
[13] Ji R, Xu J, Yang L. Five-port optical router based on microring switches for photonic networks-on-chip[J]. IEEE Photonics Technology Letters, 2013, 25(5): 492-495.
[14] Huang L, Wang K, Qi S, et al. Panzer: A 6× 6 photonic router for optical network on chip[J]. IEICE Electronics Express, 2016, 13(21): 20160719-20160719.
[15] Chen Q, Zhang F, Ji R, et al. Universal method for constructing N-port non-blocking optical router based on 2×2 optical switch for photonic networks-on-chip[J]. Optics express, 2014, 22(10): 12614-12627.
[16] Zhao Z, Guo B, Shang Y, et al. Hierarchical and reconfigurable optical/electrical interconnection network for high-performance computing[J]. Journal of Optical Communications and Networking, 2020, 12(3): 50-61.
[17] Li Y, Zhang Y, Zhang L, et al. Silicon and hybrid silicon photonic devices for intra-datacenter applications: state of the art and perspectives[J]. Photonics Research, 2015, 3(5): B10-B27.
[18] Nikolova D, Rumley S, Calhoun D, et al. Scaling silicon photonic switch fabrics for data center interconnection networks[J]. Optics express, 2015, 23(2): 1159-1175.
[19] Junyong Deng, Haoyue Wu, Rui Shan, Yiwen Fu, Xinchuang Liu, Ping Wang, NPFONoC: A Low-loss, Non-blocking, Scalable Passive Optical Interconnect Network-on-Chip Architecture[C]// Asia-Pacific Signal and Information Processing Association (APSIPA), 2019: 1443-1448.
[20] Jia H, Zhao Y, Zhang L, et al. Five-port optical router based on silicon microring optical switches for photonic networks-on-chip[J]. IEEE Photonics Technology Letters, 2016, 28(9): 947-950.
[21] Tani K, Okumura T, Oda K, et al. On-chip optical interconnection using integrated germanium light emitters and photodetectors[J]. Optics Express, 2021, 29(18): 28021-28036.
[22] Briere M, Girodias B, Bouchebaba Y, et al. System level assessment of an optical NoC in an MPSoC platform[C]//2007 Design, Automation & Test in Europe Conference & Exhibition. IEEE, 2007: 1-6.
[23] Asadinia S, Mehrabi M, Yaghoubi E. Surix: Non-blocking and low insertion loss micro-ring resonator-based optical router for photonic network on chip[J]. The Journal of Supercomputing, 2021, 77(5): 4438-4460.
[24] 罗佳莹, 邓军勇, 杨博文, 山蕊, 王萍, 惠超. LONE：一种低损耗无阻塞可扩展的 8 端口光路由器[J]. 激光与光电子学进展, 2022,59(03):140-146.
[25] Junyong D, Haoyue W, Jiaying L, et al. LOOKNoC: a low-loss, non-blocking, scalable passive optical interconnect network-on-chip architecture[J]. The Journal of China Universities of Posts and Telecommunications, 2021, 28(1): 94.
[26] Poon A W, Luo X, Xu F, et al. Cascaded microresonator-based matrix switch for silicon on-chip optical interconnection[J]. Proceedings of the IEEE, 2009, 97(7): 1216-1238.
[27] Tan X F,Yang M,Zhang L,et al. A Generic Optical Router Design for Photonic Network on- Chips[J]. Lightwave Technology, Journal of, 2012, 30(3):368-376.
[28] Feng M, Wang J, Zhou R, et al. On-chip integration of GaN-based laser, modulator, and photodetector grown on Si[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2018, 24(6): 1-5.
[29] Zhu L, Chen Z, Gu H. A new multicast aware optical Network-on-Chip[C]//2016 15th International Conference on Optical Communications and Networks (ICOCN). IEEE, 2016: 1-3.
[30] Zhu K, Zhang B, Tan W, et al. Votex: A non-blocking optical router design for 3D Optical Network on Chip[C]//2015 14th International Conference on Optical Communications and Networks (ICOCN). IEEE, 2015: 1-3.
[31] Werner S, Navaridas J, Luján M. Designing low-power, low-latency networks-on-chip by optimally combining electrical and optical links[C]//2017 IEEE International Symposium on High Performance Computer Architecture (HPCA). IEEE, 2017: 265-276.
[32] Zhang B, Gu H, Wang K, et al. Low polling time TDM ONOC with direction-based wavelength assignment[J]. Journal of Optical Communications and Networking, 2017, 9(6): 479-488.
[33] Huang L, Qi S, Wang K, et al. LACE: A non-blocking on-chip optical router by utilizing the wavelength routing technology[C]//2017 16th International Conference on Optical Communications and Networks (ICOCN). IEEE, 2017: 1-3.