Optical cross-connect circuit using hitless wavelength selective switch

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Abstract: We have proposed and demonstrated the basic elements of a full matrix optical switching circuit (cross-connect circuit) using a hitless wavelength selective switch (WSS). The cross-connect circuits are made of a multi-wavelength channel selective switch consisting of cascaded hitless WSSs, and a multi-port switch. These switching elements are realized through the individual Thermo-Optic (TO) tuning of a series-coupled microring resonator, and can switch arbitrary wavelength channels without blocking other wavelength channels during tuning. We demonstrate a four wavelength selective switch using a parallel topology of double series coupled microring resonators and a three wavelength selective switch using a parallel topology of quadruple series coupled microring resonators. Since the spectrum shape of quadruple series coupled microring is much more box-like than the double series, a high extinction ratio of 39.0-46.6 dB and low switching cross talk of 19.3-24.5 dB were achieved.

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1. Introduction

While pass control using wavelengths is a promising method of implementing next-generation dense wavelength division multiplexing (DWDM) systems, it requires reconfigurable optical add/drop multiplexers (ROADM) [1, 2]. Microring resonator filters have a number of features that make them seem well-suited as add/drop filters: filter response synthesis by series-coupling [3], compactness using high-index-contrast waveguides [4], and the possibility for dense integration [5]. We have proposed and demonstrated a vertically coupled microring resonator [5, 6, 7, 8] that is suitable for dense integration via a stacked configuration [7, 9] and cross grid topology [7].

In addition, the Thermo-Optic (TO) effect can be utilized to create a tunable add/drop filter. However, the 0.011 nm/K thermo-optics (TO) coefficient of silica waveguide limits the tuning range to 1-2 nm. This restriction was lessened through the introduction of a cascaded topology of two different tunable fifth order microrings with FSR of 575 GHz and 650 GHz [10]. This tunable filter exploits the Vernier effect to digitally tune the center wavelength over a 40 nm wavelength range with 50 GHz channel spacing. However, this tunable filter blocks other wavelength channels during tuning and it can only select one wavelength due to the cascading of switching elements. One of the authors was involved in the development of another wide range (9.4nm) tunable microring filter using a polymer core that has a ten-fold greater TO coefficient than silica waveguide [11, 12]. This filter, however, also blocks other wavelength channels during tuning. To solve this problem, a hitless wavelength selective switch (WSS) is needed.

The hitless WSS can be realized by the combination of three 1×2 optical switches, one tunable filter and two bypass lines. However, in this configuration, the optical switches and tunable filter must be operated synchronously, which results in a response time delay making this circuit not suitable for dense integration. We proposed and demonstrated two hitless wavelength selective switches that resolve this issue; one uses a polymer core [13] and the other a dielectric core [14].

The operating principle behind this device is based on the control of the individual resonant...
wavelengths of a series-coupled microring resonator using TO effect. In a series-coupled microring resonator, when the resonant wavelengths of individual microrings are not matched, all wavelength channels are transmitted to the through port and no spectrum response peak appears in the drop port (OFF-state). After shifting and adjusting all the resonant wavelengths, a spectrum peak in the drop port response appears at other wavelength channels, allowing for the creation of a hitless wavelength selective switch [13, 14]. In addition, this switch can select multiple wavelengths simultaneously to the drop port because of its parallel configuration.

We thus decided to try to demonstrate the N input, N output, M wavelength channel full matrix switch shown in Fig. 1 for use as the building block of a full matrix optical switching circuit [15] for next generation photonic networks. In this study, as examples of a multi-wavelength channel selective switch node as shown in the upper part of Fig. 1, we demonstrate a four wavelength selective switch using a parallel topology of double series coupled microring resonators and a three wavelength selective switch using a parallel topology of quadruple series coupled microring resonators. Since the spectrum shape of quadruple series coupled microring is much more box-like than the double series, fundamental characteristics such as the extinction ratio and the switching cross talk of double and quadruple series coupled devices were compared. In addition, the effect of phase control between the switching elements of parallel topology is discussed. The multi-port switching circuit shown in the lower part of Fig. 1 has already been demonstrated in Ref. [15].

2. Device fabrication

The structure of the hitless wavelength selective switch is shown in Figs. 2 and 3. Si was used as a substrate. The core material and the upper cladding material were sputter deposited 17mol%Ta$_2$O$_5$-SiO$_2$ ($n=1.657$ @ $\lambda=1550$nm) and SiO$_2$ ($n=1.446$ @ $\lambda=1550$nm), respectively. The lower cladding material was thermally-grown SiO$_2$ ($n=1.442$ @ $\lambda=1550$nm).

Since a ring radius of less than 100 $\mu$m is needed for the microring, the index difference between the core and the cladding must be greater than 0.15. Therefore, we adopted the compound material of SiO$_2$ and Ta$_2$O$_5$, because the refractive index of Ta$_2$O$_5$ is 2.0 and the refractive index of core deposited by an RF sputtering can be controlled by the ratio of SiO$_2$ and Ta$_2$O$_5$ in the sputtering target.

The resonator was shaped like a race track to enhance coupling efficiency. The busline waveguide and microring resonator were laterally coupled with a gap width of 1.0 $\mu$m. The coupling efficiency between busline and microring was controlled by changing the length of straight part of racetrack resonator, and that between microrings was controlled by changing the overlap length of racetrack resonator. The core height and width were 1.3 $\mu$m and 1.3 $\mu$m, respectively, satisfying the single mode condition. The round trip length of the racetrack resonator for the double series-coupled and quadruple series-coupled microring resonator were approximately 700 $\mu$m and 610 $\mu$m, respectively, and the bending radius of the curved part in racetrack resonator was 55 $\mu$m. The corresponding FSR was approximately 2nm, which is not wide enough for telecommunications applications. However, the Vernier effect can be used to expand the FSR by using two different ring radii, which has already been demonstrated by some groups. The authors also demonstrated use of the Vernier effect to expand the FSR from 2nm to 25nm in Ref. [14].

The optical microscope photo of the quadruple series-coupled microring resonator is shown in Fig. 3. In the device shown in Fig. 4, racetrack shaped heaters were formed on top of individual racetrack resonators. The width and thickness of the Cr heater were 10 $\mu$m and 500 nm, respectively. The top surface of upper cladding was planarized using the process described in Ref. [16] to form the micro-heater on the upper cladding.
3. Experiment

3.1. Switch element using double series-coupled microring resonator

The multi-wavelength channel selective switch shown in the upper inset of Fig. 1 was realized by supplying electric current to resonators in each switch element. Using a parallel topology layout of four elements of double series-coupled microring resonators, we demonstrated how the state of individual switch elements can be used to generate five states that correspond to the selection of \( M \) wavelengths where \( M \) ranges from 0 to 4.

The measured switching characteristics at through port are shown in Fig. 5. In the initial stage, no electric current was applied and the resonant wavelengths of individual microrings were slightly different due to fabrication error. Fabrication errors can be reduced to the extent that the drive current would be the same within each pair of rings, (R\(_1\)-R\(_2\)), (R\(_3\)-R\(_4\)), (R\(_5\)-R\(_6\)), and (R\(_7\)-R\(_8\)). By supplying electric current to each double series-coupled microring resonator of switching elements shown in the inset of Fig. 5, we measured through port switching characteristics for zero to four wavelength selection. The power consumption of individual microheaters fabricated on each microring is summarized in Table 1.

Since optical path lengths of all racetrack resonators were designed to be equal, the resonant wavelengths of switch elements are nearly equal within the fabrication error. Therefore, powers
Fig. 2. Perspective view of hitless wavelength channel selective switch.

Fig. 3. Definition of parameters of quadruple series-coupled microring resonator.

Fig. 4. Optical microscope image of quadruple series-coupled microring resonator with heaters.
Fig. 5. Four wavelengths channel selective switching spectrum of through port response (Double-series coupled microring WSS).

Table 1. Power consumption of individual resonators (4~0λ selection). The number pairs in the parenthesis indicate the supplied electric power of individual microring pairs indicated in the top line of each column. ON and OFF indicate the switching status of each switch element.

| Initial state | SW#1 (R₁, R₂) | SW#2 (R₃, R₄) | SW#3 (R₅, R₆) | SW#4 (R₇, R₈) |
|---------------|----------------|----------------|----------------|----------------|
| 4λ selection  | (0, 2.8) ON    | (0, 45) ON     | (39, 196) ON   | (39, 53) ON    |
| 3λ selection  | (0, 39) OFF    | (0, 45) ON     | (39, 196) ON   | (39, 53) ON    |
| 2λ selection  | (0, 39) OFF    | (0, 77) OFF    | (39, 196) ON   | (39, 53) ON    |
| 1λ selection  | (0, 39) OFF    | (0, 77) OFF    | (39, 330) OFF  | (39, 53) ON    |
| 0λ selection  | (0, 39) OFF    | (0, 77) OFF    | (39, 196) OFF  | (39, 132) OFF  |

(unit: mW)
to individual switch elements were increased from $\lambda_1$ to $\lambda_4$ shifting the resonant wavelengths to be equal in spacing.

In Fig. 5, measured through port responses were independently displayed by shifting fire spectra by 40dB for clarity. This is because the flat parts of through port responses are almost the same and the change of spectrum could not be shown clearly if all responses are displayed in the same frame of figure.

The power levels of flat (off-resonant) parts of individual responses are almost equal, and the fiber-to-fiber insertion loss of each measured characteristic was approximately 18dB. This loss is mostly caused by the coupling loss resulting from the spot size mismatch, because the width and height of busline waveguide were 1.3$\mu$m and 1.3$\mu$m, respectively. This loss can be improved by inserting a spot size converter at the input/output ends.

When each wavelength channel was selected (ON-state), the measured dip of through port response was greater than -15dB. This value was equal to the extinction ratio. For the measured zero wavelength selection switching characteristic, the loss of OFF-state in the through port response was about 3.5dB. This loss can be reduced through optimizing coupling efficiency between the bus-line and the ring resonator and by adopting high-order series-coupling. Similar switching characteristics were also obtained for TM polarization.

Fig. 5 shows that a double peak appeared in the dip of through port response. This double peak is caused by the strong coupling efficiency between resonators. If the resonator involves some amount of propagation loss, the optimum level of coupling efficiency is different for the drop port and the through port. Therefore, if the coupling efficiency between resonators is designed to optimize the drop port response for the box-like spectrum shape, the coupling efficiency is stronger than the optimum coupling efficiency for the through port response, which can provide a deep and single dip in the spectrum. In our device, since the resonator’s propagation loss of resonator was 0.1-0.2 dB/round, we designed the coupling efficiency to optimize the drop port response for the box-like spectrum shape ($K_0=0.2$, $K_1=0.02$). Therefore, the coupling efficiency was stronger than the optimum coupling efficiency for the through port response, and a double peak appeared in the through port response.

In Fig. 5 the FSR was 2nm, but this does not mean that the number of wavelength channels is limited to several wavelengths. The FSR of hitless WSS has been shown to be easily expanded by the Vernier effect using two different ring radii [14]. Specifically, in Ref. [14], the FSR was expanded to 26nm from the original FSR of 2nm and the expansion ratio can be increased by controlling the ratio of the ring radii. Since the purpose of the current paper is to demonstrate the operation of a multi-wavelength selective switch by quadruple series coupling, we chose not to adopt the Vernier structure.

The measured four wavelength selective switching spectrum for drop port response is shown in Fig. 6. The four peaks in Fig. 6 correspond to the four switching elements shown in the inset of Fig. 6. The ON-states of $\lambda_1$, $\lambda_2$, $\lambda_3$ and $\lambda_4$ were realized by supplying the amount of current shown in Fig. 6 to individual rings. The separation between channels was about 0.5nm. The crosstalk at $\lambda=1549.38$nm ($\lambda_1$) was -30.2dB. The shape factor, defined by the ratio of -1dB bandwidth to -10dB bandwidth, was 0.5 and the full width at half maximum (FWHM) bandwidth of $\lambda_4$ was 0.11nm. Similar switching characteristics were also obtained for TM polarization except for the PD$f$ (polarization dependence of resonant wavelength) of 0.23nm. In this measurement, the polarization state of input light was fixed using a polarization maintaining fiber. Since the peak power of orthogonal polarization is about -20dB smaller than that of the main peak ($\lambda_1$, $\lambda_2$, $\lambda_3$ and $\lambda_4$), the polarization rotation in the ring resonator is very small.

We also measured the switching characteristics of four switching states representing zero to three wavelength selections, respectively. Since the measured results were almost similar to the two wavelength selective switching characteristics, only the measured two wavelength
Fig. 6. Four wavelengths selective switching spectrum of drop port response (Double-series coupled microring WSS).

Fig. 7. Two wavelength selective switching spectrum of drop port response (Double-series coupled microring WSS).
selective switching spectrum is shown in Fig. 7. In the ON-state of all wavelengths, the OFF-states of $\lambda_1$ and $\lambda_2$ were realized by supplying electric current to $R_2$ (63mW) and $R_3$ (84mW). However, an unintended wavelength shift of 0.23nm was observed due to thermal interference. Therefore, the extinction ratio at $\lambda=1549.38\text{nm}$ ($\lambda_1$) and $\lambda=1549.84\text{nm}$ ($\lambda_2$) was reduced to 14.7dB and 14.6dB, respectively. This thermal interference can be reduced by forming grooves between switching elements. The switching crosstalks at $\lambda_1$ and $\lambda_2$ were -7.58dB and -6.78dB, respectively. Similar switching characteristics were also obtained for TM polarization.

The switching time of the double series coupled WSS is available in Ref. [14]. The fall time of double series coupled WSS with a Ta$_2$O$_5$ core was measured to be 15$\mu$s [14], which was a hundred-fold faster than that of the device made of polyimide core [13].

3.2. Switch element using quadruple series-coupled microring resonator

To improve the shape factor, we used the quadruple series-coupled microring instead of the double series-coupled microring for the switch element. The measured switching characteristics at through port are shown in Fig. 8. In the initial stage, no electric current was supplied and the resonant wavelengths of individual microrings were slightly different due to fabrication error. By supplying electric current to each quadruple series-coupled microring resonator of switch elements shown in the inset of Fig. 8, we measured through port switching characteristics corresponding to the selection of zero to three wavelengths. Table 2 summarizes the power consumption of individual microheaters fabricated on each microring. Fig. 8 displays the measured through port responses by shifting four spectra vertically by 20dB for clarity. The flat (off-resonant) part of individual responses are almost the same, and the fiber-to-fiber insertion loss of each measured characteristic was approximately 20dB. This loss is mostly caused by the coupling loss resulting from spot size mismatch, because the width and height of the busline waveguide were 1.3$\mu$m and 1.3$\mu$m, respectively. When each wavelength channel was selected (ON-state), the measured dip of through port response was greater than -10dB. This value was equal to the extinction ratio. The measured switching characteristics of zero wavelength selection showed the loss of through port response in the OFF-state at about 1.35dB, which is a 1.7dB reduction compared to the double series-coupled microring resonator switch [14]. Similar switching characteristics were also obtained for TM polarization.

Fig. 8 shows that the spectrum responses of three switching elements were all different. In this device, the coupling efficiency $K_2$ was designed to be slightly different for all three switching elements ($K_0=0.5$, $K_1=0.04$, $K_2=0.017$, 0.018, 0.019), because the theoretical value of optimum coupling efficiency involved a small amount of ambiguity.

The measured three wavelength selective switching spectrum for drop port response is shown in Fig. 9. The three peaks in Fig. 9 correspond to the three switching elements shown in the inset of Fig. 9. First, the resonant wavelengths of individual resonators were not equal due to fabrication error. The ON-states of $\lambda_1$, $\lambda_2$, and $\lambda_3$ were realized by supplying a small amount of current to individual rings as shown in Fig. 9. The crosstalk at $\lambda=1549.29\text{nm}$ ($\lambda_1$) was -51.5dB. The shape factor was 0.65 and the FWHM bandwidth of $\lambda_2$ was 0.15nm. Similar switching characteristics were also obtained for TM polarization except for a PD$\lambda$ (polarization dependence of resonant wavelength) of 1.13nm. In this measurement, the polarization state of input light was fixed using a polarization maintaining fiber. Since the peak power of orthogonal polarization is about -40dB smaller than that of the main peaks ($\lambda_1$, $\lambda_2$ and $\lambda_3$), the polarization rotation in the ring resonator was very small.

We also measured the switching characteristics of two and zero wavelength selection. Since the measured results were similar to those of one wavelength selection, only the measured one wavelength selective switching spectrum is shown in Fig. 10. After realizing once the state of all ON-state, the OFF-states of $\lambda_2$ and $\lambda_3$ were realized by supplying electric power to
Fig. 8. Three wavelength channel selective switching spectrum of through port response (Quadruple-series coupled microring WSS).

Table 2. Power consumption of individual resonators (3~0 λ selection). The combination of numbers in the parenthesis indicate the supplied electric power of individual microrings indicated in the top line of each column. ON and OFF indicate the switching status of each switching element.

| Initial state | SW#1 (R₁-R₄) | SW#2 (R₅-R₈) | SW#3 (R₉-R₁₂) |
|---------------|---------------|---------------|---------------|
| 3λ selection  | (57, 28, 0, 431) ON | (96, 32, 36, 120) ON | (146, 0, 0, 75) ON |
| 2λ selection  | (57, 28, 0, 431) ON | (96, 32, 36, 120) ON | (146, 0, 57, 400) OFF |
| 1λ selection  | (57, 28, 0, 431) ON | (96, 32, 185, 217) OFF | (146, 0, 57, 400) OFF |
| 0λ selection  | (57, 28, 57, 602) OFF | (96, 32, 185, 217) OFF | (146, 0, 57, 400) OFF |

(unit: mW)
Fig. 9. Three wavelength selective switching spectrum of drop port response (Quadruple-series coupled microring WSS).

Fig. 10. One wavelength selective switching spectrum of drop port response (Quadruple-series coupled microring WSS).
However, an unintended wavelength shift of 0.58 nm was observed due to thermal interference. This thermal interference can be reduced by forming grooves between switching elements. The extinction ratio at $\lambda = 1550.64$ nm ($\lambda_3$) was 39.6 dB. The switching crosstalk at $\lambda_3$ was -25.0 dB. These extinction ratio and switching crosstalk values showed a marked improvement (24.9 dB and 18.3 dB, respectively) in drop port characteristics over the double series coupled microring resonator switch. Similar switching characteristics were also obtained for TM polarization.

| $\lambda$ | Extinction ratio (dB) | Switching crosstalk (dB) | Thermal interference (nm) | Total power consumption (mW) |
|-----------|----------------------|--------------------------|---------------------------|-----------------------------|
|           | max       | min       | max       | min       | max       | min       | max       | min       |                          |
| $4\lambda$ | Double    | -         | -         | -         | -         | -         |                  | 362.8                  |
|           | Quadruple | -         | -         | -         | -         | -         |                  | 999                    |
| $3\lambda$ | Double    | 37.0      | -9.56     | 0.14      | 0.11      | 0.15      |                  | 423                    |
|           | Quadruple | -         | -         | -         | -         | -         |                  | 1256                   |
| $2\lambda$ | Double    | 19.7      | 14.6      | -6.78     | -7.58     | 0.23      | 0.22      | 462                    |
|           | Quadruple | -         | -         | -         | -         | -         |                  | 1256                   |
| $1\lambda$ | Double    | 15.8      | 10.2      | -5.87     | -10.9     | 0.36      | -         | 593                    |
|           | Quadruple | 39.0      | 31.6      | -19.3     | -25.0     | 0.49      | -         | 1473                   |
| $0\lambda$ | Double    | 29.5      | 9.57      | -6.23     | -11.1     | -         | -         | 785                    |
|           | Quadruple | 43.7      | 34.1      | -24.5     | -28.9     | -         | -         | 1977                   |

Table 3. Comparison of drop port responses between double and quadruple series coupled microring WSS

| $\lambda$ | Extinction ratio (dB) | Loss of OFF-state (dB) | Thermal interference (nm) | Total power consumption (mW) |
|-----------|----------------------|------------------------|---------------------------|-----------------------------|
|           | max       | min       | max       | min       | max       | min       | max       | min       |                          |
| $4\lambda$ | Double    | -         | -         | -         | -         | -         |                  | 374.8                  |
|           | Quadruple | -         | -         | -         | -         | -         |                  | 1071                   |
| $3\lambda$ | Double    | 11.7      | 3.71      | 0.09      | 0.08      | 0.10      |                  | 411                    |
|           | Quadruple | -         | -         | -         | -         | -         |                  | 1203                   |
| $2\lambda$ | Double    | 15.5      | 11.7      | 3.95      | 3.71      | 0.19      | 0.18      | 443                    |
|           | Quadruple | 11.2      | 1.50      | 0.33      | 0.29      | 0.31      |                  | 1403                   |
| $1\lambda$ | Double    | 15.5      | 11.7      | 3.95      | 3.71      | 0.36      | -         | 577                    |
|           | Quadruple | 13.4      | 11.2      | 1.62      | 1.50      | 0.57      | -         | 1649                   |
| $0\lambda$ | Double    | 15.5      | 11.7      | 3.95      | 3.31      | -         | -         | 656                    |
|           | Quadruple | 13.4      | 8.02      | 1.62      | 1.37      | -         | -         | 1877                   |
Finally, the comparisons of drop and through port responses between double and quadruple series coupled microring WSS are shown in Tables 3 and 4. These tables clearly show that the extinction ratio and the switching crosstalk of quadruple series coupled microring WSS are better than those of double series coupled microring WSS.

3.3. Effect of phase-control in parallel topology layout channel selective switch

Using a parallel topology of switch elements and incorporating a phase-control unit between switch elements, as shown in the inset of Fig. 11, we can realize some novel functionality in switches: wavelength channel selective with close channel spacing, optical code division multiplexing (OCDM) [17], and so on. The principle of these switches is the path control of certain wavelength channels using the phase shift difference between two arms of busline waveguides as shown in the inset of Fig. 11. In this work, we demonstrated the use of phase control to conduct path control. The length of phase-control unit was 1505µm, and the amount of the phase shift was π by increasing the temperature about 50 degrees.

First, we adjusted the resonant wavelength of SW#1(λ1) to that of SW#2(λ2). After tuning the resonant wavelengths of SW#1 and SW#2, we controlled the phase between switches. Figures 11 and 12 show the drop port and through port responses before and after the phase shift of π. In Fig. 11, the wavelength channel splits into two peaks by the phase shift of π. This is the same phenomenon seen in the parallel coupling of the single ring resonator reported in Ref. [18]. In addition, Fig. 12 demonstrates the ON/OFF switching of amplitude via phase shift. Therefore, it can be concluded that phase control is necessary for proper operation of a multi-wavelength channel selective switch.

![Fig. 11. Adjacent two wavelength channel selective switching spectrum of drop port response (Double-series coupled microring WSS).](image)
4. Conclusion

Since this hitless WSS can be used in scalable integration, multi-wavelength and multi-port channel selective switch matrices with more than four wavelengths can be created. Thus we demonstrated the fundamental switch circuits for optical cross-connect. In addition, we clarified that the hitless WSS based on a quadruple series-coupled microring resonator was more suitable as a switch element than the double series-coupled device. The thermal interference can be reduced by optimizing the layout of the electrodes and by incorporating a buried vacuum cladding structure [19] as a thermal isolation region.

Since the TO coefficient of this device is about 0.011 nm/K, which is almost the same as that of silica waveguide filters, changes in ambient temperature can cause a shift of wavelength in the ON state. However, it does not affect the OFF state.

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