Coupling-loss reduction of a vertically coupled microring resonator filter by spot-size-matched busline waveguides

Tomoyuki Kato, Shuichi Suzuki, Yasuo Kokubun, and Sai Tak Chu

To improve the input–output coupling loss of a vertically coupled microring resonator filter, we fabricated microring resonators on an antiresonant reflecting optical waveguide (ARROW) with a large spot size and on the rectangular busline waveguide with a spot-size transformer. The spot size and the tapered structure were optimally designed from the viewpoint of spot-size matching to single-mode fibers and the reduction of radiation loss. Clear dropping responses were demonstrated for the ARROW-based microring resonator filters, and the coupling loss was successfully reduced by 22 dB. © 2002 Optical Society of America

OCIS codes: 230.7380, 130.3120, 060.4230.

1. Introduction

A vertically coupled microring resonator filter is an attractive add–drop wavelength filter because of its functionality^{1,2} and compactness³ and the possibility of dense integration resulting from the cross-grid configuration.^{4,5} However, the input–output coupling loss from the busline waveguide to the single-mode fiber was as large as 30 dB⁴ and was mainly caused by the spot-size mismatch between the busline waveguide and the single-mode fiber.

In the vertically coupled microring resonator filter, the top surface of the busline must be flattened to permit the stacking of a microring resonator on the crossing point of busline waveguides.^{4,5} The thickness of the busline waveguide was limited to be less than 0.7 μm owing to the lift-off process,⁶ which was required for the planarization of the top surface. Therefore the spot size of the busline waveguide is as small as 0.95 $\mu\text{m} \times 0.55 \mu\text{m}$ (core size is 2.0 $\mu\text{m} \times 0.5 \mu\text{m}$), and this is too small to couple the light efficiently to single-mode fibers.

In this study we adopted an antiresonant reflecting optical waveguide (ARROW)⁷ and a rectangular waveguide with a horizontal spot-size transformer (SST) as the busline waveguides to improve the input–output coupling loss. The spot size of the ARROW busline and the shape of the tapered structure were optimally designed to the spot-size-mismatch loss and the radiation loss. The measured results were compared with the theoretical values.

2. Analysis of Coupling Loss

To reduce the coupling loss between the busline waveguide and the single-mode fiber, we must design the busline waveguide so that its spot size matches that of the single-mode fiber.

In the calculation of spot size in this section, we used the following equation⁸:

$$w = \left\{ \frac{4 \int_{-\infty}^{\infty} x^2 [\psi(x)]^2 dx}{\int_{-\infty}^{\infty} [\psi(x)]^2 dx} \right\}, \quad (1)$$

where w is the spot size in the x direction, which is defined by the $1/e$ radius of the beam approximated to the Gaussian beam by the least-squares fit, and $\psi(x)$ is the amplitude profile of the electromagnetic field. For the two-dimensional case, we calculated the approximated spot size in the x and y directions

T. Kato, S. Suzuki, and Y. Kokubun (kokubun@ynu.ac.jp) are with the Graduate School of Engineering, Yokohama National University, 79-5 Tokiwadai, Hodogayaku, Yokohama 240-8501, Japan. S. T. Chu is with Little Optics, Incorporated, 9020 Junction Drive, Suite D, Annapolis Junction, Maryland 20701.

Received 10 September 2001; revised manuscript received 5 February 2002.

0003-6935/02/214394-06\$15.00/0

© 2002 Optical Society of America

Fig. 1. Spot-size-mismatch loss in the one-dimensional case. The spot size of one waveguide is assumed to be 5 μm .

independently by using the field profiles along the center axes of x and y .

The coupling loss between the busline waveguide and the single-mode fiber is shown in Fig. 1, assuming that the spot size in the horizontal direction is matched to that of the fiber and the spot size in the vertical direction is varied. Here w_1 and w_2 are the spot sizes of the single-mode fiber and the busline waveguide, respectively, and δ is the offset of the center axis between them. That is, Fig. 1 shows the spot-size-mismatch loss in the one-dimensional case. The input-output coupling loss was numerically calculated with the following equation:

$$\eta = \frac{\left| \int_S \mathbf{E}^{(1)} \mathbf{E}^{(2)} d\mathbf{a} \right|^2}{\left[\int_S |\mathbf{E}^{(1)}|^2 d\mathbf{a} \right] \left[\int_S |\mathbf{E}^{(2)}|^2 d\mathbf{a} \right]}, \quad (2)$$

where E is the electric field profile and S is the cross-sectional area at which boundary the electric field is infinitesimally small. The electric field was calculated by an optical waveguide mode solver by use of a semivectorial finite-difference method.⁹ It can be seen that the spot-size-mismatch loss can be reduced to almost zero when the spot sizes are matched. However, the loss reaches as large as 5–10 dB when the mismatch ratio w_2/w_1 is as small as 0.2.

Figures 2(a)–2(d) show the field profiles calculated by the same finite-difference mode solver⁹ as used in the above calculation. The spot size of the single-mode fiber is 5–6 μm as shown in Fig. 2(a) and that of the conventional busline waveguide is 0.95 $\mu\text{m} \times 0.55 \mu\text{m}$ as shown in Fig. 2(b). Thus the spot-size-mismatch loss between the single-mode fiber and the conventional busline waveguide is as large as 15 dB/end facet. Therefore a busline waveguide with a large spot size was required to improve the input-output coupling loss.

3. Busline Waveguide with an AntiResonant Reflecting Optical Waveguide

A. Design

ARROW-type waveguides⁷ can be designed to act as a quasi-single-mode waveguide with a large spot size when the thickness of interference cladding layers are optimized. Thus we designed a vertically coupled microring resonator with an ARROW busline as shown in Fig. 3. The interference cladding layers of ARROW-B¹⁰ consist of two layers, which are the low-index first cladding layer and the second cladding layer with the same index as that of the core. In addition, by adoption of the stripe lateral confinement (SLC) configuration,¹¹ a thick-channelled waveguide can be fabricated with a flat top surface.⁶

To make the spot size of the busline waveguide match that of the single-mode fiber, we need to design the width and the thickness of the busline core to be the same size as those of the single-mode fiber. In the ARROW-type waveguides, the relation between the core thickness and the spot size is simply given by¹²

$$w = \frac{d_{ce}}{2.844}, \quad (3)$$

where d_{ce} is the equivalent core thickness. Therefore the optimum core thickness is 14.2 μm when the spot size of a single-mode fiber is 5.0 μm . Because the lateral confinement by the SLC structure is based on the positive index difference in the same manner as for the single-mode fiber, the core width should be designed to be 10 μm . Because the spot-size mismatch between the ARROW busline waveguide and the single-mode fiber can be reduced to nearly zero by this design, the ARROW is suitable for the busline of the vertically coupled microring resonator.

In the practical fabrication, however, the width of the SLC stripe window was designed to be 2.0 μm because we used the same photomask as for the conventional busline waveguide. To increase the vertical spot size as much as possible, we designed the thickness of the core to be 5.0 μm , which provides a spot size of approximately 2.65 $\mu\text{m} \times 2.33 \mu\text{m}$. Other parameters are as follows: the thicknesses of the first cladding and the SLC layer are 0.86 and 0.50 μm , respectively, the refractive indices of both the core and the second cladding are 1.603, and those of both the first cladding and the SLC layer are 1.451. Figure 2(c) shows the field profile of the ARROW busline calculated by a finite-difference mode solver.⁹ Because the core thickness is much larger than the core width, the field profile is like a bottleneck. Although the coupling loss is not reduced to zero by this design, we can expect the reduction of the coupling loss to be approximately 20 dB owing to the expansion of the spot size. In this structure, the coupling loss to the single-mode fiber was calculated to be 2.3 dB/end facet from the field profiles shown in Figs. 2(a) and 2(c) by use of Eq. (2).

Fig. 2. Electric field profiles of busline waveguides at the wavelength of $1.55\ \mu\text{m}$: (a) single-mode fiber; (b) conventional busline waveguide ($n_1 = 1.782$, $n_2 = 1.451$); (c) SLC-ARROW ($n_c = n_2 = 1.603$, $n_1 = n_{\text{SLC}} = 1.451$); and (d) horizontally enlarged waveguide ($n_1 = 1.782$, $n_2 = 1.451$).

B. Experimental Result

First, we fabricated the vertically coupled microring resonator filter with the ARROW busline as shown in Fig. 3. Because the ARROW is channeled by use of the SLC structure,¹¹ in which the light is confined by the insertion of a thin low-index layer with a stripe-opened channel, the top surface can be easily planarized.⁶

We fabricated the ARROW busline core by using the Ta_2O_5 - SiO_2 compound glass with a Ta_2O_5 mole fraction of 12% ($n = 1.603$ at $\lambda = 1.55\ \mu\text{m}$) and the microring waveguide core with a Ta_2O_5 mole fraction of 30% ($n = 1.782$ at $\lambda = 1.55\ \mu\text{m}$). The thickness and width of the ring core are $1.6\ \mu\text{m}$ and $1.5\ \mu\text{m}$, respectively. The ring radius is $15\ \mu\text{m}$. Because the ARROW strongly confines the light in its core, the

Fig. 3. Structure of a vertically coupled microring resonator with the ARROW busline.

Fig. 4. Scanning-electron-microscopy cross-sectional view of the ARROW.

equivalent index is close to that of the core ($n_{eq} = 1.58$), which is close to that of the microring resonator ($n_{eq} = 1.68$). In the conventional study that uses the ARROW busline, the dropping response has not been observed owing to the difficulty of coupling between the ARROW busline waveguide and the microring waveguide. This is due to the mismatching of equivalent indices of the ARROW busline and the ring and the small field penetration from the ARROW to the buffer layer. Therefore the thickness of the buffer layer between the busline and the ring was reduced from 0.7 to 0.4 μm . Thus the coupling between the ARROW busline and the microring waveguide was improved.

All the glass layers were formed by rf sputtering deposition, and the stripe and ring patterns were formed by reactive ion etching by use of CF_4 gas. The top surface of the busline was planarized by the lift-off process⁶ as shown in Fig. 4. Owing to the improved coupling between the ARROW and the microring waveguide, the dropping response was ob-

Fig. 5. Dropping response of the vertically coupled microring resonator with the ARROW busline. FSR, free spectral range.

Fig. 6. Magnification of the dropping response shown in Fig. 5.

served for the first time as shown in Figs. 5 and 6. In addition, the insertion loss of the throughput response was reduced to 8 dB, which is smaller by approximately 22 dB than that of the conventional busline. Further improvement of the insertion loss will be possible by enlargement of the core size of the ARROW busline.

Although the dropping response was clearly observed, a clear throughput response was not observed. This fact implies that the coupling efficiency from the busline to the ring core is not large enough. This is seems to be caused by the imperfect matching of equivalent indices of the busline ($n_{eq} = 1.58$) and the ring core ($n_{eq} = 1.68$). The solution of this problem requires a deposition technique that can continuously control the refractive index from 1.45 to 1.78, and this will be the subject of our next study with the plasma chemical vapor deposition.

4. Busline Waveguide with Spot-Size Transformer

A. Design

In the alternative method to improve the coupling loss, we inserted a SST¹³ into the busline waveguide. This configuration consists of conventional busline waveguides in the filter region and tapered busline waveguides at input–output ends, as shown in Fig. 7.

Fig. 7. Structure of the vertically coupled microring resonator with a SST.

Fig. 8. Coupling efficiency to the second-order mode.

To reduce the radiation loss at the tapered region, we adopted a horn waveguide,¹⁴ of which width as a function of propagation distance z is given by

$$W(z) = (2\alpha\lambda_g z + W_0^2)^{1/2}, \quad (4)$$

where λ_g is the cavity wavelength ($0.87 \mu\text{m}$ for $\lambda = 1.55 \mu\text{m}$ and $n_{\text{eq}} = 1.78$) and W_0 is the width of a tapered waveguide at the starting point. α is a parameter determining the shape of the tapered structure.

Figure 8 shows the coupling efficiency from the fundamental mode to the second-order mode as a function of α . The optimum value of α is obtained when the value of the coupling efficiency is minimized to the second-order mode $|a_2|$ under the condition of the adiabatic transition, which is given by $\alpha < 1.0$.¹⁴ Thus we adopted $\alpha = 0.056$. Using this value of α , we designed the horn waveguide so that W_0 is $2.0 \mu\text{m}$, the enlarged width $W(L)$ is $10.0 \mu\text{m}$, and the length of tapered region L is 0.98 mm . The calculated field profile at the output end is shown in Fig. 2(d). In this structure, the radiation loss was evaluated to be 0.06 dB by use of the two-dimensional finite-difference time-domain simulation, as shown in Fig. 9. Thus by adopting this structure, we can expect to reduce the coupling loss at input-output ends to less than 6.2 dB/end facet .

Fig. 9. Finite-difference time-domain simulation of the horn waveguide SST.

Table 1. Comparison of Theoretical and Experimental Values of Coupling Losses

Waveguide	Calculated Input-Output Coupling Loss (dB)	Insertion Loss (dB)
Conventional busline	30	30–40
ARROW busline	4.6	8
Busline with SST	12.4	22

The remaining loss is due to the spot-size mismatch in the vertical direction, and this may be reduced by introduction of the vertical tapered structure.¹³

B. Experimental Result

Next, we fabricated the vertically coupled microring resonator filter with the SST as shown in Fig. 7. The SST used in this study is the parabolic horn type as described in Subsection 4.A, which can achieve the low-loss single-mode propagation. It can be seen from the comparison of Figs. 2(a) and 2(d) that the spot size at the end of the busline waveguide can be matched to that of the single-mode fiber in the horizontal direction. In addition, the width of the busline waveguide in the device region is $2 \mu\text{m}$, which is the same as that of the conventional busline waveguide. The spot size of the busline waveguide in the device region is approximately $0.95 \mu\text{m} \times 0.55 \mu\text{m}$. Thus the coupling between the busline and the microring waveguide is the same as that of the conventional device.

However, the thickness of the core is $0.7 \mu\text{m}$, which is the limit resulting from the lift-off process to planarize the top surface of the busline waveguide. We matched the spot size of the busline waveguide to that of the single-mode fiber only in the horizontal direction. Therefore the input-output coupling loss can be theoretically reduced by approximately 15 dB .

The materials and the fabrication process of this structure are the same as those used for the ARROW-based microring resonator filter. The ring radius was $15 \mu\text{m}$. The insertion loss of the throughput response was reduced to 22 dB , which is approximately 10 dB of improvement from the conventional busline waveguide.

5. Conclusion

By adopting the ARROW-B waveguide and the rectangular waveguide with SST, we reduced the input-output coupling loss. The experimental results of the input-output coupling losses are summarized in Table 1. The input-output coupling losses were calculated from the calculated field profiles shown in Figs. 2(a)–2(d) by use of Eq. (2).

Although it is impossible to measure a coupling loss separately, each coupling loss was evaluated by the insertion loss at the throughput port. Because the insertion loss of the throughput response was reduced to 8 dB , we can conclude that the coupling loss

was successfully reduced by adopting an ARROW as the busline waveguide.

This study was partly supported by Grant-in-Aid for Scientific Research (A) 11305028 by Japan Society for the Promotion of Science; Grant-in-Aid for Scientific Research on Priority Areas (A) 13026210 from the Ministry of Education, Culture, Sports, Science and Technology; Research for the Future of Japan Society for the Promotion of Science; and International Communication Foundation.

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.* **4**, 1256–1258 (1992).
2. B. E. Little, S. T. Chu, J. Forsi, G. Steinmeyer, E. Thoen, H. A. Haus, E. P. Ippen, L. Kimerling, and W. Greene, "Microresonators for integrated optical devices," *Opt. Photon. News*, September 1998, pp. 32–33.
3. C. K. Madsen, "Efficient architectures for exactly realizing optical filters with optimum bandpass designs," *IEEE Photon. Technol. Lett.* **10**, 1136–1138 (1998).
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 Photon. Technol. Lett.* **11**, 691–693 (1999).
5. S. T. Chu, B. E. Little, W. Pan, T. Kaneko, and Y. Kokubun, "Second-order filter response from parallel coupled glass microring resonators," *IEEE Photon. Technol. Lett.* **11**, 1423–1425 (1999).
6. W. Pan, S. T. Chu, S. Sato, T. Maeda, T. Kato, and Y. Kokubun, "Planarization of film deposition and improvement of channel structure for fabrication of anti-resonant reflecting optical waveguide type x-crossing vertical coupler filter," *Jpn. J. Appl. Phys.* **37**, 3713–3717 (1998).
7. Y. Kokubun, T. Baba, T. Sakaki, and K. Iga, "Low-loss anti-resonant reflecting optical waveguide on Si substrate in visible-wavelength region," *Electron. Lett.* **22**, 892–893 (1986).
8. Y. Kokubun and S. Tamura, "Precise recursive formula for calculating spot size in optical waveguides and accurate evaluation of splice loss," *Appl. Opt.* **34**, 6862–6873 (1995).
9. 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.* **4**, 652–654 (1996).
10. T. Baba and Y. Kokubun, "New polarization-insensitive anti-resonant optical waveguide (ARROW-B)," *IEEE Photon. Technol. Lett.* **1**, 232–234 (1989).
11. T. Baba, Y. Kokubun, and Y. Mera, "A novel 3-dimensional ARROW by thin film patterning-stripe lateral confinement of ARROW," in *Integrated Guided-Wave Optics*, Vol. 4 of 1989 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1989) paper TuBB5, pp. 164–167.
12. T. Baba and Y. Kokubun, "Dispersion and radiation loss characteristics of antiresonant reflecting optical waveguides—numerical results and analytical expressions," *IEEE J. Quantum Electron.* **28**, 1689–1700 (1992).
13. N. Yamaguchi, Y. Kokubun, and K. Sato, "Low-loss spot-size transformer by dual tapered waveguides (DTW-SST)," *J. Lightwave Technol.* **8**, 587–594 (1990).
14. W. K. Burns and A. F. Milton, "Waveguide transitions and junctions," in *Guided-Wave Optoelectronics*, T. Tamir, ed. (Springer-Verlag, Berlin, 1988), Chap. 3.