Triple series coupled microring resonator filter for pass band flattening and expansion of FSR

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Abstract—**Triple coupled microring resonator Add/Drop filters with stacked configuration were designed and fabricated. The box-like filter response with flat pass band was successfully obtained and the FSR was expanded to 25.8nm owing to the Vernier effect.**

I. Introduction

We have proposed and demonstrated a vertically coupled microring resonator (VCMRR) filter as an Add/Drop wavelength filter for the wavelength division access networks. This device is promising due to their functionality, compactness, and the possibility of dense integration resulting from the cross-grid configuration [1], [2]. Generally speaking, the flatness of passband, the sharp roll-off from pass band to stop band, and the large out-of-band rejection are necessary to enlarge the tolerance of wavelength error of signals 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,

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

However, since the filter response shape of a single microring resonator is expressed by so called the Lorenzian shape, the shape factor is as small as 0.17 [3], and the cross talk is limited to -20dB due to the large wing of Lorentzian shape[1]. In addition, the FSR was limited to be smaller than 20 nm due to the limitation of ring radius ($\sim 10\mu$m) resulting from the bending loss. To cover the whole bandwidth of EDFA, the ring radius must be less than 5μm, 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 of solutions, and a triple coupled microring based on the planar structure has been reported [4]. However, the cross talk was about -10dB and the FSR was still smaller than 20nm. In addition, a very fine etching was required to form a narrow ($< 0.5\mu$m)gap, because all the microrings and the busline waveguides were formed in the same layer.

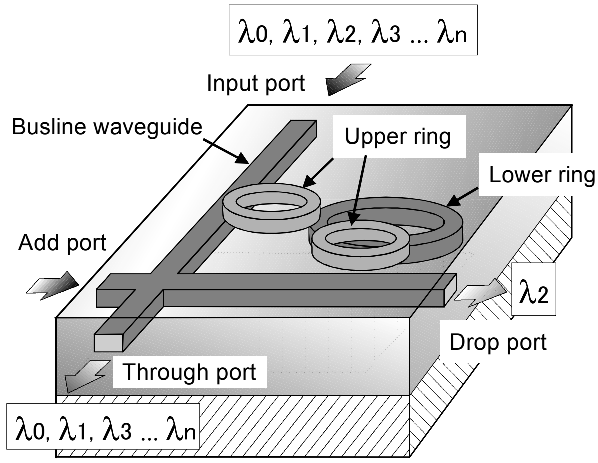

Fig.1: Structure of triple series coupled microring resonator filter with stacked configuration.

In this study, the authors have proposed a vertically triple coupled microring resonator as shown in Fig.1, and have demonstrated the box-like filter response shape and the expansion of FSR to $\geq$ 20nm.

II. Analysis and design

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. Therefore, sharper roll-off and lower cross talk than the single microring resonator can be expected. In addition, the FSR can be expanded due to the least common multiple of FSRs of individual microring resonators.

We calculated the theoretical values of filter response such as the FSR, cross talk, 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 [1], [3]. The results are summarized in Table I.
A series coupled microring resonator can improve the performance of VCMMR filter. For example, the pass band flatness and the roll-off can be improved by the double and the triple microring resonators as shown in Fig.2. In particular, using the triple coupled microring resonator, the shape factor is increased to 0.55, and the cross talk can be reduced to -40dB as shown in Fig.3. In addition, the FSR can be expanded to the least common multiple of FSRs of individual microring resonators as shown in Fig.3.

Table 1: 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

Although the triple coupled microring resonator can achieve the ideal filter response, a precise control of the coupling strength is required to realize it. In the planar structure, however, all the microring resonators and busline waveguides are fabricated in the same layer and the coupling between them is controlled by the gap distance, which is not so 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 buffer layer.

When the balance of the coupling strength of each coupling region is lost, however, the flatness of pass band response is easily deteriorated. Therefore, it is very important to design the structure symmetric. Thus we designed and fabricated the vertically coupled triple microring resonator filter as shown in Fig.4. In order to control the coupling strength precisely by the control of buffer layer thickness, the busline waveguide and the Ring#2 are laid in the lower layer, and the Ring#1 and #3 are located in the upper layer. Thus all the coupling 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 Ring#1 and Ring#3 are made equal so that the input and the output structures are symmetric with respect to the M axis defined in Fig.4.

The core thickness of busline waveguides of previously fabricated single microring resonators was 0.5μm, because the lift-off process was used to obtain the flat top surface of busline waveguide. In the vertically triple coupled microring resonator filter as shown in Figs.1 and 4, the core thicknesses of the busline waveguide and Ring#2 must be equal, because these are fabricated in the same layer and are buried by SiO_2. In this buried structure, the radiation loss of buried ring is an important issue, and we analyzed the radiation loss using the finite difference mode solver [5]. Fig.5 shows the relation between the radiation loss of TM mode and the ring radius when the core thickness of microring is varied as h = 0.5, 0.7, and 1.0μm. The radiation loss of TE mode is smaller than that of TM mode. The core width is assumed to be 1.5μm, and the cladding is SiO_2. 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

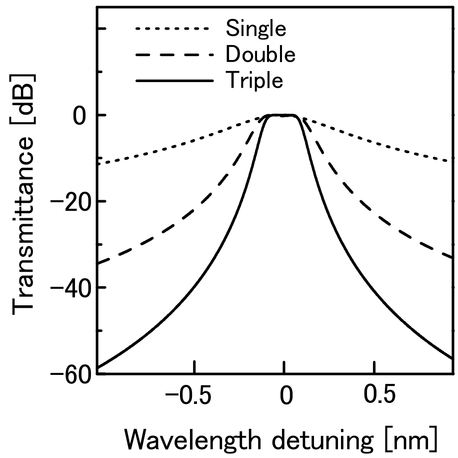

Fig.2: spectrum shape of multiple coupled microring resonator filter.

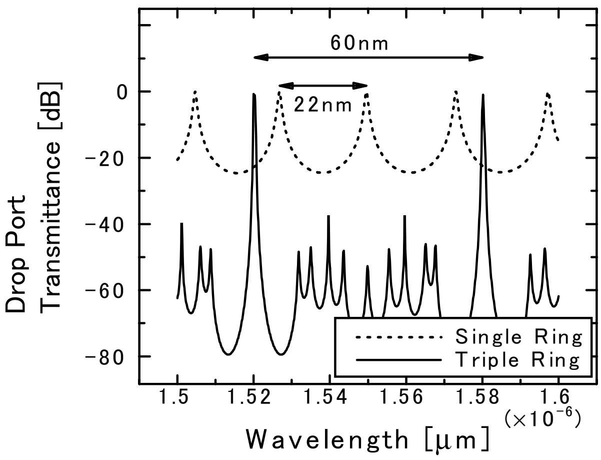

Fig.3: Filter response of multiple coupled microring resonator filter.

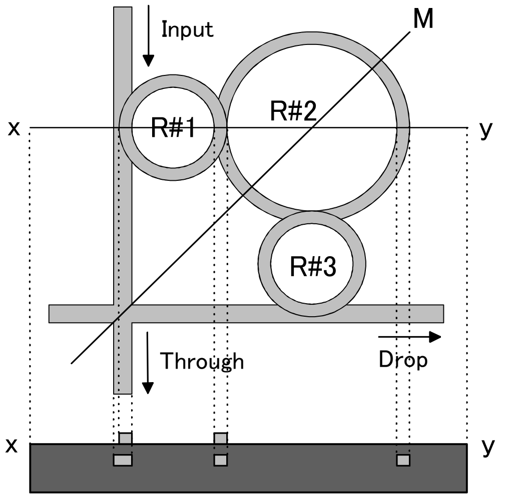

Fig.4: Top and side view of symmetric tripple coupled microring resonator filter.

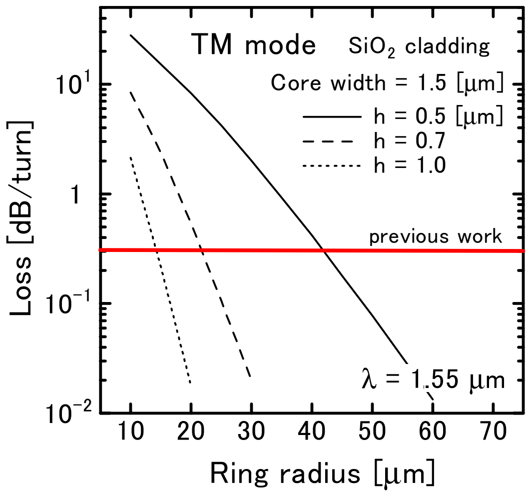

Fig.5: Radiation loss of microring resonator with SiO_2 cladding (TM mode).

observed. When the core thickness is 0.5μm, it can be seen that a ring radius larger than 40μm is required to obtain an allowable loss level in the TM mode. In this case, the FSR is limited to only 6nm.

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

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

III.Experiments

Fig.6 shows the SEM top view of the fabricated triple coupled microring resonator filter. The busline waveguide and the Ring#2 lie in the lower layer, and the Ring#1 and #3 are located in the upper layer.

The filter response was measured by a tunable LD and an optical spectrum analyzer which was synchronously operated with the tunable laser. The core of busline waveguides and microrings is made of Ta_2O_5-SiO_2 compound glass ($Ta_2O_5 : SiO_2 = 30 : 70$ mol%) of which refractive index is 1.782, and the cladding and buffer layers are SiO_2 (n = 1.452). All the glass layers were deposited by RF magnetron sputtering method and the waveguide patterns were formed by the photolithography technique and the reactive ion etching with CF_4 gas.

Fig.7 shows the spectrum response of the triple coupled microring resonator with the ring radii of 22.78μm(FSR=10nm) for the Ring#1 and #3 and 39.32μm(FSR=6nm) for the Ring#2. It is seen that the FSR was expanded to 25.8nm, which is larger than the FSR of single ring resonator filter. However, the measured FSR is a little smaller than the theoretical value (30nm). This discrepancy seems to be caused by the difference of effective index between the calculated and actual values. In addition, the cross talk in the stop band is not so satisfactorily small, and we can see some small peaks. This is attributed to the strong coupling.

Fig.8 shows the spectrum response of the other device using the combination of ring radii of 28.5μm (FSR=8nm) and 39.3μm (FSR=6nm). The magnified response of the second peak shown by the arrow in Fig.8 is shown in Fig.9. 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 FWHM was 0.61nm.

At the present stage, the insertion loss is about 30-40dB, which is mainly attributed to the large spot size mismatch loss at the input/output ends (about 30dB). This spot size mismatch has been improved by incorporating spot size transformers at the input/output ends and the loss has been reduced to 8dB, which will be presented later [6].

IV. Summary

A vertically triple coupled microring resonator was

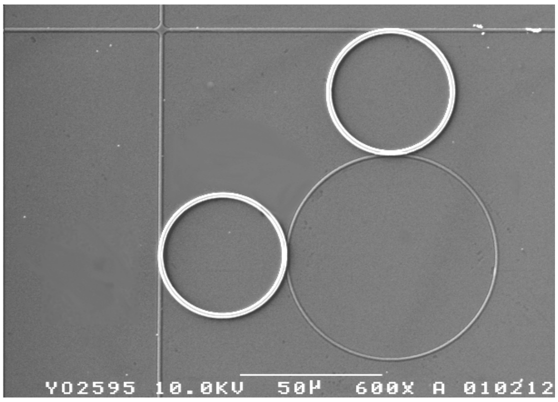

Fig.6: SEM top view of vertically triple coupled MRR

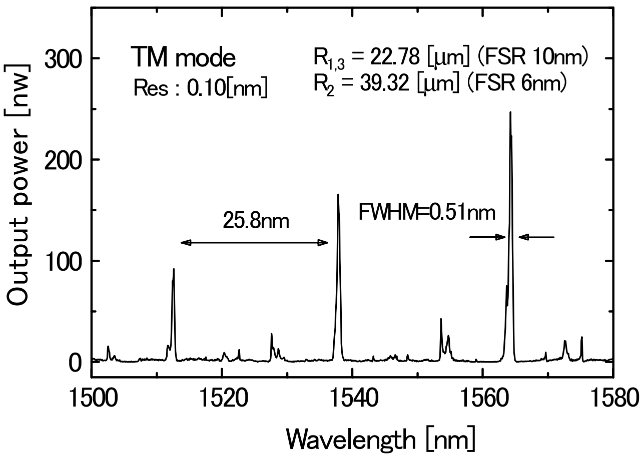

Fig.7: Measured filter response of triple VCMRR

proposed to achieve a box-like filter response. The core thickness of burried 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 25.8nm.

Acknowledgments

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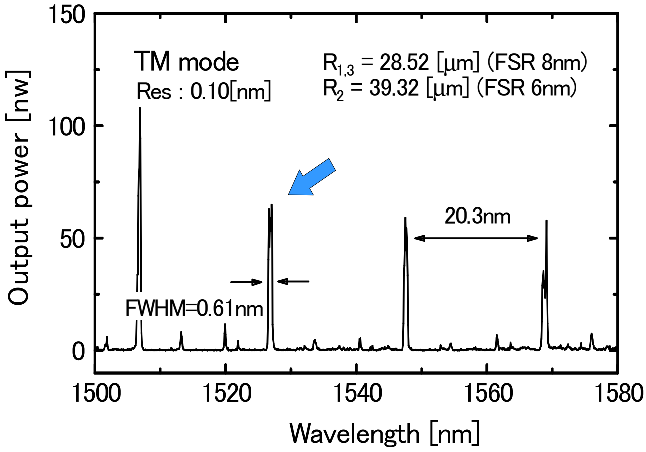

Fig.8: Measured filter response of triple VCMRR

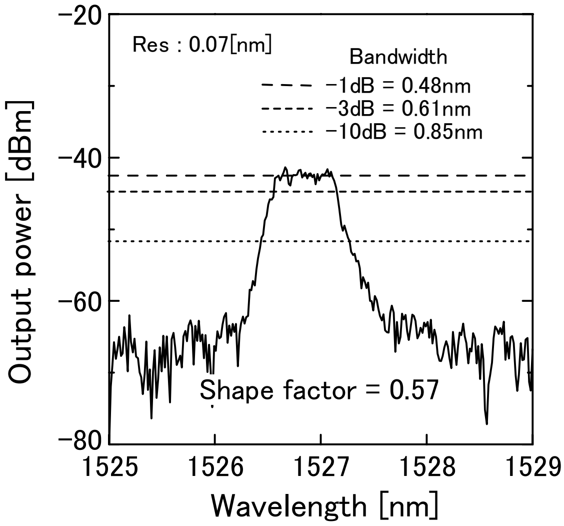

Fig.9: Magnified filter response of the peak shown by the arrow in figure 8

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