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Box-Like Response of Microring Resonator Filter by Stacked Double-Ring Geometry

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SUMMARY The Lorentzian-shape filter response of a microring resonator filter is not suitable to the practical use in WDM systems, because of the lack of pass band flatness, high cross talk, and the large wing in the stop band. Therefore, the tailoring of filter response shape is required to improve the performance. In this paper, the authors designed and demonstrated the box-like filter response of microring resonator filter by using the supermodes of stacked double microring resonators. The thicknesses of microrings and the separation between them were optimally designed to give the maximally flat response. A fine fabrication process was developed to achieve the deep and very smooth side wall. The shape factor, which is defined by the ratio of −1 dB bandwidth to −10 dB bandwidth, was successfully improved by three factors from 0.17 of Lorentzian shape to 0.51.
key words: *optical filter, optical waveguide, ring resonator, pass band flattening, stacked configuration*

1. Introduction

Microring resonator filters are attractive Add/Drop wavelength filters due to its functionality [1], [2], and compactness [3]–[5]. We have proposed and demonstrated a vertically coupled microring resonator (VCMRR) filter as shown in Fig. 1 [6]–[9]. The ultra-compact ring resonator can be realized by the high index contrast waveguide consisting of glass core and air cladding and the vertically coupled configuration [6]–[9], where a microring resonator with a few tens micron radius is stacked on the crossing point of cross-grid bus waveguides. Due to the stacked configuration, the upper and lower waveguides play different roles, i.e., the lower buried channel waveguides serve as input/output bus guides while the ring functions as the frequency selective element. In addition, the coupling strength between the ring and bus waveguides can be controlled more precisely than the lateral coupling [6]–[10], because the vertical separation is obtained by the well controlled deposition, rather than etching fine gaps. This leads to the demonstration of high Q micro-ring resonator filters with very small radius of 10 to 20 μm which exhibit the bandwidth of 0.2 to 1.0 nm and the free spectral range (FSR) of 10 to 25 nm. Due to the cross-grid configuration and the small size of element device, a dense integration up to 10^4–10^5 devices/cm^2 will be possible.

Generally speaking, however, the flatness of passband, the sharp roll-off from pass band to stop band, and the large out-of-band rejection are necessary to minimize the pulse broadening and to maximize the packing efficiency of wavelength channels. From this point of view, the single microring resonator does not satisfy the requirements. Let us define the shape factor as the measure of flatness of the pass band by

$$\text{shape factor} = \frac{-1\,\text{dB bandwidth}}{-10\,\text{dB bandwidth}} \tag{1}$$

The ideal response shape is a box-like function with the shape factor of 1.0, which has a very flat pass band and a very sharp roll-off from pass band to stop band. On the other hand, the response shape of the single microring resonator filter is expressed by the Lorentzian function, and the shape factor is as small as 0.17. In the AWG filters of which response shape can be approximated by the Gaussian function, the theoretical value of shape factor is 0.32. Therefore, the tailoring of filter response shape is requied to improve the shape factor. The higher order response by series coupled microring [11] is one of solutions, but the precise control of coupling strength was difficult due to the planar structure.

In this study, the authors proposed and demonstrated the box-like response shape by stacking two identical microring resonators as shown in Fig. 2. In this stacked configuration, the coupling strength can be controlled precisely by the thickness control of buffer

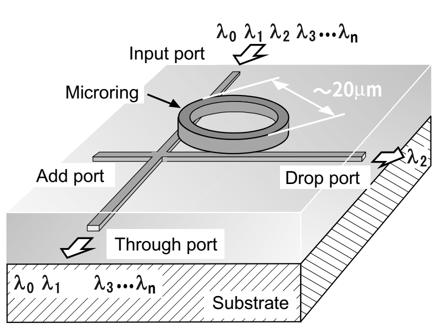

Fig. 1 Vertically coupled microring resonator filter.

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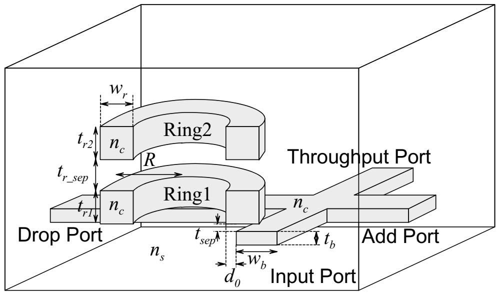

Fig. 2 Perspective view of vertically coupled double microring resonator filter.

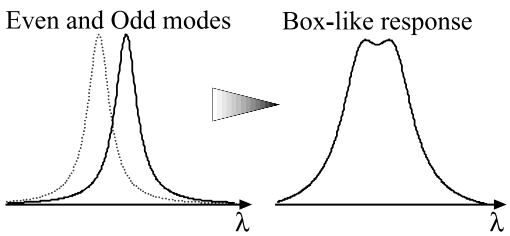

Fig. 3 Principle of pass band flattening by stacked double-ring.

layers [6].

2. Principle and Device Design

When two identical microrings are stacked with close spacing as shown in Fig. 2, the coupling occurs between them and the even and odd modes are guided. The stacked double ring acts as a single resonator and these two quasi-degenerated modes resonate at closely spaced wavelengths. Thus, the whole response shape of the filter spectrum can be flattened as shown in Fig. 3. However, when the resonant wavelengths of even and odd modes are not close enough, the filter response is double peaked, and the center dip of the response will deteriorate the transmission characteristics of the filter. Therefore, a careful design is needed to obtain the box-like filter response using the stacked double ring resonator.

First we analyzed the difference of equivalent indices ($n_{eq} = \beta/k_0$) between even and odd modes against the thickness of separation layer between two stacked rings. The calculated results are shown in Fig. 4 for several different values of core thickness. A finite different mode solver [12] was used in this analysis. In Fig. 4, the horizontal dotted line marked as "overlap at $m = 0$" corresoponds to the overlapping of even and odd modes with the same resonance order, and that marked as "overlap at $m = 1$" corresoponds to the overlapping with the difference of resonance order by unity. In other words, the horizontal dotted line marked as "overlap at $m = 1$" corresponds to the FSR. As seen from Fig. 4, the pass band flattening is also possible by overlapping the resonant wavelengths of even and odd

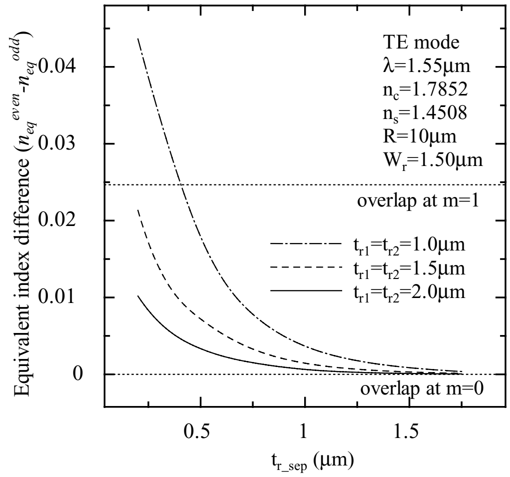

Fig. 4 Difference between equivalent indices of even and odd modes vs. separation of microrings.

modes with different resonance order. However, the fabrication tolerance is too small and so this method is not practical. Therefore, we designed the box-like filter response using the same resonace order.

It can be seen from Fig. 4 that the difference of equivalent indices can be reduced by increasing the thickness of separation layer and also increasing the core thickness. The separation of resonant wavelengths between even and odd modes $\lambda_e - \lambda_o$ is simply expressed in terms of the difference of equivalent indices $n_{eq}^{even} - n_{eq}^{odd}$ by

$$\lambda_e - \lambda_o = \frac{\lambda_e}{n_{eq}^{even}} (n_{eq}^{even} - n_{eq}^{odd}). \tag{2}$$

However, the response shape is determined by both the separation of resonant wavelengths and the bandwidth of individual filter response of even and odd modes. When the ratio of the bandwidth of individual response to the separation of resonant wavelengths is too small, the response shape is rather double peaked than box-like. Therefore, there is an optimum value of bandwidth when the separation of resonant wavelengths is given. This relation can be expressed as the shape factor against the Finess, which is defined by the ratio of FSR (spacing of adjacent resonant wavelengths) to −3 dB bandwidth.

The relation between the shape factor and the Finess of even mode of coupled double microring resonators is shown in Fig. 5. The shape factor is calculated for the given value of Finess assuming the Lorentzian response shape of each mode. It is seen from Fig. 5 that for a given thickness of separation layer the shape factor can be improved by increasing the value of Finess, but it rapidly decreases to a value lower than that of the single ring beyond a certain value of Finess. This is because the response shape has no longer a flat top pass band but has a double peak response shape, when the Finess is too high.

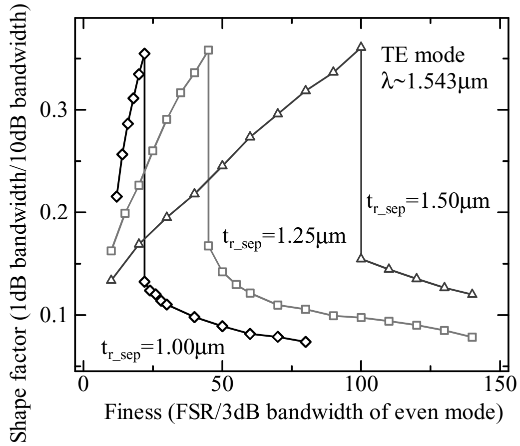

Fig. 5 Calculated result of shape factor against Finess of even-mode.

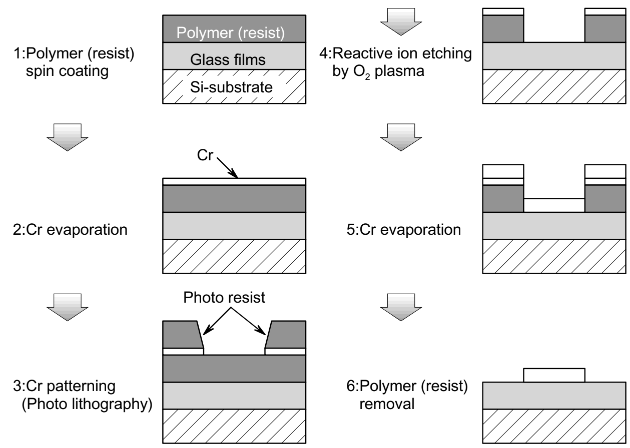

Fig. 6 Formation process of thick Cr mask by three-layer photoresist method.

According to these design issues, we designed several different types of stacked double microring resonator filters by changing the value of structural parameters as follows: The core thickness to be 1.5–2.0 μm, the thichness of separation layer to be 1.0–2.0 μm, the core width to be 1.5–2.0 μm.

As for the polarization dependence of resonant wavelength, the polarization independent design for the single ring is possible by two methods, one is the control of the aspect ratio of core cross section and the other is the loading of a birefringent layer on top of the microring. A polarization independent microring has been demonstrated by the latter method [13]. In the stacked double microring, however, the latter method is not applicable because the birefringent layer affects only on the upper core. 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 single ring resonators, and this value is thinner than the optimum core thickness for the pass band flattening. Therefore, a more detailed calculation is needed to cope with the polarization independent design and the pass band flattened design, and this will be the next subject. In this work, we aimed at achieving the pass band flattening for the TE polarization.

3. Fabrication

To demonstrate the box-like microring resonator filter, we developed a fine etching technique of stacked double ring with a vertical side wall. The core and separation layer materials are Ta_2O_5–SiO_2 compound glass (Ta_2O_5 30% : SiO_2 70% mol fraction) with refractive index of 1.7852 at $\lambda = 1.55\,\mu$m and SiO_2 with refractive index of 1.4508 at $\lambda = 1.55\,\mu$m, respectively, deposited on a Si substrate by a sputtering deposition technique. The total thickness of the stacked double ring is as thick as 5 μm and the angle of the etched side wall must be as close to 90° as possible. Otherwise the ring radius and the width of the ring core are different with upper and lower ring cores, and the two stacked microrings are no more coupled. To achieve the deep and very precise etching of stacked layers, we developed a precise formation method of thick Cr mask, and a fine and deep etching technique of thick stacked glass layers consisting of two different materials, i.e. a pure SiO_2 and Ta_2O_5–SiO_2 compound glass.

Figure 6 shows the formation process of the thick Cr mask for etching. To achieve a deep etching, a thick Cr mask is needed because the thickness of Cr mask decreases during the etching. The selectivity of Cr mask and glass material by the reactive ion etching (RIE) using CF_4 gas is about 20. Thus a thick Cr mask with square cross section is required for this process.

In the process using the three-layer photoresist method shown in Fig. 6, a thin Cr mask is sandwiched by thick photoresist layers. We used the photoresist AZ5206E (supplied by Clarant Japan Corp.) as the nega-resist by using the UV exposure condition for the image reversal posi-resist. The thicknesses of the lower and upper photoresist layers were 1.0 μm and 0.4 μm, respectively. The intermediate Cr layer was 100 nm thick, and this layer was patterned by the upper photoresist and wet etching using HY solution (made by Wako Pure Chemical Industries. Ltd., composition is Cerium (IV) diammonium nitrate 13.3 wt%, perchloric acid ~70%, and the remainder is water). The resolution of the lower thick photoresist layer is determined by the resolution of thin Cr layer. Since the selectivity of Cr mask and photoresit against the RIE using O_2 gas is quite large, a thick photoresist mask with vertical side wall can be obtained. After the RIE of lower photoresist layer, a thick Cr layer was evapolated and patterned by so-called lift-off technique, in which the lower photoresist layer was removed using the photoresist remover solution. After the lift-off process, a thick (500 nm) Cr layer with almost square cross section was

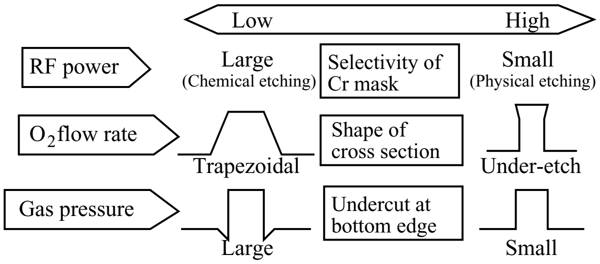

Fig. 7 Dependence of cross section of etched glass film on various etching parameters.

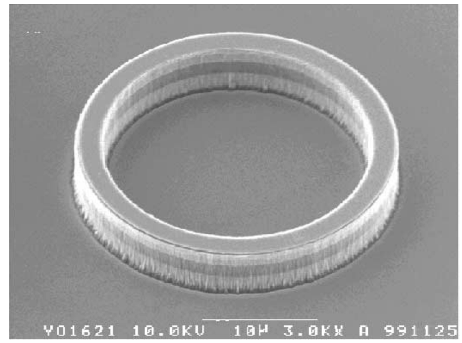

Fig. 8 SEM view of stacked double microring resonator.

obtained.

Next we developed a fine etching condition of stacked layers consisting of Ta_2O_5–SiO_2 compound glass ring cores and SiO_2 cladding by the RIE using CF_4 gas. The etching rates of Ta_2O_5–SiO_2 compound glass core layer and SiO_2 cladding layer are almost the same under various etching conditions, and this fact made it easy to etch the thick layers of stacked double rings consisting of different matterials. The dependence of cross section of etched glass film on various etching parameters were investigated under various ething conditions of RIE, and the dependency is summarized in Fig. 7.

The selectivity of Cr mask and the glass film is improved by decreasing the RF power. Therefore, low RF power is more suitable to etch the thin pattern with the width of less than 2 μm. Next we found that the cross sectional shape can be controlled by adding O_2 gas to CF_4 gas and by controlling the ratio of flow rate of O_2 gas to CF_4 gas. This enables us to obtain a vertical side wall of stacked double ring with almost 90°. The undercut at the bottom surface after the RIE can be eliminated by increasing the gas pressure. According to these investigations, we developed an optimum etching condition as follows:

- RF power: 300 mW (Wafer size: 3 inch ϕ)
- Gas flow rate:CF_4:O_2 = 10.0 sccm:2.5 sccm
- Gas pressure: 5.0 mTorr (0.66 Pa)

Using the designed structure described in the preceeding section and the optimum fabrication condition described in this section, we fabricated several stacked double microring resonator filters. Figure 8 shows the SEM top view of the fabricated device. It is seen that a vertical and smooth side wall with almost 90° was successfully obtained.

4. Measurement

The dropping filter response was measured by a tunable LD (Anritsu MG9638A) and an optical spectrum analyzer (Anritsu MS97103) which was synchronously operated with the tunable laser. The output light from the tunable laser was guided through a polarization maintaining fiber, and the output light from the device was launched to a single-mode fiber.

The measured filter response for TE polarization of one of fabricated devices is shown in Fig. 9. The structural parameters of this device are as follows: Core width of ring $W_r = 1.5\,\mu$m, core thicknesses of double ring $t_{r1} = t_{r2} = 1.0\,\mu$m, thickness of intermediate cladding $t_{r_sep} = 0.3\,\mu$m, core width of busline $W_b = 2.0\,\mu$m, core thickness of busline $t_b = 0.5\,\mu$m, thickness of buffer layer between the busline waveguide and the lower ring $t_{sep} = 0.7\,\mu$m, and the ring radius is 11.5 μm. Since the core thicknesses of double ring ($t_{r1} = t_{r2} = 1.0\,\mu$m) is thinner than the optimum value (1.5–2.0 μm) and the thickness of intermediate cladding ($t_{r_sep} = 0.3\,\mu$m) is also thinner than the optimum value (1.0–2.0 μm), the resonant wavelengths of even and odd modes are too separated as seen from Fig. 4, and so the two separated resonant peaks corresponding to even and odd modes are observed in the measured result shown in Fig. 9. The spacing between resonant wavelengths of even and odd modes was 5.0 nm, and the FSR was 16.3 nm. According to the numerical result shown in Fig. 4, the difference of equivalent indices between even and odd modes is evaluated to be 0.031, which corresponds to the FSR of 20.6 nm. Therefore, the resonance order of the pairs of resonant wavelengths shown in Fig. 9 actually differs by unity, and the spacing of resonant wavelengthes between even and odd modes is evaluated to be 21.3 nm (16.3+5.0), which almost coincides with the theoretical value.

Next, we fabricated the device with the optimum values of $t_{r1} = t_{r2}$ and t_{r_sep}, and the measured filter response is shown in Fig. 10. The structural parameters of this device are the same as the device shown in Fig. 9, except for the core thicknesses of double ring $t_{r1} = t_{r2} = 2.0\,\mu$m and the thickness of intermediate cladding $t_{r_sep} = 1.0\,\mu$m. In this device, the resonant wavelengths of even and odd modes are closely separated and the filter response shape is double peaked. Figure 11 shows the magnified response of the first peak in Fig. 10. It is seen from Fig. 11 that the shape factor was successfully improved to 0.51, although the center dip was a little larger than 1 dB (2 dB). This center dip will be improved by decreasing the spacing of res-

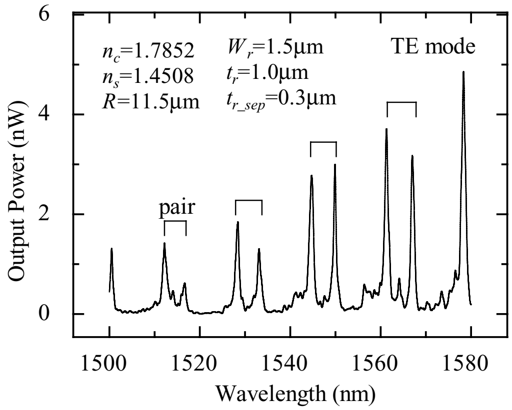

Fig. 9 Filter response of stacked double microring resonator filter with $t_{r1} = t_{r2} = 1.0\,\mu$m and $t_{r_sep} = 0.3\,\mu$m.

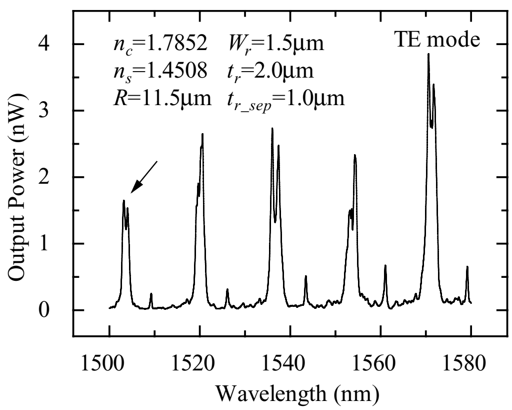

Fig. 10 Filter response of stacked double microring resonator filter with $t_{r1} = t_{r2} = 2.0\,\mu$m and $t_{r_sep} = 1.0\,\mu$m.

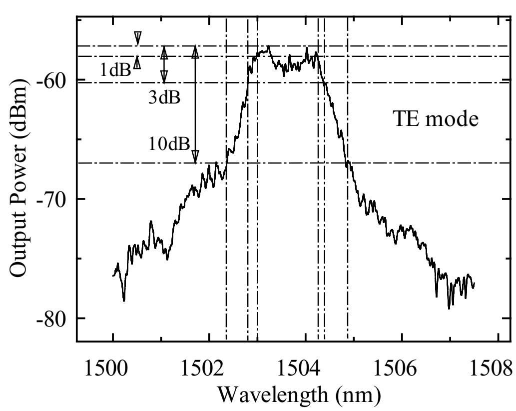

Fig. 11 Magnified filter response of first resonance peak in Fig. 10.

onant peaks between even and odd modes, which can be achieved by increasing the separation of two stacked microrings t_{r_sep} as seen from Fig. 4.

In the fabricated device, the polarization dependence of the resonant wavelength was less than 0.1 nm. However, this polarization independent response was not intended but was obtained by chance. As discussed in Sect. 2, the design for the pass band flattening described here is not consistent with the polarization independent design, and the consistent design with these two characteristics will be the next subject.

The loss is classified into the input/output coupling loss between the busline waveguide and the single mode fiber, the radiation and scattering losses in the microring, and the coupling loss between the busline and the microring. At the present stage, the input/output coupling loss is quite large (30–40 dB), because the spot size of the input/output waveguides is as small as $1.95 \times 1.55\,\mu$m which is much smaller than that of single mode fiber ($\sim 10\,\mu$m). This coupling loss to the optical fiber can be reduced to almost zero by introducing the spot size transformer and the large core waveguide like ARROW. The reduction of insertion loss to 8 dB was demonstrated by introducing the ARROW busline with large spot size [14]. The radiation and scattering losses in the microring affect the Finess and the dropping efficiency of the filter response. Although it is difficult to relate the measured finess of the stacked double microring to the loss in the microring, the best result of the finess was evaluated to be 39.8 (-3 dB bandwidth = 0.42 nm, FSR = 16.7 nm) from the measured filter response of a single ring device fabricated by the same fabrication process. However, it is difficult to evaluate these losses separately from the coupling loss from the busline waveguide to the microring. The radiation loss was evaluated to be less than 0.2 dB/turn from the numerical analysis. The coupling loss between the busline and the microring differes for individual devices, and it was difficult to evaluate that of the devices shown in Figs. 9 and 10 because the clear drop of the filter response at the throughput port was not observed. However, the best data for the dropping efficiency from the input port to the drop port through the microring has been evaluated to be about 97% for the single microring resonator from the filter response at the throughput port (-15 dB) [6]. This fact implies that a carefull design for the buffer layer thickness and the precise alignment of the photo-lithograhpy are needed to achieve a low coupling loss between the busline waveguide and the microring resonator.

5. Conclusion

A vertically stacked double microring resonator was proposed to achieve a box-like filter response. Since the principle is based on the overlapping of the resonant wavelengths of even and odd modes in the coupled double mocrorings, the relation between the equivalent indices of even and odd modes and the thicknesses of ring core and separation layers were numerically analyzed. From this analysis, it was clarified that the optimum values of the core thickness to be 1.5–2.0 μm and that of the thichness of separation layer to be 1.0–2.0 μm. According to this design, we farciated several devices. From the measured result of the device with much thinner ring core and the separation layers than the optimum values, a clear and separated resonant peaks of even and odd modes were observed. The spacing of resonant wavelengths between even and odd modes was confirmed to be coincide with the theoretical value. Next a device with almost optimum design was fabricated and a box-like filter response was observed. The shape factor was successfully increased to 0.51, which is larger by three factors than 0.17 of the single ring.

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