Wavelength-Routed Optical Networks-on-Chip Built with Comb Switches[1]

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Abstract

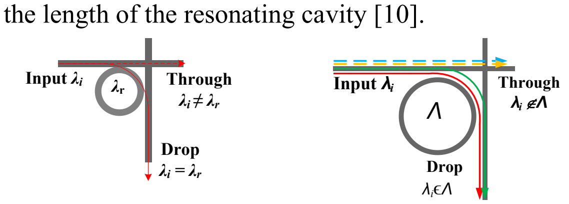
Comb switches are used to improve the bandwidth of wavelength-routed optical networks-on-chip (ONoC) without changing the network structure. A method is proposed to determine a minimal size comb MRR with given number of resonance wavelengths.

1. Introduction

Optical/photonic networks-on-chip (ONoC), with the advantages in high power efficiency, negligible latency and extremely high bandwidth, are considered as a promising solution to meet the communication requirements of future multi/many core systems [3][8]. The heart of an ONoC is the optical interconnection network which is composed of silicon waveguides and optical switches [5]. Micro-ring resonators (MRR) have been widely used as optical switches in ONoC. Fig. 1(a) shows the structure and operation of a basic 1×2 MRR-based switch. An input light signal is coupled to the drop port if the input wavelength $\boldsymbol{\lambda}_i$ satisfies

$$m\lambda_r = n_{eff}L \qquad (1)$$

where, m is an integer, λ_r is the resonance wavelength, n_{eff} is the effective index of the optical mode, and L is the length of the resonating cavity [10].



(a) General switch (b) Comb switch

Fig. 1 MRR-based 1×2 optical switch.

For a given L, there may exist a set of resonance wavelengths (λ_0, λ_1, λ_2, …) corresponding to different integers m_i (i=0, 1, 2, ….) that satisfy the resonance condition of Eqn. (1), i.e.,

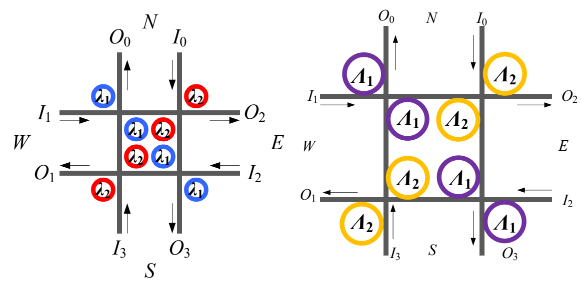
$$m_0\lambda_0 = m_1\lambda_1 = \ldots = n_{eff}L \qquad (2)$$

A comb switch (Fig. 1(b)) is one that satisfies Eqn. (2). The size of the MRR in a comb switch shall be carefully chosen so that the desired set of wavelengths can be dropped. A broadband 1×2 optical comb switch is presented in [2]. However, it is not clear how to determine the size of a comb switch for a given number of wavelengths.

MRR-based wavelength-routed ONoC route data with predetermined wavelengths [1][4-7]. To improve the bandwidth of wavelength-routed ONoC, wavelength division multiplexing (WDM) technology can be applied, which motivates the design of redundant network structures [6][7]. However, such structures significantly increase the network complexity and power loss. In this paper, we propose to use comb switches to improve the bandwidth of wavelength-routed ONoC without increasing the complexity of network structures. A method is proposed to determine a minimal size comb MRR with given number of resonance wavelengths.

2. ONoC Built with Comb Switches

Without loss of generality, we will use the Generic Wavelength-routed Optical Router (GWOR) [6] as an example to describe how to use comb switches to construct WDM-enabled wavelength-routed ONoC. Fig. 2(a) shows a 4×4 GWOR with the routing wavelength assignment given in Tab. 1.



(a) 4×4 GWOR (b) 4×4 4-GWOR

Fig. 2 Structures of basic/WDM-enabled GWOR.

Table 1. Wavelength assignment of 4×4 GWOR

	O_0	O_1	O_2	O_3
I_0	-	λ_1	λ_2	λ_3
I_1	λ_1	-	λ_3	λ_2
I_2	λ_2	λ_3	-	λ_1
I_3	λ_3	λ_2	λ_1	-

Note: "-" stands for not applicable.

Table 2. Wavelength assignment of 4×4 4-GWOR

	O_0	O_1	O_2	O_3
I_0	-	$\lambda_1, \lambda_4, \lambda_7, \lambda_{10}$	$\lambda_2, \lambda_5 \lambda_8, \lambda_{11}$	$\lambda_3, \lambda_6, \lambda_9, \lambda_{12}$
I_1	$\lambda_1, \lambda_4, \lambda_7, \lambda_{10}$	-	$\lambda_3, \lambda_6, \lambda_9, \lambda_{12}$	$\lambda_2, \lambda_5 \lambda_8, \lambda_{11}$
I_2	$\lambda_2, \lambda_5 \lambda_8, \lambda_{11}$	$\lambda_3, \lambda_6, \lambda_9, \lambda_{12}$	-	$\lambda_1, \lambda_4, \lambda_7, \lambda_{10}$
I_3	$\lambda_3, \lambda_6, \lambda_9, \lambda_{12}$	$\lambda_2, \lambda_5 \lambda_8, \lambda_{11}$	$\lambda_1, \lambda_4, \lambda_7, \lambda_{10}$	-

To improve the bandwidth of an N×N GWOR by M times, we can replace the MRRs with comb MRRs, each of which resonates the exact M wavelengths in a set Λ_i, where $|\Lambda_i|=M$, and $\Lambda_1 \cap \Lambda_2 \cap \ldots = \Phi$. We denote such type of GWOR as M-GWOR. Fig. 2(b) shows

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the 4×4 4-GWOR structure with the routing wavelength assignment shown in Tab. 2.

Noticeably, with the same routing wavelength assignment but much simpler structure, an M-GWOR can achieve the same bandwidth improvement as the same size redundant GWOR (RGWOR) does. In general, the number of MRRs used in an $N\times N$ M-GWOR is reduced by $(M-1)/M$ compared with that of an $N\times N$ M-RGWOR. Similarly, using comb switches, the bandwidth of other wavelength-routed ONoC can be improved without changing the network structure.

3. Determination of Comb MRR Size

In designing an ONoC with comb switches, it is preferred to minimize the size of comb switches [5]. Next we will show how to determine the minimal size comb MRR for a given number of resonance wavelengths. Assume the spectrum range of the input wavelengths λ_0, λ_1, …, λ_{W-1} is $[\gamma_0, \gamma_{W-1}]$, where $\gamma_{W-1}=\gamma_0+(W-1)\Delta\gamma$, W is the total number of available channels, and Δγ is the constant channel spacing. Each comb MRR is capable of resonating M different wavelengths and $M\leq W$. The problem is to determine the minimal size of the comb MRR (with cavity L) with M resonance wavelengths such that

$$m_0\frac{c}{\gamma_0}=m_1\frac{c}{\gamma_1}=\cdots=m_{M-1}\frac{c}{\gamma_{M-1}}=n_{eff}L. \qquad (3)$$

A heuristic method is proposed to solve this problem. Let γ_r be the reference frequency in the resonance wavelength set and m_r be the smallest integer satisfying Eqn. (1). For any other frequency γ_i in this set, let $\gamma_i = \gamma_r + k\Delta\gamma$ and $m_i=m_r+n$, where, k, n are positive integers and $k\leq W$. From Eqn. (3), we can derive that

$$m_r\frac{k}{n}=\frac{\gamma_r}{\Delta\gamma}. \qquad (4)$$

Eqn. (4) shows that the value of $\gamma_r/\Delta\gamma$, which is an integer, is determined once γ_r is chosen. As such, the size of a comb MRR (L) will be determined by m_r only. The smaller m_r is, the smaller the MRR size L is. The following procedure is developed to choose m_r and determine k and n.

Step 1: Let $\gamma_r=\gamma_0$. Find all the prime divisors of $\gamma_r/\Delta\gamma$, denoted as a_0, a_1, …. , a_p, where, $a_i\leq a_j$ for $i<j$. If $p<2$, which means $\gamma_r/\Delta\gamma$ is a prime, increase γ_r by $\Delta\gamma$. Repeat this step until $p\geq 2$.

Step 2: From Eqn. (4) and Step 1, we have $m_rk/n=a_0\times a_1\times\ldots\times a_p$. Let m_r be the smallest factor of $\gamma_r/\Delta\gamma$ (i.e., the smallest product of any a_i's, e.g., $a_0\times a_p$) satisfying $m_r\geq\gamma_r/(\Delta\gamma W)$ as $k\leqslant W$ and $n\geq 1$.

Step 3: Determine the values of n, k by Eqn. (4). Let n be 1, 2, ⋯, M, calculate the corresponding k value as long $k\leqslant W$. If the number of <n, k> pairs is less than M, which means we cannot find M different resonance wavelengths for the selected m_r, then go back to Step 2 and change m_r to the next smallest factor of $\gamma_r/\Delta\gamma$ satisfying $m_r\geq\gamma_r/(\Delta\gamma W)$.

Step 4: For each pair of <n, k>, calculate $\gamma_i=\gamma_r+k\Delta\gamma$ and $m_i=m_r+n$. Then calculate the comb MRR cavity L using Eqn. (3).

Example: Determine the size of a comb switch for 4×4 4-GWOR (i.e., M=4) in spectrum range γ: 192.10~195.90THz (λ: 1530~1560nm, $\Delta\gamma$=100GHz and W=39).

Step 1: Let γ_r=192.6THz, then $\gamma_r/\Delta\gamma=1926=1\times2\times3\times3\times107$.

Step 2: For $m_rk/n=1\times2\times3\times3\times107$, let m_r=107, then we have k/n =18.

Step 3: For $n=M-1=3$, as k/n =18, and then we have k=54 ($k>W$), which means that with m_r=107, we cannot find 4 wavelengths. Let m_r=107×2, then we get k/n=9. For $n=M$=4, we have k=36 ($k<W$).

Step 4: The resonance wavelengths are calculated and listed in Tab. 3. Then the comb MRR size (L) can be determined by Eqn. (3).

Table 3. One resonance wavelength set.

i	m_i	n_i	k_i	γ_i (THz)	$\lambda_i(nm)$
0	214	-	-	192.6	1556.55
1	215	1	9	193.5	1549.32
2	216	2	18	194.4	1542.14
3	217	3	27	195.3	1535.04
4	218	4	36	196.2	1527.99

3. Conclusion

In this paper, MRR-based comb switches are proposed to improve the bandwidth of wavelength-routed ONoC without changing the network structure. Given the number of resonance wavelengths, the minimal size comb MRR can be determined with the proposed method.

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