Wavelength-Routed Optical Networks-on-Chip Topology

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Optical networks-on-chip (NoCs) have emerged as a next-generation solution to overcome the limitations of electrical NoCs. In particular, wavelength-routed optical networks-on-chip (WRONoCs) are well known for their high bandwidth and ultra-low signal delay. Despite these advantages, WRONoCs are challenged by reliability concerns, because the main components in WRONoCs, i.e., microring resonators (MRRs), are susceptible to fabrication inaccuracies. When an MRR along a signal path is defective, the signal transmitted on that path will fail to reach its designated destination, which leads to transmission errors and data loss.

wavelength-routed optical networks-on-chip fault-tolerant topology reliability

1. Introduction

Stimulated by recent breakthroughs in silicon photonics, optical networks-on-chip (ONoCs) have emerged as a next-generation solution to overcome the bandwidth and energy limitations of the electrical interconnects in multiprocessor system-on-chip (MPSoC) [1][2]. As the name suggests, ONoCs use optical signals to transmit data [2]. Taking advantage of the wavelength-division multiplexing (WDM) technology and the ultra-low propagation delay of light in silicon, ONoCs promise to meet the high bandwidth demands while maintaining low latency and power [3].

Current ONoC architectures can be classified into two categories: control-networks-based and wavelength-routed [3]. On control-networks-based ONoCs, before a sender (master) can transmit data to a receiver (slave), a signal path needs to be reserved through an additional control network [4][5]. On the other hand, wavelength-routed ONoCs (WRONoCs) fix collision-free signal paths between all master–slave pairs at the time of the design so that all masters can communicate to all slaves simultaneously [6][7][8][9][10]. Therefore, WRONoCs are free from the energy and latency overhead for arbitration and are gaining increasing research interest.

Typically, the WRONoC design is divided into two consecutive steps: a topological and a physical design. A WRONoC topology specifies the interconnection and configuration of the network components, and a physical tool implements the interconnection of the input topology on a layout plane [11]. **Figure 1**a shows a simple WRONoC topology, where one master sends signals to three slaves. The signals sent from the master are modulated on three different wavelengths, represented by the blue, red, and green arrows. The signals travel along the same waveguide until they are demultiplexed by different optical switching elements (OSEs). **Figure 1**b shows one typical structure of the 2-input × 2-output OSEs, called a crossing switching element (CSE). A 2 × 2 CSE consists of a pair of orthogonal waveguides and two microring resonators (MRRs) configured to be on-resonance with the wavelength λi. As shown in **Figure 1**c, when signals on λi enter the CSE, they are coupled to the MRR and experience a 90◦◦ change in their propagation directions. On the other hand, when signals on the wavelengths other than λi enter the CSE, they will pass through the CSE and keep their propagation directions, as shown in **Figure 1**d.

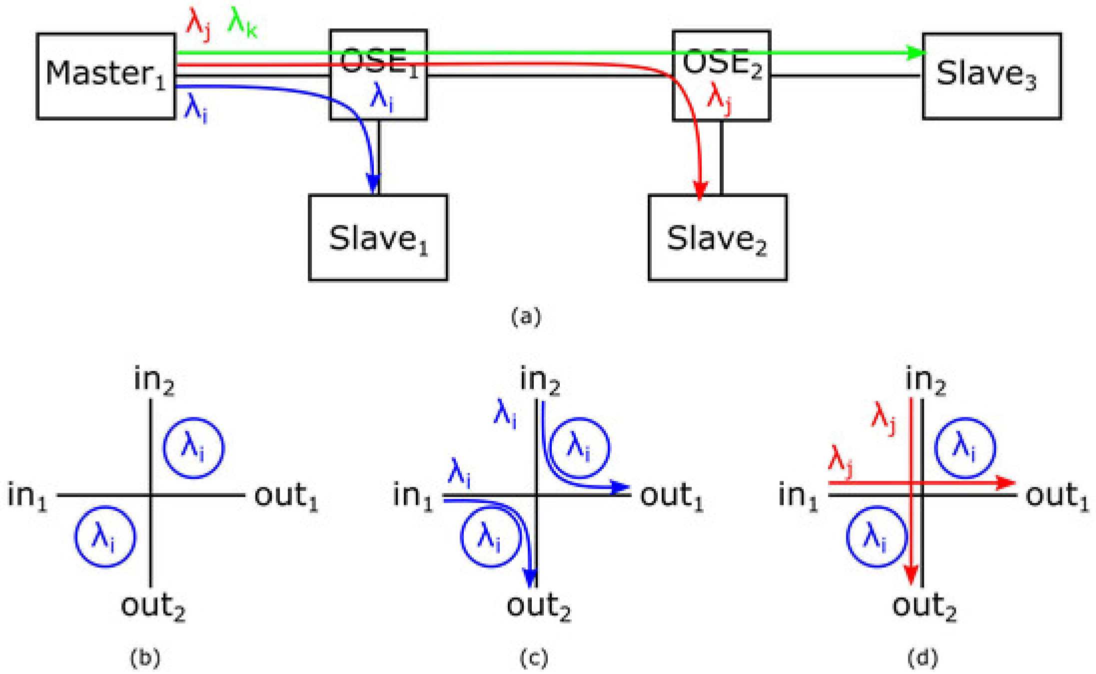

Figure 1. (**a**) A simple WRONoC topology. (**b**) A 2 × 2 CSE structure. (**c**) On-resonance signals change their propagation directions. (**d**) Off-resonance signals pass through the CSE without direction change.

Due to the complexity of the manufacturing process, MRRs are susceptible to fabrication errors [12][13][14]. Defective MRRs can cause malfunctions and even data loss in WRONoCs, which lowers the fabrication yield. For example, if the MRR in OSE$_1$ shown in **Figure 2** is defective and fails to resonate with its designed wavelength λi, the signal on λi will fail to reach Slave$_1$, causing data loss. Therefore, enhancing the reliability of WRONoCs is of great importance.

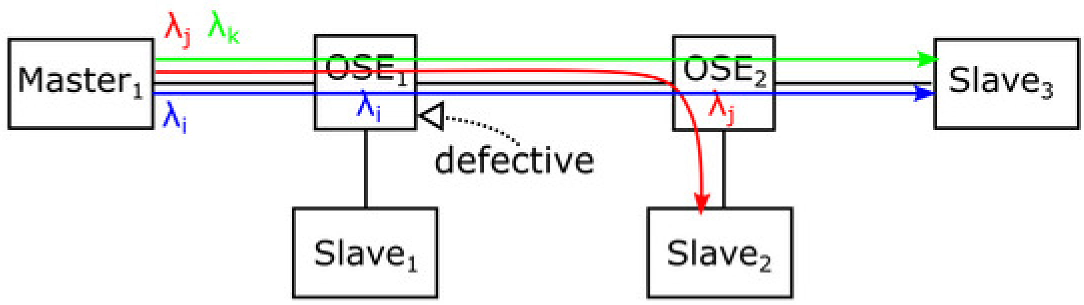

Figure 2. The MRR in OSE$_1$ is defective and the signal on λi fails to be coupled to the MRR.

2. Parallel Switching Elements

In ONoCs, OSEs have various structures. Aside from the CSE, shown in **Figure 1**b, another typical structure of OSEs is called the parallel switching element (PSE). In a PSE, an MRR is placed between a pair of parallel waveguides so that signals entering the PSE will experience a 180-degree direction change [15]. **Figure 3** illustrates the working mechanism of a PSE. Compared to the CSE, where two MRRs are placed close to a pair of crossed waveguides, a PSE avoids the crossing loss and crosstalk noise generated by the waveguide crossing and requires only one MRR to route the signals among two inputs and two outputs. Considering these advantages, a PSE is considered as an appealing component to construct WRONoCs [2].

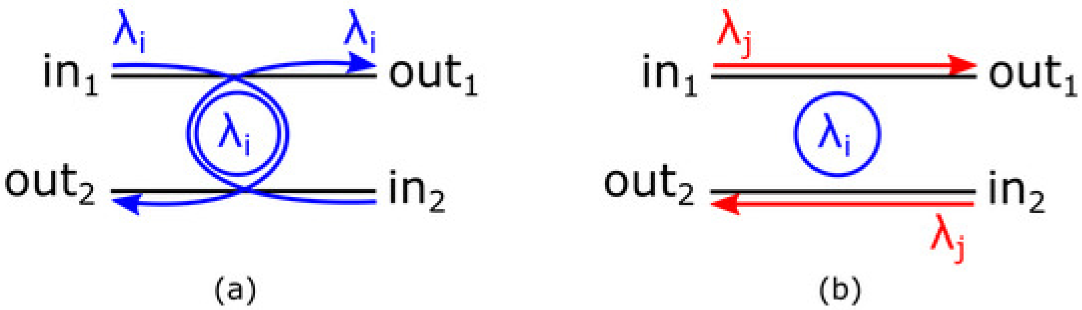

Figure 3. A 2 × 2 PSE supports (**a**) two on-resonance signals and (**b**) two off-resonance signals.

3. Performance Factors

In ONoCs, insertion loss and crosstalk noise are two important performance factors, which can decrease the signal-to-noise ratio (SNR) and cause power penalties [16].

Insertion loss is the power loss of signals. Typically, in a WRONoC topology, the insertion loss of a signal can be considered as the summation of three main losses [6][15]: the crossing loss that depends on the number of waveguide crossings that the signal passes; the drop loss when the signal is on-resonance with an MRR; the through loss when the signal passes through an off-resonance MRR. In particular, the worst-case insertion loss of a WRONoC topology is the maximum insertion loss of all signals, which determines the power consumption of the network.

Crosstalk noise refers to the noise signals generated at MRRs and waveguide crossings [16]. As shown in **Figure 4**, when a signal passes through a waveguide crossing or an off-resonance MRR, or when a signal is on-resonance with an MRR, a portion of the signal power will leak to other outputs and become noise. Noise generated by the original signals is denoted as the first-order noise and has the same wavelength as the original signals [17]. When a noise signal reaches a slave, it will decrease the SNR of the desired signals on the same wavelength. Specifically, the SNR of a signal on wavelength λi is calculated as $10log\frac{P_{output}^{\lambda_i}}{P_{noise}^{\lambda_i}}$, where $P_{output}^{\lambda_i}$ denotes the output power of the desired signal, and $P_{noise}^{\lambda_i}$ denotes the power of the noise signals [17]. For the calculation of the SNR, we only consider the first-order noise, since the power of the noise generated by other noise signals is relatively small.

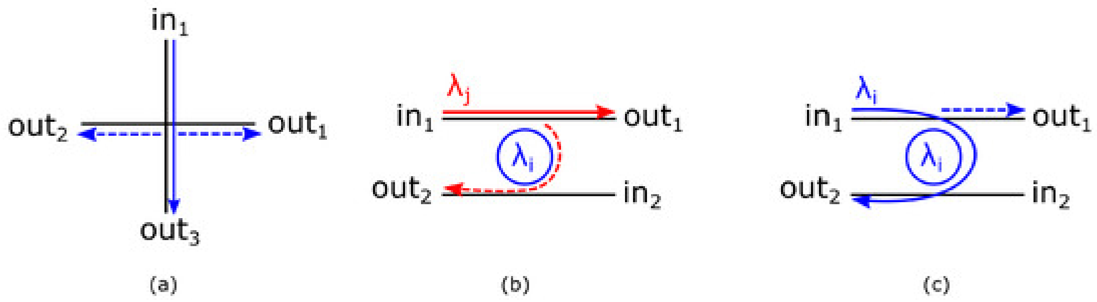

Figure 4. The first-order noise is generated (**a**) when a signal passes a waveguide crossing, (**b**) when a signal passes an off-resonance MRR, and (**c**) when a signal is on-resonance with an MRR.

4. MRR Faults and Signal Faults

An MRR fault can either be temporary or permanent [13]. Temporary faults are caused by environmental changes. For example, a change of 1 ∘C∘C in temperature can shift the resonant wavelength of an MRR by 0.10.1 nnmm, which causes the MRR to resonate with a different wavelength than was intended [13][14]. Some researchers have worked on that problem and proposed some ONoC resilience techniques, such as trimming [18], to correct the faults. On the other hand, permanent faults are caused by fabrication errors. For example, some changes in the physical dimensions, e.g., the radius of the MRRs, the width of the waveguides, and the thickness of the wafer, can affect the resonant wavelengths of the MRRs [14][19]. These permanent faults cannot be corrected by those resilience techniques. Therefore, permanent faults, which can significantly lower the fabrication yield of WRONoCs, should be carefully considered in the design phase, not as an afterthought.

When an MRR is permanently faulty, its resonant wavelength deviates from its designated wavelength, which causes two types of signal faults: stuck-at-zero (s-a-0) and stuck-at-one (s-a-1). The s-a-0 signal fault is that a signal fails to be coupled to the MRR, which is designed to be on-resonance with the signal. As shown in **Figure 5**a, the MRRs do not resonate with the designated wavelength, and thus the signals cannot be coupled to the MRRs and suffer the s-a-0 faults. On the other hand, a signal suffers an s-a-1 fault when it is coupled to an MRR that is not designated to be on-resonance with the signal. For example, the MRRs designed to resonate with λi are now resonant with another wavelength λj, and the signals on λj are coupled to the MRRs as shown in **Figure 5**b. When a signal suffers either an s-a-0 or s-a-1 fault, it deviates from its planned propagation direction and may fail to reach its designated destination. As a result, the data carried on the signals are lost, which raises the reliability concern of WRONoCs.

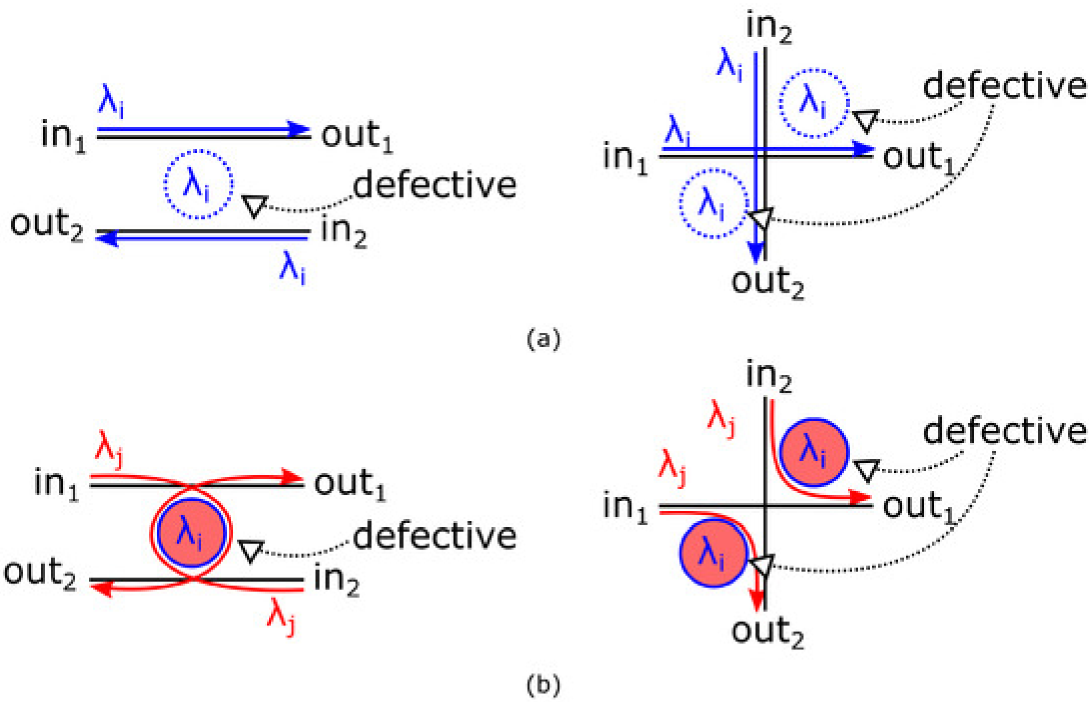

Figure 5. (**a**) The s-a-0 signal fault. (**b**) The s-a-1 signal fault.

5. State-of-the-Art WRONoC Topologies

For each master–slave pair that requires communication, state-of-the-art WRONoC topologies construct one fixed signal path [6][15][20][21][22]. In addition, most topologies, such as λ-router [20], Snake [22], and GWOR [21], use CSEs with two identical MRRs, where each MRR is designed to be on-resonance with one signal, which corresponds to one signal path.

Figure 6a shows the logic scheme of a 4×44×4 λ-router, which consists of six CSEs. For example, the MRRs of the top-left CSE are on-resonance with the signals from m1 to s3 and from m2 to s4, respectively.

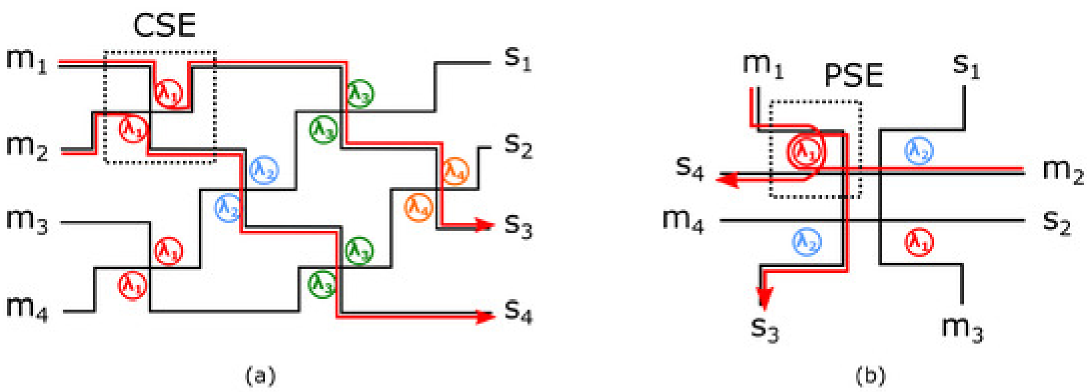

Figure 6. (**a**) A 4×44×4 λ-router. (**b**) A 4×44×4 Hash.

Figure 6b shows the logic scheme of a 4×44×4 Hash [15], which uses PSEs instead of CSEs. In the Hash, the MRR of a PSE is configured to be on-resonance with two signals. For example, the signals from m1 to s4 and from m2 to s3, represented by red lines in **Figure 6**b, are coupled to the MRR of the top-left PSE.

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