Precise Control of Wavelength Channel Spacing of Microring Resonator Add-Drop Filter Array

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Abstract—The vertically coupled microring resonator filter is an attractive add-drop wavelength filter due to its functionality and compactness and the possibility of dense integration resulting from the cross-grid configuration. However, in the concatenated 1×8 filter array in which the ring radii are changed with the increments of 50 nm, the wavelength channel spacing was limited to 5.7 nm due to the resolution limit of photomask (50 nm). Therefore, we developed a new technique to control precisely the channel spacing by an ultraviolet (UV)-trimming technique using polysilane as the overcladding layer. As a result, we successfully decreased the channel spacing to 0.5 nm, and also controlled the channel spacing precisely to 1.0 nm using the same trimming technique.

Index Terms—Add-drop filter, microring resonator, optical waveguide device, polysilane, ultraviolet (UV) trimming.

I. INTRODUCTION

MICRORING resonator devices are attractive as add-drop wavelength filters for wavelength multiplexed access networks, due to their functionality and compactness [1], [4]. We have proposed and demonstrated a vertically coupled microring resonator (VCMRR) filter array [5]. Fig. 1 shows the basic structure of the VCMRR filter element. Due to the stacked configuration, the upper and lower waveguides play different roles, i.e., the lower buried channel waveguides serve as input-output busline waveguides, whereas the upper ring functions as the frequency selective element. Owing to the large index difference ($\sim 34\%$) of the upper ring waveguide, the ring radius can be reduced to $10 \mu\text{m}$, which results in a large free spectral range (FSR) of 20 nm. In addition, due to the cross-grid topology and the compactness of filter element, a large scale integration up to 10^4 – 10^5 elements/ cm^2 is possible. Recently, a multichannel add-drop filter has been realized by concatenating cross-grid VCMRR elements, as shown in Fig. 2 [5]. However, the wavelength channel spacing of the add-drop filter array is realized by changing the radius of each ring is about 5.7 nm, because the differences of ring radius are limited by the resolution of the photomask, i.e., 50 nm. The channel spacing between the center wavelength of adjacent ports should be reduced to less than 1 nm for the dense wavelength division multiplexing (WDM) systems. Thus, we applied an ultraviolet

Manuscript received July 10, 2001. This work was supported in part by the Japan Society for the Promotion of Science through Grant-in-Aid for Scientific Research A 11305028, a Grant-in-Aid for Scientific Research on Priority Area A 13026210 of the Ministry of Education, Culture, Sports, Science, and Technology, by Research for the Future of Japan Society for the Promotion of Science, and by the International Communication Foundation.

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Publisher Item Identifier S 0733-8724(02)03342-X.

Fig. 1. Structure of VCMRR filter element.

Fig. 2. VCMRR filter array.

(UV)-trimming technique [6], [7] to the multichannel add-drop filter. In this report, we describe the design of UV-trimming range and demonstrated a precise control of channel spacing of multichannel add-drop filter array using the UV-trimming technique.

II. DESIGN OF TRIMMING RANGE

Fig. 3 shows the cross-sectional structure of the VCMRR filter, in which the overcladding is formed by UV-sensitive polymer. When the index of overcladding is reduced by UV irradiation, the equivalent index of the ring waveguide is also changed and the center wavelength of the filter is shifted. The polymer used in this study is polysilane $(\text{MeSi})_n [\text{Me}(\text{EtO})\text{Si}]_m$ (n/m : mixture ratio) [8], [9]. The measured refractive index change of the polysilane by UV irradiation is shown in Fig. 4. The peak wavelength of the UV light (Hg lamp) used in this experiment was 370 nm and the intensity was $20 \text{ mW}/\text{cm}^2$. The refractive index was decreased from 1.51 to 1.43 by the UV irradiation for 400 s.

We calculated the amount of center wavelength shift and the bending loss of the ring waveguide when the index of overcladding was assumed to be reduced from 1.51 to 1.43. The

Fig. 3. Principle of UV trimming.

Fig. 4. Measured refractive index change of polysilane versus UV exposure time.

Fig. 5. Calculated center wavelength shift by trimming.

Fig. 6. Calculated radiation loss of ring vs index of overcladding.

parameters used in the calculation are given in Fig. 3. The calculated result of the wavelength shift and the bending loss for the ring radius of 15 μm is shown in Figs. 5 and 6, respectively. The semivectorial finite difference method [10] was used

Fig. 7. Parameters of fabricated VCMRR filter.

Fig. 8. Way of UV irradiation on each ring with different exposure time.

in this analysis to calculate the complex propagation constant. The center wavelength was calculated from the real part of the propagation constant, and the bending loss was calculated from the imaginary part of the propagation constant.

It can be seen that when the core thickness of ring waveguide is smaller, the range of center wavelength shift by trimming is larger. However, because the bending loss is also larger as the decrease of core thickness, we designed the thickness of the ring core to be 1.6 μm , so that the bending loss of the ring waveguide is the same level as the value for which we could previously obtain a clear spectrum response [11]. For this designed structure, the trimming range of 8 nm can be obtained, whereas the bending loss is kept smaller than the allowable loss level (0.3 dB per turn).

Fig. 9. Problem of conventional liftoff process.

III. DEVICE FABRICATION

We fabricated a 1×8 filter array, as shown in Fig. 2, in which the ring radii ($15 \mu\text{m}$) and the ring core thicknesses ($1.6 \mu\text{m}$) are identical for all ports. Those microrings are named ring 1–8, respectively. The channel spacing between adjacent ports is $250 \mu\text{m}$. Fig. 7 shows the cross-sectional structure of the basic element of fabricated VCMRR filter array. The substrate cladding and separation layer are made of SiO₂ ($n = 1.452$ at $\lambda = 1.55 \mu\text{m}$). The ring and busline cores are made of the Ta₂O₅/SiO₂ compound glass to give a refractive index of 1.782 (Ta₂O₅ mol fraction is 30%). The microring cores were covered by the polysilane with the thickness of $10 \mu\text{m}$. Other sizes of the device are shown in Fig. 7. Each ring was irradiated by UV light with different exposure time by shifting a metal mask using a manipulator, as shown in Fig. 8.

Details of the fabrication process were reported in [12]. SiO₂ and Ta₂O₅/SiO₂ compound glass layers were deposited by a radiofrequency (RF) sputtering technique. A Cr mask was formed by vacuum evaporation and was patterned by photolithography. The channel waveguide was fabricated by reactive ion etching (RIE) using CF₄ gas. The polysilane overcladding was dip coated. It is especially important for the stacked configuration, such as the VCMRR filter, to flatten the top surface of the lower buried waveguide layer. We have used the liftoff process shown in Fig. 9 to flatten the lower waveguide. There was a problem, however, that the voids arise at the vertical side walls of the lower core, and this causes the dent to appear on the top surface of the buried waveguide. Thus, we used a bias-sputtering technique to bury the lower waveguide core by SiO₂ cladding. The comparison between the surface roughness by the previous liftoff process and that by the improved process using a bias sputtering is shown in Fig. 10(a) and (b), which show the cross-sectional SEM images of the buried busline waveguide. It can be seen that the dent on the top surface of the lower waveguide was improved to be less than $0.1 \mu\text{m}$. Fig. 11 shows the optical microscope image of the fabricated device.

IV. MEASUREMENT OF VCMRR FILTER ARRAY

Using the improved fabrication process, we fabricated a 1×8 concatenated filter array with identical ring radius ($15 \mu\text{m}$) for all microring resonators. Although eight filter elements were integrated in this device, we used rings 2 and 7 for the demonstration of the precise control of channel spacing. This is because the initial channel spacing between these two was the largest due to the thickness nonuniformity of the core layer, and was suitable for the demonstration of large amount of trimming. In the

(a)

(b)

Fig. 10. Cross-sectional structure of busline waveguide. (a) Conventional liftoff. (b) Improved liftoff.

measurement of filter response, a tunable laser diode [LD (Anritsu MG9638A)] was used as the light source and the output spectrum was measured by an optical spectrum analyzer (Anritsu MS9710B, Tokyo, Japan) that was synchronously operated with the tunable laser.

Fig. 12 shows the measured spectrum responses of rings 2 and 7 in the filter array before controlling the channel spacing. After the fabrication, UV light from an Hg lamp was irradiated to overall filter array for 80 s through a bundle fiber. The exposure condition of the UV light source used in this experiment was the same as used for the measurement of index change of the polysilane film, i.e., the power density was 20 mW/cm^2 and the peak wavelength was 370 nm . This irradiation was needed to obtain a clear spectrum by reducing the index of polysilane overcladding because the initial refractive index of polysilane

Fig. 11. Optical microscope image of fabricated ring resonator.

Fig. 12. Measured spectrum responses of rings 2 and 7 before channel spacing control.

Fig. 13. Measured spectrum responses of rings 2 and 7 after UV irradiation on ring 2.

(1.51) is a little larger than the value required to guarantee the low-loss propagation in the ring. Therefore, to improve the confinement in the ring waveguide and to reduce the radiation loss of the ring waveguide, the preexposure of UV light was needed. The channel spacing between rings 2 and 7 shown in Fig. 12 is about 2.5 nm. To reduce the spacing, we irradiated the UV light only on ring 2 which has a longer center wavelength than that of ring 7. The spectrum responses after 140-s irradiation on ring 2 are shown in Fig. 13. Comparing Fig. 12 with Fig. 13, it can be seen that the channel spacing between rings 2 and 7 was successfully reduced from 2.5 to 0.5 nm.

Fig. 14 shows the change of the spectrum response of ring 2 for different irradiation time. The center wavelength was shifted over 9.7 nm by 220-s irradiation. Fig. 15 is the spectrum responses after 500 h and shows the spectrum change due to the aging. The center wavelengths of rings 2 and 7 changed from those in Fig. 13 by 0.07 and 0.31 nm, respectively, and the channel spacing was increased to 0.7 nm. The center wavelength change seems to be caused by the index change of polysilane

Fig. 14. Change of spectrum response of ring 2 by UV irradiation.

overcadding due to the effect of the oxidation or humidity absorption. The difference of center wavelength change between rings 2 and 7 can be attributed to the difference of UV irradiation time. Because ring 2 was irradiated for more time (220 s) than 7 (80 s), the index change of polysilane was nearly saturated and

Fig. 15. Change of spectrum response due to 500-h aging.

Fig. 16. Measured spectrum responses of rings 2 and 7 after UV irradiation on ring 7.

Fig. 17. Change of channel spacing between rings 2 and 7 by UV irradiation.

the aging effect was smaller than that of ring 7. To prevent this aging effect, a hermetic packaging will be required for practical use.

Fig. 16 shows the spectrum responses when only ring 7 was exposed to UV light for 15 s and the channel spacing was increased to 1.0 nm from 0.7 nm. The change of channel spacing between rings 2 and 7 by UV irradiation is summarized in Fig. 17. First, both rings 2 and 7 were irradiated for 80 s. Next, only ring 2 was irradiated for 140 s, and the channel spacing was decreased to 0.5 nm. The vertical broken line means the time interval of 500 h, and the channel spacing was slightly increased to 0.7 nm. For the last 15 s, only ring 7 was

exposed to the UV light and the channel spacing was increased to 1.0 nm.

V. CONCLUSION

We demonstrated the precise control of channel spacing of vertically coupled microring resonator add-drop filter array by using a UV-trimming technique. In the design, we found the optimum structure which satisfies both the wide trimming range (~ 8 nm) and the low bending loss of the ring waveguide (≤ 0.3 dB/turn). In the fabrication, we improved the liftoff process and reduced the dent on the top of the lower waveguide. By the step-by-step UV irradiation on the ring resonator in the filter array, a narrow channel spacing of 0.5 nm was successfully obtained and the channel spacing was inversely increased to 1.0 nm by exchanging the filter under exposure. Thus, we successfully demonstrated the precise control of center wavelength and the channel spacing.

ACKNOWLEDGMENT

The authors wish to thank Dr. T. Imai, Dr. T. Fujimoto, and Dr. K. Ando of GE Toshiba Silicones Company, Ltd., for supplying polysilane.

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