(1) Title of letter

Ultra compact vertically coupled microring resonator with buried vacuum cladding structure

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(5) Abstract

We developed a novel fabrication process for the stacked dense integration of a microring resonator (VC-MRR) buried a SiO₂ cladding with vacuum cladding in the lateral direction. Owing to the vertical coupling and the lateral vacuum cladding, the radiation loss can be greatly reduced without affecting the coupling strength between the busline waveguide and the microring resonator. The reduction of radiation loss by ten orders of magnitude compared with the SiO₂ buried cladding was theoretically and experimentally demonstrated. Using this technique, an ultracompact VC-MRR with the ring radius of 5 μ m was realized, and the free spectral range (FSR) of 29nm was successfully obtained.

I. Introduction

We have proposed and demonstrated a vertically coupled microring resonator (VCMRR) filter [1]-[3]. The stacked configuration [1],[4] has many features, such as the independent optimum design of lower busline and upper ring waveguides, and the possibility of dense integration [5] resulting from the compactness of the microring and the cross-grid topology of the busline waveguide[2]. To increase the integration scale of the VC-MRR in a single chip, it is important to stack the device in the direction perpendicular to the substrate. To accomplish this, we developed a fabrication process for the stacked dense integration of a microring resonator by bias sputtering deposition [6], and realized a perfectly flat surface of each waveguide layer. In this structure, however, there remains the problem that the radiation loss of the ring resonator increases due to the decrease of the index contrast, because the ring core is covered with the cladding material.

To solve this problem, we propose a VC-MRR with a buried vacuum structure (BVS), as shown in Fig.1, and develop a novel fabrication process utilizing the characteristics of RF sputtering deposition to obtain the structure. Using this process, some microring resonators with buried vacuum claddings were fabricated and clear filter responses were observed.

II. Fabrication process of buried vacuum structure

When a thin film of dielectric material such as SiO_2 is deposited on a flat substrate by RF sputtering deposition, a flat thin film grows in the vertical direction. On the other hand, when a film is deposited on a substrate with a ridge structure, the film grows not only in the vertical direction but also in the lateral direction on the rib structure. In this case, no film is deposited just under the wing of the ridge structure and a void is formed after the ridge structure is completely buried. Therefore, when two ridge structures are close together, a buried vacuum channel can be formed between the two ridge structures by burying them with the dielectric film. Utilizing this property, we can fabricate an optical waveguide, in which the core is buried by cladding material in the vertical direction, but sandwiched by the vacuum cladding in the lateral direction. Thus a high-index contrast, which is needed to achieve ultra-small bending radius ($<10\mu\text{m}$), can be realized in the lateral direction, and vertical coupling can be achieved through the dielectric cladding layer, as shown in Fig.1.

According to the numerical calculation using a finite difference mode solver, the radiation loss of a microring with $5\mu\text{m}$ ring radius can be reduced from 2.1 dB/turn of the buried SiO_2 cladding structure to 0.23 dB/turn of the buried vacuum cladding structure. Even though the scattering loss may increase by two or three factors due to the reduction of cladding index, the overall loss reduction can be expected.

The fabrication process is as follows. First a planar waveguide structure with a SiN ($n=2.06$ at $\lambda=1550\text{nm}$) core and SiO_2 ($n=1.452$ at $\lambda=1550\text{nm}$) cladding is formed, as shown in Fig. 2(a). In our experiment, the SiN core

layer was deposited by plasma enhanced chemical vapor deposition (PE-CVD) and the SiO₂ cladding layers were deposited by RF sputtering deposition. Next a groove is formed through the upper SiO₂ cladding and SiN core layers, as shown in Fig.2(b), by photolithography and reactive ion etching (RIE) using a Cr mask and a gas mixture of C₂F₆ and O₂. The key point of this process is that the side wall of the upper cladding must be formed obliquely at an angle of about 70-80 degrees; this oblique angle is realized by using the gas mixture of C₂F₆ and O₂ in the RIE process. Next the SiN core layer is selectively etched, as shown in Fig.2(c), by H₃PO₄ at the temperature of 160 °C. Then, in the final process, the wing of the upper SiO₂ cladding is buried with SiO₂ deposited by RF sputtering, as shown in Fig.2(d).

The cross-sectional SEM image after the process shown in Fig.2(c) is presented in Fig.3(a), and that after the process shown in Fig.2(d) is given in Fig.3(b). It is seen in Fig.3(b) that the vacuum layer was successfully buried by the SiO₂ upper cladding and that a flat top surface was formed.

The sputtering deposition was done using Ar and O₂ gases with 0.6Pa to form the buried vacuum cladding. Therefore, exactly speaking, the cladding is not a pure vacuum. However, there is no actual difference of refractive index between air and vacuum.

III. Fabrication of VCMRR and measurement

Using this technique, a single ring resonator with 5μm ring radius was fabricated and the filter response was measured using a tunable laser and an optical spectrum analyzer. The measured result of the drop port response is shown in Fig.4. A clear filter response with the FSR of 29nm (3.6THz) and the FWHM bandwidth of 1.2nm was observed. To our knowledge, the FSR of

29nm is a world record, realized through the use of the single-ring resonator including semiconductor microrings.

Fig.5 shows the filter responses of VCMRRS fabricated by this process and by the previous process. The structures and the indices of all layers are the same for both devices, except for the vacuum layer. This figure indicates that the loss in the ring was reduced because the FWHM of the device fabricated by this process is smaller than that of the device fabricated by the previous process. The loss α in the ring resonator and the coupling ratio K between the busline waveguide and the microring resonator can be evaluated using^[7]

$$\alpha = \frac{2FWHM(1 - \sqrt{D})}{\pi R \left(\frac{\lambda_0^2}{\pi^2 n_{eff} R} - FWHM \right)} \quad (1)$$

$$K = \frac{2FWHM(1 - \sqrt{D})}{\frac{\lambda_0^2}{\pi^2 n_{eff} R} - FWHM} \quad (2)$$

where n_{eff} is the effective index and D is the depth of through-port response at on-resonance. Table.1 shows the calculated results by these equations. The calculated results of loss in the devices fabricated by this process and by the previous process are 0.13dB/turn and 1.4dB/turn (TM mode, $R=15\mu m$), respectively. The coupling coefficients K are also calculated to be 0.089 and 0.082. At this moment, the TE filter response of the device fabricated by the previous process was not observed. It can be seen that even though coupling coefficients are not changed, the propagation loss in the microring is successfully reduced by one-tenth with the introduction of the buried vacuum structure.

IV. Conclusion

The buried vacuum cladding structure was proposed and demonstrated to reduce the radiation loss of the VC-MRR filter with a very small ring radius. A new fabrication technique was developed to obtain this structure. Owing to the presence of this structure, an ultra high-index contrast in the lateral direction and a high coupling ratio in the vertical direction were simultaneously realized. Clear filter responses were observed and the loss in the ring resonator was evaluated to be reduced to about 95% of that of the device fabricated by the previous process.

Acknowledgments

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Figure captions

Fig. 1 Vertically coupled microring resonator with buried vacuum lateral cladding.

Fig. 2 Fabrication process of buried vacuum structure.

Fig. 3(a) Cross sectional SEM image after process (c) shown in Fig.2. The side wall of the upper cladding is formed oblique to the substrate surface.

Fig. 3(b) Cross sectional SEM image after process (d) shown in Fig.2.

Fig. 4 Measured filter response of VCMRR with buried vacuum cladding

Fig. 5 Drop port responses of VCMRR with buried vacuum cladding and buried vacuum cladding.

Fig. 6 Through port responses of VCMRR with buried SiO_2 cladding and buried vacuum cladding.

Table 1: Calculated results of loss coupling coefficients in the devices

	α , K
Buried SiO ₂ structure	----- $\alpha = 1.4$ dB/turn $K=0.082$ (TM mode)
Buried vacuum structure	$\alpha = 0.21$ dB/turn $K=0.072$ (TE mode) $\alpha = 0.13$ dB/turn $K=0.089$ (TM mode)

Fig. 1 Vertically coupled microring resonator with buried vacuum structure as lateral cladding.

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