Box-Like Filter Response and Expansion of FSR by a Vertically Triple Coupled Microring Resonator Filter

Yuji Yanagase, Shuichi Suzuki, Yasuo Kokubun, *Member, IEEE, Member, OSA*, and Sai Tak Chu, *Member, IEEE*

Abstract—The Lorentzian-shape filter response of a microring resonator filter is not suitable for practical use in wavelength division multiplexing (WDM) systems because of the lack of passband flatness, high crosstalk, and the large wing in the rejection band. Therefore, the tailoring of filter response shape is required to improve the performance. The series coupled microring resonator is one of the solutions. We designed and fabricated vertically triple coupled microring resonator add/drop filters with a stacked configuration. The box-like filter response with a flat passband was successfully obtained, and the free spectral range (FSR) was expanded to 25.8 nm owing to the Vernier effect.

Index Terms—Add/drop filter, bandpass filters, microring resonator, optical waveguide device, wavelength division multiplexing.

I. INTRODUCTION

MICRORING resonator filters are attractive add/drop wavelength filters for the wavelength division access networks because of their functionality [1], [2] and compactness [3], [4]. We have proposed and demonstrated a vertically coupled microring resonator (VCMRR) filter [5]–[7]. This configuration has many features, such as the independent optimum design of the lower waveguide and upper ring and the possibility of dense integration resulting from the cross-grid configuration [5]. In addition, the coupling strength between the ring and bus waveguides can be controlled more precisely than the lateral coupling, because the vertical separation is obtained by the well-controlled deposition, rather than etching fine gaps [5]–[8].

Generally speaking, however, flatness of the passband, sharp roll-off from passband to stop band, and large out-of-band rejection are necessary to minimize the pulse broadening and the packing efficiency of wavelength channels. The ideal response shape is the box-like function with the unity shape factor, which is defined by the ratio of -1 dB bandwidth to -10 dB bandwidth. However, since the response shape of the single microring resonator filter is expressed by the so-called Lorentzian function, the shape factor is as small as 0.17 [9].

Manuscript received September 12, 2001; revised April 30, 2002. This work was supported in part by the Japan Society for the Promotion of Science through Grant-in-Aid for Scientific Research (A) 11305028 and Grant-in-Aid for Scientific Research on Priority Area 13026210 by the Ministry of Education, Culture, Sports, Science and Technology, by Research for the Future of the Japan Society for the Promotion of Science, and by the International Communication Foundation.

Y. Yanagase, S. Suzuki, and Y. Kokubun are with the Graduate School of Engineering, Yokohama National University, Yokohama 240-8501, Japan (e-mail: kokubun@ynu.ac.jp).

S. T. Chu is with Little Optics, Inc., Annapolis Junction, MD 20701 USA (e-mail: sai@littloptics.com).

Digital Object Identifier 10.1109/JLT.2002.800296

Fig. 1. Structure of a triple series-coupled microring resonator filter with stacked configuration.

In the arrayed waveguide grating (AWG) filters of which the response shape can be approximated by a Gaussian function, the theoretical value of the shape factor is 0.32. In addition, the crosstalk is limited to -20 dB due to the large wing of a Lorentzian shape, and the free spectral range (FSR) was limited to be smaller than 20 nm due to the limitation of ring radius ($\sim 10 \mu\text{m}$) resulting from the bending loss. To cover the whole bandwidth of an erbium-doped fiber amplifier (EDFA), the ring radius must be less than $5 \mu\text{m}$, which will result in a large bending loss. Therefore, the tailoring of filter response shape is required to improve the performance of microring resonator filters.

The series-coupled microring resonator is one solution, and a triple-coupled microring based on the planar structure has been reported [10]. However, the crosstalk was about -10 dB and the FSR remained smaller than 20 nm. In addition, very fine etching was required to form a narrow ($< 0.5 \mu\text{m}$) gap, because all of the microrings and the busline waveguides were formed in the same layer.

In this study, the authors propose a vertically triple-coupled microring resonator, as shown in Fig. 1, and demonstrate the box-like filter response shape and the expansion of FSR to ≥ 20 nm.

II. PRINCIPLE OF SERIES-COUPLED MICRORINGS

The output filter response at the dropping port of series-coupled microring resonator filters is expressed by the product of filter responses of individual single microring resonators, as shown in Fig. 2. Therefore, sharper roll-off and lower crosstalk can be expected than what is yielded by the single microring resonator. In addition, the FSR can be expanded due to the least common multiple of FSRs of individual microring resonators.

Fig. 2. Principle of filter synthesis by a series-coupled microring resonator filter.

TABLE I
COMPARISON OF SERIES-COUPLED MICRORING
RESONATOR FILTER (THEORY)

Filter order	Single	Double	Triple
Expansion of FSR	No	Yes	Yes
Cross talk	-20dB	-20dB	-40dB
Shape factor	0.17	0.40	0.55

We calculated the theoretical values of filter response such as the FSR, crosstalk, and the shape factor of single, double, and triple series-coupled microring resonator filters, assuming the same value of structural parameters as the previously demonstrated single-ring resonator filter [6], [9]. The results are summarized in Table I.

Let us define the shape factor as the measure of flatness of the passband by

$$\text{Shape factor} = \frac{-1\text{-dB bandwidth}}{-10\text{-dB bandwidth}}. \quad (1)$$

Since the filter response shape of the single microring resonator filter is expressed by the Lorentzian function, the shape factor is as small as 0.17, and the large wing of the function limits the crosstalk to be about -20 dB. In addition, the FSR is limited to about 20 nm because of the limitation of the ring radius resulting from the bending loss. A series-coupled microring resonator can improve these problems. For example, the passband flatness and the roll-off can be improved by the double and triple microring resonators, as shown in Fig. 3. In particular, using the triple-coupled microring resonator, the shape factor is increased to 0.55, and the crosstalk can be reduced to -40 dB, as shown in Fig. 4. In addition, the FSR can be expanded to the least common multiple of the FSRs of individual microring resonators, as shown in Fig. 4.

III. DEVICE LAYOUT

Although the triple series-coupled microring resonator can achieve the ideal filter response, a precise control of the coupling strength is required to realize it. In a planar structure, however, all the microring resonators and busline waveguides are fabricated in the same layer and the coupling between them is con-

Fig. 3. Theoretical spectrum response shape of a multiple-coupled microring resonator filter.

Fig. 4. Theoretical filter response of a multiple-coupled microring resonator filter.

Fig. 5. Top and cross-sectional view of symmetric triple-coupled microring resonator filter.

trolled by the gap distance, which is not precisely controlled by etching.

On the other hand, in the vertically coupled structure, the coupling strength can be controlled precisely by the thickness control of the buffer layer. When the balance of the coupling strength of each coupling region is lost, however, the flatness of the passband response is easily deteriorated. Therefore, it is very important to design the structure to be symmetric. Thus, we designed and fabricated the vertically coupled triple microring resonator filter, as shown in Fig. 5. In order to control the coupling strength precisely by controlling buffer layer thickness, the

Fig. 6. Radiation loss of a microring resonator with SiO₂ cladding (TE mode). Fig. 7. Radiation loss of a microring resonator with SiO₂ cladding (TM mode).

busline waveguide and ring #2 are laid in the lower layer, and rings #1 and #3 are located in the upper layer. Thus, all of the couplings between the busline and microring and between the microrings can be controlled by the control of vertical distance, i.e., the thickness of buffer layer. In addition, the radii of rings #1 and #3 are made equal so that the input and output structures are symmetric with respect to the M axis defined in Fig. 5.

IV. ANALYSIS AND DESIGN

The core thickness of busline waveguides of previously fabricated single microring resonators was 0.5 μm because the lift-off process was used to obtain the flat top surface of the busline waveguide. In the vertically triple series-coupled microring resonator filter shown in Figs. 1 and 5, the core thicknesses of the busline waveguides and ring #2 must be equal because these are fabricated in the same layer and are buried by SiO₂. In this buried structure, the radiation loss of the buried ring is an important issue, and we analyzed the radiation loss using the finite difference mode solver [11]. Figs. 6 and 7 show the relation between the radiation loss and the ring radius when the core thickness of the microring is varied as $h = 0.5, 0.7$, and $1.0 \mu\text{m}$. The core index and width are assumed to be 1.785 and $1.5 \mu\text{m}$, respectively, and the cladding is SiO₂ ($n = 1.452 @ \lambda = 1.55 \mu\text{m}$). The horizontal line marked as “previous work” corresponds to the radiation loss calculated using the same parameters as the previously fabricated device for which a clear filter response was observed. When the core thickness is 0.5 μm , it can be seen that a ring radius larger than

Fig. 8. SEM top view of vertically triple coupled MRR.

40 μm is required to obtain an allowable loss level in the TM mode. In this case, the FSR is limited to only 6 nm.

On the other hand, we can reduce the ring radius to 20 μm when the thickness of the buried ring is 70 μm . In addition, the flat top surface can also be realized by the lift-off process even when the thickness is increased to 0.7 μm . Therefore, we designed and fabricated the core thickness of the lower layer to be 0.7 μm .

In the triple series-coupled microring resonator, the resonant wavelengths of individual microrings must be equal at the designed wavelength. However, since the propagation constant of the lower ring is greater than that of the upper ring due to the buried structure, matching of resonant wavelengths is not obtained by using the least common multiple of the ring radii of individual microrings. Therefore, the ring radii of the constituent microrings were designed by taking into account the difference between the propagation constants of the lower buried ring #2 and the upper air-clad rings #1 and #3.

V. EXPERIMENTAL RESULTS

Fig. 8 shows the scanning electron microscope (SEM) top view of the fabricated triple series-coupled microring resonator filter. The busline waveguide and ring #2 are located in the lower layer, and rings #1 and #3 are located in the upper layer.

The filter response was measured by a tunable laser diode (LD) (Anritsu MG9638A) and an optical spectrum analyzer (Anritsu MS97103) which was synchronously operated with the tunable laser. The core of the busline waveguides and microrings is made of Ta₂O₅-SiO₂ compound glass (Ta₂O₅:SiO₂ = 30:70 mol%) of which the refractive index is 1.782 at 1.55 μm wavelength, and the cladding and buffer layers are SiO₂ ($n = 1.452 @ \lambda = 1.55 \mu\text{m}$). All of the glass layers were deposited by the RF magnetron sputtering method and the waveguide patterns were formed by the photolithography technique and reactive ion etching with CF₄ gas.

Fig. 9 shows the spectrum response of the triple series-coupled microring resonator with the ring radii of 22.78 μm (FSR = 10 nm) for rings #1 and #3 and 39.32 μm (FSR = 6 nm) for ring #2. It is seen that the FSR was expanded to 25.8 nm, which is larger than the FSR of a

Fig. 9. Measured filter response of a triple VCMRR with the combination of ring radii 22.78 μm (FSR = 10 nm) and 39.32 μm (FSR = 6 nm).

Fig. 10. Measured filter response of a triple VCMRR with the combination of ring radii 28.52 μm (FSR = 10 nm) and 39.32 μm (FSR = 6 nm).

Fig. 11. Magnified filter response of the peak shown by the arrow in Fig. 10.

single-ring resonator filter (20 nm). However, the measured FSR is slightly smaller than the theoretical value (30 nm). This discrepancy seems to be caused by the difference of the effective index between the calculated and actual values. In addition, the crosstalk in the rejection band is not sufficiently small, and we can see some small peaks. This is attributed to the strong coupling.

Fig. 10 shows the spectrum response of the other device using the combination of ring radii of 28.5 μm (FSR = 8 nm) and 39.3 μm (FSR = 6 nm), of which the theoretical FSR is 24 nm. The magnified response of the second peak shown by the arrow in Fig. 10 is shown in Fig. 11. It is seen that the filter response is successfully improved from the Lorentzian shape to box-like. The shape factor was increased to 0.57 and the full-width at half-maximum (FWHM) was 0.61 nm.

Fig. 12. Spectrum response of another device with the combination of ring radii of 38.1 μm (FSR = 6 nm) and 59.1 μm (FSR = 4 nm).

Fig. 12 shows the spectrum response of another device using the combination of ring radii of 38.1 μm (FSR = 6 nm) and 59.1 μm (FSR = 4 nm). The solid line expresses the measured value, and the broken line expresses the calculated value. It is seen that the measured value coincides with the calculated value well except for the noise floor. In this device, the shape factor was also 0.57, but the insertion loss and the crosstalk were better than Fig. 11.

The spectrum responses shown in Figs. 9 and 12 were measured only for the TM mode, and no TE spectrum response was observed. This seems to be caused by the polarization dependence of the resonant wavelengths of individual microrings. Because in the series-coupled microring resonators the spectrum response is obtained only when all of the resonant wavelengths of individual microrings are identical, the polarization dependence of the resonant wavelengths of all individual resonators must be eliminated. The polarization-independent design for the single ring is possible by two methods: the control of the aspect ratio of the core cross section and the loading of a birefringent layer on top of the microring. A polarization-independent microring has been demonstrated by the latter method [12]. In the vertically triple series-coupled microring, however, the latter method is not applicable because the birefringent layer affects only the upper microrings. On the other hand, to eliminate the polarization dependence by the former method, i.e., the control of the aspect ratio, the optimum core thickness is about 1.1 μm according to the calculated results for air-clad single-ring resonators, and this value is greater than that of the lower microring. Therefore, more detailed calculation is needed to cope with the polarization-independent design and the passband flattened design, and this will be the subject of our next study.

At the present stage, the insertion loss is about 30–40 dB, which is mainly attributed to the large spot-size mismatch loss at the input/output ends (about 30 dB). This spot size mismatch has been improved by incorporating spot-size transformers at the input/output ends and the loss has been reduced to 8 dB [13].

VI. SUMMARY

A vertically triple series-coupled microring resonator was proposed to achieve a box-like filter response. The core thick-

ness of the buried lower microring was optimally designed to reduce the bending loss, and the ring radii were carefully designed to match the resonant wavelengths of individual microrings. The shape factor was successfully increased to 0.57, which is larger by three factors than 0.17 of the single ring. The FSR was also enlarged to 25.8 nm.

REFERENCES

- [1] S. Suzuki, K. Shuto, and Y. Hibino, "Integrated optic ring resonators with two stacked layers of silica waveguides on Si," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 1256–1258, Nov. 1992.
- [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 Photon. Technol. Lett.*, vol. 10, pp. 549–551, Apr. 1998.
- [3] C. K. Madsen, "Efficient architectures for exactly realizing optical filters with optimum bandpass designs," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 1136–1138, Aug. 1998.
- [4] D. Rafizadeh, J. P. Zhang, S. C. Hagness, A. Taflov, K. A. Stair, S. T. Ho, and R. C. Tiverio, "Waveguide-coupled AlGaAs/GaAs microcavity ring and disk resonators with high finesse and 21.6 nm free spectral range," *Opt. Lett.*, vol. 22, no. 16, pp. 1244–1246, 1997.
- [5] 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 Photon. Technol. Lett.*, vol. 11, pp. 691–693, June 1999.
- [6] B. E. Little, S. T. Chu, W. Pan, D. Ripin, T. Kaneko, Y. Kokubun, and E. P. Ippen, "Vertically coupled glass microring resonator channel dropping filters," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 215–217, Feb. 1999.
- [7] B. E. Little, S. T. Chu, and Y. Kokubun, "Microring resonator arrays for VLSI photonics," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 323–325, Mar. 2000.
- [8] D. V. Tishinin, P. D. Dapkus, A. E. Bond, I. Kim, C. K. Lin, and J. O'Brien, "Vertical resonant couplers with precise coupling efficiency control fabricated by wafer bonding," *IEEE J. Photon. Technol. Lett.*, vol. 11, pp. 1003–1005, Aug. 1999.
- [9] S. T. Chu, W. Pan, S. Suzuki, B. E. Little, S. Sato, and Y. Kokubun, "Cascaded microring resonators for crosstalk reduction and spectrum cleanup in add-drop filters," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 1423–1425, Nov. 1999.
- [10] J. V. Hryniewicz, P. P. Absil, B. E. Little, R. A. Wilson, and P.-T. Ho, "Higher order filter response in coupled microring resonators," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 320–322, Mar. 2000.
- [11] W. P. Huang, C. L. Xu, W. Lui, and K. Yokoyama, "The perfectly matched layer boundary condition for modal analysis of optical waveguides," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 649–651, May 1996.
- [12] Y. Kokubun, S. Kubota, and S. T. Chu, "Polarization-independent vertically coupled microring resonator filter," *Electron. Lett.*, vol. 37, no. 2, pp. 90–92, 2001.
- [13] T. Kato, S. Suzuki, Y. Kokubun, and S. T. Chu, "Coupling loss reduction of vertically coupled microring resonator filter by spot size matched busline waveguide," *Appl. Opt.*, vol. 41, no. 21, pp. 4394–4399, July 20, 2002.

Yuji Yanagase was born in Nagano, Japan, on March 2, 1979. He received the B.E. degree in electrical and computer engineering from Yokohama National University, Yokohama, Japan, in 2001. He is currently working toward the M.E. degree at the same university.

His main research interests include optical waveguide-type functional devices.

Mr. Yanagase is a Member of the Japan Society of Applied Physics.

Shuichi Suzuki was born in Kanagawa, Japan, on October 6, 1976. He received the B.E. and M.E. degrees in electrical and computer engineering from Yokohama National University, Yokohama, Japan, in 1999 and 2001, respectively. He is currently working toward the Ph.D. degree at the same university.

His main interests include waveguide-type functional devices.

Mr. Suzuki is a Member of the Institute of Electrical, Information, and Communication Engineers (IEICE) of Japan.

Yasuo Kokubun (M'85) was born in Fukushima, Japan, on July 7, 1952. He received the B.E. degree from Yokohama National University, Yokohama, Japan, in 1975 and the M.E. and Dr. Eng. degrees from Tokyo Institute of Technology, Tokyo, Japan, in 1977 and 1980, respectively.

From 1980 to 1983, he worked as a Research Associate for the Research Laboratory of Precision Machinery and Electronics, Tokyo Institute of Technology. In 1983, he joined the Yokohama National University as an Associate Professor. From 1984 to 1985, he was a Visiting Researcher with AT&T Bell Laboratories, Holmdel, NJ, and was engaged in a novel waveguide on 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. He is currently a Professor of the Department of Electrical and Computer Engineering, Yokohama National University. His current research is in integrated photonics, especially waveguide-type functional devices and three-dimensional integrated photonics.

Prof. Kokubun is a Member of the Japan Society of Applied Physics.

Sai Tak Chu (M'90), photograph and biography not available at the time of publication.