A 2-Layer Laser Multiplexed Photonic Network-on-Chip

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***Abstract*—In Recent times many two-dimensional photonic NoC architectures have been proposed with laser sources. Such Photonic NoCs meet high-bandwidth requirements but at the cost of significant power consumptions. In this paper, we propose a low-power and low cost solution to photonic NoC. A 2-layer photonic NoC architecture with laser multiplexing has been designed using a separate ring waveguide layer towards realizing a 3D photonic NoC. This approach is first of its kind in designing high-performance and low-power Photonic NoC architecture. The design approach is scalable. The proposed design results in 75% reduction in the number of on-chip lasers and 50% reduction in power dissipation compared to recently reported results.**

I. Introduction

Photonic links are reliable and attractive alternative to traditional electrical interconnects. Photonics interconnects employing wavelength-division multiplexing (WDM) provide higher bandwidth with low power dissipation[1]. Photonic network-on-chip (PNoC) uses high speed micro-ring resonators as switches and low power dissipating optical waveguides as transmission medium.

Several 2D Photonic NoC architecture based on mesh[2], torus[1], crossbar[4] and clos[5] topologies have been proposed in recent years. To decrease the cross sectional area and cross over points several 3D topologies have also been proposed[7][10].

In this paper we have considered nano-photonic interconects involving WDM in conjunction with mode division multiplexing (MDM) to design PNoC[3]. MDM exploits each spatial mode as an independent channel of communication in multimode fibres to increase the aggregate band-width by manifolds. This paper introduces a two-layer approach to design PNoC architecture that reduces the number of hops, crossover points, and cross-sectional area. Fig.1 shows the proposed architecure wherein the bottom-layer includes a mesh of routers connecting processing cores and the top-layer includes mode-locked lasers and waveguides.

The paper has following contributions:- (1) A novel WDM compatible MDM based 2-layer PNoC architecture has been proposed which is first of its kind, (2) A novel laser multiplexing scheme was introduced and (3) The proposed design was evaluated using circuit level simulator and the following results were reported: (a) 40-Gbps aggregate bandwidth which is $4\times$ higher than the recently reported result[11], (b) power consumption of 2.4fW/bit per optical path which is 50% less than the best reported result[7], (c) -2dB insertion loss for the longest optical path which is 75% less than the recently reported result[10].

The paper is organized as follows:- Section II gives the basics of switching in PNoC and multi-layer stacking. Section III presents the design details of the 2-layer PNoC. Section IV includes experimental setup, results, and comparative analysis followed by conclusion in section V.

II. Photonic Interconnects and Multi-layer Stacking

Switches and through-slicon vias(TSVs) are the building blocks of the proposed architecture. TSVs are used for multi-layer stacking. The following sections explain switches and multi-layer stacking in details.

A. Switches

The switching technique adopted for the proposed PNoC architecture is circuit-switching where the routing pattern is set dynamically beforehand by an electronic controller [1]. Circuit-switching offers higher aggregate bandwidth compared to other switching techniques applicable in PNoC, by adopdt-ing WDM technology[4]. Also, circuit swicthing offers more compact and scalable implementations[6].

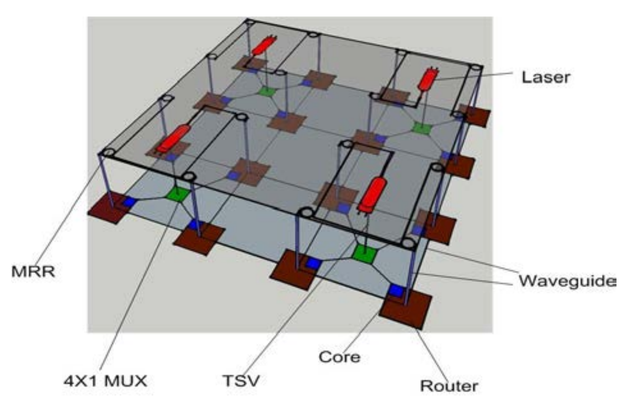
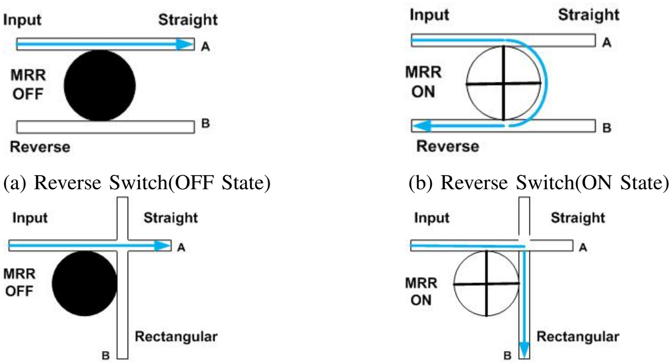


Fig. 1: Two Dimensional Photonic mesh network

The basic switching element of a photonic router is micro-ring resonator(MRR). An MRR is a circularly coiled wave-guide that filters optical signals. As shown in Fig.2a and Fig.2c MRR in OFF state allows the optical signal to be transmitted from the input port in the straight line without deflection. When in ON state (Fig.2b and Fig.2d), MRR couples the optical signal of specific wavelength from waveguide A to waveguide B.



(a) Reverse Switch(OFF State)

(b) Reverse Switch(ON State)

(c) Rectangular Switch(OFF State)

(d) Rectangular Switch(ON State)

Fig. 2: MRR Switching

For reverse-switching we use two parallel waveguides as seen in Fig.2b. Two waveguides are placed with an angle of 90 degree to each other for rectangular-switching as shown in Fig.2d.

B. Multi-layer Stacking

Multi-layer stacking is a prevalent technology to connect multiple photonic or electrical layer using TSVs. The proposed multi-layer architecture uses TSVs for communication between the bottom and the top layers. TSVs have very small cross-sectional diameter (4μm-10μm) and extremely low delay (20 ps for a 20 layer-3D stack)[7].

III. 2-LAYER PNOC ARCHITECTURE

In the proposed 2-layer PNoC architecture, the bottom layer is a network layer and top layer is a laser layer (Fig.1). The network layer cosists of a two dimensional 4×4 mesh network with 16 cores interconnected by 5×5 non-blocking fully photonic routers and waveguides. Each of the waveguides has two channels incorporating WDM. The laser layer consists of several ring waveguides each integrated with one mode-locked laser. Each laser serves four cores using a 4×1 multiplexer located in the network layer. The communication between the laser layer and the network layer is carried out by TSVs. This arrangement reduces the number of on-chip lasers thereby reducing overall cost and power consumption.

This paper uses a novel five-port photonic router that integrates MDM with WDM and TDM schemes to design a high-performance scalable PNoC.One of the router ports is connected to the network-interface (NI) whereas other four ports are connetced to neighbouring routers. Apart from the communication with the local core, NI has an electronic controller that establishes circuit switching between a sourec and its destination using adaptive MDM and WDM schemes. The router has 14 waveguide crossings and 16 MRRs as shown in Fig. 3. There are 2 more MRRs within NI to setup MDM (Fig.4) and 4 MRRs in the laser layer for laser multiplexing (Fig.1).

Each core sends a READY signal to the corresponding 4×1

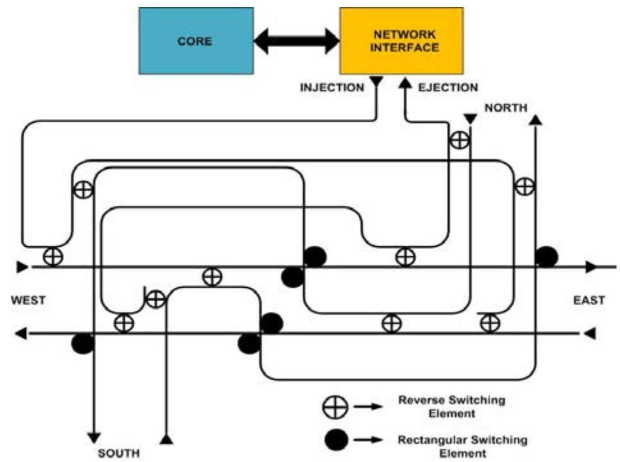


Fig. 3: Logical layout of 5×5 photonic router

multiplexer (MUX) to check its availability. After receiving an acknowledgement from MUX, the core sends the message through MUX to the mode-locked laser through TSV. The mode-locked laser is controlled by router's electronic controller that deploys adaptive MDM-WDM algorithm as depicted in Algorithm 1. According to the algorithm, the mode-locked laser produces optical signal of specific wavelength and mode for transmitting the message to the destination core.

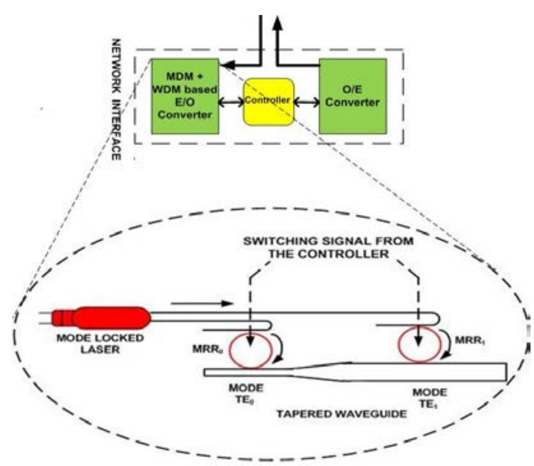


Fig. 4: Modelocked laser employing MDM

IV. EXPERIMENTS AND RESULTS

IPKISS[9] platform has been used for design and simulation of the 2-layer PNoC. This tool allows photonic component

Algorithm 1 Controller Algorithm for adaptive mode division multiplexing and wave division multiplexing

procedure CORE1 WANTS TO SEND DATA TO CORE2
  N = no. of signals transmitting fully or partially along the path
  Controller checks for the shortest availale path using adaptive modified XY routing
  if (N=0) **then**
    Switch ON MRR_0 with λ_0
    Send signal from Mode-Locked Laser
  if (N=1) and (mode = TE_0) **then**
    Switch ON MRR_1 with λ_0
    Send signal from Mode-Locked Laser with a (τ+pulse-width) delay
  if (N=2) **then**
    Switch ON MRR_0 with λ_1
    Send signal from Mode-Locked Laser with a 2(τ+pulse-width) delay
  if (N=3) and (mode = TE_0) **then**
    Switch ON MRR_1 with λ_1
    Send signal from Mode-Locked Laser with a 3(τ+pulse-width) delay

layout design, virtual fabrication of components in different technologies, physical simulation of components, and optical circuit design and simulation. We custom-designed photonic components like MRR, waveguide, mode-locked laser, tapered waveguide, and photodiode required for the proposed architecture.

A. PNoC Component Simulations on IPKISS

The design parameters adopted to carry out various experiments are depicted in TABLE I. MRR of diameter 10μm was adopted to keep the area of the PNoC foot-print as small as possible without letting the waveguides interfere much. The multimode waveguide supports four optical modes TE_0, TE_1, TE_2 and TE_3 with a refractive index of 2.46. The waveguide also supports multiple wavelengths. The mode-locked laser used has a frequency of 10-GHz. It produces optical signal with a pulse width of 10ps. Each of the pulses contains multiple wavelengths ranging from 1595nm to 1605nm. The laser also produces hundreds of modes. But we're considering modes TE_0, TE_1, TE_2 and TE_3 as the proposed MDM scheme supports 4 modes. Using all these fundamental components, we built the2-layer PNoC in IPKISS and performed the physical simulation.

MRRs and waveguides were integrated to virtually fabricate the router. Routers, lasers, TSVs, and waveguides were connected and virtually fabcricated. After virtual fabrication to cater design issues, we carried out simulation using CAMFR. CAMFR provides the refractive index profile and optical transmission profile of the fabricated design. Uniform refractive index across the PNoC is necessary for ripple free photonic

TABLE I: Design Parameters for Experimental Setup

Design Parameters	Value
MRR diameter	10μm
Waveguide(MRR) width	450nm
Waveguide(Signal Transmission) height	250nm
Waveguide(Signal Transmission) width	450nm
Refractive index Of waveguides	2.46
Pulse-width of Optical Signal	10ps
Frequency(mode-locked laser)	10GHz
Wavelength	1547.5nm and 1550nm

transmission. After testing the uniformity of refractive index across the router, we simulated the 2-layer PNoC in CAPHE. CAPHE is an optical circuit simulator for time-domain and frequency-domain analysis. It is also used to evaluate the insertion loss in an optical circuit. The insertion loss in the MRR is found to be 0.12dB. Each MRR can be tuned to multiple wavelengths.

B. Comparitive Analysis

A comparative analysis of the proposed 2-layer PNoC with similar architectures like R-3PO[7], Corona[10], and Firefly[11] was carried out. We analyzed important parameters of all these architectures like the required number of MRRs, optical insertion losses, and power consumptions.

1) Number of MRRs: The number of MRRs utilized in a PNoC architecture determines the area overhead and cost. We compared the number of MRRs used to design each of the photonic architectures. The proposed 2-layer PNoC uses 19 MRRs per core . It is 33% less than the R-3PO which is based on crossbar routers. Fig. 5 shows the comparison of number of MRRs among various architectures. The graph clearly shows that the proposed design outperforms all other

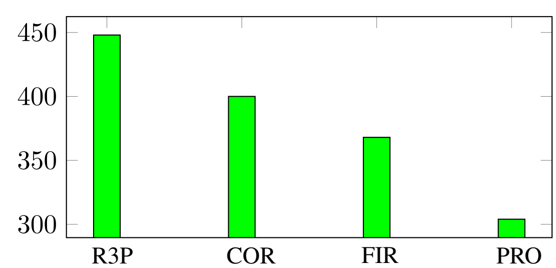


Fig. 5: Comparing number of MRRs for 4×4 PNoC; R3P:R-3PO, COR:Corona, FIR:Firefly, PRO:proposed 2-layer PNoC

2) Power Comparison: The power consumption of PNoC can be divided into two parts, optical power and electrical power. The optical power in 2-layer PNoC is the sum of the laser power and the optical insertion loss. The laser power can be determined by the following equation.

$$P_{Laser} = P_{Det} + P_{Channel} + M_{Sys} \quad (1)$$

Here P_{Det} is the photodetector sensitivity, $P_{Channel}$ is the photonic channel loss, and M_{Sys} is the system margin. The optical insertion loss is the loss in signal power whenever there is a waveguide crossing or bending. The total insertion loss is determined by

$$P_{Insertion} = \sum P_{Bending} + \sum P_{Crossing} + \sum P_{MRR} \quad (2)$$

As per Equation 2, insertion loss along an optical path accounts for the total number of bending, crossing, and MRR in that path. To perform a fair comparison with other four architectures, we use the same optical device parameters and loss values, as listed in Table II.

TABLE II: Electrical and optical losses

Component	Value	Unit
Laser efficiency	5	dB
Splitter	0.2	dB/cm
Ring Drop	1	dB
Photodetector Sensitivity	-26	dBm

Electrical power consumption in a PNoC is mainly because of power to turn on an MRR. We analytically determined the electrical power consumption of the proposed design using dimension order routing scheme. We evaluated the average power consumption per optical path in the network [E_{path}] and also the average power consumption per router [E_{router}]. We calculated E_{path} using Equation 3. Here E_j represents the power consumed on j-th path when the bandwidth is 'B'. 'P' represents the total number of photonic paths in the NoC. E_{router} is calculated using Equation 4 where 'R' is the average number of photonic routers in all the optical paths.

$$E_{path} = \frac{\sum_{j=1}^{P} E_j}{P \times B} \quad (3)$$

$$E_{router} = \frac{E_{path}}{R} \quad (4)$$

Network-level analysis in Fig. 6 shows that the proposed 2-layer PNoC consumes the lowest average power per optical path, 2.4fW/bit. It is 75% less than Firefly and 71% less than Corona architectures. In the proposed router based network, average router power consumption is 0.38fW/bit, which is also 75% less than the Corona architecture. A deeper analysis shows that the maximum power consumption of the proposed architecture is also 2.4fW/bit irrespective of network size. The MRRs in the routers of the proposed archirecture are placed in such a manner that it does not need to switch on any MRR for a packet to travel along the row or column. This makes the proposed 2-layer PNoC highly scalable without worrying about the power consumption in additional routers on a longer path.

Fig. 7 shows the average power consumption per optical path in NoC of different sizes. It is evident from the graph that the proposed 2-layer PNoC has the lowest average power consumption across all sizes that demonstrates scalability.

3) Optical Insertion loss: Insertion loss of an NoC determines its feasibility and also the power required by the NI to transmit, and receive optical singals. Waveguide-crossings and MRRs are the major sources of insertion loss in a photonic

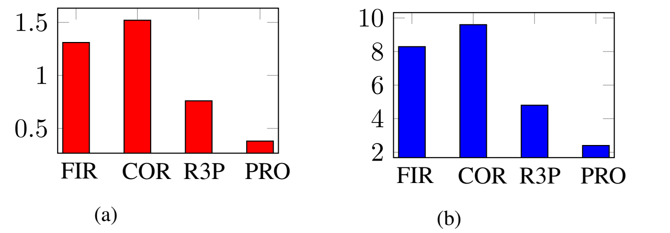


Fig. 6: Comparison of power consumption (a)per router and (b) optical path, in fW/bit

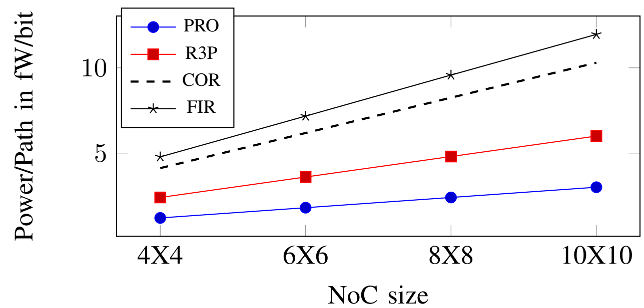


Fig. 7: Average power per Path for different NoC sizes

architecture. Insertion losses for an MRR and a waveguide crossing are 0.5dB and 0.12 dB respectively.

Insertion loss varies across input output pairs in a network. Hence we evaluated the best-case, average-case, and the worst-case insertion losses in all the architectures. It is clear from the result shown in Fig. 8 that the proposed architecture has the lowest insertion loss for all the cases. Compared to R-3PO, the proposed router has 65% less best-case loss, 45% less average-case loss, and 30% less worst-case loss. Similarly it outperforms other reported architectures.

4) Bandwidth comparison: Photonic-links deployed in the proposed PNoC has a data rate of 10-Gbps. Deploying MDM and WDM, the proposed architecture offers an overall bandwidth of 40-Gbps. The architecture enhances the photonic-link data rate by $4\times$ compared to $1\times$ enhancement in the most recently reported architecture[7].

5) Number of Laser-sources: The laser-multiplexing technique deployed in the proposed architecture allows each laser-

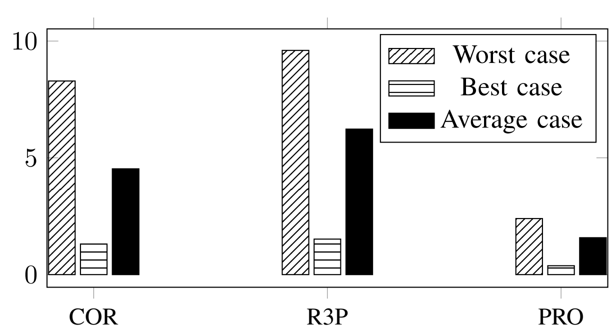


Fig. 8: Insertion loss in 4×4 PNoC in dB

source to serve four cores. This technique reduces the number of on-chip lasers by 75% compared to architectures deploying one laser-source per core[11].

V. Conclusion

This article introduced a 2-layer PNoC architecture by integrating WDM, MDM and TDM techniques. A virtual prototype implementation demonstrates significant improvements in the performance and power consumptions compare to some other PNoC architectures. This approach can be extended to realize efficient 3D PNoC design in the future. MRR properties vary with temperature which affects the overall performance of PNoC. Research will be carried out to design a thermal model to figure out the effect of temperaure on the proposed PNoC.

VI. Acknowledgement

We would like to sincerely thank Dr. Eun Jung Kim of Texas A&M University for her timely guidance. We are grateful to Dr. Suman Mandal ,Intel for his valuable inputs. This paper would not have been possible without the support of Dr. Martin Fiers of Luceda photonics and the Photonic Research group of Ghent university, Belgium as IPKISS was used to build, simulate and validate the photonic components and circuits.

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