Design of 3D Optical Network on Chip

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***Abstract*— Optical network on chip is an emerging research topic, which can provide low latency and high bandwidth with significantly lower power dissipation. A 3D mesh based optical network on chip is developed together with a new optical router architecture as the basic units. The new router fully utilizes the properties of dimension order routing in 3D mesh networks, and reduce the number of microresonators required for ONoCs. We compared the loss property of the new router with four other schemes. The results show that the new router achieves the lowest loss for the longest path in the network of the same size. The proposed 3D mesh ONoC is compared with 2D counterpart in three aspects, i.e. energy, latency and throughput. The comparison of power consumption with electronic and 2D counterpart show that 3D ONoC can save about 79.9% energy compared to electronic one, 24.3% energy to the 2D ONoC, all containing 512 IP cores. The simulation of the network performance of the 3D mesh ONoC is carried out by OPNET under different configurations. The results also show the performance improvement over the 2D ONoC.**

Keywords-Network on chip; 3D technology; Optical interconnet

I. INTRODUCTION

As the single chip will incorporate more and more cores, the traditional methods for communication such as bus will have their limitations for system on chip (SoC) [1][2]. A new paradigm called NoC (Network on Chip) appears as a solution for the communication architecture for future SoC. It employs packet switched network structure and borrows results from interconnection networks area. However, one of the problems faced by NoC is the huge energy consumption by the electronic interconnect including links and routers [3][4]. Hence, the researchers turn their eyes to optical network on chip (ONoC) for its low loss waveguide and bit transparency [5].Optical interconnect has been applied to many areas besides NoC, such as parallel computers, terabit routers and inter-chip communication. Thanks to the recent advances in nanophotonic technologies, optical NoC becomes possible for practical system. Low loss waveguide, high speed modulator, compact switching element are continually reported with improved parameters [6][7].

Like Internet, there are also optical routers in ONoC, which takes charge of relaying the information between IP cores. But optical routers for ONoC have its own design principles and building blocks. For example, the basic switching elements in optical routers are the microring resonators, which can be fabricated on SOI substrate and is only 12 μm in diameter [8]. 3D integration is an emerging technology for NoC, which stacks several smaller wafers to reduce wire length. It offers advantages over 2D design in many aspects, such as shorter wire length, higher packing density, smaller footprint etc [9]. It also allows for the integration of hybrid technologies. The combination of optical and 3D technologies will bring further performance improvement of NoC. In this paper, we propose a 3D NoC, which takes advantage of both optical and 3D technologies.

II. THE NEW ROUTER ROUTER ARCHITECTURE

A. *TRADITIONAL CROSSBAR*

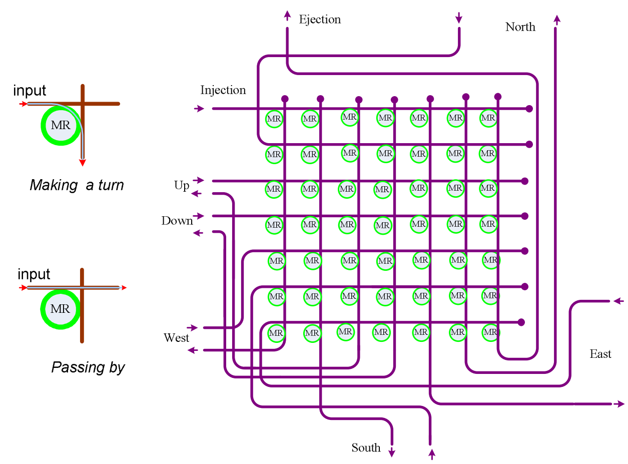

Figure 1. 7x7 full-connected crossbar

Optical routers are the key components of an ONoC. They implement the routing and flow control functions. The switching fabric is the core of the optical router, which switches packets from an input port to an output port. It can be built up by using multiple basic switching elements. Microresonator is the good choice to implement the basic 1x2 switching, as is shown in Figure 1. The microresonator has a resonance wavelength λ_{mr}, which is determined by the material and structure of the microresonator. If the wavelength of an optical signal is the same with λ_{mr}, it will make turns as Figure 1 shows. Otherwise, it will pass by the microresonator.

An easy way to implement the switching fabric of optical router architecture is to use the traditional full-connected crossbar. An *n*x*n* optical router requires an *n*x*n* crossbar, which is composed of n^2 microresonators and 2*n* crossing waveguides. Each router in the 3D mesh network needs 7 ports, so the switching fabric should be 7x7 crossbar architecture. Figure 1 shows a 7x7 full-connected crossbar, which has 7 input ports and 7 output ports in each direction.

B. *OPTIMIZED PARTIAL CROSSBAR*

The full-connected crossbar can be optimized for dimension order routing algorithm, because some turns are not required. We propose an optimized partial crossbar, for 3D ONoC using dimension order routing algorithm, as is shown in Figure 2.

The new router is a strictly non-blocking 7x7 optical router for optical 3D mesh NoC. It consists of two parts, data information processing unit (DIPU) and control information processing unit (CIPU). DIPU is the proposed optimized partial crossbar, which uses 30 microresonators and 14 waveguides. The microresonators in the switching fabric are identical, and have the same resonance wavelengths. The CIPU is made up with a control unit and 6 control interfaces (CIs). It uses electrical signals to configure the switching fabric according to the routing requirement of each packet.

There is no optical processing device available nowadays. Hence, the control information should be processed in the electronic domain. The control unit is built from traditional CMOS transistors and uses electrical signals to control each microresonator according to the routing requirement of each packet. The control units of all the new routers in an optical NoC use the same optical network with data information to setup and maintain optical paths. Hence, the control information uses a different wavelength from that by the data information. CI is used to convert optical control information into electronic signals or vice versa. Each port is equipped with a CI, which contains two microresonators. The microresonators in CIs are the same with those in DIPU but work in a passive ways. Its resonance wavelength is configured to be equal to the wavelength of the optical control information.

The new router has seven bidirectional ports, which connects EAST, WEST, NORTH, SOUTH, UP, DOWN and local links respectively. DIPU implements a 7x7 switching function for these seven bidirectional ports. U-turn function is not implemented because routing and flow control algorithms normally avoid it. Hence, seven microring resonators are saved. Since packets will not make turns until they finish their path in one dimension, with dimension order routing employed, twelve unnecessary microring resonators are also omitted. Compared with the full-connected crossbar, the 7x7 partial crossbar saves 19 microresonators. The external structure of the DIPU is designed to minimize waveguide crossings. The number of external crossing is significantly reduced. For optical 3D mesh NoCs using dimension order routing algorithm, the new router is strictly non-blocking. This can be proved by listing all the possible cases. The non-blocking property can help to increase the network throughput.

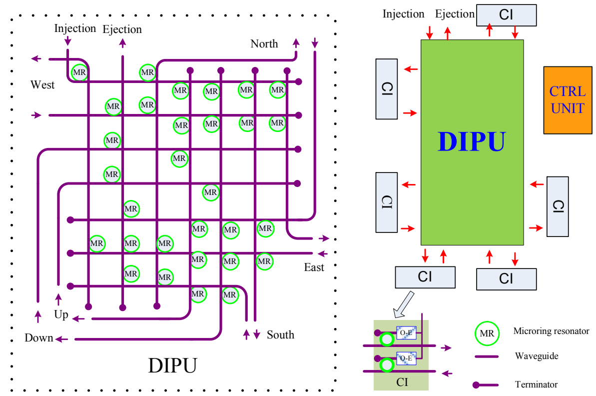

Figure 2. New router architecture for 3D NoC

We analyzed and compared the new crossbar with other available crossbars including the traditional 2D crossbar, 2D partial crossbar, traditional 3D crossbar and the optimized 2D crossbar proposed in [7]. Optical power loss of an ONoC decides how much energy will be provided by the off chip laser. In our comparison, we considered two major sources of optical power losses, the waveguide crossing insertion loss and microresonator insertion loss. The waveguide crossing insertion loss is 0.12dB [7] per crossing, and the microresonator insertion loss is 0.5dB [8]. Different input-output pairs of an optical router may have different losses. We compared the maximum loss, minimum loss, and average loss of all possible cases (Table 1). The proposed 3D optimized partial crossbar has the lower loss in three loss values compared to the traditional 3D crossbar.

Table 1 Comparison of loss for each crossbar architecture

Router architecture	Min loss (dB)	Average loss (dB)	Max loss (dB)
2D crossbar	1.22	1.36	1.70
2D partial crossbar	1.22	1.36	1.70
2D optimized crossbar	0.62	1.08	1.58
3D crossbar	1.46	1.84	2.30
3D optimized partial crossbar	0.50	1.22	1.82

Another key factor is loss in the longest path in the network. This factor has a significant effect on the power of laser and also the sensitivity of the receiver in the ONoC system. The comparison results are shown in Figure 3. It is obvious that the proposed 3D ONoC has the lowest loss in this comparison.

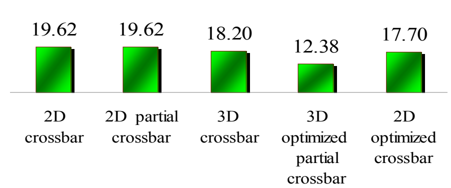

Figure 3. Loss on the longest path of 64 node networks

III. OPTICAL 3D MESH NOC

A. NETWORK TOPOLOGY

With the new router proposed in last section, as is shown in Figure 4. A 3D mesh network G_k connects N nodes in *3* dimensions. There are *k* nodes in each dimension. Each node is labeled as (*x,y,z*). In our optical 3D mesh NoC, the IP cores are connected to the proposed 3D optimized partial crossbar through an optical/electronic (O/E) and electronic/optical (E/O) interfaces. OE-EO interface is used to convert optical signal into electronic signal and vice versa. The IP core could be a processor, MPEG decoder, memory controller, etc.

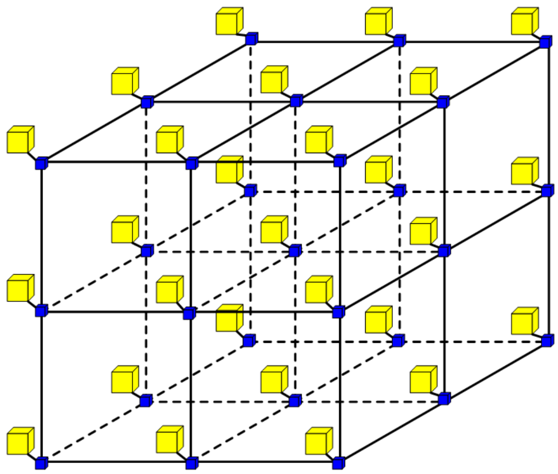

Figure 4. 3D mesh based ONoC (27 nodes)

Logically, our proposed 3D mesh ONoC consists of two overlapped networks, a data network for payload packets and a control network for control packets. In fact, these two networks share the same interconnect of waveguides. Payload packets carry data and processor instructions, while control packets carry the signaling information. The data network connects the DIPU of all the new routers in the same topology as the control network connects the CIPUs through CI. They share the same optical interconnect and use different wavelength to distinguish data information from control information. The optical interconnects are all bidirectional and are 1-bit wide on each direction. The path diversity in optical 3D mesh NoC can help to design adaptive routing of fault tolerant and load balancing properties.

B. COMMUNICATION PROTOCOL

As the optical buffer is not available by the photonic technology nowadays, optical packet switching is difficult to implement in the macro networks, and even more difficult for nanoscale on chip networks. Therefore, we employ connection oriented communication in the 3D mesh based optical NoC which fully utilizes the property of optical transmission.

Before sending the data packet, the source node first issues a setup packet to the destination node. The setup packet will route along the path determined by the routing algorithm. At each hop, the setup packet will reserve the resource required for the later transmission of data packet. The destination node will send an ack packet back to the source node when it receives the setup packet. Data packet will begin to transmit when ack packet arrives at the source node along the reserved path. When the transmission is finished, the reserved path will be tore down by a release packet.

By using such communication protocol, no buffer is needed for the optical data. Once the connection is established, the latency performance is guaranteed. Data arrives at the destinations in the same order when they are generated, which can help to save the overhead of re-ordering in the destination nodes.

C. ROUTING ALGORITHM

The routing algorithm chooses the output port for the setup packet at each hop in the network. The routing algorithm is required to be simple and distributed in NoC design. Dimension order routing algorithm is just the one which can meet these requirement. It is widely accepted by the researchers in Noc area. In dimension order routing algorithm, the algorithm leads the packet to walk first in x dimension until it reach the node, which is of the same y coordinate with the destination, and then along the y dimension. When the node, which has the same y coordinate with the destination, is arrived, the packet will go along the z dimension until the destination. A formal description is listed as follows.

Dimension order routing Algorithm

/* INPUT Destination node (x_d, y_d,z_d), current node (x_c,y_c,z_c) */
/* RETURN output port p_{out} */
Begin
if $x_c = x_d$ and $y_c = y_d$ and $y_c = y_d$ /*Destination is arrived.*/
  p_{out}= EJECTION;
  else if $x_c > x_d$
    p_{out}= WEST;
    else if $x_c < x_d$
      p_{out}= EAST;
      else if $y_c > y_d$
        p_{out} =SOUTH;
        else if $y_c < y_d$
          p_{out}= NORTH;
          else if $z_c > z_d$
            p_{out}= UP;
            else
              p_{out}= DOWN;
END

IV. EVALUATION AND ANALYSIS

A. ENERGY OMPARISON AND ANALYSIS

Low power consumption is a one of the advantages of optical NoC design. In this section, we will use the energy model in [10] to evaluate the energy consumption of the proposed 3D ONoC. Figure 5 shows the energy consumption by optical and electronic 3D mesh NoC as the network size increases. It is obvious that compared with the electronic 3D mesh, optical 3D mesh saves much energy. The energy consumed by electronic NoC goes ups quickly when the network scales to large size. The energy consumed by ONoC keeps almost constant, which makes the network scales without power penalty. It can be seen that about 79.9% energy is saved by optical 3D mesh compared to electronic one, both containing 512 IP cores.

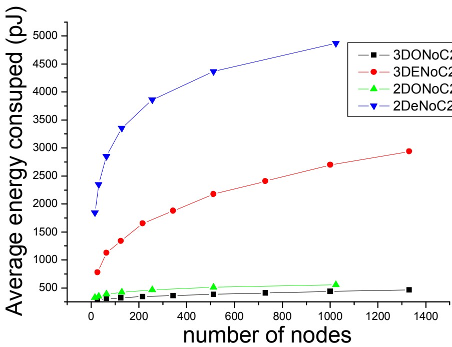

Figure 5 Power consumption of 3D ONoC and 3D electronic NoC with 2D ones with 256 bits

The comparison with 2D optical NoC and 2D electronic NoC is also shown in Figure 5. It can be seen that 2D electronic NoC consumes more energy than any other three. 3D ONoC consumes the least energy among the four because of the introduction of 3D technology. It can be seen that about 24.3% energy is saved by optical 3D mesh compared to 2D ONoC, both containing 512 IP cores.

B. NETWORK PERFORMANCE AND ANALYSIS

We built 3D mesh ONoC using the new router and dimension order routing algorithm, and studied its network performance including ETE delay and throughput. In our simulation, each node generates packets independently and at time intervals following a negative exponential distribution. The uniform traffic pattern is tested, i.e. each node sends packets to all other nodes with the same probability. The ONoC is simulated using a network simulator, OPNET [11]. We assumed a moderate peak bandwidth, 12.5Gbps, for each injection port, which is reported to be achieved by using a single modulator based on microresonators.

We compare the network performance of 3D ONoC with its 2D counterpart, both of which containing 64 nodes. Figure 6 and Figure 7 show the results in ETE delay and throughput with 32 and 64 bytes packets employed. The average ETE delay is defined as the average time from the packet generation to the time it arrives at the destination. The throughput of the ONoC is normalized under a given offered load.

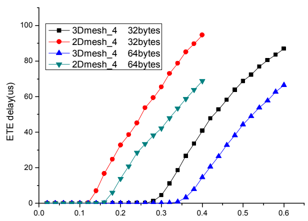

Figure 6 ETE delay performance

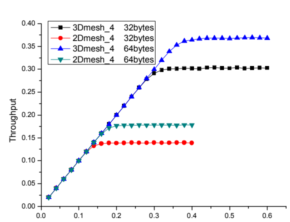

Figure 7 Throughput performance

In Figure 6, it is obvious that 3D ONoC achieves lower delay than 2D ONoC for both packet sizes. The 3D ONoC saturates at the offered load of 0.3 for 32 bytes packet, 2.3 times as large as that of 2D ONoC. From Figure 7, we can see that 3D ONoC obtain high throughput than 2D ONoC for both packet sizes. In all, the performance of 3D NoC is better than that of 2D NoC.

V. CONCLUION

In this paper, a 3D mesh based ONoC is developed. A new optical router for 3D ONoCs which uses dimension order routing algorithm is proposed to build up the 3D mesh ONoC. The new router is compared with the traditional crossbar, and the comparison results show that the new router has the lower losses and requires the smaller number of microring resonators. We simulated 3D mesh ONoCs based on the new router and dimension order routing algorithm, and showed the ETE delay and throughput under different configurations.

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