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Modern architecture for photonic networks-on-chip

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Abstract

Development in photonic integrated circuits (PICs) provides a promising solution for on-chip optical computation and communication. PICs provides the best alternative to traditional networks-on-chip (NoC) circuits which face serious challenges such as bandwidth, latency and power consumption. Integrated optics have substantiated the ability to accomplish low-power communication and low-power data processing at ultra-high speeds. In this work, we propose a new architecture for NoC, which might improve overall on-chip network performance by reducing its power consumption, providing large channel capacity for communication, decreasing latency among nodes and reducing hop count. Some of the key features of the proposed architecture are to reduce the waveguide network for communication among nodes, and this architecture can be used as a brick to construct other architectures. In this architecture, we use micro-ring resonator (MRR) and it is used to provide a high bandwidth connection among nodes with a lesser number of waveguide networks. Furthermore, results show that this architecture of PICs provides better performance in terms of low communication latency, low power consumption, high bandwidth. It also provides acceptable FSR value, FWHR value, finesse value and *Q*-factor of micro-ring resonators used for the design of MRR in this architecture.

Keywords Photonic integrated circuits · Micro-ring resonator · Networks-on-chip

1 Introduction

NoC is a concept to integrate different IP cores on a single chip in a network topology [1]. Its main purpose is to combine all elements like RAM, ROM, computing processors, sensors in the form of MEMS, GPU and other operating units on a

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single chip. These connections between elements play a major role in communication among them. It consists of specific routers that act as a medium to route packets between destination and source. These routers act as per the routing algorithm and topology used in NoC to decide further hops [2]. Some of the main features of network-on-chip are: (a) scalability: to use all elements efficiently and reduce system size, (b) power efficiency: to enhance overall communication on a single chip which reduces power consumption, (c) reduced latency: to make dedication connection between elements which reduces high communication latency and (d) predictability: As connection among devices is well controlled and optimized under electrical parameters, we can predict NoCs throughput in terms of power consumption as well as transmission delay.

To understand the importance of NoC, it is important to consider past challenges [2]. Let us look in the past years; one of the main issues is to enhance computation power in computers. Computation means to increase the performance of systems in terms of calculation, solving problems and yielding high throughput. By using a large number of processing cores and switching elements in multi-core architecture, the design is only focused on computational processing. As these IP cores are connected through a common bus, the computation power is increasing exponentially. Wire routing congestion increases with the increased number of IP cores. The common bus architecture is not suitable for the IP cores working on high frequencies. In recent years, NoC is capable of providing desired communication as per the computation power, scalability and globally asynchronous locally synchronous (GALS) implementation. But the exponential increase in computations leads to the limitations in electric NoC. A few of the major limitations are complexity, heating dissipation, bandwidth issue and the number of hop counts as per routing algorithm [1–4]. Thus, the increase in computations makes the performance faster but emergers with the new challenge of exchanging information from one component to another. This challenge acts as a bottleneck in terms of communication.

As far as the computation and communication are concerned, NoC may have upcoming major issues in the future like less bandwidth and complexity. This makes researchers move from computational design to communicational design. Computation of any system requires a high communication interface between the nodes. The higher the communication, the higher will be the computation power [5]. As a result, the industry, as well as the researchers, is focusing on finding new alternatives like using wireless connections, providing a direct interface between devices and reducing hop count [6, 7]. Another promising solution involves the use of hybrid connections which makes use of both wired and wireless connections. This solution provides high efficiency in terms of communication and reduced hop count. One of the most promising solutions is using on-chip photonics [4, 5]. These photonic connections are also known as optical connections between nodes; the researchers have been working in the field of optics for the last 30 years. But, recently the concept of photonics on-chip has helped in providing a promising solution. The use of optical connections among nodes increases both data speed and data capacity regardless of power consumption and also provides high throughput and reduced latency as well.

Photonic networks-on-chip is introduced to provide auspicious solutions regarding problems like communication power, latency and low bandwidth [5]. In photonic

NoC communication, power efficiency is large as compared to traditional techniques like buses and wires used in NoC. As compared to the power consumption in electric centric architecture, it gives better results. Communication time between nodes plays a major role; traditional NoC requires more communication time which affects overall performance. With the use of optical signals, communication time is reduced which provides high throughput. Similarly, low bandwidth or we can say limited bandwidth reduces overall performance. Introducing photonic NoCs results in increases in bandwidth which sums up in high performance.

In this paper, we discuss different methodologies and solutions proposed by many authors to tackle problems, as discussed in Sect. 2. Many solutions are illustrated to encounter problems like communication playing bottleneck, bandwidth, latency and power consumption. One of the major solutions is to use photonic NoC which provides a better result and overcome all major limitations. Next, we propose a new architecture design that manages to overcome some of the challenges. In our architecture, we wisely use the waveguide design to cover all nodes without reducing the quality of service (QoS). This architecture doesn't require a dedicated connection among nodes or any type of point-to-point connections. To our best knowledge, this paper pays attention to the recent challenges in photonic networks-on-chip. In particular, this paper makes the following contribution:

- Providing wise use of waveguide network among nodes, which covers all nodes without reducing the QoS.
- Using a definite number of wavelengths independent of network size. That results in less complex structure as well as reduced power usage.
- This architecture may be used as a brick-like structure to construct other big architecture.

The rest of the paper is organized as follows: Introduction is followed by related work in Sect. 2 which covers some surveys about NoC and new techniques to form NoC to enhance throughput as well as communication between devices. Section 3 includes the simulation of the proposed architecture. Section 4 covers simulated as well as mathematical results followed by conclusion and future work discussed in Sect. 5.

2 Related work

New technology and innovation attract different researchers for major contributions in the field of NoC. Mostly, NoCs are introduced to replace traditional wire base circuits or buses to make dedicated connections between elements. These NoCs make direct connections and eliminate barriers between the elements which degrades QoS. NoCs are the combination of computational design as well as communicational design. These are employed to enhance the throughput in devices, which plays a major role in the performance of any device or system.

In the past, researchers used dedicated connections between major elements to make faster execution of high-priority operations. These point-to-point connections between elements gave rise to the very concept of NoC [8, 9]. Initially, NoCs used simply wired connections between nodes, which overcome the problem for a particular time period. As the demand for computation power became dominant, the structure of NoCs became more complex. Some interesting solutions are presented to use maximum throughput from these NoCs. An interesting solution is presented in [10], in which the author proposed a new algorithm which uses to map different IP cores as well as cost functions. This algorithm enhances the reliability among nodes and provides direct communication between GPU and CPU. The main idea behind this is to make one hop between high-priority elements like GPU and CPU. The result shows less power consumption and enhanced quality of service. In [11], the authors used MAC benefits for different nodes. This MAC-based criterion uses a specific wireless node which eliminates other nodes at a particular time. The negligence of other nodes during communication, improves the QoS. Results show the elimination of unwanted nodes, low latency and a simultaneous decrease in power consumption. Another solution is introduced to achieve low energy consumption; in [6] author proposed Floyd base inter-chip traffic distribution to provide deadlock-free routing. In this, they proposed to use specific traffic patterns in network while using the routing algorithms. The results show that it sums up a reduction in energy use, reducing hop count, reducing average delay and an increase in average throughput. In [12], the authors proposed to use virtual channels between nodes. These virtual channels have pros as well cons; on the one hand, it makes throughput high by providing direct connections between high-priority nodes, while on the other hand, it forms NoC highly complexible in nature. This results in an increase in energy use as well as throughput. The author gives better ways to use virtual channels in a limited way. Further results show proper packet delivery at a low-cost effect. In [11], authors achieve significant latency as well as throughput improvement. Both wired and wireless connections between nodes have been used. By employing the dual-plane network-on-chip architecture, the authors get better results in terms of proper channel communication. Further results show 30% improvement in latency, 25% throughput improvement and 33% energy usage. Both wired and wireless connections are employed by many researchers [13, 14], as per the requirements of reducing hop count and maintaining the quality of service. This technique enhances the communication power as well as the throughput of any system, but as a limitation, it increases the complexity of both architecture and routing algorithms. Some interesting solutions to using artificial intelligence are proposed by authors in order to get better results regarding traffic patterns in NoCs [15–18]. This traffic pattern makes the proper allocation of data traffic among nodes and thus provides an intelligent road mapping solution with the help of artificial intelligence. The use of these techniques may reduce deadlock situations and enhance overall throughput.

In recent years, the complexity in the design, as well as algorithms, gave rise to the use of optical connections among devices. The approach of using optical connections in NoC is also known as photonic integrated connections. Applying optical connections is a traditional approach, but nowadays using optical connections is emerging on small scales like NoC. In [1, 2, 5], the authors discussed optical connections and their advantages over wired and wireless connections. In [19], the author focused on making waveguide connections among nodes. They proposed to use two waveguide-based switches instead of regular switches. This replacement enhances the communication power and makes data rate faster as compared to other switches. Further results show the decrease in power consumption up to 178 mW. In [20]; the author used Vivaldi antennas coupled with silicon waveguide in wireless optical NoC. By using wireless in optical connection, it enhances the communication power and provides point-to-point link between nodes. Further results show the high network transparency and result in better communication between nodes. An optical ring architecture is proposed by [21]; in this, they use a ring-like structure to provide the connection between nodes. These nodes are well connected by the waveguide and provide a direct connection between the nodes. This approach provides better results in terms of high throughput and low latency. The major limitation of this paper is that they used a large number of wavelengths and waveguides which increases power consumption. An interesting solution to using the wireless and optical connection is presented in [22]. In this paper, the author used waveguide connection between nodes. Some of the nodes have a wireless connection to eliminate hop count and decrease traffic between waveguides. This technique shows high efficiency in terms of hop count, improvement in latency and throughput by 15% and energy-efficient up to 50%. One of the major limitations is of using wireless communication with waveguide design in 256 node designs. Thus, it provides a highly complex nature and communication complexity. The use of optical connections among nodes is mainly used to overcome problems like heat dissipation, power usage and complex nature [2, 5]. In comparison with traditional techniques, they provide high bandwidth and less communicational latency, thus reflecting high dominant factors for any NoC design. These optical connections provide less heat dissipation, reduced latency rate and increased data rate. Despite the complex nature of optical connections, they provide far better results in case of communication.

Although wireless connections are far better than wired connections, wireless connections nearly equate optical connection in some aspects like hop count, power dissipation and complex nature. Optical connections provide tremendous results in various cases like (1) Bandwidth: In optical connections, the bandwidth provided among nodes is much higher as compared to any other means [19, 23]. Researchers are still trying to develop better techniques for enhancing bandwidth in optical connections. (2) Latency: Optical connections are widely used for the solution of latency among nodes. As compared to other means like wired and wireless, optical connections provide better results [1]. (3) Power efficiency: Optical connections are much better as compared to wired connection, but as compared to wireless connection results are one and the same [2, 5]. Crosstalk or disturbances while communicating in wireless connection are one of the major issues. In wireless communication another signal like a radio wave, other node's Wi-Fi signal and other interference may cause noise and thus affect QoS [11]. On the other hand, the optical connection increases QoS and prevents outer interferences. Thus, optical connections may help NoCs to achieve equilibrium between computation and communication. This technique of integrating optics in NoCs is known as photonic integrated circuits (PICs) or integrated photonic connections. The detailed description related to photonic integrated circuits is discussed in Sect. 2.1.

2.1 Photonic integrated circuits

PIC or integrated optical connection is a technique for combining optical connections between nodes in NoCs instead of previous methods like wired connection or wireless connection. PIC consists of basically three main parts as shown in Fig. 1: generation of waveform to transport information from origin to destination, routing of information or control over the waveform to manipulate optical waves and reception which is the last step where it will collect all the optical information, including conversion and representation for the node [1, 2]. The major concern regarding PIC architecture is to construct connections between nodes with a wise use of waveguide. This waveguide plays a major role in connecting different nodes, while excessive use of waveguide may imbalance the architecture and cause power dissipation as well as heat dissipation problems [5]. The wise use of waveguide among nodes reduces cost factors as well as heat and power dissipation problems. Figure 1 shows a detailed description of PIC communication system.

2.1.1 Generation

It includes the conversion of Electric data or information into the optical domain. The generation of data includes four main steps: First, electric data are transferred through the encoding section. Encoding is error detection, and correction methods which are implemented to provide a better quality of service. Then, data are transferred to serialization which controls the packet latency rate and data rate. Then, it passes through the drive circuit which provides an electrical interface between elec-

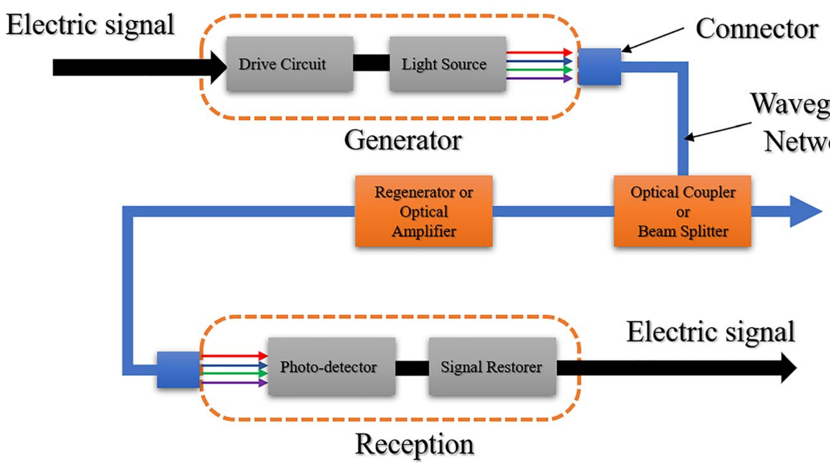


Fig. 1 A photonic integrated circuit communication system

tric data and light source. The last part is a modulator which includes a light source and medium of transportation.

2.1.2 Routing

It is the backbone of every communication device. Routing provides a specific path for the transmitter and receiver for the transfer of data. Routing provides extra features like the quality of service, fast communication, easy error detection and low miss rate. In optical routing, the important routing techniques used between elements are presented as optical links. These are also known as optical busses that provide a special waveguide network between receiver and transmitter in O-NoC. These busses are capable of transferring multiple wavelengths in a single waveguide. There are mainly four types of optical busses: single writer–single reader (SWSR), multiple writer–single readers (MWSR), single writer–multiple readers (SWMR) and multiple writers–multiple readers (MWMR).

2.1.3 Reception

It includes a collection of optical data at the destination and converts it into electric data. This includes four major parts: The first optical signal is detected by a detector which converts the optical signal into the electric signal. Then electric data are passed through an amplifier, which boosts the gain of an electrical signal to execute further operations. These signals are then converted into a low clock rate for the electronic bus by deserialization. At last, the decoder is used to convert data into a pure form for processing.

Nowadays, optical NoC is emerging and providing the backbone for high-end services. The services like edge computing systems, data centers and Web servers in cloud services [24, 25] require high-end components. These components consume high computation power and large communication channels; thus, PIC might provide desired computation power. In recent years, a lot of commercial interest has been focused on using optical networks to create next-generation servers and data centers. This is mainly because of the impending death of traditional Moore's law-based scaling, which implies computation is increasing twice a rate every year while communication between those high-end components is not up to the mark.

3 Proposed architecture

In this section, we briefly explain our novel architecture composed of a waveguide network over a silicon chip. In our architecture, we use SiO_2 as waveguide material and *Si* as a substrate. The proposed architecture mainly focuses to resolve complex waveguide networks in photonic integrated circuits [2, 5]. This architecture eliminates wired connections as well as wireless connections among nodes and makes a dedicated connection through waveguide between nodes. This connection provides less communication latency, as well as the distance between nodes, as discussed in Sect. 4. Figure 2 shows our novel photonic integrated circuit architecture. In this, we connect four nodes, namely Node 1, Node 2, Node 3 and Node 4.

These Node 1, Node 2, Node 3 and Node 4 form one cluster. This one cluster also works as a brick as shown in Fig. 2a, b. One cluster acts as a brick-like structure, which helps to form other full architecture like 4x4 O-NoC. As shown in Fig. 2c, 4×4 O-NoC architecture uses five bricks. This architecture uses limited waveguide design among nodes, while MRR providing a direct connection between nodes and waveguide. This brick-like cluster may help to construct other big architecture like 8×8, 10×10 - - -, 16×16 O-NoC. Complex waveguide connections may achieve a direct link between the nodes without using MRR but also results in high power consumption. Efficiency in terms of power and energy is one of the main dominant factors for any system. Thus, proposed architecture might provide less waveguide design among nodes. This might result in terms of energy-efficient systems as well as power efficient.

3.1 Architecture overview

Proposed architecture composed of SiO_2 glass for waveguide and Si for the substrate as shown in Fig. 3. In the proposed architecture, we use a ring-like structure as a major waveguide and micro-ring is used for the input as well as the

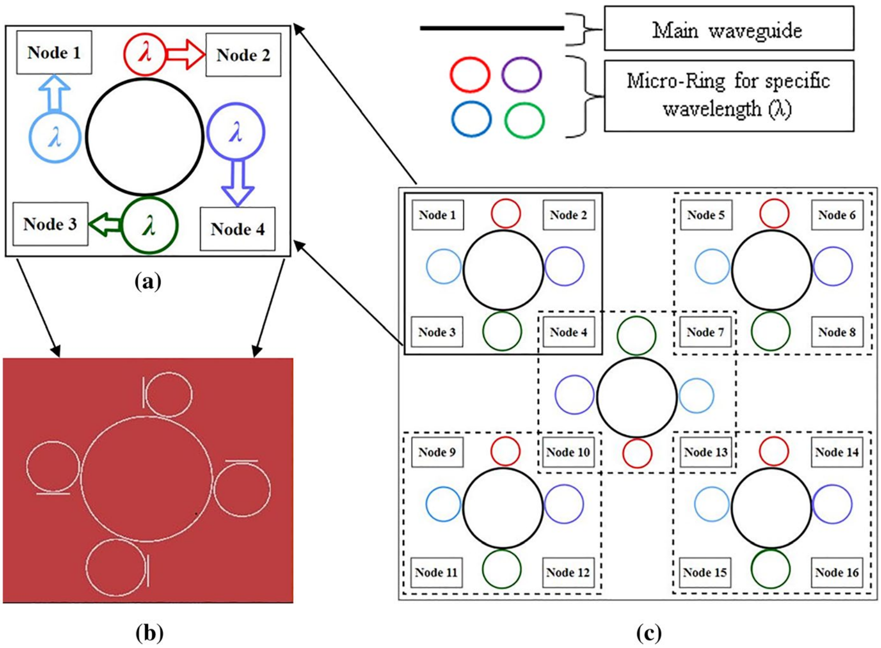


Fig. 2 **a** Graphical representation of one cluster of nodes as brick, **b** simulated proposed architecture and **c** 4×4 2D architectural design for NoC

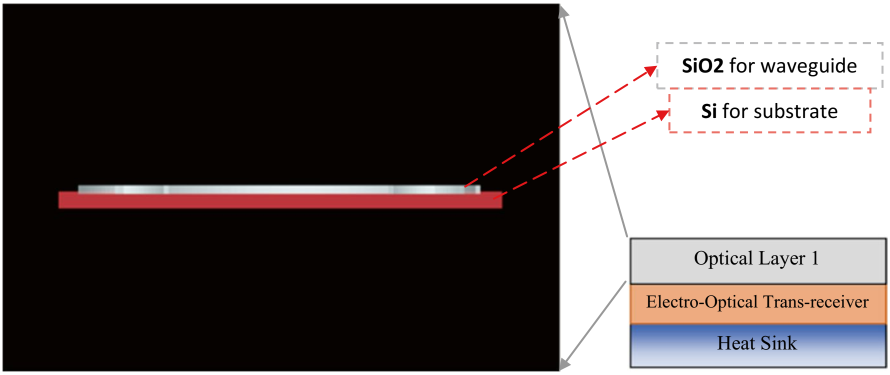


Fig. 3 Side view of architecture consists of SiO_2 as waveguide and Si for substrate

output optical signal from nodes. We use the coupling effect between micro-ring and major waveguide.

3.1.1 Waveguide

We assume a ring-like structure for major waveguide between nodes. A cross section of 500 nm × 220 nm is fabricated and denoted by "$W \times H$," respectively. Typically, the width of the waveguide is below 600 nm to ensure mode operations. The radius of the assumed major waveguide ring is 20,000 nm as shown in Fig. 4 denoted by "R."

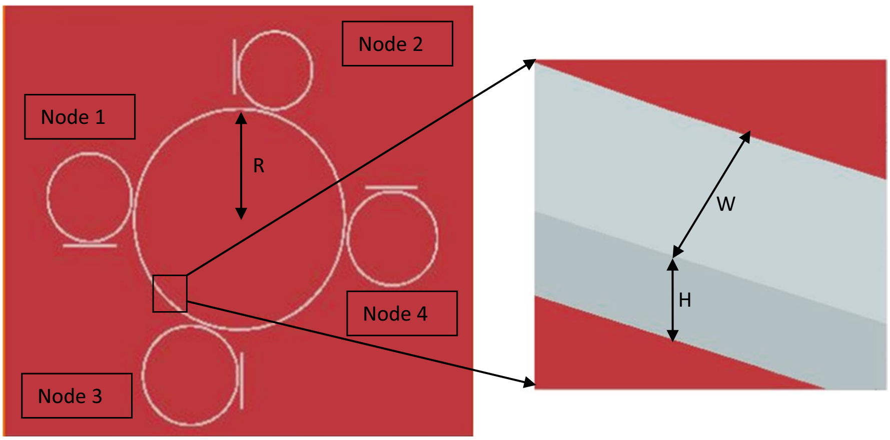


Fig. 4 SiO_2 waveguide network between Node 1, Node 2, Node 3 and Node 4 over *Si* substrate

3.1.2 SiO_2 material

The main advantage of SiO_2 waveguide on Si substrate is its cheap cost as well as the quality of service provided by SiO_2. SiO_2 waveguide provides a high quality of service as well as less light intensity loss. This material shows high mechanical strength against pulling and even bending and thus provides a high damage threshold. Although SiO_2 is chemically very stable in particular, the material is not hygroscopic which is one of the bad factors for any electric component. This material shows good optical transparency, especially in the region around 1.5 μm wavelength [26]. Photonic paths rely on a property of the photonic medium, known as bit rate transparency (number of bits processed per unit time). As in CMOS technology, using switches for every bit of data requires a large amount of energy dissipation. This energy dissipation scales with bit rate, while in PICs energy dissipation depends on the wavelength used while communicating among nodes. Another feature of the optical waveguide is power dissipation which is independent of transmission distance. Energy dissipation remains constant whether it travels 2 mm or 2 cm apart.

3.1.3 Light intensity

Light intensity refers to the strength of light inserted or transmitted from one node to another. It is the count of wavelength-weighted power inserted at a particular point. We use to transmit light intensity of wavelength 1300 nm to 1600 nm from one node to another node.

3.1.4 Node design

Fundamental building block for micro-ring based nodes design is to achieve optical filtering. In this proposed architecture, each node design is unique and has different dimensions. These micro-rings are designed to filter the specific light source of a specific wavelength (λ) from the main waveguide as input and ignore all other light sources of different wavelengths. The design of micro-ring for each node is precise with a specific radius as well as the gap between the micro-ring and major waveguide. The gap between micro-ring and waveguide plays a major role in filtering a specific wavelength (λ) from major waveguide as well as the radius of micro-rings. These radii of the micro-rings vary from 7000 to 9000 nm, and the gap between waveguide and micro-ring varies from 100 to 300 nm. These nodes work on a specific wavelength (λ), refractive index n_{eff} [27], radius (R) and comparable mode m as shown in Table 1. From Eq. (1) [28], we can derive resonant wavelength (λ) for a specific radius (R) for each node attached to the main waveguide. These refractive indexes are taken for SiO_2 material from the database [27].

$$m\lambda = 2\pi n_{\mathrm{eff}} * R \tag{1}$$

Table 1 Regarding node design specifications

Nodes	Radius (nm)	λ (nm)	n_{eff}	Mode	FSR (nm)	FWHM (nm)	Finesse	Q-factor
Node 1	8000	1400	1.5297	55	25.20	0.62	40.72	2235.29
Node 2	7000	1300	1.5310	52	24.83	0.70	35.35	1830.12
Node 3	9000	1600	1.5270	54	29.23	0.59	48.80	2632.33
Node 4	8500	1530	1.5280	53	28.31	0.66	42.32	2256.08

From the literature survey, micro-rings are described by a certain figure of merits, FSR (free spectral range): this represents the distance between resonant peaks, from Eq. (2) [28]. FSR can be calculated where λ represents the wavelength in which micro-ring works, n_g represents group refractive index taken from an online database [27] and L stands for the circumference of a proposed micro-ring given by $L = 2\pi r$.

$$\mathrm{FSR} = \frac{\lambda^2}{n_g * L} \tag{2}$$

The second figure of merit for micro-ring is finesse value which is derived by the ratio of FSR to the width of a specific wavelength (FWHD). F is derived from Eq. (3) [28]:

$$F = \frac{\mathrm{FSR}}{\mathrm{FWHD}} = \pi * \frac{t}{1 - t^2} \tag{3}$$

In Eq. (3), coupling time is denoted by (t) and π is constant. In PIC architecture, light travels in femtoseconds, for solving Eq. (3). Coupling time from the simulation in finite-difference time domain (FDTD) is between 200 femtoseconds and 300 femtoseconds. By solving Eq. (3),

$$\begin{aligned} &F = \pi * \frac{\mathrm{t}}{1 - \mathrm{t}^2} \\ &O(t) = 10^{-15} \\ &O\left(t^2\right) = 10^{-30} \\ &O\left(1 - t^2\right) \approx 1 \\ &F = \pi * \mathrm{t} \end{aligned} \tag{4}$$

Thus, the finesse value is calculated by Eq. (4).

Another figure of merit which is closely related to finesse value is the resonator quality factor (Q-factor) denoted by (Q), which is the measure of the resonator sharpness. They are defined by Eq. (5) [28]:

$$Q = \pi * \frac{n_{\mathrm{eff}} * L}{\lambda} * \frac{t}{1 - t^2}$$
$$Q = \frac{n_{\mathrm{eff}} * L}{\lambda} * F \tag{5}$$

From the above equations, we have calculated these values shown in Table 1, for node design for our proposed architecture as shown in Fig. 2a. Q-factor also gives the value regarding the quality of a micro-ring. The average Q-factor is 2238.45, and it exceeds 2000 at 1500 nm + wavelength as shown in Table 1, which is better as compared to [22].

3.2 Algorithm

Algorithm 1 is used to transmit an optical signal from one node to another. In our proposed architecture, we use single write and multiple read (SWMR)-type waveguides as shown in Fig. 5. In SWMR waveguide, one node sends data and several nodes take input. We use the token-based protocol in SWMR waveguide, which provides starvation-free mutual exclusion on a shared waveguide or resource. The setup token time range for each node is in femtoseconds or picoseconds. Token grants the node permission to transmit signals at a particular time in the waveguide, while other nodes at that time become a receiver and wait for the token to transmit their signal. In general, this token protocol is an effective and efficient technique that provides shared medium or waveguide to the nodes fairly and gives high-throughput, high-channel usage with low latency.

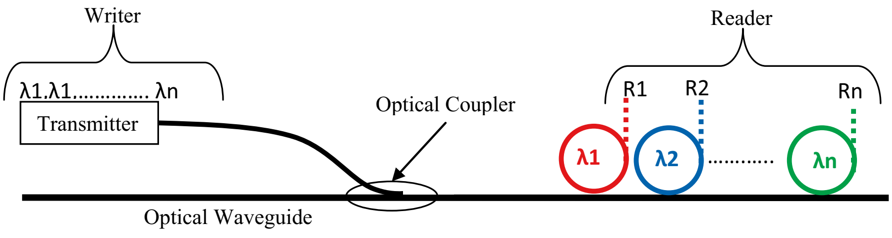


Fig. 5 SWMR physical organization optical resources needed for transmitter and receiver

Algorithm 1: For optical transmission in cluster.

Inputs: Electric data, Token achieved by Node.

```
01 Begin
02 Wait turn receiver off;
03 Check optical data
04 for i = 1 to 3
05     if data(i) = = 1 (node 1)
06         select W = λ1 (for node 1)
07     else if data(i) = = 2 (node 2)
08         select W = λ2 (node 2)
09     else if data(i) = = 3 (node 3)
10         select W = λ3 (for node 3)
11     else
12         go to line 03 (check data again)
13         break
14     end if
15 end for
16 convert electric data into optical data
17 Use W (desired wavelength) to transmit optical signal
18 if token remains
19 repeat line 03
20     endif
21 End
```

Output: Optical signal transmitted, Token Expires.

4 Experimental results and setup

In this paper, Lumerical 2018a FDTD [29] simulation framework is used for performance evaluation. In this simulator, the construction of proposed architecture with specific dimensions is performed. These dimensions are mentioned in the above section under the architecture overview. The proposed architecture is evaluated by passing an optical signal of a specific wavelength as shown in Table 1. In this setup, simulation only focuses on the design of the new architecture for waveguide allocation between nodes. These nodes are connected by waveguide with the help of MRR. These MRRs provide specific filtering of the optical signal from the main waveguide. This simulation covers one brick (cluster) in which we pass the light signal of the desired wavelength between nodes.

There are certain figures of merit by which MRR can be evaluated like finesse value, free spectral range (FSR value), full width at half maximum (FWHM value) and quality factor (Q-factor). In this, we consider [22], as authors used the same material for the design of MRR and use those MRR to connect the desired node to the main waveguide. In this section, we compare finesse value, FSR value, FWHM value and Q-factor of micro-ring resonator used in our proposed architecture. The performance of the proposed architecture is evaluated on the basis of latency and power consumption.

4.1 Finesse value

Finesse value of an optical resonator is defined as its FSR value divided by the FWHM value bandwidth of its resonances. It is fully determined by the resonator losses and is independent of the resonator length. The higher the resonator value, the higher will be its Q-factor. In Fig. 6a, the proposed architecture provides the finesse value of each micro-ring designed, while in Fig. 6b we compare the average finesse value of our four MRRs with [22]. It is obtained up to 41.79.

4.2 FSR value

The FSR of an optical resonator is the frequency spacing of its transmission peaks. It often limits the optical frequency range in which it can be used. A large free spectral range can be desirable. However, for a given finesse, a larger free spectral range also leads to a larger resonator bandwidth and higher finesse value. In Fig. 7a, the proposed architecture provides the FSR value of each micro-ring, while in Fig. 7b we compare the average FSR value of four micro-rings to [22]. It is obtained up to 26.89 nm.

4.3 FWHM value

FWHM is a way of describing the transmission characteristics of an optical micro-ring resonator or filter. This describes the width of the spectrum at the wavelengths that the optical filter passes (in nanometer). The proposed architecture provides the

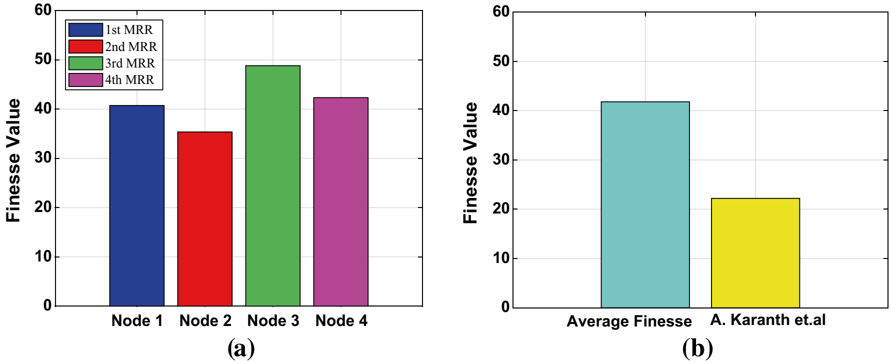


Fig. 6 Finesse of micro-ring resonator. **a** Finesse of four micro-ring resonators used in the proposed architecture. **b** Comparison between avg. finesse of four micro-rings compared to [22]

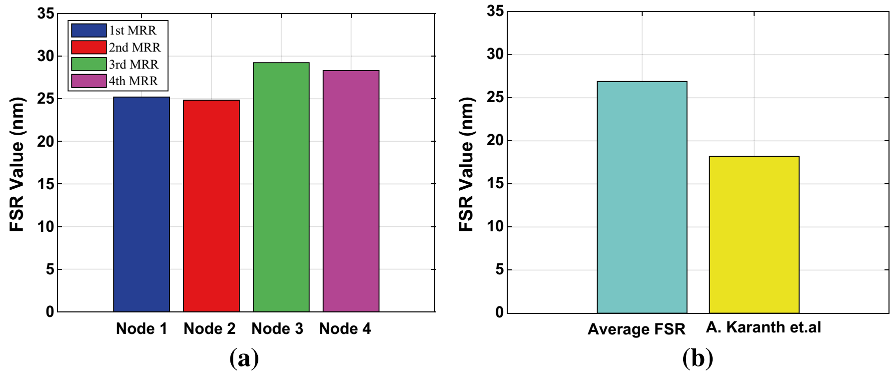


Fig. 7 FSR of micro-ring resonator. **a** FSR of four micro-ring resonators used in the proposed architecture. **b** Comparison between avg. FSR of four micro-rings compared to [22]

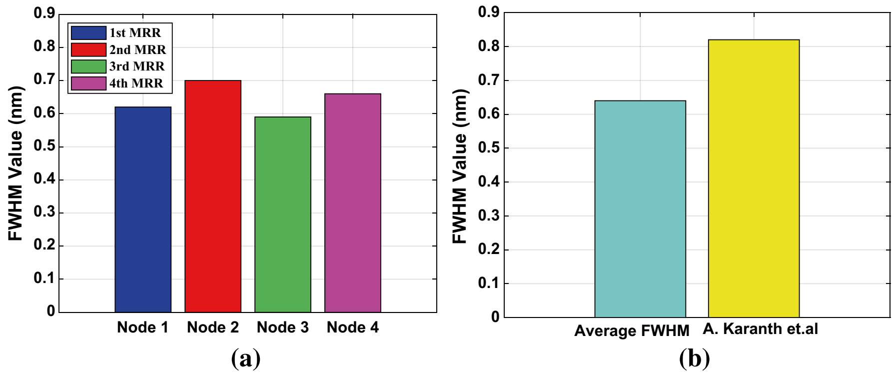


Fig. 8 FWHM of micro-ring resonator. **a** FWHM of four micro-ring resonators used in the proposed architecture. **b** Comparison between avg. FWHM of four micro-rings compared to [22]

FWHM value of each micro-ring as shown in Fig. 8a, while we compare the average FWHM value of four micro-rings to [22] as shown in Fig. 8b. It is obtained up to 0.64 nm.

4.4 *Q*-factor

Q-factor is considered as one of the main merits of any micro-ring resonator. The higher the *Q*-factor, the higher will be the quality of signal filtered. *Q*-factor of micro-ring provides good filtering of an optical signal from the main waveguide or parent waveguide to a specific node or destination. In Fig. 9a, results show different *Q*-factors of four different micro-ring resonators. These micro-rings are used to filter different optical signals from parent waveguide. *Q*-factor shows the quality of optical signal filtered from parent waveguide, or it can be said that higher *Q*-factor is directly proportional to the signal quality received at the destination. In Fig. 9b,

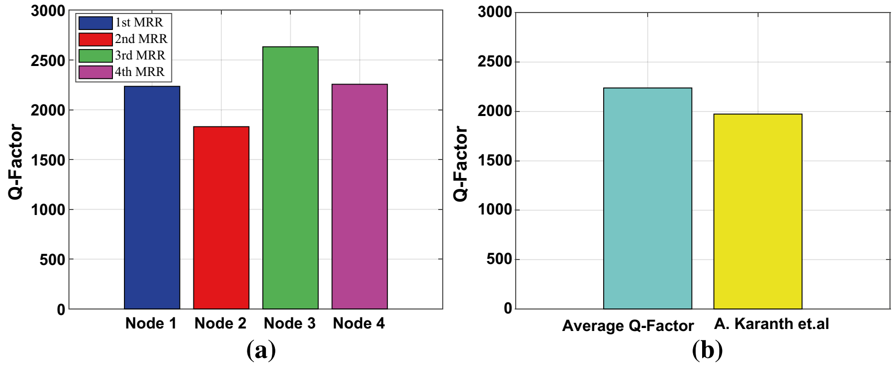


Fig. 9 Q-factor of micro-ring resonator. **a** Q-factor of four micro-ring resonators used in the proposed architecture. **b** Comparison between avg. Q-factor of four micro-rings compared to [22]

results show the comparisons of the average Q-factor of the proposed four micro-rings with [22], which is better and exceeds 2000 at 1500 + nm wavelengths. It is achieved up to 2238.4.

4.5 Latency analysis

In the proposed architecture, we transmit a specific optical signal from one node to another node. These optical signals differ from one another, as each node transmits different wavelengths as per algorithm 1, while each node filters specific wavelength as per micro-ring design. Latency in photonic integrated circuits is very low, and it provides communication in femtoseconds. It is one of the promising and most

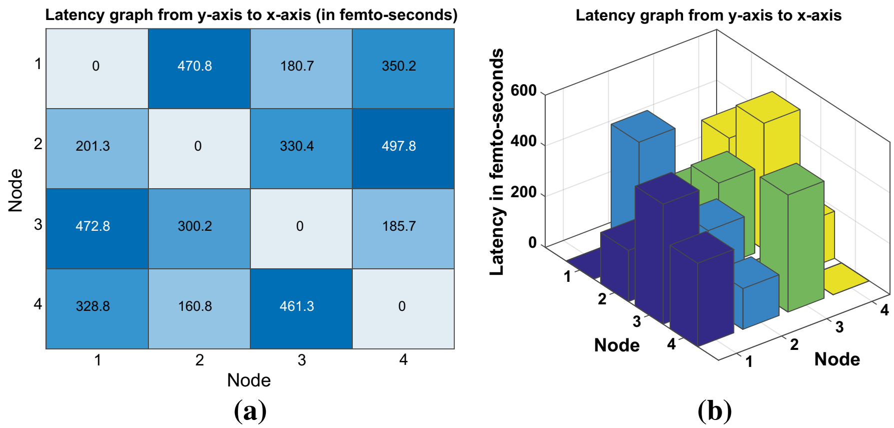


Fig. 10 Simulation results show the latency between different nodes. **a** Latency between nodes in 2D graph representation, **b** latency between nodes in 3D graph presentation

attractive factors for optical NOC. The proposed architecture only considered optical latency from one node to different nodes as shown in Fig. 10.

In Fig. 10a, the result shows the latency of an optical signal from one node to another node in femtoseconds. In this figure nodes in the x-axis represents the receiver nodes of an optical signal whereas the y-axis represents sender nodes. Figure 10b represents the 3D representation graph in which an optical signal is received by nodes in the *x*-axis from the *y*-axis and latency in femtoseconds shown in the *z*-axis.

4.6 Optical signal analysis

In Table 2, the proposed architecture is simulated using Lumerical 2018a, which provides a visual representation of optical signal transmission from one node to another. As you can see, optical signals transmitted from one node and filtered at a specific node depending upon the properties of the optical signal as well as the micro-ring filter. These optical signals are of a certain wavelength with respect to algorithm 1, while each node has its own micro-ring resonator which filters specific wavelengths.

Table 2 Simulation of optical signal from one node to another

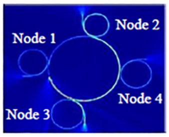
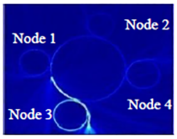
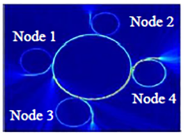
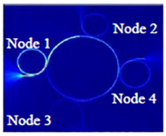
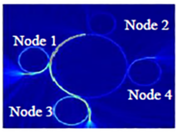
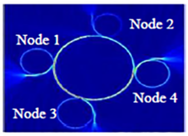
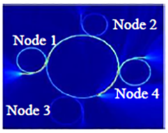
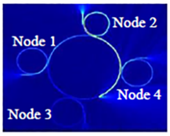
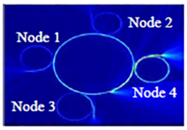
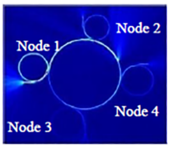
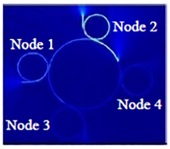
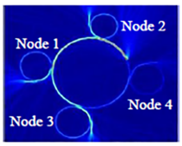
From \ To	Node 1	Node 2	Node 3	Node 4
Node 1	Null			
Node 2		Null		
Node 3			Null	
Node 4				Null

Table 3 Values of energy in joule and power in db

S. no.	Wavelength (nm)	Frequency (Hz)	Energy (J)	Power (Watt)	Power (db)
1	1300	$2.30 * 10^{14}$	$15.24 * 10^{-20}$	$1.79 * 10^{-5}$	−47.47
2	1400	$2.14 * 10^{14}$	$14.18 * 10^{-20}$	$1.54 * 10^{-5}$	−48.12
3	1530	$1.95 * 10^{14}$	$12.59 * 10^{-20}$	$1.24 * 10^{-5}$	−49.06
4	1600	$1.87 * 10^{14}$	$11.93 * 10^{-20}$	$1.13 * 10^{-5}$	−49.46

From Eqs. (6–9)

Table 4 Photonic loss while transmitting optical signal [3, 30]

Photonic loss type	Loss in db
Waveguide propagation per cm	−0.274
Active modulator	−0.6
Passing detector	−0.005
Detecting detector	−1.6
Waveguide bending loss	−0.005 per 90°

4.7 Power analysis

In the proposed architecture, we use an optical signal to transmit data from one node to another at different wavelengths. The optical signal at different wavelengths can transmit data. From Eq. (6) we can calculate the energy in joules.

$$E = h * v \tag{6}$$

while E denotes energy for different optical signals at different wavelengths and frequencies, h is plank's constant and v denotes frequency of the optical signal in Hz. From the above-computed energy, we can calculate the power used in Watt. From Table 3, the average power is −48.52 db. While transmitting, the optical signal faces some loss in waveguide while propagating from source to destination as shown in Table 4 [3, 30].

$$\text{Power (watt)} = \text{Energy/pulse width} \tag{7}$$

$$\text{Average power (dbm)} = 10 * \log_{10}\left(\frac{P_{\text{watt}}}{1_{\text{watt}}}\right) \tag{8}$$

$$\text{Average power(db)} = (P_{\text{dbm}} - 30) \tag{9}$$

From the above-mentioned losses in Table 4, approximation optical loss estimated to be −3 db while transmitting an optical signal in a PIC. The losses are mentioned in Table 4. There are some unknown losses that may affect the intensity of light from one node to another node. The optical signal from one node to another

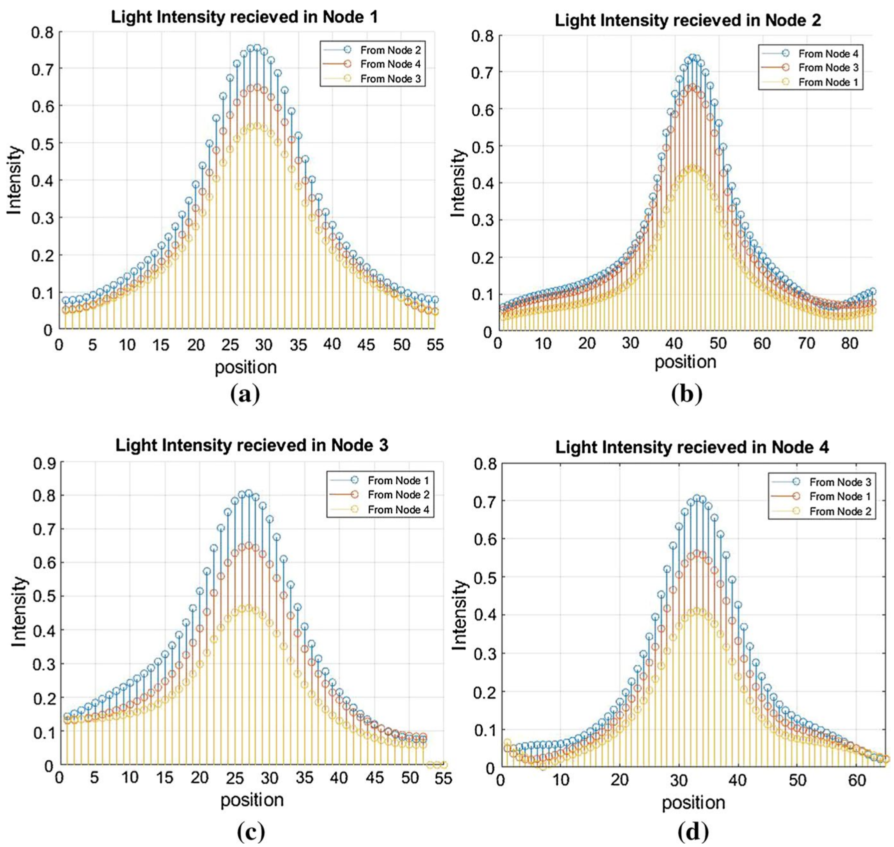


Fig. 11 Light intensity received at: **a** Node 1, **b** Node 2, **c** Node 3 and **d** Node 4

is simulated as shown in Fig. 11; optical signals are received from different nodes which shows the intensity loss. Each node has to pass optical data for three nodes. So far, it receives optical intensity for the first node with respect to another node which is around 0.7 to 0.8, while the second node receives around 0.55 to 0.65 and the last node receives around 0.44 to 0.5. This loss is occurred due to the above-mentioned loss in Table 4, which includes waveguide propagation loss, passing through other filters loss and sometimes optical coupling loss also. These losses may overcome by the use of amplifiers while sending optical data or by using better detectors at the receiver nodes.

5 Conclusion

Today, these photonic technologies become core "optical engine" which powers communicational network and enhance the computational power of any system. The bandwidth of the optical signal is very high as compared to an electric signal which automatically enhances the data rate of any ordinary system. In today's world, a high data rate at low communication latency may change the performance of NoC. Further results show acceptable finesse value, FSR value, FWHM value and *Q*-factor of the MRR which provides good quality of the optical signal filtered from the main waveguides. These MRRs are placed at each node in clusters which provides specific optical signals for each node. MRR provides a direct connection between node and waveguide and thus makes less complexible waveguide architecture. Furthermore, these clusters use only a definite number of wavelengths (i.e., four wavelengths) which results in lesser power consumption approx. up to 0.8 mW. The latency of the optical signal from one node to another node in the cluster is achieved by up to 200 to 497 femtoseconds. This achieved latency between nodes may enhance communication time and increase network throughput.

The future work will undergo a crucial need for better photonic IC design and routing algorithm which reduces optical loss. These reduced optical losses may result in high communication power and enhance the throughput of the system.

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