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Noncritical Waveguide Alignment for Vertically Coupled Microring Using a Mode-Expanded Bus Architecture

C. W. Tee, K. A. Williams, R. V. Penty, I. H. White, and M. Hamacher

***Abstract*—Vertically coupled microrings in an all-pass filter configuration are fabricated with a range of waveguide misalignments deliberately introduced into the lithography masks to demonstrate noncritical fabrication requirements. The microrings have a mode-expanded bus design which allows a greatly reduced variation in power coupling coefficient—only 6% for fabrication misalignments as high as 1 μm. This represents a five-fold improvement in fabrication tolerance when compared with conventional designs.**

***Index Terms*—Active–passive integration, coupling coefficient, microring resonator, mode-expanded bus waveguide, vertical coupling, wafer bonding, waveguide coupling, waveguide misalignment.**

I. INTRODUCTION

IN RECENT years, growing research activity has been concentrated on photonic components using microring resonators. Due to their compact feature size and the ability to perform optical signal processing, microring resonators have become an attractive candidate building block for large-scale integrated photonic circuits [1]. To date, practical components including add–drop filters [2], switch fabrics [3], all-optical logic gates [4], and lasers [5] have been demonstrated. The majority of the components are realized using two-dimensional laterally coupled architectures, where the microring resonator and the bus waveguides lie in the same epitaxial plane. This results in a tight fabrication tolerance since the coupling gap between the microring and the bus waveguide has to be defined by electron-beam lithography. It has been argued that a vertically coupled architecture offers a much wider flexibility from the fabrication point of view [6]. Here waveguides are integrated in three dimensions with microring resonators in one epitaxial plane and single-moded input–output bus waveguides in a second plane for the purpose of coupling light in and out of the microring. The vertical separation is now controlled to the enhanced tolerance of epitaxial growth. The fact that the two waveguides now lie on different epitaxial planes further facilitates active–passive integration.

The fabrication of vertically coupled microring components based on III–V semiconductors may be implemented by means of a wafer bonding process in order to facilitate waveguide fabrication on both sides of the same wafer [6]. This, however, leads to a critical lithographic lateral alignment requirement for the ring and bus waveguides, which will induce a variation in waveguide offset and a resultant deviation of coupling coefficient from wafer to wafer [7]. While precision alignment marks can be implemented in the mask set, the run-out experienced for even low levels of wafer warping or contraction in the adhesive materials can also lead to deviation in waveguide misalignment across a wafer, causing significant device-to-device performance variation. Recent simulation studies have, however, shown that a relaxed fabrication tolerance can be achieved by employing a mode-expanded bus waveguide design [10]. This letter reports the first experimental verification of the reduced variation in coupling coefficient with bus waveguide misalignment for such mode-expanded bus waveguides.

II. DEVICE STRUCTURE

A series of vertically coupled passive microring waveguides are fabricated with lateral misalignment deliberately introduced onto the lithography mask. The bus waveguides are first fabricated by epitaxial growth and selective etching. An insulating cladding layer is then applied to the structure prior to wafer bonding to another substrate. The sample is then inverted, and the substrate of the original wafer is removed by etching. Finally, the microring waveguide is patterned and fabricated by standard lithography and etching subsequent to mask alignment. The devices are fabricated in all-pass filter configurations, with the microring waveguide vertically coupled to a single bus waveguide. The ring and bus waveguide are InGaAsP quaternaries having bandgaps of 1.4 and 1.3 μm and thicknesses of 280 and 400 nm, respectively. The waveguide geometries are designed to enhance the coupling of the fundamental mode between the microring and bus. Fig. 1(a) shows an optical microscope image of the top view of two fabricated devices.

Cross-sectional views of the coupling regions between the microrings and the bus waveguides of different widths are shown in Fig. 1(b). Lateral misalignment is defined as the offset measured between the center of the microring and bus waveguide, as indicated in Fig. 1(b).

III. EXPERIMENT

Transmission measurements across a series of design variants have been carried out in order to quantify the influence of the

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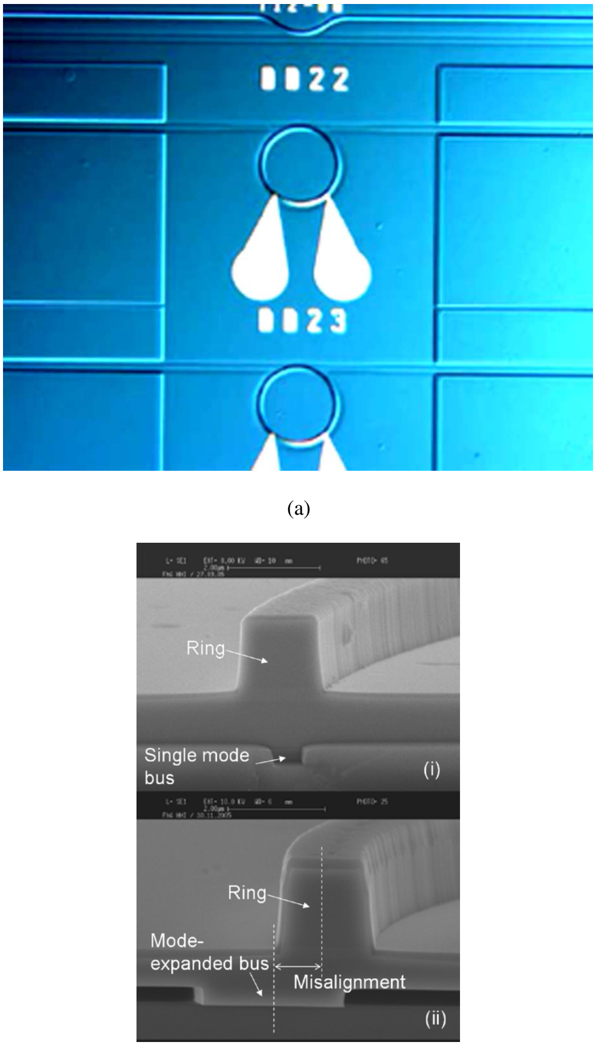
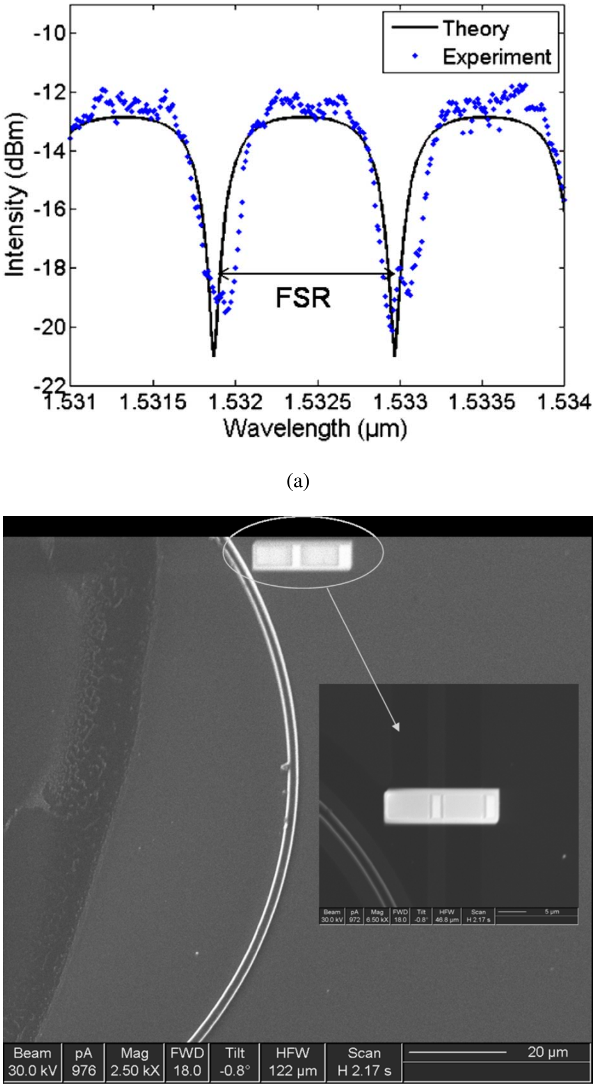


(a)

(b)

Fig. 1. (a): Top view of vertically coupled microrings. (b) Cross-sectional view of fabricated vertically coupled microring architecture with (i) narrow single-mode bus, (ii) wide mode-expanded bus. (Color version available online at http://ieeexplore.ieee.org.)



(a)

(b)

Fig. 2. (a) Example of a measured and fitted transmission spectrum. (b) Focused ion beam microscope image of ring and bus waveguide. (Color version available online at http://ieeexplore.ieee.org.)

waveguide offset on the power coupling between the ring and bus waveguide using a continuous-wave tunable external-cavity laser. A polarizer consisting of a TM polarization-stripping fiber is used to provide a polarization extinction ratio in excess of 20 dB. While this work focused on the TE polarization, the results obtained on coupling sensitivity are general and the trend can be applied to TM polarization as well. The polarized light is coupled to the bus waveguide using a polarization-maintaining lensed fiber. The light transmitted through the device is collected using a second lensed fiber for spectrally resolved intensity measurement to subsequently extract the coupling coefficient. The effective index of the ring waveguide is first calculated from the free spectral range of the transmission spectrum. A least squares algorithm is subsequently used to implement a Z-transform analytical fit to the transmission spectrum. A good estimation of waveguide loss in the microring can be obtained using the method elaborated in [8].

Fig. 2(a) shows an example of the measured and fitted transmission spectrum. Polarization mode splitting is observed in a number of the transmission spectrum due to the existence of polarization rotation in the microring [9]. Devices are subsequently assessed using focused-ion-beam etching to measure the exact waveguide misalignment. Fig. 2(b) shows a focused ion beam microscope image of a device with a 20 μm× 5 μm etch profile to a depth of 0.7 μm to reveal the buried bus waveguide. The misalignment value is subsequently measured.

The extracted coupling coefficient is plotted against the measured waveguide misalignment in Fig. 3. The solid diamonds in the figure denote the coupling coefficient dependence on waveguide misalignment between a 1.8-μm-wide microring with a radius of 80 μm and a 1.8-μm bus waveguide. Here a maximum coupling of above 0.8 is achieved for a -0.5-μm offset, reducing significantly to 0.6 for a relative offset of only 0.2 μm. A variation in coupling coefficient of 29% is observed across a misalignment range of 1 μm. The solid squares show the coupling coefficients for otherwise identical 60-μm radius microrings as the bus waveguide is moved even further from the microring.

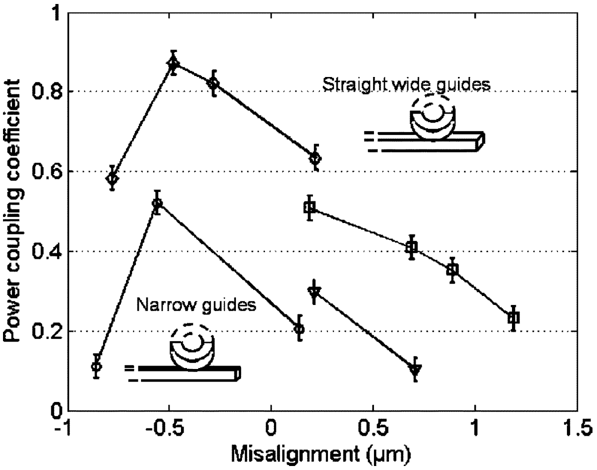


Fig. 3. Coupling coefficient between microring and single-mode bus. ◇: wide bus width = 1.8 μm, ring width = 1.8 μm, radius = 80 μm; □: wide bus width = 1.8 μm, ring width = 1.8 μm, radius = 60 μm; ▽: wide bus width = 1.8 μm, ring width = 1.8 μm, radius = 20 μm; o: narrow bus width = 0.8 μm, ring width = 1.8 μm, radius = 70 μm.

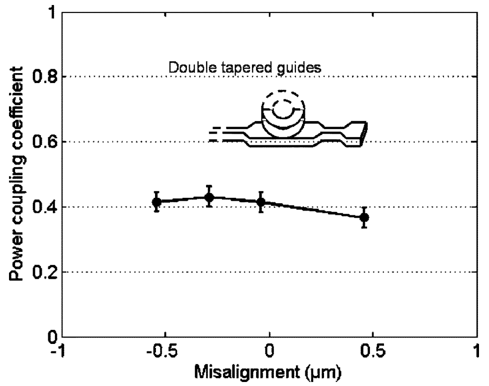


Fig. 4. Coupling coefficient between microring and mode-expanded bus. •: bus width = 2.0 μm, ring width = 1.0 μm, radius = 10 μm.

Consistent trends are shown with a reduction in coupling coefficient of down to below 0.3 for an offset exceeding 1 μm. Small ring radii of 20 μm have also been characterized, as shown by the solid triangles.

Further measurements were performed for 70-μm radius rings coupled to single-mode 0.8-μm bus waveguides. These are shown in Fig. 3 with unfilled circles. Here an even starker sensitivity to bus-microring misalignment is observed—the variation in coupling coefficient is over 40% across a misalignment range of 1 μm. This effect is attributable to the smaller mode size within the narrow bus waveguide, where precise alignment is required to ensure a good modal overlap. The cavity losses of the microrings are found to range from 1.65 dB/round-trip for 80-μm rings to 5 dB/round-trip for 20-μm rings.

Theoretical study has indicated that the alignment tolerance may be significantly relaxed through the implementation of a tapered bus waveguide design with a width wider than that of the ring in the coupling region [10]. Such structures have been fabricated and assessed and data are presented in Fig. 4. The solid circles in Fig. 4 denote the coupling coefficient between a 1.0-μm microring with a radius of 10 μm and a 2.0-μm mode-expanded bus waveguide. The device consists of a double-taper waveguide architecture, as shown in the inset of Fig. 4, to provide discrimination against higher order modes and to facilitate enhanced fiber coupling efficiency. The length of the mode-expanded waveguide and the taper section are both 200 μm. Negligible alignment sensitivity is observed for the mode-expanded bus design, even for such low radius designs. A coupling variation of only 6% is measured across a misalignment range of 1 μm. This shows a marked improvement in coupling coefficient sensitivity to waveguide misalignment when compared to straight waveguide designs.

IV. CONCLUSION

The influence of misalignment between the microring and bus waveguide on the coupling coefficient is investigated experimentally. A mode-expanded bus waveguide design for reduced sensitivity of the coupling coefficient to waveguide misalignment is validated. A variation in coupling coefficient of only 6% is measured for a misalignment range of 1 μm, showing the applicability of the proposed design for relaxed mask alignment tolerance which may facilitate wafer scale fabrication.

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REFERENCES

[1] B. E. Little, S. T. Chu, W. Pan, and Y. Kokubun, "Microring resonator arrays for VLSI photonics," *IEEE Photon. Technol. Lett.*, vol. 12, no. 3, pp. 323–325, Mar. 2000.

[2] D. G. Rabus, M. Hamacher, U. Troppenz, and H. Heidrich, "Optical filters based on ring resonators with integrated semiconductor optical amplifiers in GaInAsP-InP," *IEEE J. Sel. Topics Quantum Electron.*, vol. 8, no. 6, pp. 1405–1411, Nov./Dec. 2002.

[3] K. Djordjev, S. J. Choi, S. J. Choi, and P. D. Dapkus, "Vertically coupled InP microdisk switching devices with electroabsorptive active regions," *IEEE Photon. Technol. Lett.*, vol. 14, no. 8, pp. 1115–1117, Aug. 2002.

[4] T. A. Ibrahim, K. Amarnath, L. C. Kuo, R. Grover, V. Van, and P. T. Ho, "Photonic logic NOR gate based on two symmetric microring resonators," *Opt. Lett.*, vol. 29, no. 23, pp. 2779–2781, 2004.

[5] M. Sorel, G. Guiliani, A. Scire, R. Miglierina, S. Donati, and P. J. R. Laybourn, "Operating regimes of GaAs-AlGaAs semiconductor ring lasers: Experiment and model," *IEEE J. Quantum Electron.*, vol. 39, no. 10, pp. 1187–1195, Oct. 2003.

[6] D. V. Tishinin, P. D. Dapkus, A. E. Bond, I. Kim, C. K. Lin, and J. O. Brien, "Vertical resonant couplers with precise coupling efficiency control fabricated by wafer bonding," *IEEE Photon. Technol. Lett.*, vol. 11, no. 8, pp. 1003–1005, Aug. 1999.

[7] R. Grover, P. P. Absil, V. Van, J. V. Hryniewicz, B. E. Little, O. King, L. C. Calhoun, F. G. Johnson, and P. T. Ho, "Vertically coupled GaInAsP-InP microring resonators," *Opt. Lett.*, vol. 26, no. 8, pp. 506–508, 2001.

[8] V. Van, P. P. Absil, J. V. Hryniewicz, and P.-T. Ho, "Propagation loss in single-mode GaAs-AlGaAs microring resonators: Measurement and model," *J. Lightw. Technol.*, vol. 19, no. 11, pp. 1734–1739, Nov. 2001.

[9] A. Melloni, F. Morichetti, and M. Martinelli, "Polarization conversion in ring resonator phase shifters," *Opt. Lett.*, vol. 29, no. 23, pp. 1–3, 2004.

[10] C. W. Tee, K. A. Williams, R. V. Penty, and I. H. White, "Fabrication-tolerant active–passive integration scheme for vertically coupled microring resonator," *IEEE J. Sel. Topics Quantum Electron.*, vol. 12, no. 1, pp. 108–116, Jan./Feb. 2006.