High Index Contrast Optical Waveguides and Their Applications to Microring Filter Circuit and Wavelength Selective Switch

Yasuo KOKUBUN^{†a)}, *Fellow*

SUMMARY Utilizing the small bending radius of high index contrast optical waveguides, ultra-compact optical devices such as waveguide branch, Mach-Zehnder interferometer, arrayed waveguide grating filter, microring resonator filter, and so on can be realized. We have proposed and demonstrated a vertically coupled microring resonator as an Add/Drop filter, and recently realized a hitless wavelength channel selective switch (hitless tunable Add/Drop filter) using Thermo-Optic (TO) effect of double series coupled dielectric microring resonator. Using a high-index dielectric material as the core, the response time was reduced to 105 μ s (rise time) and 15 μ s (fall time), which are fifteen-fold and hundred-fold faster than that of polymer material, and the reproducibility by the heat cycle test was also improved to less than 0.01 nm. The tuning range of wavelength selective switch was expanded to 13.3 nm using the Vernier effect, and a large extinction ratio of more than 20 dB was realized. In this review, the principle and recent progress of microring resonator based wavelength selective switch will be introduced and some basic switching circuits required to optical cross connect will be discussed.

key words: high index contrast, microring resonator, wavelength selective switch, thermo-optic effect, Vernier effect, optical cross connect

1. Introduction

From the last several years of 20th century, special waveguides with extremely large index difference between the core and the cladding have been attracting considerable attention of researchers in optoelectronics. These waveguides are called high index contrast (HIC) waveguides [1], and have much higher index contrast than that of optical fibers and PLC's. Owing to their ultra-small bending radius, HIC waveguides are advantageous to ultra-compact and ultra-dense photonic integrated circuits.

The recent research activities on HIC waveguides can be divided into two types depending on the refractive index of core: one is the so-called silicon wire with the core index of 3.5 [2] and the other is the moderate high index material with the core index around 2.0 [3], [4], such as Ta₂O₅ ($n=2.3$), Ta₂O₅-SiO₂ with high Ta₂O₅ content ($n=1.65$ – 1.8), SiN ($n=2.0$), and SiON with high SiN content ($n=1.75$ – 1.9). The silicon wire is usually fabricated on a silicon-on-insulator (SOI) wafer and the waveguide pattern is formed using the electron beam writer. On the other hand, HIC waveguides using moderate high index materials such as Ta₂O₅-SiO₂ and SiON can be fabricated using the thin film deposition and ordinary UV lithography technique. In addition, these HIC waveguide components can be integrated

into a three-dimensional configuration, enabling dense integration of large scale circuit.

Utilizing the silicon wire ($\Delta=45\%$), ultra-compact waveguide components such as bends and branches, microring resonator (MRR) filter, Mach-Zehnder interferometer (MZI) filter, arrayed waveguide grating (AWG) filter, modulator and so on, have been realized within the footprint of several μm^2 to several tens μm^2 .

On the other hand, we have proposed and demonstrated a vertically coupled microring resonator (VC-MRR) Add/Drop filter using high index core materials such as Ta₂O₅-SiO₂ [3]–[13], [15], [19], polymers [14], [17], SiN [16], [18] and SiON [20]. The ultra-compact ring resonator can be realized by the HIC waveguide ($\Delta=34$ – 37%) and the vertically coupled configuration, where a microring resonator with a few tens micron radius is stacked on the crossing point of cross-grid busline waveguides. Owing to the cross-grid topology and greater freedom of layout design of elements, the vertically coupled microring resonator filter can serve as the building block of many integrated filter circuits utilizing series coupled, parallel coupled, and cascaded configurations. In addition, we recently developed a new wavelength selective switch (WSS) using the series coupling of TO tunable microring resonators [21], [22].

In this review, the advantageous characteristics and drawbacks of HIC are discussed first. Next, the vertically coupled microring is introduced and the history of the research on microring resonator filters is briefly reviewed. However, since the detailed techniques and advantages of VC-MRR, such as the fabrication process [23], multilevel busline [15], center wavelength trimming and tuning [11], [14], [16], [17], [20] and a new integration technology with vacuum cladding [18], have already been discussed in the author's previous review paper [24], the details of VC-MRR will not be discussed in this review. Instead, a new wavelength selective switch using the series coupling of tunable microring resonators and some switching circuits, which can serve as an element of optical cross-connect, will be introduced. Silicon wire components will not be discussed in this review, since they have already been discussed in other review papers.

2. High Index Contrast Optical Waveguides

Some lightwave circuits such as interferometer and resonator are needed to realize the filtering function, because optical waveguide itself can serve as only the guiding struc-

Manuscript received October 5, 2006.

[†]The author is with the Graduate School of Engineering, Yokohama National University, Yokohama-shi, 240-8501 Japan.

a) E-mail: yokubun@ynu.ac.jp

DOI: 10.1093/ietele/e90–c.5.1037

ture. Since the optical waveguide must be bent in order to store the long light wiring in the substrate, the size of optical device and circuit is limited by the bending radius of optical waveguide. The allowable bending radius of optical waveguide is determined by the bending loss, and it depends on the refractive index difference (index contrast in other words) between the core and the cladding. Classifying optical waveguides using the parameter called relative index difference Δ , it is 1% or less in single mode optical fiber, at largest 4% in silica-based waveguides, and about 8% even in semiconductor optical waveguides.

However, the optical waveguide with very large index difference like 20–45% have recently appeared, and this is called high index contrast (HIC for short) optical waveguide. The bending radius of conventional low index contrast optical waveguide is about several mm to several cm. In contrast, miniature bending radius less than $10\mu\text{m}$ becomes possible using HIC waveguide. In this chapter, some features of HIC waveguides advantageous to ultra-compact optical devices are introduced.

2.1 Definition and Features of HIC Waveguides

The definition of relative index difference Δ is given by

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \quad (1)$$

where n_1 and n_2 are the refractive indices of the core and the cladding, respectively. This definition implies that the maximum value of Δ is not 100% but 50% in the limit of $n_1 \rightarrow \infty$. Figure 1 shows the relation between the index contrast Δ and the refractive index of the core n_1 when the cladding is SiO_2 ($n_2=1.45$) and the air ($n_2=1.0$).

It can be seen from this figure that an ultra-high index contrast of $\Delta=35\text{--}45\%$ can be realized using high index dielectric materials such as SiON and $30\%\text{Ta}_2\text{O}_5\text{-SiO}_2$ with $n_1=1.8\text{--}2.3$ and silicon with $n_1=3.5$. Even when $n_1=1.8$, the index contrast reaches 35% using air cladding. This value

Fig. 1 Relation between relative refractive index difference and core index.

of index contrast larger than 35% is quite huge in comparison with several % of the conventional optical waveguide. The high index contrast enables the miniaturization of single mode core size, bending radius, the coupling length of directional coupler, and so on.

In particular, the drastic reduction of the bending radius contributes to the miniaturization of optical circuit. The relation between the maximum single mode core size and Δ is shown in Fig. 2 for the case of square core. The single mode core size is about $4\mu\text{m}$ for $\Delta=1.5\%$, while it is $1\mu\text{m}$ or less when Δ is greater than 20%. However, the reduction is only one order of magnitude.

On the other hand, Fig. 3 shows the relation between the bending radius for which the allowable radiation loss is 0.1 dB/round and the index contrast Δ , assuming the square core and the maximum single mode condition. This result was calculated using a finite difference mode solver (APSS by Apollo Optics Inc.). It is seen that the allowable bending radius is several mm for the conventional optical waveguide with $\Delta < 3\%$ while it decreases to be less than $100\mu\text{m}$ for $\Delta > 10\%$ and the ultra-compact bending radius of $10\mu\text{m}$

Fig. 2 Relation between maximum single mode core size and relative index difference.

Fig. 3 Relation between minimum bending radius and relative index difference.

Table 1 Combinations of materials used for high index contrast optical waveguides.

Core	Index of core	Cladding ^(*)	Δ	Reference	Ring radius	FSR ^(**)	Core size $w \times t$
GaAs/AlGaAs	~ 3.5	Air ⁽¹⁾	46 %	[25]	5.25 μm	21.6 nm	0.5 μm x 0.45 μm
Poly Si	~ 3.5	Air ⁽¹⁾	46 %	[2]	4 μm	24 nm	0.5 μm x 0.2 μm
Ta ₂ O ₅ -SiO ₂	1.78-1.8	Air ⁽¹⁾	34 %	[3]-[13], [15]	5 μm	37 nm	(1.0-1.5) μm x (1.0-1.5) μm
Si (SOI)	3.5	Air ⁽¹⁾	46 %	[26]	3 μm	24 nm	0.4 μm x 0.4 μm
Hydex TM	1.46 - 1.8	SiO ₂ ⁽²⁾	18 %	[27]	20 μm	~ 10 nm	1.5 μm x 1.5 μm
SiN	1.9-2.0	Air ⁽¹⁾	36-37 %	[18]	5 μm	29 nm	1.2 μm x 0.6 μm
SiON	1.74-1.86	Air ⁽¹⁾	33-36 %	[20]	20 μm	10.3 nm	1.5 μm x 0.9 μm
Polyimide	1.74	Teflon ⁽³⁾	22 %	[14], [17]	10 μm	~ 20 nm	1.5 μm x 1.1 μm

*Index of cladding materials is (1) air ($n_2=1.0$), (2) SiO₂ ($n_2=1.45$), and (3) Teflon ($n_2=1.30$).

**FSR: Free Spectrum Range

Fig. 4 Coupling length of square core directional coupler vs relative index difference assuming silica cladding ($n_2=1.45$).

Fig. 5 Sensitivity of propagation constant against fabrication error of core thickness [19].

or less is possible for $\Delta > 20\%$. Therefore, the reduction of bending radius by three orders of magnitude becomes possible using a high index contrast optical waveguide. It is also seen that the allowable bending radius decreases exponentially (linearly in logarithmic scale) in the region $\Delta > 10\%$ and this shape is different from that for $\Delta < 10\%$. Though it is very difficult to define the boundary of conventional low index contrast and high index contrast, the author has defined HIC waveguide as a waveguide with $\Delta=10\%$ from the specific characteristic of Fig. 3.

Table 1 summarizes some examples of core materials for HIC waveguide and their index contrast. In this table, the ring radius means the radius of ring resonator which is composed of materials described in this table. Although the assumed cladding material in Fig. 3 is SiO₂ while air was used as the cladding in many HICs summarized in Table 1, the ring radius shown in Table 1 almost coincides with the minimum bending radius in Fig. 3. The core sizes in Table 1 also coincide with the maximum core size shown in Fig. 3.

The coupling length of directional coupler is also an important parameter for the miniaturization of optical device as well as the bending radius. The coupling length of directional coupler (shortest coupler length for which the 100% of electromagnetic power shifts from the input waveguide to the other side) is shown in Fig. 4, assuming the square

core just satisfying the single mode condition and the gap of $w_{sm}/2$. The coupling length is also several mm for conventional waveguides with $\Delta < 4\%$, while it is reduced to about 300 μm when $\Delta > 10\%$. However, the coupling length is still 100 μm for $\Delta > 40\%$, which is the reduction of one order of magnitude but not significantly large size reduction in comparison with the bending radius. The coupling length can be shortened to several μm , if a strong coupling is used at the cost of the deterioration of cross talk. It should be noted that the polarization dependence of coupling length becomes greater than 10% when Δ increases over 33%.

Another cautionary note is the fabrication tolerance of high index contrast optical waveguides. Figure 5 shows the change of equivalent refractive index against the variation of core thickness assuming the square core satisfying the single mode condition. In this figure, Δ in the horizontal axis is scaled in the logarithmic scale.

It is seen that the equivalent index becomes sensitive by two orders of magnitude for $\Delta > 20\%$ and by three orders of magnitude for $\Delta > 40\%$ in comparison with conventional low index contrast optical waveguides of $\Delta < 4\%$. This means that a very precise fabrication technique is needed to realize some phase-sensitive devices such as interferometers and resonators using HIC waveguide. In Fig. 5, the unit of

Fig. 6 Perspective view of vertically coupled microring resonator element.

vertical axis is $[\mu\text{m}^{-1}]$, and one may expect that the fabrication tolerance can be relaxed by the reduction of core size of HIC waveguides if the ratio of fabrication error to the core size is constant. However, since the reduction of core size of HIC is only one order of magnitude as shown in Fig. 2, the increase in phase error resulting from the fabrication error is not dissolved by the reduction of the core size. In addition, it should be noted that the polarization dependence of phase error resulting from the fabrication error increases, when Δ exceeds 10%.

The propagation constant of TE and TM polarizations should be equal, when the core cross section is perfectly square (aspect ratio is 1.0) and there is no stress-induced birefringence. In low index contrast optical waveguides, the birefringence does not so rapidly increase even when the core aspect ratio is deviated from 1.0. However, a highly precise fabrication technique is required to control the birefringence by the control of aspect ratio in HIC waveguides.

2.2 Microring Resonators Using HIC Waveguides

Using high index contrast optical waveguides, some ultra-compact optical devices are recently reported, such as wavelength filter, optical interconnects, optical cross connects, and so on. As a wavelength filter, microring resonator utilizing the feature of the minute bending radius is a representative example, and the basic structure of vertically coupled microring resonator developed by the author's group is shown in Fig. 6.

In this stacked structure, a microring resonator with the ring radius of $5\text{--}30\mu\text{m}$ is stacked on the crossing point of cross grid busline waveguides. Since only the resonant wavelength is transmitted to the cross port (drop port in other word) and other wavelength channels are transmitted to the through port, this device can serve as an Add/Drop filter. This device has the following features advantageous to integrated photonic filter circuit.

- (1) Due to the stacked configuration, the upper and lower waveguides can be optimally designed to adjust their roles independently.
- (2) Due to the high index contrast in the upper layer, an ultra-compact ring resonator with a very small radius of 5 to $30\mu\text{m}$, which exhibits the bandwidth of 0.1 to 1.0 nm,

and the free spectral range (FSR) of 10 to 37 nm, is possible. This narrow bandwidth leads to the high Q (1,500–15,000) of the microring resonator filters.

- (3) Due to the ultracompact element and the cross-grid configuration, a dense integration of up to $10^4\text{--}10^5$ devices/ cm^2 is possible.
- (4) The coupling strength between the ring and busline waveguides can be controlled more precisely than the lateral coupling, because vertical separation is achieved via well-controlled deposition, rather than the etching of fine gaps.
- (5) In vertical coupling, the fabrication tolerance of the lateral misalignment between the upper microring and the lower busline waveguide is relaxed (because the overlap of the field profile is maximum at the point of zero offset) and is much less sensitive to the offset than in lateral coupling.
- (6) Desired filter response shape can be synthesized by the series coupled, parallel coupled, and cascaded topologies.
- (7) The individual control of resonant wavelengths of series coupled microring makes it possible to achieve a new function of hitless wavelength channel selective switch.

The combination of core and cladding materials are summarized in Table 1. Among these reported devices, the references [3]–[18] are the vertically coupled type and others are the planar type in which the core and cladding are formed in the same layer.

Note that the cladding in Table 1 means the upper and side cladding, and the lower cladding in most cases are made of SiO_2 because the core layer must be sustained on a substrate (the membrane type is the exception).

The filter response spectrum of single ring resonator, which is expressed by the Lorentzian function, is not satisfactorily good, because the pass band is not flat and the roll-off from the pass band to stop band is not so sharp like the wing of bird, and the cross talk in the stop band is not low enough (about -20 dB). Therefore, the synthesis of filter spectrum response by the combination of several filter elements is required to improve the filter spectrum response. Fortunately a very dense integration of filter elements is possible using the vertically coupled microring resonator, due to its ultra-compact device size and the flexibility of layout resulting from the cross grid topology. This is advantageous to the filter synthesis by the combination of filter elements.

There are three basic topologies in the combinations of ring resonators, (a) cascade connection (cascaded topology), (b) parallel coupling, and (c) series coupling, as shown in Fig. 7.

Table 2 summarizes the advantages and drawbacks of these topologies. One can realize the flattening of pass band and the sharpening of roll-off (box-like response) by the series coupling as shown in Figs. 7(c) and (d). The theoretical filter spectrum of some higher order series coupling is shown in Fig. 8. It should be noted that the flattening of pass band is realized and the cross talk in the stop band is de-

Fig. 7 Basic topologies of combinations of ring resonators.

Table 2 Features of topologies of ring filter circuit.

Topology	Advantages	Drawbacks
Cascading	Expansion of FSR Reduction of crosstalk	Loss increase due to center wavelength mismatch
Series coupling	Expansion of FSR Flat-top pass band	Small fabrication tolerance
Parallel coupling	Flat-top pass band	Small fabrication tolerance

Fig. 8 Theoretical filter spectrum response of series coupled microring resonator.

creased without increasing the loss in the pass band by the series coupling. However, these optimized filter response is obtained by the optimized values of coupling efficiency between the busline waveguide and microring and between microring resonators. Therefore, these optimized coupling coefficients are assumed in Fig. 8.

On the other hand, the parallel coupling shown in Fig. 7(b) was applied to an interleaving filter, which can similarly realize the box-like filter response and alternately di-

vides wavelength channels in through port and drop port.

In the previous section, we have seen that the sensitivity of phase error due to the fabrication error increases in high index contrast optical waveguides. For this reason, the error of resonant wavelength reaches 2–3 nm. This problem can be solved by the trimming technique using UV light, of which the basic phenomena of high UV sensitivity of SiN and SiON films were discovered by the author's group [16], [20]. Using this technique, a wide range trimming over 12 nm was demonstrated [16].

On the other hand, a wide range wavelength tuning over 9 nm was demonstrated using the large thermo-optic (TO) effect of polymer core [17]. Although the TO coefficient of dielectric materials such as SiON and Ta₂O₅-SiO₂ is one order of magnitude smaller than that of polymer materials, the tuning wavelength range and free spectrum range (FSR) can be expanded using the Vernier effect of series couple microrings with different ring radius. The group of Little Optics Inc. demonstrated a wide range tunable microring filter over 40 nm using the Vernier effect [21]. Other group utilized a double cascaded tunable ring resonator as an external reflector of tunable laser, and demonstrated 160 nm tuning range of lasing wavelength [29].

3. Hitless Wavelength Selective Switch Using Microring Resonators

3.1 Principle of Hitless Wavelength Selective Switch

Using the thermo-optic effect, we can control the resonant wavelength of microring resonator. We have demonstrated a wide range tuning of 9.4 nm using a large thermo-optic effect of polymer material [14]. However, this tunable filter has a problem of blocking other wavelength channels during the tuning as shown in Fig. 9(a). In addition, the direction of wavelength shift is limited to shorter wavelength side, corresponding to the negative TO coefficient of polymer core.

To solve this problem, we proposed and demonstrated a hitless wavelength selective switch, of which the operation principle is shown in Fig. 9(b). This device consists of a series coupled tunable microring resonators, as shown in Fig. 10. When resonant wavelengths of resonators are made equal by controlling individual resonant wavelengths of a series coupled microring resonator, only the resonant wavelength channel can be transmitted to the drop port (ON-state). On the other hand, when resonant wavelengths of resonators are different, no wavelength channel transmits to the drop port (OFF-state). Therefore, the resonant wavelength can be shifted to another wavelength channel without blocking other wavelength channels.

3.2 Demonstration of Hitless Wavelength Selective Switch

The structure of hitless tunable microring resonator is shown in Fig. 10. Busline waveguides and ring resonator waveguides were formed in the same layer to simplify the fabrication process. Si was used as the substrate. The core

Fig. 9 Comparison of operational trajectory of resonant peaks.

Fig. 10 Structure of element of hitless wavelength selective switch using series coupled tunable microring resonators.

material and the upper cladding material were sputter deposited 17 mol%Ta₂O₅-SiO₂ ($n=1.657$ @ $\lambda=1550$ nm) and SiO₂ ($n=1.446$ @ $\lambda=1550$ nm), respectively. The lower cladding material was thermally-grown SiO₂ ($n=1.442$ @ $\lambda=1550$ nm). The busline waveguide and microring resonator were laterally coupled with the gap width of $1.0\mu\text{m}$. The coupling efficiency between busline and microring was designed to 0.25 and that between microrings was designed to 0.001–0.2 by changing the overlap length of the straight part of racetrack resonator. The core height and width were $1.2\mu\text{m}$ and $1.4\mu\text{m}$, respectively. The round trip length of racetrack resonator was $700\mu\text{m}$, which corresponds to the FSR of 2.1 nm. The microheater was made of Cr.

By supplying electric current to each Cr thin film heater above individual ring resonators separately, we measured hitless tuning characteristics [22]. When the electric current was changed according to the sequence shown in Fig. 11, the measured TM-mode drop port response varied as shown in Fig. 11, and the through port response varied as shown in Fig. 12, respectively. In the initial stage when no electric current was supplied, the resonant wavelengths of individual microrings were slightly different due to the fabrication error. When an electric current was supplied to the microheater above the Ring#2, the response reached ON-state. The change of TE-mode response was almost the same as

Fig. 11 Measured hitless wavelength selective switching characteristics of drop port of dielectric core device.

Fig. 12 Measured hitless wavelength selective switching characteristics of through port of dielectric core device.

that of TM-mode response except for the polarization dependence of center wavelength (1.25 nm). The split of dip in the through port response at the ON-state was observed as shown in Fig. 12. This is because the coupling coefficient between ring resonators was stronger than the critical coupling condition. In this device, the coupling coefficient between resonators was almost equal to the critical coupling condition for drop port response. However, the critical coupling condition for drop port is stronger than that for through port when the resonator suffers propagation loss [28].

OFF-state was realized by increasing the electric current supplied to the microheater above Ring#2. The ON-state in the TM-mode drop port response appeared again when an electric current of 21.4 mA was supplied to Ring#1 and 22.5 mA was supplied to Ring#2. The ON-state in the TE-mode drop port response appeared again under the same condition as for the TM-mode. Also by supplying an electric current of 22.9 mA to Ring#1 and 24.1 mA to Ring#2, a sharp drop appeared again at the wavelength of 1550.95 nm in the TM-mode through port response and by

Fig. 13 Wavelength switching of double series coupled ring with different ring radii (TE-mode, through port response).

supplying an electric current of 23.8 mA to Ring#1 and 24.8 mA to Ring#2, a sharp drop appeared again in the TE-mode through port response. The power consumption was evaluated to be 136 mW. From these figures, it is seen that a hitless wavelength selective switch was successfully demonstrated.

In the drop port response, the extinction ratios were 38.8 dB for TM-mode and 38.0 dB for TE-mode, respectively. In the through port response, the extinction ratios were 16.5 dB for TM-mode and 14.7 dB for TE-mode, respectively. The switching crosstalk for drop port was -20.3 dB for TM-mode and -21.1 dB for TE-mode. However, the switching loss for through port at the OFF-state was -3 dB. This loss can be reduced by optimizing the coupling efficiency between the busline and the ring resonator. In this measurement, fiber-to-fiber insertion loss was approximately -20 dB due to the large spot size mismatch between the busline waveguide and single mode fiber.

In the drop port response, the tuning ranges were 1.18 nm for TM-mode and 1.21 nm for TE-mode, respectively. In the through port response, the tuning ranges were 1.34 nm for TM-mode and 1.47 nm for TE-mode, respectively. To increase the FSR and the tuning range, we fabricated a wavelength selective switch using two microrings with different curvature radius of racetrack resonator (105 μm and 95 μm). As a result, we successfully expanded the FSR to 23.2 nm and the tuning range to 13.3 nm in the TE-mode through port response due to the Vernier effect as shown in Fig. 13. It should be noted that the center wavelength can be shifted to either longer or shorter wavelength side by changing the ring resonator for heating. Similar switching characteristics were also obtained for TM polarization. In this measurement, an LED was used as a light source and an EDFA was used to amplify the power.

Figure 14 shows the measured temporal response when the current was switched off. This temporal response was measured at the wavelength of 1548.45 nm, which corresponds to the peak wavelength of ON-state for TE mode

Fig. 14 Temporal response of drop port switching.

Fig. 15 Multi-wavelength channel selective switch with cascaded arrangement.

in the drop port response. After supplying an electric current of 20 mA to the Ring#1, the output power from the drop port was switched to the OFF-state. The fall time was 15 μs , which is hundred times faster than the TO tunable filter made of polymers [21]. On the other hand, the rise time from 0 mA (initial state) to 7.6 mA (ON-state) at $\lambda=1548.45$ nm was 0.105 ms. This value was larger than the fall time of 15 μs , because the sifted wavelength (0.1 nm) induced by the TO effect was smaller than that of the case from ON-state to OFF-state (0.96 nm).

3.3 Multi-Wavelength Channel Selective Switch

We fabricated a multi-wavelength channel selective switch shown in Fig. 15 by cascading the hitless wavelength selective switch shown in Fig. 10.

By applying electric current to each Cr thin film heater above individual ring resonators separately, we measured multi-wavelength switching characteristics. When the electric current was changed, the measured drop port responses varied as shown in Figs. 16–18.

In the initial stage when no electric current was applied, the resonant wavelengths of individual microrings were slightly different due to the fabrication error. By applying the electric current of 22.7 mA to Ring#1 and 11.8 mA to Ring#3, sharp peaks appeared at the wavelengths of 1548.28 nm and 1548.79 nm in the drop port response as shown in Fig. 16. Other two peaks at $\lambda=1549.17$ nm and 1549.66 nm are the slightly mixed orthogonal polarization

Fig. 16 Drop port filter response when two wavelength channels were selected.

Fig. 18 Drop port filter response when no wavelength channel was selected.

Fig. 17 Drop port filter response when one wavelength channel was selected.

responses resulting from the small misalignment of polarization axis at the input port.

By applying the electric current of 15.5 mA to Ring#2 and 11.1 mA to Ring#3, a sharp peak appeared at the wavelength of 1548.23 nm in the drop port response and the peak at $\lambda=1548.79$ nm disappeared as shown in Fig. 17. By applying the electric current of 18 mA to Ring#2 and 15.1 mA to Ring#4, no sharp peak appeared in the drop port response as shown in Fig. 18.

Comparing the peak transmittance of Fig. 16 (two wavelengths selected) with that of Fig. 18 (no wavelength selected), the extinction ratio and the switching crosstalk at $\lambda=1548.28$ nm (λ_2) were 22.3 dB and -10.8 dB, respectively. The separation between two channels was 0.51 nm. Comparing Fig. 16 with Fig. 17, the extinction ratio and the switching crosstalk at $\lambda=1548.79$ nm (λ_1) were 24.6 dB and -14 dB, respectively.

4. Conclusion

We have proposed and demonstrated a hitless wavelength selective switch utilizing the series coupled microring resonator and individual control of resonant wavelength of coupled resonators. The switching crosstalk and wavelength range can be improved by the higher order series coupling and Vernier effect. Multiport switch matrix will be possible by increasing the number of busline waveguides and switching elements. This type of multi-wavelength hitless switch matrix with large scale integration will play very important role in the next generation optical cross-connect utilizing wavelength routing.

Acknowledgments

This work was supported in part by Grant-in-Aid for Scientific Research on Priority Areas No.17068009 from the Ministry of Education, Culture, Sports, Science and Technology, and the 21st Century COE Program in the Ministry of Education, Culture, Sports, Science and Technology.

References

- [1] C. Manolatou, S.G. Johnson, S. Fan, P.R. Villeneuve, H.A. Haus, and J.D. Joannopoulos, "High-density integrated optics," *J. Light-wave Technol.*, vol.17, no.9, pp.1682–1692, Sept. 1999.
- [2] B.E. Little, J.S. Foresi, G. Steinmeyer, E.R. Thoen, S.T. Chu, H.A. Haus, E.P. Ippen, L.C. Kimerling, and W. Greene, "Ultra-compact Si/SiO₂ microring resonator optical channel dropping filters," *IEEE Photonics Technol. Lett.*, vol.10, no.4, pp.549–551, April 1998.
- [3] B.E. Little, S.T. Chu, W. Pan, D. Ripin, T. Kaneko, Y. Kokubun, and E. Ippen, "Vertically coupled glass microring resonator channel dropping filters," *IEEE Photonics Technol. Lett.*, vol.11, no.2, pp.215–217, Feb. 1999.
- [4] S.T. Chu, B.E. Little, W. Pan, T. Kaneko, S. Sato, and Y. Kokubun, "An eight-channel add-drop filter using vertically coupled microring resonators over a cross grid," *IEEE Photonics Technol. Lett.*, vol.11, no.6, pp.691–693, June 1999.

- [5] S.T. Chu, W. Pan, S. Sato, T. Kaneko, B.E. Little, and Y. Kokubun, "Wavelength trimming of a microring resonator filter by means of a UV sensitive polymer overlay," *IEEE Photonics Technol. Lett.*, vol.11, no.6, pp.688–690, June 1999.
- [6] S.T. Chu, W. Pan, S. Suzuki, B.E. Little, S. Sato, and Y. Kokubun, "Temperature insensitive vertically coupled microring resonator Add/Drop filters by means of a polymer overlay," *IEEE Photonics Technol. Lett.*, vol.11, no.9, pp.1138–1140, Sept. 1999.
- [7] S.T. Chu, B.E. Little, W. Pan, T. Kaneko, and Y. Kokubun, "Cascaded microring resonators for crosstalk reduction and spectrum cleanup in Add-Drop filters," *IEEE Photonics Technol. Lett.*, vol.11, no.11, pp.1423–1425, Nov. 1999.
- [8] S.T. Chu, B.E. Little, W. Pan, T. Kaneko, and Y. Kokubun, "Second-order filter response from parallel coupled glass microring resonators," *IEEE Photonics Technol. Lett.*, vol.11, no.11, pp.1426–1428, Nov. 1999.
- [9] B.E. Little, S.T. Chu, W. Pan, and Y. Kokubun, "Microring resonator arrays for VLSI photonics," *IEEE Photonics Technol. Lett.*, vol.12, no.3, pp.323–325, March 2000.
- [10] Y. Kokubun, S. Kubota, and S.T. Chu, "Polarisation independent vertically coupled microring resonator filter," *Electron. Lett.*, vol.37, no.2, pp.90–92, Feb. 2001.
- [11] S. Suzuki, Y. Hatakeyama, Y. Kokubun, and S.T. Chu, "Precise control of wavelength channel spacing of microring resonator Add/Drop filter array," *IEEE/OSA J. Lightwave Technol.*, vol.20, no.4, pp.745–750, April 2002.
- [12] T. Kato, S. Suzuki, Y. Kokubun, and S.T. Chu, "Coupling loss reduction of vertically coupled microring resonator filter by spot size matched busline waveguides," *Appl. Opt.*, vol.41, no.21, pp.4394–4399, July 2002.
- [13] Y. Yanagase, S. Suzuki, Y. Kokubun, and S.T. Chu, "Box-like filter response and expansion of FSR by vertically triple coupled microring resonator filter," *IEEE/OSA J. Lightwave Technol.*, vol.20, no.8, pp.1525–1529, Aug. 2002.
- [14] Y. Yanagase, S. Yamagata, and Y. Kokubun, "Wavelength tunable polymer microring resonator filter with 9.4 nm tuning range," *Electron. Lett.*, vol.39, no.12, pp.922–924, June 2003.
- [15] Y. Hatakeyama, T. Hanai, S. Suzuki, and Y. Kokubun, "Loss-less multilevel crossing of busline waveguide in vertically coupled microring resonator filter," *IEEE Photonics Technol. Lett.*, vol.16, no.2, pp.473–475, Feb. 2004.
- [16] T. Naganawa, H. Haeiwa, and Y. Kokubun, "UV induced refractive index change of SiN film and its application to center wavelength trimming of vertically coupled microring resonator filter," *Jpn. J. Appl. Phys.*, vol.43, no.8B, pp.5780–5784, Aug. 2004.
- [17] S. Yamagata, Y. Yanagase, and Y. Kokubun, "Wide range tunable microring resonator filter by thermo-optic effect in polymer waveguide," *Jpn. J. Appl. Phys.*, vol.43, no.8B, pp.5766–5770, Aug. 2004.
- [18] M. Ogata, Y. Yoda, S. Suzuki, and Y. Kokubun, "Ultra-compact vertically coupled microring resonator with buried vacuum cladding structure," *IEEE Photonics Technol. Lett.*, vol.17, no.1, pp.103–105, Jan. 2005.
- [19] T. Ito and Y. Kokubun, "Fabrication of 1×2 interleaver by parallel-coupled microring resonator," *Electronics and Communications in Japan*, John Wiley, Part 2, vol.89, no.3, pp.56–64, March 2006. (Translated from *IEICE Trans. Electron. (Japanese Edition)*, vol.J88-C, no.1, pp.13–21, Jan. 2005.)
- [20] S. Ueno, T. Naganawa, and Y. Kokubun, "High UV sensitivity of SiON film and its application to center wavelength trimming of microring resonator filter," *IEICE Trans. Electron.*, vol.E88-C, no.5, pp.998–1004, May 2005.
- [21] S. Yamagata, T. Kato, and Y. Kokubun, "Non-blocking wavelength channel switch using TO effect of double series coupled microring resonator," *Electron. Lett.*, vol.41, no.10, pp.593–595, May 2005.
- [22] Y. Goebuchi, T. Kato, and Y. Kokubun, "Fast and stable wavelength selective switch using double-series coupled dielectric microring resonator," *IEEE Photonics Technol. Lett.*, vol.18, no.3, pp.538–540, Feb. 2006.
- [23] Y. Kokubun, Y. Hatakeyama, M. Ogata, S. Suzuki, and N. Zaizen, "Fabrication technologies for vertically coupled microring resonator with multilevel crossing busline and ultra-compact ring radius," *IEEE J. Sel. Top. Quantum Electron.*, vol.11, no.1, pp.4–10, Jan.-Feb. 2005.
- [24] Y. Kokubun, "Vertically coupled micro-ring resonator filter for integrated Add/Drop node," *IEICE Trans. Electron.*, vol.E88-C, no.3, pp.349–362, March 2005.
- [25] D. Rafizadeh, J.P. Zhang, S.C. Hagness, A. Taflove, K.A. Stair, S.T. Ho, and R.C. Tiverio, "Waveguide-coupled AlGaAs/GaAs micro-cavity ring and disk resonators with high finesse and 21.6 nm free spectral range," *Opt. Lett.*, vol.22, no.16, pp.1244–1246, Aug. 1997.
- [26] A. Vörckel, M. Münster, W. Henschel, P.H. Bolivar, and H. Kurz, "Asymmetric coupled silicon-on-insulator microring resonators for compact Add-Drop multiplexers," *IEEE Photonics Technol. Lett.*, vol.15, no.7, pp.921–923, July 2003.
- [27] B.E. Little, S.T. Chu, P.P. Absil, J.V. Hryniewicz, F.G. Johnson, F. Seifert, D. Gill, V. Van, O. King, and M. Trakalo, "Very high-order microring resonator filters for WDM applications," *IEEE Photonics Technol. Lett.*, vol.16, no.10, pp.2263–2265, Oct. 2004.
- [28] T. Kato and Y. Kokubun, "Optimum coupling coefficient of second-order series coupled ring resonator for non-blocking wavelength channel switch," *IEEE/OSA J. Lightwave Technol.*, vol.24, no.2, pp.991–999, Feb. 2006.
- [29] Y. Deki, M. Takahashi, K. Suzuki, M. Ishizaka, S. Takaesu, M. Horie, K. Sato, K. Kudo, and H. Yamazaki, "A 160-nm-wavelength tunable laser using a waveguide double-ring resonator," *OECC2005, 7F3-3*, Seoul, 2005.

Yasuo Kokubun received his B.E. degree from Yokohama National University, Yokohama, Japan, in 1975 and M.E. and Dr. Eng. degrees from Tokyo Institute of Technology, Tokyo, Japan, in 1977 and 1980, respectively. After he worked for the Research Laboratory of Precision Machinery and Electronics, Tokyo Institute of Technology, as a research associate from 1980 to 1983, he joined the Yokohama National University as an associate professor in 1983, and is now a professor in the Department of Electrical and Computer Engineering. From 2006 he is serving as the dean of Faculty of Engineering. His current research is in integrated photonics, particularly waveguide-type functional devices and three-dimensional integrated photonics. From 1984 to 1985 he was with AT&T Bell Laboratories, Holmdel, NJ, as a visiting researcher and was engaged in the study of a novel waveguide on a semiconductor substrate (ARROW) for integrated optics. From 1996 to 1999, he served as the project leader of the "Three-dimensional microphotonics" project at the Kanagawa Academy of Science and Technology. Professor Kokubun is a senior member of the Institute of Electrical and Electronics Engineers, a member of the Japan Society of Applied Physics, and the Optical Society of America.