Characterizations of Cascaded Micro-ring Resonators

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Abstract. The effects of cascading the ring resonator to form wavelength filters is a major focus
of this paper, the results tested between the two methods of cascading the rings are the trends
between the two types of cascaded rings for the ON-OFF ratio where the serially cascaded
method was found to make better filters, -3dB bandwidth which is the width of the pass-band of
through-port and drop-port where both the two cascading methods have the same effect as the
numbers of rings increases. The delay times of the output for use in telecommunication are also
simulated illustrating that only the parallel cascaded method provides this property.

1. Introduction
Silicon photonics provide faster ways of transmitting signals when compared to standard ways of
transmitting data. In silicon photonic chips, these signals being transmitted are in the form of light
pulses; this means data travels faster in silicon photonics when compared to traditional electrical signals.
There have been researches done in order to design digital logic gates in optical domain using Fabry
Perot Laser Diode [1, 2], but these designs cannot be incorporated and fabricated at CMOS-level circuits,
thus electro-optic circuits have been proposed using one of the widely researched silicon photonic
devices, the micro-ring resonator [3-5]. It is possible to connect multiple micro-ring resonators to create
a cascaded effect. Cascaded micro-ring resonators have multiple benefits; cascaded micro-ring
resonators are an important part of wave division multiplexing networks. The benefits include their
small-volume, lightweight, tunability, re-configurability and electromagnetic immunity [6].
Micro-rings are very important, as the world is quickly moving towards replacing electronic communication systems with optical communication systems. Figure 1 shows the output of a typical micro-ring resonator and its parameters. These parameters include the free spectral range (FSR), full width half max, finesse and Q-factor [7]. In a paper done done in 2002 titled “Box-like filter response and expansion of FSR by vertically triple couples microring resonator filter” illustrates the design and the nature of ring resonators when they are coupled and when multiple resonators are set adjacent to each other in a vertical manner. The output filter response at the dropping port of micro-ring resonator filters (series-coupled) is found by the product of filter responses of each individual single micro-ring resonators. Due to this, a sharper roll-off and lower crosstalk can be expected. The FSR is also expanded [8]. From the two previous works mentioned, it is clear that higher order filter designs yield better filter like responses. A paper done by Fengnian Xia, Mike Rooks, Lidija Sekaric and Yuri Vlasov compares the outputs of a 5th order ring resonator optical filters to a 3rd order filter. The result from this paper show that increasing the number of rings in a filter structure will provide better filters and will change aspects of the output of the micro-ring resonator.

2. Methodology
This paper will set about to characterize the effects of cascading the rings between two different methods of cascading, namely the parallel cascading and the serially cascading method. For a parallel and series cascaded micro-ring are designed to be analyzed, the topography of these two cascaded micro-ring configurations differentiated by the positions of the consecutive micro-ring resonator within the system.
The block diagram in Figure 2 of parallel micro-ring shows that the micro-rings are adjacent to one another in between two straight waveguides, for this configuration, the incoming signal at the input will be coupled into the first ring with a coupling coefficient of $K_1$ as the remaining signal propagates through the straight waveguide to the through port, the part of the signal that propagates in the ring will be coupled into the waveguide below the ring with a coupling coefficient of $K_2$ to travel to the drop port of the micro-ring configuration \[10\]. This propagation action continues for all the rings. This process is reversed for signals from the add port to the through port of this parallel combination.

![Figure 2. Block diagram of parallel micro-ring configuration.](image)

Figure 3 shows a serially cascaded ring resonator filter. In serially cascaded micro-ring resonator filters, a part of the signal from the input port will be coupled into the first ring with a coupling coefficient of $K_1$ while the remaining part of the signal will travel through the straight bus waveguide to the through-port, a part of the signal coupled into the first ring from the top waveguide will be coupled into the second ring, a distance of half the ring length will be travelled by the signal before it is coupled to the consecutive rings with their respective coupling coefficients until the signal reaches the drop port of the lower waveguide.

In parallel configuration, the arrangement is formed in such a way that the rings do not interact between one another, the interaction between these consecutive rings are indirect, however, via the waveguides between the rings, because of this, the light propagates in a unique way and there is no counter propagation of the wave.

In series combination, the arrangement is formed in such a way that the rings interact between one another, the interaction between the rings are direct in the form of propagation between the rings themselves, in this configuration, only 2 rings will interact with the straight waveguides, the top and bottom most rings will be the rings that interact with the waveguides leading to the through-port and drop-port.

For the simulation of these cascading ring structures, the number of rings will be increased from one ring to 5 rings, this corresponds to the order of the rings. The parameters for the rings will all be set to the same value. As only the effects of cascading are being tested for results, the coupling coefficient will be set of 0.1 for all rings and the length will be set of 40 um for all tests except when stated otherwise.

The parameters to be tested are:

1. **Widening effect on the free spectral range both cascading methods**
2. **Rejection/ON-OFF ratio**
3. 3dB width at drop-port and through-port
4. Propagation delay.

3. Simulation Results
The simulation procedure and the results will be gone through in this section. For all the rings, the parameters will be the same [11] as shown in Table 1. This is to ensure that the effects of cascading are isolated and no other parameters will disrupt the results.

Table 1. Cascaded ring resonator parameters.

| Parameter         | Settings       |
|-------------------|----------------|
| Configuration     | Bidirectional  |
| Resonant wavelength | 1550 nm       |
| Length            | 40 µm          |
| Loss              | 3 dB/m         |
| Effective index   | 2.5            |
| Group index       | 5              |
| Coupling Coefficient | 0.1           |

3.1. Widening effect on Free Spectral Range
An important quality that’s brought about by cascading is its ability to increase the free spectral range of the entire micro-ring resonator system. This can be simulated and tested. To test this, two rings are cascaded with different lengths to find the effects of the free spectral range of the micro-ring resonator.

Figure 4. Superimposed output of 70um and 40um ring resonator.

In simulation testing, the FSR outputs of two micro-ring resonator configurations need to be known. The lengths used in this simulation are a 70 um ring resonator and a 40um ring resonator cascaded according to Figure 3 and 4 to achieve a 2nd order ring resonator structure. Other parameters for these two ring resonator parameters will be the same for both rings.

The output of the 2nd order rings to be tested is expected to be an interaction between the two spectral outputs shown in Figure 4 of the 70 and 40 um ring resonators.
Figure 5. Spectral output and FSR widening effect of parallel cascaded ring resonator.

The two values of length chosen to test the effects of cascading the rings on the FSR are 40um and 70um. A 40um micro-ring resonator has 2 minima in the spectral output while the 70um has 3 minima. This is shown in Figure 5.

From these simulation results, it is seen that to achieve a high free spectral range value by cascading the rings a serial configuration is suitable as the output of a cascaded ring structure in this fashion will yield the desired result as shown in Figure 6, for parallel cascaded ring resonator however this is not achieved, the free spectral range value does change however it does not become wider as the minima from each individual ring appears in the overall spectral output of the cascaded ring resonator structure.

Figure 6. Spectral output and FSR widening effect of serially cascaded ring resonator.

In conclusion, a serially cascaded ring resonator will result in a wider FSR but a parallel cascaded ring resonator will only add the gain values of the spectral output if the spectral dips are aligned with each other.

3.2. ON-OFF ratio

The performance of the device can be determined by the ON-OFF ratio this is determined at the drop-port response of the micro-ring filter configuration shown in Figure 7.
For the results of this parameter, the ON-OFF ratio is measured for the cascaded ring structures from its 1st order to its 5th order for both cascading methods as shown in Table 2. It is illustrated in Table 2 that the value of the ON-OFF ratio has different trends for the different cascading methods.

**Table 2. ON-OFF Ratio.**

| Order | Parallel Cascaded | Serially Cascaded |
|-------|-------------------|-------------------|
| 1st   | -25.57 dB         | -25.57 dB         |
| 2nd   | -19.58 dB         | -41.36 dB         |
| 3rd   | -16.10 dB         | -58.82 dB         |
| 4th   | -13.65 dB         | -74.62 dB         |
| 5th   | -11.79 dB         | -90.41 dB         |

3.3. **3dB bandwidth at through-port an drop-port**

The gain at the through-port and drop of the ring resonators structures can also be simulated at the through-port and drop-port; the outputs can then be compared between the 1st order and the 5th order. This simulation comparison will be done with the 3dB bandwidth [Figure 8] of the response. The 3dB bandwidth comparison is shown in Table 3.
Table 3. 3dB width for cascaded ring resonators.

| Order | Parallel | Serial |
|-------|----------|--------|
| 1st   | 11.61 nm | 11.61 nm |
| 2nd   | 11.21 nm | 10.61 nm |
| 3rd   | 10.79 nm | 10.35 nm |
| 4th   | 10.38 nm | 10.06 nm |
| 5th   | 9.940 nm | 9.910 nm |

The drop-port has a different affect however, the output of the drop-port will have the opposite effect of the through-port and this is because the output results for the same wavelength band from the input, and the summation of the output at the drop-port and the through-port will result in the input signal. Table 4 shows the 3dB width of the drop-port of the parallel ring resonator [Figure 9] increasing as the number of rings increases, vice versa to the 3dB width at the through-port.

Figure 9. Drop-port output for parallel cascaded ring resonator.

Figure 10. Drop-port of serially cascaded ring resonator.
From Figure 10 it is illustrated that the output of the drop-port at the 3\textsuperscript{rd} order has a gain of less than -10 dB, this is a value that is too low, receivers will not be able to detect this signal. The reason for this is because of the topography of the serially cascaded ring resonator, when light propagates from the input port to the drop-port the signal has to propagate between many rings that traps some of that signal.

Table 4. 3dB width for drop-port of parallel cascaded ring resonator.

| Order | Parallel ring resonator |
|-------|-------------------------|
| 1\textsuperscript{st} | 0.23 nm |
| 2\textsuperscript{nd} | 0.43 nm |
| 3\textsuperscript{rd} | 0.69 nm |
| 4\textsuperscript{th} | 0.92 nm |
| 5\textsuperscript{th} | 1.17 nm |

3.4. Propagation delay

An important characteristic also tested in cascaded simulation is the delay [as shown in Table 5] Fcaused by cascading the rings. Delays in micro-ring resonators are used in Optical time division multiplexing networks in foe the demultiplexing of the channels as well as in antenna beam forming networks in telecommunications.

Coupled micro-ring resonators can be used for this purpose, as the number of micro-ring resonators increase, the signal will need time (in picoseconds) to complete propagate from the input port to the through-port (output) due to this mechanism, delays can be achieved.peak delay of each micro-ring resonator configuration can be simulated to achieve a value of time for the delay of transmission for the through-port, this value is tabulated for the rings, and this value is shown to increase as the value of the rings increases.

Table 5. Propagation delay

| Order | Parallel | Serial |
|-------|----------|--------|
| 1\textsuperscript{st} | 0.01765 ps | 0.01765 ps |
| 2\textsuperscript{nd} | 0.03350 ps | 0.01805 ps |
| 3\textsuperscript{rd} | 0.05230 ps | 0.01805 ps |
| 4\textsuperscript{th} | 0.06930 ps | 0.01805 ps |
| 5\textsuperscript{th} | 0.15030 ps | 0.01805 ps |

4. Conclusion

This paper simulates the cascading of ring resonators in two different methods; this includes the serially cascaded and the parallel cascaded ring resonator structure. The results measured are the widening effects of the FSR, ON-OFF ratio, the 3dB width of the through-port and the drop-port and the propagation delay caused by cascading. The actual parameters of the ring resonator are kept constant so that the effects of cascading on the output can be isolated from the effects of the other parameters of the ring.

It is seen that the serial and parallel cascaded rings differ slightly, in terms of widening the FSR, the serial cascaded ring is the only structure that achieves this effect. The ON-OFF ratio which is an indicator of the performance of the ring resonator shows that the serially cascaded ring is a better filter than the parallel cascaded. For the 3dB width for the through and drop-port, both of the ring structures have the same effect occur at the output however, the output at the drop-port of the serial cascaded ring resonator is no viable for use as the gain of the signal is too small. Moving on the propagation, it is illustrated that only the parallel cascaded ring resonator filter provides this property so for synchronization in telecommunication components that implement micro-ring resonators, this structure can be used for synchronization.
References

[1] B. Nakarmi, M. Rakib-Uddin, T. Q. Hoai, and Y. H. Won, "A simple controlled all-optical on/off switch using gain modulation in single mode FP-LD," *IEEE Photonics Technology Letters*, vol. 23, no. 4, pp. 212-214, 2010.

[2] M. R. Uddin, J. Lim, Y. Jeong, and Y. Won, "All-optical digital logic gates using single-mode Fabry–Perot laser diode," *IEEE Photonics Technology Letters*, vol. 21, no. 19, pp. 1468-1470, 2009.

[3] F. K. Law, M. R. Uddin, and H. Hashim, "Photonic D-type flip flop based on micro-ring resonator," *Optical and Quantum Electronics*, vol. 50, no. 3, p. 119, 2018.

[4] F. K. Law, M. R. Uddin, H. Hashim, and Y. H. Won, "Demonstration of photonic micro-ring resonator based digital bit magnitude comparator," *Optical and Quantum Electronics*, vol. 51, no. 1, p. 1, 2019.

[5] W. Bogaerts, P. Heyn, T. Vaerenbergh, K. Vos, S. Selvaraja, T. Claes, P. Dumon, P. Bienstman, D. Thourhout and R. Baets, "Silicon microring resonators", Academia.edu, J. Clerk Maxwell, A Treatise on Electricity and Magnetism.

[6] Parallel-Cascaded Semiconductor Microring Resonators for High-Order and Wide-FSR Filters R. Grover, Student Member, IEEE, V. Van, Member, IEEE, T. A. Ibrahim, P. P. Absil, L. C. Calhoun, F. G. Johnson, J. V. Hryniewicz, and P.-T. Ho.

[7] Q. Xu, B. Schmidt, J. Shakya and M. Lipson, "Cascaded silicon micro-ring modulators for WDM optical interconnection", Optics Express, 2006.

[8] Y. Yanagase, S. Suzuki, Y. Kokubun and Sai Tak Chu, "Box-like filter response and expansion of FSR by a vertically triple coupled microring resonator filter", Journal of Lightwave Technology, 2002.

[9] F. Xia, M. Rooks, L. Sekaric and Y. Vlasov, "Ultra-compact high order ring resonator filters using submicron silicon photonic wires for on-chip optical interconnects", Optics Express, 2007.

[10] R. Katti and S. Prince, "Analysis of serial and parallel cascaded microring resonators: An FDTD approach", Optik, vol. 152, pp. 36-48, 2018.R. Nicole.

[11] F. Law, M. R. Uddin, N. M. Masri, and Y. H. Won, "Digital Photonic Even Parity Bit Generator," in *2018 IEEE Photonics Conference (IPC)*, 2018, pp. 1-2: IEEE.