Reducing Insertion Loss of Wavelength-Routed Optical Network Based on Microring Resonator Optical Switches

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REDUCING INSERTION LOSS OF WAVELENGTH-ROUTED OPTICAL NETWORK BASED ON MICRORING RESONATOR OPTICAL SWITCHES

by

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With the ever-increasing demand for high-performance computing systems, on-chip interconnection networks, serving as the communication links in multicore architectures, have become the key to the system performance. Compared with bandwidth-limited power-hungry electrical interconnection networks, optical network-on-chip (ONoC) architectures are emerging as a promising alternative to enable future computing performance gains owing to the recent advancements in silicon photonics. One major issue of ONoC is its insertion loss, which is the optical link loss along the waveguide and through the network. Once the optical power budget is established, the maximum insertion loss through the network can be determined. If insertion loss exceeds optical power budget, the network will fail to transmit and recover the optical data. Moreover, insertion loss also decides the scale of the network since a network with less insertion loss can use more wavelength channels to increase the aggregate bandwidth.

In this thesis, a new methodology to construct ONoC topologies with lower insertion loss is proposed. It is realized by transforming the network structure, which is much simpler and less expensive. First, the insertion loss of two basic types of microring resonator optical switch, which is the key component in the ONoC are analyzed using the coupling model. Three-dimensional FDTD-based simulation is performed to verify the theoretical analysis. Results show that parallel-coupled switch has better performance than cross-coupled switch in terms of insertion loss. Next, the proposed method is applied to the generalized wavelength-routed ONoC, which is built solely with cross-coupled switches. To reduce insertion loss in this network, the first step is to replace the cross-coupled switches with parallel-coupled ones as many as possible, which is denoted as
Replaced Parallel Network (RPN). The second step is to replace the rest cross-coupled switches in the RPN with the combination of a parallel-coupled switch and a waveguides crossing, and such network after replacement is denoted as Low Insertion-loss Network (LIN). RPN and LIN are proved to be equivalent to the original network as they use the same number of waveguides and microring resonator switches. Theoretical analysis and numerical results confirm that the average insertion loss of the generalized wavelength-routed network can be effectively reduced by the proposed method.
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CHAPTER 1 INTRODUCTION

Multi-core chip or chip multiprocessor (CMP) has emerged as an important architecture for building up high-performance computing system. As the number of cores in future CMPs is growing, system performance is increasingly confined to its communication rather than computation capabilities [1]. On-chip interconnection networks have become a critical factor that impedes the performance scalability of CMP with limitations in power dissipation, chip packaging and the date throughput. The conventional electric interconnection is approaching its performance bottleneck that will eventually make it infeasible to meet the performance requirements. Previous studies have shown by Magen that over half of the dynamic power in some high-performance microprocessors is dissipated by interconnects [2]. Owing to recent advances in silicon photonics, photonic interconnection is believed to have more potential of providing much higher data capacity with lower energy consumption and lower latency than electric interconnection. Figure 1 illustrates the concept of an optical interconnect network to communicate between a single processor and memories and I/O.

Figure 1, Illustration of a computing system using a photonic interconnection network [1].
1.1 Overview of photonic interconnect

The general photonic interconnect systems comprise of three elements (as shown in Figure 2): (1) generation, which transforms the electrical signal to the optical domain, (2) routing, which consists of waveguides and optical routers to route the optical signal, and (3) reception, to convert the optical signal back into electrical domain [1]. The required optical components for a photonic interconnection system are waveguides, couplers, modulators, optical switches, photodetectors, as well as optical filters and amplifiers. Recent development in nanoscale silicon photonics is making the photonic on-chip communication system closer to fruition, for example the hybrid III-V/silicon laser with small footprint and modest power dissipation [3], high speed low voltage silicon microring modulator [4], a high bandwidth and responsivity waveguide-integrated Germanium-on-insulator photodetector [5], SiON spot-size converting waveguide couplers [6].

![Figure 2, Block diagram of photonic interconnect link [1].](image)

Waveguide is the most fundamental element in the photonic interconnection system. It is the physical link connecting all the source and destination nodes as well as all the photonic devices. It has different shapes such as straight, bend and crossings,
which will introduce power loss as light propagates through it. Straight waveguide has simplest design and lowest loss. Straight waveguide which has loss as low as 0.1dB/cm has been reported using silicon nitride [37]. Bend waveguide and crossing are essential for forming proper optical link, however, they induce extra losses.

The electrical signal is translated to optical signal by the modulator together with a light source which is typically a laser. The laser can be either integrated onto the chip or off the chip.

The optical router plays a very important role in the on-chip photonic communication network. It provides the desired switching functionality and selects the optical paths from each input to the designated node. Among all the available optical switches, microring resonator is the most popular structure due to its small footprint, simple-mode resonances, and ease of phase-matching [7].

Photodetector receives the optical signal and converts it back to electrical current, which needs to be further processed. The electrical current is converted to a voltage via a trans-impedance amplifier. And the data needs to be recovered by decoding to address any error of the transmission.

1.2 Motivation of this work

When light is inserted into an optical link, it will suffer attenuation introduced by the photonic devices and optical paths. The amount of attenuation is called the insertion loss [1]. One major issue of the ONoC is the insertion loss. It will deteriorate the quality of signal transmission and increase bit error rate. Moreover, insertion loss also determines how well the network can scale in size, as the network which has less insertion loss will support more channels of optical signal and thus increase the aggregate bandwidth.
The optical power budget reported can achieve 23.5 dBm, which is the difference between the laser power injected 11.5 dBm and the sensitivity of the photodetector -12 dBm [33]. In comparison, in an 8×8 folded-torus network, the maximum insertion loss is about 15.5 dB [34]. Considering of the loss induced by the modulator and the waveguides, the total insertion loss may be equal to or even larger than the optical power budget, which may result in the failure of data transmission for the optical interconnection network. Besides, as the scalability of the network increases, insertion loss will soar and finally be large enough to bury the data into the noise. Therefore, insertion loss must be taken into account of designing an optical network.

The motivation of this paper is to design ONoC that can transmit data across the chip in comparatively low insertion loss, without greedy demanding for high-energy lasers and photodetectors.

1.3 Thesis organization

This thesis is focused on the study of insertion loss of microring resonator optical switch and the optical network built with it.

This thesis is organized as follows.

The theoretical background and properties of microring resonator are discussed in Chapter 2. The basic all-pass and add-drop configurations of microring resonator are introduced. The coupling model theory is adopted to analyze the transmission relations in these structures. The basic spectral characters and tuning property are then discussed.

Chapter 3 first introduces the three categories of optical networks-on-chips. Then the recent progress on networks constructed based on microring resonators are given,
classified according to their tuning mechanism. Generalized wavelength-routed optical network architecture is presented last.

In Chapter 4, the cross-coupled microring resonator is first studied using the theory in Chapter 2. The power transmissions and insertion loss of the parallel-coupled and cross-coupled switches are simulated and compared. A new scheme is introduced to construct the network with low insertion loss. This method is applied to the generalized wavelength-routed network. Theoretical analysis and simulation results are given to compare the proposed architectures with the original network.

Chapter 5 concludes this thesis and future work is given.
CHAPTER 2 THEORY OF MICRORING RESONATOR

2.1 Introduction of microing resonator

Microring resonator is a wavelength-selective optical device in a ring or rack-track shaped structure. The microring is usually formed by bending rectangular dielectric optical waveguide into a close loop. By placing a straight waveguide in close proximity to the close loop, there will be evanescent coupling between the loop and straight waveguide, which leads to power transfer from the waveguide into the ring. The light coupled to the ring will then propagate along the ring by total internal reflections. When the length of the optical path equals to exactly the whole number of wavelength or the phase change of the trip in the close loop is an integer multiple times of $2\pi$, the waves interfere constructively, in which case resonance occurs, and there will be dip around each resonance for the transmission spectrum of the ring resonator, as shown in Figure 3. In this way, microring resonator acts as an optical filter, which is its most common application for optical communication, especially wavelength division multiplexing [8].

![Figure 3, Transmission spectra of a ring resonator.](image-url)
Microring resonator also plays a very important role in building the photonic interconnection networks. Owing to its compact footprint with very high refractive index contrast, and CMOS compatibility [1], various functions and devices have been realized by utilizing the ring resonator, such as microring modulator [9], optical switches [10], microring lasers [11], optical multiplexers [12].

2.2 The basic configuration

2.2.1 All-pass microring resonator

The theoretical analysis of microring resonators has been extensively studied using the coupling model proposed by Yariv in 2000 [13]. The simplest configuration of a ring resonator, which is called all-pass ring resonator, is constructed by positioning a straight waveguide properly next to the ring structure with radius \( r \), as shown in Figure 4.

![Figure 4, Model of all-pass ring resonator](image)
Under the assumption that a single unidirectional mode of the resonator is excited and that the coupling between the waveguide and the ring is lossless and that single polarization is considered, the interaction can be described by the matrix relation:

\[
\begin{bmatrix}
E_{t1} \\
E_{t2}
\end{bmatrix} =
\begin{bmatrix}
t & k \\
-k^* & t^*
\end{bmatrix}
\begin{bmatrix}
E_{i1} \\
E_{i2}
\end{bmatrix}
\]  

(1)

where \(E_{it}\) and \(E_{et}\) (\(i=1,2\)) are the normalized complex mode amplitudes. \(t\) and \(k\) are transmission coefficient and coupling coefficient respectively, which depend on the particular coupling mechanism employed. The * denotes the conjugate complex values of \(t\) and \(k\), respectively. The coupler under consideration is reciprocal, therefore

\[|t|^2 + |k|^2 = 1\]  

(2)

The transmission of the round trip in the ring is given by

\[E_{i2} = \alpha e^{i\theta} E_{t2}\]  

(3)

where \(\alpha\) is the inner circulation factor, which relates to the power attenuation coefficient \(a\) [1/cm] as \(\alpha^2 = \exp(-aL)\) (for zero internal loss \(\alpha = 1\)). The power attenuation coefficient is decided by the material of the waveguide and the processing techniques. \(\theta = \omega L/c\) is the phase change of mode propagation. \(L = 2\pi r\) is the circumference of the ring, where \(r\) is the radius of the ring. \(c = c_0/n_{eff}\) is the phase velocity of the ring mode, where \(c_0\) is speed of light in vacuum, and \(n_{eff}\) is effective refractive index. From equation (1) and (3), we obtain

\[\frac{E_{t2}}{E_{t1}} = \frac{-\alpha + te^{-i\theta}}{-\alpha t^* + e^{-i\theta}}\]  

(4)

\[\frac{E_{i2}}{E_{i1}} = \frac{-\alpha k^*}{-\alpha t^* + e^{-i\theta}}\]  

(5)
Suppose that the input wave $E_{i1} = 1$, so all the field amplitudes will be normalized to the input wave. The power of transmission in the output waveguide can be derived as

$$P_{t1} = |E_{t1}|^2 = \frac{\alpha^2 + |t|^2 - 2\alpha|t|\cos(\theta + \varphi_t)}{1 + \alpha^2|t|^2 - 2\alpha|t|\cos(\theta + \varphi_t)}$$  \hspace{1cm} (6)$$

where $t = |t|\exp(i\varphi_t)$, $\varphi_t$ is the phase change in the coupler. The circulating power in the ring can be given by

$$P_{i2} = |E_{i2}|^2 = \frac{\alpha^2(1 - |t|^2)}{1 + \alpha^2|t|^2 - 2\alpha|t|\cos(\theta + \varphi_t)}$$  \hspace{1cm} (7)$$

Resonance occurs when $(\theta + \varphi_t) = 2\pi m$, where $m$ is an integer. At resonance, the following relations can be obtained

$$P_{t1} = |E_{t1}|^2 = \frac{(\alpha - |t|)^2}{(1 - \alpha|t|)^2}$$  \hspace{1cm} (8)$$

and

$$P_{i2} = |E_{i2}|^2 = \frac{\alpha^2(1 - |t|^2)}{(1 - \alpha|t|)^2}$$  \hspace{1cm} (9)$$

From equation (8), it can be seen that when $\alpha = |t|$, the power transmitted to the output waveguide becomes 0. This condition is known as critical coupling, which is caused by destructive interference.

2.1.2 Add-drop microring resonator configuration

This coupling model can be applied to various types of microring resonator configurations. Another basic geometry is by coupling the all-pass ring resonator to a second waveguide, as shown in Figure 5.
Based on the above analysis, the transmission relations in the add-drop microring resonator can be derived as

\[
\begin{vmatrix}
E_t \\
E_{t1}
\end{vmatrix} = \begin{vmatrix} t_1 & k_1 \\ -k_1^* t_1 \end{vmatrix} \begin{vmatrix} E_t \\
E_{t2}\end{vmatrix} \quad (10)
\]

\[
\begin{vmatrix}
E_d \\
E_{t2}
\end{vmatrix} = \begin{vmatrix} t_2 & k_2 \\ -k_2^* t_2 \end{vmatrix} \begin{vmatrix} E_a \\
E_{t2}\end{vmatrix} \quad (11)
\]

\(E_t, E_t, E_d, E_a\) are the normalized complex mode amplitudes at the input port, throughput port, drop port and add port respectively. \(i=1\) and 2 indicate the upper and lower coupling regions respectively.

The transmission to the throughput port and drop port can thus be derived as:

\[
\frac{E_t}{E_i} = \frac{t_1 - t_2^* \alpha e^{i\theta}}{1 - t_1^* t_2^* \alpha e^{i\theta}} \quad (12)
\]

\[
\frac{E_d}{E_i} = \frac{-k_1^* k_2^* \alpha^{1/2} e^{i\theta/2}}{1 - t_1^* t_2^* \alpha e^{i\theta}} \quad (13)
\]
The power at the throughput port and drop port can be given by

\[ P_t = \frac{|E_t|^2}{|E_i|^2} = \frac{|t_1|^2 + |t_2|^2 \alpha^2 - 2|t_1||t_2| \alpha \cos(\theta - \varphi_t)}{1 + |t_1|^2 |t_2|^2 \alpha^2 - 2|t_1||t_2| \alpha \cos(\theta - \varphi_t)} \] (14)

\[ P_d = \frac{|E_d|^2}{|E_i|^2} = \frac{(1 - |t_1|^2)(1 - |t_2|^2) \alpha}{1 + |t_1|^2 |t_2|^2 \alpha^2 - 2|t_1||t_2| \alpha \cos(\theta - \varphi_t)} \] (15)

The power at the throughput port and drop port at resonance can be obtained:

\[ P_t = \frac{(|t_1| - |t_2| \alpha)^2}{(1 - |t_1||t_2| \alpha)^2} \] (16)

\[ P_d = \frac{(1 - |t_1|^2)(1 - |t_2|^2)^2 \alpha}{(1 - |t_1||t_2| \alpha)^2} \] (17)

In equations (16) and (17), if \( \alpha = 1 \) and \( |t_1| = |t_2| \), the power from the input port will be fully transferred into the drop port, and the power to the throughput port will become zero. However, the condition \( \alpha = 1 \) cannot be satisfied without gain in the ring to compensate the losses in the waveguide. For a purely passive microring resonator, the value of \( \alpha \) is always fixed which is less than 1. In order to achieve minimum intensity at the throughput port at resonance, the following relation must be satisfied

\[ \alpha = \frac{|t_1|}{|t_2|} \] (18)

Since the attenuation is not negligible, the full transfer from the input port to the drop port can only be achieved under the critical coupling condition.

The physical meaning of critical coupling is that the coupled power is equal to the power lost in the ring. It occurs at asymmetric coupling. However, it is difficult to meet the condition of critical coupling due to the manufacture technologies.
2.3 Parameters of ring resonator

2.3.1 Free spectral range

One important parameter of microring resonator is spectral span between two successive resonance peaks, which is called free spectral range (FSR). The FSR can be derived from the resonance condition of the microring resonator given by

\[ m\lambda = n_{\text{eff}}L \]  \hspace{1cm} (19)

Since \( \theta = \omega L/c \), and \( \theta = \beta L \), where \( \beta \) is the propagation constant of the circulating mode [8], this leads to

\[ \beta = kn_{\text{eff}} = \frac{2\pi}{\lambda}n_{\text{eff}} \]  \hspace{1cm} (20)

\[ \theta = \frac{k c_0 L}{c} = kn_{\text{eff}}2\pi r = \frac{2\pi}{\lambda}n_{\text{eff}}2\pi r = 4\pi^2 n_{\text{eff}} \frac{r}{\lambda} \]  \hspace{1cm} (21)

where \( k = 2\pi/\lambda \) is the vacuum wavenumber, \( n_{\text{eff}} \) is related to group refractive index \( n_g \) as

\[ n_g = n_{\text{eff}} - \lambda \frac{\partial n_{\text{eff}}}{\partial \lambda} \]  \hspace{1cm} (22)

The group index takes into account of the dispersion of the waveguide [7], and can be written as

\[ n_g = \frac{\partial \beta}{\partial k} = \frac{\partial \beta}{\partial \left(\frac{2\pi}{\lambda}\right)} = \frac{\partial \beta}{\left(-\frac{2\pi}{\lambda^2}\right) \partial \lambda} \]  \hspace{1cm} (23)

Since FSR is the difference between the wavelengths corresponding to two resonant peaks, therefore
FSR = Δλ = \frac{-2\pi}{L} \left( \frac{\partial \beta}{\partial \lambda} \right)^{-1} = \frac{-2\pi}{L} \frac{1}{\lambda^2 n_g} = \frac{\lambda^2}{n_g L} \quad (24)

2.3.2 Resonance width ∆ω or ∆λ

The resonance width is defined as full width at half maximum (FWHM) or 3dB bandwidth of the resonance line shape. Taking the expression of the transmission in the drop port of add-drop microring resonator as an example, we can obtain

\[
\begin{align*}
\frac{(1 - |t_1|^2)(1 - |t_2|^2)\alpha}{1 + |t_1|^2|t_2|^2\alpha^2 - 2|t_1||t_2|\alpha \cos(\theta - \varphi_{t_1} - \varphi_{t_2})} &= \frac{1}{2} \frac{(1 - |t_1|^2)(1 - |t_2|^2)\alpha}{(1 - |t_1||t_2|\alpha)^2} \\
&= \frac{1}{2} (1 - |t_1|^2)(1 - |t_2|^2)\alpha
\end{align*}
\]

(25)

Let \( \phi = \theta - \varphi_{t_1} - \varphi_{t_2} \). By solving equation (25), we have

\[
1 + |t_1|^2|t_2|^2\alpha^2 - 2|t_1||t_2|\alpha \cos(\phi) = 2(1 - |t_1||t_2|\alpha)^2
\]

(26)

For small \( \phi \), using the real parts of the series expansion of the Euler formula, we have \( \cos\phi \approx 1 - \phi^2/2 \), so

\[
\phi^2 = \frac{(1 - |t_1||t_2|\alpha)^2}{|t_1||t_2|\alpha}
\]

(27)

Assume that there is no loss in the microring resonator, i.e., \( \alpha = 1 \), and the two coupling regions are symmetric, i.e., \( t_1 = t_2 = t \), then FWHM / FSR = 2ϕ / 2π,

\[
\text{FWHM} = \frac{\phi}{\pi} \quad \text{FSR} = \frac{\lambda^2}{\pi n_g L} \frac{1 - t^2}{t}
\]

(28)

2.3.3 Finesse

The finesse is defined as the ratio of FSR and resonance width. It is a parameter that describes the sharpness of resonances relative to their spacing, and physically, the
finesse represents the number of round trips the light can travel in the ring before its energy is reduced to 1/e of its initial value [7].

\[
F = \frac{\text{FSR}}{\text{FWHM}} = \frac{\pi t}{1 - t^2}
\]  

Assume that the coupling is very weak, i.e. \( k \ll 1 \), we have

\[
F \approx \frac{\pi}{k^2}
\]  

2.3.4 Quality factor

The physical meaning of quality factor is the energy stored in the resonator divided by the power lost in each optical cycle. Quality factor of a microring resonator is closely related to the finesse. It measures the sharpness of resonance relative to its resonant wavelength, and is defined as

\[
Q = \frac{\lambda}{\text{FWHM}}
\]

2.4 Properties of ring resonator

One unique optical performance of the microring resonator is that it can be tuned using different approaches. From the resonance condition of microring resonator, we can see that by changing the effective index of the mode will cause a shift of the resonance wavelength \( \Delta \lambda = \lambda \Delta n_{\text{eff}} / n_{\text{eff}} \) [17]. Thus the transmission can change significantly at or near resonances.

2.4.1 Thermal-optical tuning

Thermal-optical tuning is the most widely used technique. It is achieved by using micro-heaters, which are usually placed on top or at the side of the waveguide in the microring resonator. The most common configuration is to place the heater on top of the
device [8]. Thermal tuning exploits heating process to change the refractive index, thus to shift the resonance. The thermal-optical effect can achieve a large wavelength shift on the order of $\Delta \lambda \sim 20\text{nm}$ [16], but the heating process is relatively slow compared with other methods.

A thermal-optically tunable microring resonator configuration is designed and fabricated [28]. The heater is formed by depositing a thin film of metal 1μm away above the device to avoid metal absorption. The heater is in an $\Omega$ shape, which is often used for microring heaters, shown in Figure 6. The device is experimentally demonstrated to have a switching power of 0.25nm/mw.

![Figure 6](image)

Figure 6, (a) Schematic view of the $\Omega$-heater. (b) $\Omega$-heater after destructive test [17].

As seen in Figure 7, the switching can be realized by applying power to the heaters, which will cause the temperature to change accordingly.

Assume that the resonance wavelength is $\lambda$ at temperature $T$, and the corresponding propagation constant is $\beta$. By locally applying a change in temperature $\Delta T$, the propagation constant will change by $\Delta \beta_T$. The resonance wavelength will also change, which introduces another propagation constant change of $\Delta \beta_\omega$ and $\Delta \beta_T + \Delta \beta_\omega = 0$ [14].

Since $n_{eff} = \beta c / \omega$ and $n_g = \frac{\partial \beta}{\partial k} = \frac{\partial \beta}{\partial \omega} c$, we can obtain
\[
\frac{\omega}{c} \left( \frac{\partial n_{\text{eff}}}{\partial T} \right) \Delta T + \frac{n_g}{c} \Delta \omega = 0
\]  
(32)

\[
\frac{\Delta \omega}{\omega} = -\frac{1}{n_g} \left( \frac{\partial n_{\text{eff}}}{\partial T} \right) \Delta T
\]  
(33)

where \( c \) is the light speed in vacuum.

Figure 7, Electric power applied to the heaters shifts the microring resonances [28].

Thus, the resonance shift can be expressed by [15]:

\[
\Delta \lambda = \frac{\lambda}{n_g} \left( \frac{\partial n_{\text{eff}}}{\partial T} \right) \Delta T
\]  
(34)

Figure 8 shows how the temperature is related to the effective index in silicon which in turn shifts the resonance wavelength. It is resulted from the shift in the effective index and the corresponding temperature change.
2.4.2 Electro-optical tuning

Another tuning mechanism is electro-optical effect, which is also known as free carrier plasma dispersion effect in silicon. It is the most effective mechanism for changing the refractive index in silicon at a fast rate, which is also polarization independent [16]. The electro-optical effect is quite small but has the advantage of being fast compared with thermal-optic effect. The wavelength shift that can be achieved is limited to about $\Delta \lambda \sim 2\text{nm}$ [28].

The induced real refractive index and optical absorption coefficient variations: $\Delta n$ and $\Delta \alpha$, produced by carrier dispersion at wavelength of $1.55\ \mu\text{m}$ are given by [17]

$$\Delta n = -[8.8 \times 10^{-22}\Delta N + 8.5 \times 10^{-18}(\Delta P)^{0.8}]$$

$$\Delta \alpha = 8.5 \times 10^{-18}\Delta N + 6.0 \times 10^{-18}\Delta P$$

In equation (36) and (36), $\Delta N$ (cm$^{-3}$) is defined as the electron concentration change, $\Delta P$ (cm$^{-3}$) is the hole concentration change. Therefore, a depletion or injection of
$10^{18}$ carriers/cm$^3$ can produce an electrorefractive change of $\Delta n \sim 2 \times 10^{-3}$ at wavelength of 1.55 $\mu$m [16].

![Figure 9](image)

Figure 9. Schematic layout of the ring-resonator-based modulator [16].

An electro-optical microring-resonator-based modulator is designed and fabricated, shown in Figure 9. The inset shows the schematic of the cross section of the ring. The micoring is laterally integrated with p-i-n diode for electro-optical modulation. The device layer has an n-type doping concentration of $10^{15}$ cm$^{-3}$, and the doping concentration of p$^+$ and n$^+$ regions are both $\sim 10^{19}$ cm$^{-3}$.

Figure 10 shows the TE-mode transmission of the modulator around the resonance of 1574 nm at different bias of the p-i-n junction. At the resonant wavelength of 1573.9 nm, the transmission spectrum performs a 15 dB drop. At the bias voltages of 0.87 and 0.94 V, the resonance spectrum is blue-shifted, because the increase of electron-
hold pair density in the device lowers the effective index. And the depths of the transmission drop decreases because the electrons and holes increase the absorption loss.

Figure 10, Transmission spectra of the microring resonator at the bias voltages of 0.58, 0.87 and 0.94 V, respectively [19].

2.4.3 Microfluidic tuning

Another tuning method using liquid flowing is proposed in [38]. It is a basic all-pass microring resonator located inside a microchannel in a microfluidic chip. Liquid is injected into the microchannel forming the upper cladding of the microring resonator. The microring resonator is tuned by dynamic variation of refractive index of the medium surrounding it, which is achieved by on-chip mixing in desired proportion of two sources of liquids with different indices of refraction. The tuning range of the resonant wavelengths it can achieve is about 2 nm, which is about 1 order of magnitude smaller than that of the thermo-optical tuning. The maximal extinction ratio can reach to 37 dB,
which is higher than that obtained by the thermo-optical and electro-optical effects. Compared with the thermo-optical and electro-optical effects which require significant consumption of power, the proposed method can potentially be used for refractive index sensing applications.

2.5 Summary

In this chapter, the basic theory of coupling model is introduced to analyze the electric and power transmission in the microring resonator. The two basic configurations of microring resonator, all-pass and add-drop, are analyzed. The spectral characteristics of the microring resonator are then discussed, and some important parameters that need to be considered when designing a microring resonator are introduced. In the last, the tuning properties of the microring resonator are introduced. The tuning mechanisms can be classified into three groups: thermo-optical, electro-optical and microfluidic tunings. The merit and demerit of each mechanism is discussed.
3.1 Photonic network overview

Due to its high bandwidth, low latency and low power consumption, photonic network on chip has become a very promising technique for the future generation of many-core system-on-chips. Various photonic network architectures have been proposed, which are normally classified based on the optical arbitration domains they are leveraging, which are wavelength, time, and space, as shown in Figure 11.

Figure 11, Routing technique based on wavelength, time, and space domains [20].
Wavelength-routed photonic networks are built based on passive microring resonator switches, where the optical signals are routed according to their wavelengths assignment. Once the transmission wavelength is selected, the light can propagate to the intended destination node from the source node through the network. One advantage of this network is that the transmission latency can be very low, since the signal travels at the speed of light once the optical path is determined. However, the proposed architecture is obtained at the cost of large numbers of light sources and switches of fixed wavelengths [21].

The photonic network architecture based on time domain profits by temporal positioning of optical signals. This architecture is constructed using the active microring resonator switches, which can be electro-optically controlled. The basic concept of this technique is to divide the transmission medium temporally into a continuous series of frames, and each frame is further divided into several specific amount of time which is called time slot [20]. In each time slot, the active switches are configured in order to connect one or more pairs of communicating nodes. Using a global clock, every switch can track the current time slot, and for any time slot, it should know its correct configuration [1]. In such way, each optical message is scheduled and will be transmitted when its appropriate time slot arrives.

Space domain utilizes multi-wavelength transmission along an optical path, which can be routed by the actively controlled optical switches. This structure requires that the entire optical path should be established before the transmission, using the circuit-switching protocol [20]. By taking advantage of the WDM to utilize optical spectrum, it can achieve high-aggregate bandwidth. However, it needs an extra plane to
electronically control the optical switches, which adds its complexity. Moreover, it also suffers higher latency compared with wavelength domain architecture resulted from the circuit-switching protocol.

3.2 Photonic network architectures based on microring resonator

According to the routing schemes, the optical interconnection network based on microring resonators can be classified into two categories: i) passive networks, which route the signals based on their wavelengths; ii) active networks, which selectively filter specific frequencies by tuning the resonators.

Figure 12, $N \times N$ $\lambda$-router architecture. (a) 4-port optical switch architecture. (b) Microring-resonator-based optical filter [23].

Among the exiting passive networks, a $\lambda$-router is proposed, which is composed of 4-port optical switches based on microring resonator [23]. Figure 12 (a) shows an example of an $N \times N$ $\lambda$-router architecture. The gray square represents an add-drop filter, which is shown in Figure 12 (b). The $N \times N$ $\lambda$-router needs $N$ wavelengths and multiple
switches to realize non-blocking routing function. However, it can be utilized only when $N$ is an even number.

A five-port non-blocking optical router called Cygnus is designed, which comprises of six waveguides, sixteen microring resonators and two waveguide terminators, as shown in Figure 13 [24]. The topology has been optimized by employing more parallel coupled microring resonators to reduce waveguide crossing to be twelve. Compared with other routers, Cygnus uses the least number of microring resonators and consumes the least power, and has the lowest optical power insertion loss.

![Figure 13, Schematic of the Cygnus router [24].](image_url)

Cascaded microring-resonator-based array networks have also been proposed in many papers [25]-[27]. The basic architecture of microring resonators vertically coupled to an $8 \times 8$ waveguides cross-grid array on a glass substrate is first demonstrated [25]. The architecture is demonstrated to be non-blocking. A matrix network which consists of 64
third-order microring resonators cross-coupled array on a silicon oxynitride substrate is proposed [26]. This architecture is compact in size, but it utilizes a large number of two-dimensionally cascaded microring resonators, which adds its design complexity. A 4×4 64-wavelength optical crossbar network designed for 64 cores is proposed [27]. This network is scalable and demonstrated to have good performance in power consumption. However, such design is internally blocking, which means that two simultaneous data transmission will cause routing confliction.

Active networks based on microring resonators have also attracted a lot of research interest.

A spatially non-blocking optical 4×4 router with a footprint of 0.07 mm² is proposed, shown in Figure 14 [28]. The microring resonators can be tuned using thermo-optical effect to achieve higher amount of wavelength shift.

![Figure 14, 4×4 non-blocking optical router [28]](image-url)
A modified two-dimensional photonic network using 4×4 blocking routers is introduced [29]. It is a novel hybrid micro-architecture that combines a broadband photonic circuit-switched network with an electronic overlay packet-switched control network. A 5×5 matrix switch comprising 20 identical microring resonators is proposed in [30]. The architecture supports two-way communication among four orthogonal directions and local injection and ejection simultaneously, as shown in Figure 15. All of the microring resonators are designed to be centered at the same resonance wavelengths, and are cross-coupled to a grid of multi-mode-interference (MMI) based waveguide crossing to reduce insertion loss and crosstalk noise. The microring resonators are integrated with lateral p-i-n diodes to be electro-optically tuned.

![Figure 15, Schematic of 5×5 matrix switch [30].](image)

Passive networks can route signals at fixed wavelengths and do not need the electronic control circuits. However, they are limited to their scalability and complicated design. Active networks need to integrate microelectronic control technology and
photonic signal transmission, which cause extra power consumption. But compared with passive networks, active ones can provide higher bandwidths.

Multi-layer silicon photonic microring resonator filter is also introduced for advanced photonic networks on chip [31]. Taking advantage of the novel silicon materials, the 3D-integrated microring resonator switch is applied to various photonic network-on-chip architectures [32]. The results show that multi-layer approaches have clear improvement over the single-layer methods in the performances of power, insertion loss and number of wavelength channels.

![Cross-coupled microring resonator filter](image)

(a) Single-layer  
(b) Multi-layer

Figure 16, Cross-coupled microring resonator filter [32].

3.3 Generalized wavelength-routed photonic network architecture

Wavelength-routed photonic networks tend to have better power and latency performance compared with those based on spatial and time domains as mentioned earlier. However, as the size of the network increases, this type of passive network architectures will run into difficulties in scalability and design complexity. In order to address these problems, a generic non-blocking architecture for the wavelength-routed photonic
network is proposed, which uses the least number of microring resonators and has the lowest power loss comparing with all other photonic networks of the same size [22].

The generalized architecture is constructed based upon a 4×4 generic wavelength-routed optical router. The generic router is composed of two horizontal and two vertical waveguides, as shown in Figure 17. I and O represent an input and output port respectively, and the two ports at each of the four directions, i.e., north (N), west (W), south (S) and east (E) of the generic router are grouped and denoted as \( P_i (I_i, O_i) \). Each waveguide directly connects input \( I_i \) and \( O_{3,i} \) (i=0, 1, 2, 3).

![Figure 17, 4×4 generic wavelength-routed optical router. (a) Type I. (b) Type II. (c) Type III. (d) Type IV [22].](image-url)
Assume that the signal from input $I_i$ is not allowed to go to $O_i$, there will be 12 possible input and output connections in the 4×4 generic router, four of which are the direct connections of the four straight waveguides, and the rest eight are realized by eight microring resonators. In order to realize the routing in wavelength domain, the microring resonators should be assigned with different resonant wavelengths. To avoid confliction, the number of wavelengths assigned should be minimal. Table 1 lists the wavelength assignment in the 4×4 generic router.

Table 1, Wavelengths assignment of 4×4 generic router

<table>
<thead>
<tr>
<th>$I_0$</th>
<th>$O_0$</th>
<th>$O_1$</th>
<th>$O_2$</th>
<th>$O_3$</th>
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<tbody>
<tr>
<td>$I_0$</td>
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<td>$\lambda_1$</td>
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According to Table 1, two types of microring resonators (assigned with $\lambda_1$ and $\lambda_2$) placing at the corners of the intersections of two waveguides will be able to route the signals to the designated outputs, and only two identical microring resonators should be opposite to each other at a single intersection. Signals with wavelength of $\lambda_3$ will not meet the resonant conditions of either of the two resonators, thus they will propagate along the straight waveguides. Figure 17 shows four different types of the 4×4 generic router. The four types are functionally the same because they use the same routing assignment, except that the input and output ports are labeled in different manners.

An $N\times N$ ($N>4$) generalized wavelength-routed network can be constructed based on the 4×4 generic router. When $N$ is even ($N=2n$, and $n>2$), the $N$ waveguides can be
divided into two groups, each consisting of \( n \) waveguides that are parallel aligned. The total numbers of microring resonators needed is \( N(N-2) \), which is the minimum number for the \( N \times N \) network, and the number of different types of microring resonators is \( N-2 \), which means that the corresponding wavelength assignment is \( \lambda_1, \lambda_2, \ldots, \lambda_{N-2} \). An example of \( 8 \times 8 \) network is shown in Figure 18, and its wavelength assignment is listed in Table 2.

![Figure 18, Structure of 8×8 network [22].](image)
Table 2, Wavelength assignment in 8×8 generalized wavelength-routed network

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<th>O₀</th>
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</table>

When $N$ is odd ($N=2n+1$, and $n \geq 2$), the total number of microring resonators is $(N-1)^2$, which is the minimum number, and $(N-1)$ different types of microring resonators are needed, the corresponding wavelengths are $\lambda_1, \lambda_2, \ldots, \lambda_{N-1}$. Figure 19 shows an example of a 5×5 network. It has sixteen microring resonators in total which are assigned four different wavelengths.

![Figure 19, Structure of 5×5 network [22]](image_url)
In general, an $N \times N$ ($N > 4$) generalized wavelength-routed network needs $N-1$ input wavelengths, and $N(N-2)$ (when $N$ is even) or $(N-1)^2$ (when $N$ is odd) microring resonators. And the network is proofed to be non-blocking.

3.4 Summary

This chapter first introduces three classes of the existing photonic networks, which are in wavelength, time, and space domains, and compares the three classes based on the techniques they utilize. In the second part, various photonic networks based on microring resonator can be classified into two categories, passive and active. Some examples of each category are given. A novel architecture based on 3D microring resonator is also introduced. In the last, the generalized wavelength-routed network architecture is introduced, which is built based on a generic $4 \times 4$ router. Compared with other networks of the same size, this architecture is demonstrated to have the minimum number of microring resonators and lowest power consumption.
CHAPTER 4 REDUCING THE INSERTION LOSS IN GENERALIZED WAVELENGTH-ROUTED OPTICAL NETWORKS

4.1 Introduction

As mentioned in the previous chapter, wavelength-routed photonic networks tend to have better power and latency performance. However in practical sense, the scalability of the network is determined by how much insertion loss of an optical signal suffers. Between a source node and a designation node in the network, optical signal loses power along the waveguide and through the network, especially when resonating through the microring resonator. The insertion loss will deteriorate the communication quality and increase bit error rate. Moreover, insertion loss also determine how well the network can scale in size, as an optical data packet must travel through more waveguides and switches in larger networks.

The total optical power budget can achieve 23.5 dBm given the laser power of 11.5 dBm and the sensitivity of photo-detector of -12 dBm (on 25Gbps) [33]. In comparison, in an 8×8 folded-torus network the maximum insertion loss is around 15.5 dB, plus the -7 dB modulator loss the total loss is very close to the power budget, in which the 5.5 dB fiber GC loss is not included yet [34]. As the scalability of the network increases, insertion loss will eventually be large enough to bury the input signals into the background noise. Therefore, insertion loss has to be taken into account in the optical network design based on the available power budget [33].

The insertion loss can be overcome by increasing the power budget, which is to increase the optical signal power, i.e. laser power, or to increase the sensitivity of the the photodetector. However, these device level techniques are expensive and limited. Other
methods have also been proposed to deal with insertion loss. For example, taking advantage of unique optical materials, such as silicon nitride and polycrystalline silicon, multilayer photonic network architectures can reduce the insertion loss and the required laser power compared with single-layer networks [32]. However, using multilayer photonic materials and devices to construct the photonic network adds design complexity and fabrication difficulties.

The rest of this chapter presents a simpler and less expensive methodology to cope with insertion loss issues, which is realized by transforming the network structures.

4.2 Microring-resonator-based optical switching elements

4.2.1 Parallel-coupled and cross-coupled microring resonator switches

Microring resonator, as an optical switch, is the key component in the optical networks. There are two different types of microring resonator switches, shown in Figure 20 and Figure 21.

(a) Resonating

(b) Off-resonating

Figure 20, Parallel-coupled microring resonator switch [35].
Both of the two switches support two bidirectional paths simultaneously, i.e. $I_1 \leftrightarrow O_1$ (blue line) and $I_2 \leftrightarrow O_2$ (green line). In the parallel-coupled switch, for the same input port, the two output ports with resonating and off-resonating conditions are non-adjacent. But for the cross-coupled switch, for the same input port, the two output ports are next to each other. As a result, there are no reported generalized photonic network architectures constructed only with parallel-coupled switches.

4.2.2 Generalized wavelength-routed optical network (GWON)

As shown in Figure 21 (a), the cross-coupled switch on resonating condition supports two paths that are functionally the same. Therefore, the generalized network architecture presented in 3.3 can be improved as shown in Figure 22, in which the number of the microring resonators can be further reduced by half.
Figure 22, Improved 6×6 generalized wavelength-routed network [35].

An $N \times N$ generalized wavelength-routed network is composed of $N$ waveguides and $M$ MRR switches ($M=N(N-2)/2$ for $N=2n$, and $M=(N-1)^2/2$ for $N=2n+1$, $n \in \mathbb{N}$) [35]. Each waveguide directly connects input port $I_i$ and output port $O_{N-i}$, $0 \leq i \leq N-1$. Totally $N-1$ different routing wavelengths (correspondingly $N-2$ types of MRRs) are required to communicate between $N$ input ports and $N$ output ports. Table 3 shows the routing wavelength assignment of the 6×6 network.

Table 3, Routing wavelengths in 6×6 network

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4.3 Insertion loss analysis in microring resonator switches

4.3.1 Insertion loss in parallel-coupled and cross-coupled microring resonators

There are five different switching patterns in the parallel-coupled and cross-coupled microring resonator switches:

- *Parallel Through*: For the parallel-coupled switch under off-resonating state, the input signal propagates through one waveguide directly without being coupled into the microring, which is either the blue path from $I_1$ to $O_1$ or the green path from $I_2$ to $O_2$ in Figure 20 (b).

- *Parallel Drop*: For the parallel-coupled switch under on-resonating state, the input signal is coupled into the microring and transmitted to the drop port in the other waveguide, which is either the blue path from $I_1$ to $O_1$ or the green path from $I_2$ to $O_2$ in Figure 20 (a).

- *Cross Through*: In a cross-coupled switch under off-resonating condition, the input signal passes through one waveguide directly without resonating, which is either the blue path from $I_1$ to $O_1$ or the green path from $I_2$ to $O_2$ in Figure 21 (b).

- *Cross Near Drop*: In a cross-coupled switch under on-resonating condition, the input signal drops to another waveguide by propagating through a quarter of the microring, which is the blue path from $I_1$ to $O_1$ in Figure 21 (a).

- *Cross Far Drop*: In a cross-coupled switch under on-resonating condition, the input signal drops to another waveguide by propagating through three quarters of the microring, which is the green path from $I_2$ to $O_2$ in Figure 21 (a).

The basic add-drop microring resonator configuration has been introduced in Chapter 2, and its transmission relations have been derived. Applying the coupling model
to the cross-coupled microring resonator configuration shown in Figure 23, we can obtain the power transmissions at the throughput port and drop port as:

\[
P_t = Lc \left| \frac{E_i}{E_i} \right|^2 = Lc \left| \frac{t_2^* \alpha e^{i\theta} - t_1}{t_1^* t_2^* \alpha e^{i\theta} - K k_1 k_2^* (\alpha e^{i\theta})^3} \right|^2
\]

\[
P_d = \left| \frac{E_d}{E_i} \right|^2 = \left| \frac{K \alpha e^{i\theta} + k_1^* k_2 (\alpha e^{i\theta})^{1/4} - t_1 t_2 K}{t_1^* t_2^* \alpha e^{i\theta} - K k_1 k_2^* (\alpha e^{i\theta})^3} \right|^2
\]

where \( Lc \) is the power loss per waveguide crossing, and \( K \) is the crosstalk coefficient per waveguide crossing.

Based on equations (14), (15), (17) and (18), the insertion loss of all the five patterns can be calculated from Matlab simulation. The power loss and crosstalk coefficient are 0.16 dB and -40 dB respectively [36]. The two coupling regions are
considered to be identical [8]. Cross Drop Average in Figure 24 is the average value of cross near drop and cross far drop.

![Figure 24, Insertion loss of parallel-coupled and cross-coupled microring resonator switches](image)

It can be seen from Figure 24 that:

- In off-resonating condition, the insertion loss of parallel through is much less than that of the cross through.

- In resonating condition, the insertion loss of parallel drop is very close to that of cross near drop, and the loss of the cross far drop is the worst. The average loss of cross near drop and cross far drop is worse than that of the parallel drop.

We denote $l_{PT}$, $l_{PD}$, $l_{CT}$, $l_{CD}$, as the insertion loss of Parallel Through, Parallel Drop, Cross Through, Cross Average respectively.
4.3.2 FDTD simulation

To verify the comparison of insertion losses in the parallel-coupled and cross-coupled microring resonators, simulation program based on three-dimensional finite-difference time domain (FDTD) method is used for modeling the optical properties and calculating the insertion losses of microring resonators.

Both the straight waveguides and microring have a rectangular cross-section of 400 nm × 180 nm, which is close to the maximal dimension for single-mode for TE mode, where light is maximally confined in the core [14]. The material of the device is silicon, which is placed on a SiO$_2$ substrate. Wavelength span is from 1.5 μm to 1.6 μm. The radius of the microring is 3.1 μm, and gap between the straight waveguide and the microring is 100 nm. The field has a fundamental TE mode and is launched relatively far from the coupler. The light is monitored at different port locations to measure the transmission for different wavelengths. Due to the limit of the computer memory, the simulation mesh step and time step are set to 0.25 nm and 0.045 fs respectively to reach a good tradeoff between accuracy and memory requirement. The FDTD stop time is set to $2^{10} \times$ time step in the simulation.

Figure 25 – Figure 27 show the simulated electric field distribution of the two switches at the center plane of the waveguide and the microring at around 1.56 μm when the gap is 100 nm. The color bar indicates the amplitude of electric field $E_x$. Figure 25 shows the parallel-coupled switch. Light is injected into the upper waveguide and is transferred to the drop port (lower left port). Figure 26 shows the cross-coupled switch. Light is injected from the left side of the straight waveguide, and propagates through 1/4
of the microring before being transferred to the drop port (lower port of the vertical waveguide).

Figure 25, Simulated electric field distribution of parallel-coupled switch.

Figure 26, Simulated electric field distribution of cross-coupled switch (1/4 ring).
In Figure 27, light is injected from the right side of the straight waveguide of the cross-coupled switch. It travels through a waveguide cross and propagates through 3/4 of the microring before finally transferred to the drop port (upper port of the vertical waveguide).

The simulations are also performed under the different widths of gap. The power transmissions at the throughput port and drop port can be collected from the monitors. From the simulation results, the insertion losses of the two switches under different width of gap are summarized in Figure 28.

Figure 28 shows that for different width of gap, the insertion loss of parallel through is much less than that of cross through, which agrees well with the theoretical results in Figure 24. The average insertion loss of parallel drop is also less than that of the cross drop for different width of gap. As the gap increases, the amount of insertion loss of both the two switches increases, but the difference between them decreases. One possible
reason is that the coupling efficiency decreases for larger gap between the straight waveguide and the microring, and the power transferred from the input port to the drop port on resonating condition also decreases, which results in more insertion loss.

Figure 28, Insertion losses of the two switches under different width of gap.

4.3.3 Insertion loss in the network

In order to analyze the insertion loss in the GWON, the following definitions are made.

- **Path set**: the set of all the paths from an input port to an output port assuming that the signal from input $I_i$ is not allowed to go to $O_i$. For an $N \times N$ GWON, there are $N \times (N-1)$ paths in the set in total.

  \[ P = \{ p_{ij} | p_{ij} : I_i \rightarrow O_j, 0 \leq i, j \leq N - 1, i \neq j \}. \]
• **Total insertion loss**: for each switch in the network, there are many different paths in $P$ that pass through it, each of which will have the insertion loss of one of five switching patterns. The summation of all these insertion losses encountered in one switch is denoted as *total insertion loss*.

• **Total paths loss**: the summation of the total insertion losses of all the switches in the network.

• **Average insertion loss**: The average insertion loss in the network equals the *total paths loss* divided by the total number of paths in the path set.

And the following statements in an $N \times N$ GWON can be deduced.

• The total insertion loss of each switch is:

$$ L_{total} = 2l_{CD} + 2(N-2)l_{CT} \quad (39) $$

• When $N$ is even ($N=2n$), the total paths loss is:

$$ L_{total paths} = N(N-2)^2l_{CT} + N(N-2)l_{CD} \quad (40) $$

When $N$ is odd ($N=2n-1$), the total paths loss is:

$$ L_{total paths} = (N-1)^2(N-2)l_{CT} + (N-1)^2l_{CD} \quad (41) $$

• When $N$ is even ($N=2n$), the average insertion loss is:

$$ L_{average} = \frac{(N-2)^2}{N-1}l_{CT} + \frac{N-2}{N-1}l_{CD} \quad (42) $$

When $N$ is odd ($N=2n-1$), the total paths loss is:

$$ L_{average} = \frac{(N-1)(N-2)}{N}l_{CT} + \frac{N-1}{N}l_{CD} \quad (43) $$
In an $N \times N$ GWON ($N = 2n$), if number of $M$ cross-coupled microring resonator switches are replaced with parallel-coupled switches, the new total paths loss will become:

$$L'_{total \ paths} = [2l_{CD} + 2(N - 2)l_{CT}] \left( \frac{(N-2)}{2} - M \right) + [2l_{PD} + 2(N - 2)l_{PT}] \times M = 2Ml_{PD} + 2M(N - 2)l_{PT} + [N(N - 2) - 2M]l_{CD} + [N(N - 2)^2 - 2M(N - 2)]l_{CT}$$

(44)

The average insertion loss of the network will be reduced to:

$$L'_{average} = \left[ [N(N - 2) - 2M]l_{CD} + [N(N - 2)^2 - 2M(N - 2)]l_{CT} + 2Ml_{PD} + 2M(N - 2)l_{PT} \right] \frac{1}{N(N - 1)}$$

(45)

When $N = 2n - 1$, if number of $M$ cross-coupled microring resonator switches are replaced with parallel-coupled switches, the new total paths loss will become:

$$L'_{total \ paths} = [2l_{CD} + 2(N - 2)l_{CT}] \left( \frac{(N-1)^2}{2} - M \right) + [2l_{PD} + 2(N - 2)l_{PT}] \times M = 2Ml_{PD} + 2M(N - 2)l_{PT} + [(N - 1)^2 - 2M]l_{CD} + [(N - 1)^2(N - 2) - 2M(N - 2)]l_{CT}$$

(46)

The average insertion loss of the network will be reduced to:

$$L'_{average} = \frac{1}{N(N - 1)} \{ 2Ml_{PD} + 2M(N - 2)l_{PT} + [(N - 1)^2 - 2M]l_{CD} + (N - 1)^2(N - 2) - 2M(N - 2) \} l_{CT} \}$$

(47)

From 4.3.1 we have analyzed that the parallel-coupled switches have less insertion loss than the cross-coupled switches. To deduce the insertion loss of the cross-
coupled switch, it can be replaced by the combination of a waveguide crossing and a parallel-coupled switch, as shown in Figure 29.

![Diagram showing combination of a waveguide crossing and a parallel-coupled switch](image)

Figure 29, Combination of a waveguide crossing and a parallel-coupled switch [35].

In off-resonating condition, the signal propagates through the waveguide directly, and the insertion loss of the off-resonating transmission is equal to $l_{CT}$. However, in resonating condition, the average insertion loss of the transmissions will be reduced from $l_{CD}$ to $l_{WPD}$.

Table 4 compares the insertion loss of the cross-coupled switch and its replacement under different values of $\alpha$.

<table>
<thead>
<tr>
<th>Insertion loss (dB)</th>
<th>$\alpha$</th>
<th>0.90</th>
<th>0.91</th>
<th>0.92</th>
<th>0.93</th>
<th>0.94</th>
<th>0.95</th>
<th>0.96</th>
<th>0.97</th>
<th>0.98</th>
<th>0.99</th>
<th>1.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_{CT}$</td>
<td></td>
<td>0.12</td>
<td>0.12</td>
<td>0.11</td>
<td>0.11</td>
<td>0.10</td>
<td>0.10</td>
<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>$l_{CD}$</td>
<td></td>
<td>3.60</td>
<td>3.26</td>
<td>2.94</td>
<td>2.61</td>
<td>2.27</td>
<td>1.93</td>
<td>1.57</td>
<td>1.21</td>
<td>0.83</td>
<td>0.43</td>
<td>0.03</td>
</tr>
<tr>
<td>$l_{WPD}$</td>
<td></td>
<td>3.34</td>
<td>3.05</td>
<td>2.76</td>
<td>2.45</td>
<td>2.14</td>
<td>1.82</td>
<td>1.48</td>
<td>1.14</td>
<td>0.78</td>
<td>0.41</td>
<td>0.03</td>
</tr>
</tbody>
</table>
4.4 Construction of low insertion loss network

4.4.1 Replaced parallel network

From the above analysis, the insertion loss of GWON can be reduced by replacing the cross-coupled switches with parallel-coupled switches as many as possible. The network after this replacement is denoted as Replaced Parallel Network (RPN). The RPN is equivalent to the GWON.

Figure 30 shows an example of a 10x10 RPN.

![Diagram](image)

Figure 30, (a) 10x10 RPN, (b) 10x10 GWON [35].

Figure 31 shows the five types of building blocks of RPN, each of which is represented by a different color, as shown in the square next to the captions (a) – (e).
Figure 31, Basic building blocks of RPN [35].

- Block (a): a parallel-coupled switch
- Block (b): three parallel-coupled switches
- Block (c): four cross-coupled switches
- Block (d): two parallel-coupled and 1 cross-coupled switches
- Block (e): one cross-coupled switch

Figure 32 shows the construction of 10×10, 12×12, 14×14, and N×N RPN with the basic building blocks.

Figure 32, (a) 10×10 RPN. (b) 12×12 RPN. (c) 14×14 RPN. (d) N×N RPN [35].
The gray square in Figure 26 is the block containing zero microring resonator switch. According to Figure 26, a general RPN can be built following these steps [35]:

- The \(N \times N\) \((N=2n, n>4, n \in \mathbb{N})\) RPN in Figure 25 (d) can be represented by an \(n \times n\) matrix \(M\)

\[
M = \begin{bmatrix}
    u_{1,1} & \cdots & u_{1,n} \\
    \vdots & \ddots & \vdots \\
    u_{n,1} & \cdots & u_{n,n}
\end{bmatrix}
\]  

(48)

where

1) \(u_{1,1}, u_{n,1}\) and \(u_{n,n}\) are block (a);
2) \(u_{2,1}\) to \(u_{n-1,1}\) and \(u_{n,2}\) to \(u_{n,n-1}\) are block (b);
3) \(\{u_{ij} | 3 \leq i \leq n - 1, 2 \leq j \leq i - 1\}\) are block (c);
4) \(u_{2,3}\) and \(u_{n-2,n-1}\) are block (d);
5) \(\{u_{kk} | 3 \leq k \leq n - 2\}\) and \(\{u_{il+1} | 3 \leq l \leq n - 3\}\) are block (e);
6) \(u_{1,2}\) and \(u_{2,2}, u_{n-1,n-1}\) and \(u_{n-1,n}\), and \(u_{1,3}, u_{2,4}, \ldots, u_{n-2,n}\) are blocks with no microring resonator switches.
7) The else elements are empty.

And the input and output ports corresponding to the elements are numbered as:

1) The two ports of \(u_{1,1}, u_{n,1}\) and \(u_{n,n}\) are \((I_1, O_0), (I_{2n-1}, O_{n-1})\) and \((I_n, O_{n+1})\), respectively.
2) Port on \(u_{2,3}\) and \(u_{n-2,n-1}\) are \(I_0\) and \(O_n\), respectively;
3) The two ports on each block from \(u_{2,1}\) to \(u_{n-1,1}\) are \((I_2, O_1), (I_3, O_2), \ldots, (I_{n-2}, O_{n-3}), (I_{n-1}, O_{n-2})\), respectively. And the two ports on each block from \(u_{n,2}\) to \(u_{n,n-1}\) \((I_{2n-2}, O_{2n-1})\), \((I_{2n-3}, O_{2n-2}), \ldots, (I_{n+2}, O_{n+3}), (I_{n+1}, O_{n+2})\), respectively.

49
The total numbers of microring resonator switches are:

\[
\begin{align*}
6n - 5 & \quad \text{parallel switches} \\
2n^2 - 8n + 5 & \quad \text{cross switches}
\end{align*}
\]  

(49)

- When the number of input and output ports are odd, the \((N-1)\times(N-1)\) RPN \((N=2n, n>4, n\in\mathbb{N})\) can be constructed based on the \(N\times N\) RPN, whose input and output ports are \(I_0, I_1, \ldots, I_{N-1}\) and \(O_0, O_1, \ldots, O_{N-1}\).

1) Remove the waveguide between ports \(I_n\) and \(O_{n-1}\) and all those \((N-2)\) MRR switches on this waveguide.

2) Update ports \(O_{n-1}, O_{2n-1}\) to \(O_{n-1}, O_{2n-2}\);

3) Update ports \(I_{n+1}, I_{2n-1}\) to \(I_{n}, I_{2n-2}\).

The total numbers of microring resonator switches are:

\[
\begin{align*}
6n - 9 & \quad \text{parallel switches} \\
2n^2 - 10n + 11 & \quad \text{cross switches}
\end{align*}
\]  

(50)

When the size of the RPN is less than or equal to 8, the above procedures cannot be applied. Figure 33 shows the 4×4, 5×5, 6×6, 7×7 and 8×8 RPN.

Figure 33, (a) 4×4 RPN. (b) 5×5 RPN. (c) 6×6 RPN. (d) 7×7 RPN. (e) 8×8 RPN [34].
4.4.2 Low insertion-loss network

The insertion loss of RPN can further be reduced by replacing the rest of cross-coupled switches with the combination of a waveguide crossing and a parallel-coupled switch, and this network is denoted as Low Insertion-loss Network (LIN).

4.5 Insertion loss analysis

According to the above conclusions, the numbers of total microring resonator switches used in GWON, RPN and LIN of different sized can be concluded in Table 5. The parallel-coupled and cross-coupled switches are denoted as P and C respectively. The combination of a waveguide crossing and a parallel-coupled switch is denoted as WP.

<table>
<thead>
<tr>
<th>Network size (even)</th>
<th>4×4</th>
<th>6×6</th>
<th>8×8</th>
<th>10×10</th>
<th>12×12</th>
<th>14×14</th>
<th>16×16</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWOR</td>
<td>4C</td>
<td>12C</td>
<td>24C</td>
<td>40C</td>
<td>60C</td>
<td>84C</td>
<td>112C</td>
</tr>
<tr>
<td>RPN</td>
<td>4P</td>
<td>12P</td>
<td>19P+5C</td>
<td>25P+15C</td>
<td>31P+29C</td>
<td>37P+47C</td>
<td>43P+69C</td>
</tr>
<tr>
<td>LIN</td>
<td>4P</td>
<td>12P</td>
<td>19P+5WP</td>
<td>25P+15WP</td>
<td>31P+29WP</td>
<td>37P+47WP</td>
<td>43P+69WP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Network size (odd)</th>
<th>5×5</th>
<th>7×7</th>
<th>9×9</th>
<th>11×11</th>
<th>13×13</th>
<th>15×15</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWOR</td>
<td>8C</td>
<td>18C</td>
<td>32C</td>
<td>50C</td>
<td>72C</td>
<td>98C</td>
</tr>
<tr>
<td>RPN</td>
<td>8P</td>
<td>16P+2C</td>
<td>21P+11C</td>
<td>27P+23C</td>
<td>33P+39C</td>
<td>39P+59C</td>
</tr>
<tr>
<td>LIN</td>
<td>8P</td>
<td>16P+2WP</td>
<td>21P+11WP</td>
<td>27P+23WP</td>
<td>33P+39WP</td>
<td>39P+59WP</td>
</tr>
</tbody>
</table>

Based on equations (39) – (50), the average insertion loss of GWON, RPN and LIN can be evaluated using the data in Figure 24, Table 4 and Table 5, as shown in the Table 6.
Table 6, Average insertion loss (unit: dB)

<table>
<thead>
<tr>
<th>Network Sizes</th>
<th>(\alpha=0.9)</th>
<th>(\alpha=0.95)</th>
<th>(\alpha=1.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GWOR</td>
<td>RPN</td>
<td>LIN</td>
</tr>
<tr>
<td>4</td>
<td>2.54</td>
<td>2.34</td>
<td>2.34</td>
</tr>
<tr>
<td>5</td>
<td>3.15</td>
<td>2.88</td>
<td>2.88</td>
</tr>
<tr>
<td>6</td>
<td>3.25</td>
<td>2.96</td>
<td>2.96</td>
</tr>
<tr>
<td>7</td>
<td>3.59</td>
<td>3.29</td>
<td>3.27</td>
</tr>
<tr>
<td>8</td>
<td>3.70</td>
<td>3.41</td>
<td>3.37</td>
</tr>
<tr>
<td>9</td>
<td>3.94</td>
<td>3.68</td>
<td>3.61</td>
</tr>
<tr>
<td>10</td>
<td>4.05</td>
<td>3.79</td>
<td>3.71</td>
</tr>
<tr>
<td>11</td>
<td>4.26</td>
<td>4.01</td>
<td>3.91</td>
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<tr>
<td>12</td>
<td>4.37</td>
<td>4.12</td>
<td>4.02</td>
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<td>13</td>
<td>4.55</td>
<td>4.31</td>
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<td>14</td>
<td>4.67</td>
<td>4.43</td>
<td>4.31</td>
</tr>
<tr>
<td>15</td>
<td>4.83</td>
<td>4.60</td>
<td>4.48</td>
</tr>
<tr>
<td>16</td>
<td>4.95</td>
<td>4.72</td>
<td>4.59</td>
</tr>
</tbody>
</table>

From Table 6, the following conclusions can be obtained:

- As the size of the network increases, the amount of reduced insertion loss increases, whereas the percentage of the loss reduction slightly decreases.
- The the internal loss factor \(\alpha\) decreases, the amount of reduced insertion loss increases, whereas the percentage of the loss reduction decreases.

The results show that the insertion loss of GWON can be effectively reduced by the transforming its structures to RPN and LIN.

4.6 Summary

In this chapter, the transmission relations of the cross-coupled microring resonator are first derived based on the coupling model introduced in Chapter 2. The power transmission and insertion losses of the parallel-coupled and cross-coupled switches are then simulated and analyzed. Results show that in both resonating and off-resonating
conditions, parallel-coupled switches have less average insertion loss than the cross-coupled ones. A new structure of switch that is functionally equivalent to cross-coupled switch while has less insertion loss than cross-coupled is introduced. It replaces the cross-coupled switch with the combination of a waveguide crossing and a parallel-coupled switch. Next, an improved GWON is introduced, which is solely built with cross-coupled switches. To reduce its insertion loss, a new scheme is presented to construct RPN and LIN. In RPN, the cross-coupled switches are maximally replaced by the parallel-coupled switches, and in LIN, the rest cross-coupled switches are further replaced with the combination of waveguide crossing and parallel-coupled switch. Compared with GWON, RPN and LIN use the same number of waveguides and microring resonators and they are proved to be equivalent to the GWON. Theoretical analysis and numerical simulation show that RPN can effectively reduce the insertion loss of GWON, and it can be further reduced by LIN.
5.1 Conclusion

In this thesis, a new methodology is proposed to reduce the insertion loss of the optical network on-chip by transforming its structures, which is simpler and less expensive compared with other exiting techniques. This method is applied to the generalized wavelength-routed optical network (GWON). Microring resonator switch is the key component in an optical network, and it has two basic types: parallel-coupled and cross-coupled. The GWON is solely built with cross-coupled switches. To reduce its insertion loss, the transmission characters of the two types of switches are first studied. Based on the coupling model theory and FDTD simulations, analyses demonstrate that parallel-coupled switches have better performance than the cross-coupled ones in terms of insertion loss. As the internal loss factor decreases, the difference of insertion loss between these two types of switches is increasing. Thus the cross-coupled switch can be replaced by the combination of a waveguide crossing and a parallel-coupled switch, which is functionally equivalent to the cross-coupled switch while has less insertion loss.

Replacing the cross-coupled switches with parallel-coupled switches as many as possible, the Replaced Parallel Network (RPN) can be constructed. Furthermore, Low Insertion-loss Network (LIN) can be built by replacing the rest cross-coupled switches in RPN with the combination of a waveguide crossing and a parallel-coupled switch. RPN and LIN are proved to be equivalent to the original network as they use the same number of waveguides and microring resonator switches. Theoretical analysis and numerical results confirm that the average insertion loss of the generalized wavelength-routed network can be effectively reduced by the proposed scheme. The amount of insertion loss...
reduced is closely related to the internal loss factor of the microring resonator. For the same size of the network, as the internal loss factor decreases, the amount of insertion loss reduced increases. And for the same value of the internal loss factor, the amount of insertion loss reduction will increase as the size of the network increases.

5.2 Future work

The future work will include applying the proposed method to various ONoC architectures not only the wavelength-routed networks. Also, the proposed method needs to be evaluated experimentally by fabricating the real optical networks with certain size.
REFERENCE


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