Redesigning active and passive microring resonators

Joyce K. S. Poon, Wesley D. Sacher, Jared C. Mikkelsen, Hasitha Jayatilleka
Department of Electrical and Computer Engineering
University of Toronto
Toronto, Ontario, Canada
joyce.poon@utoronto.ca

William M. J. Green, Solomon Assefa, Tymon Barwicz, Huapu Pan, Steven M. Shank, Yurii Vlasov
IBM T. J. Watson Research Center
Yorktown Heights, New York

Richard J. Bojko
Microfabrication Facility
University of Washington
Seattle, Washington

***Abstract*— Even after decades of investigation, microring resonator devices remain mostly in the realm of research. Reconsiderations of microring designs lead to improved fabrication tolerance, modulation performance, and functionality, paving the path toward practical implementations.**

Keywords—optical resonators, modulators, integrated optics

I. Introduction

Optical waveguide ring resonators were first proposed in 1969 by Marcatilli, and their potential for integrated optics was quickly recognized [1]. However, it was not until low-loss optical waveguides were fabricated in moderate and high index-contrast material systems that micro-scale ring resonators began to attract significant interest for wavelength (de)multiplexers, filters, modulators, and lasers [2]. The multi-round-trip interference enables microring devices to be orders of magnitude more compact in size, spectrally selective and energy-efficient than those relying on single-pass interference or absorption. These benefits have spurred extensive research in microrings and other microcavities in the past 10 to 20 years [2]. However, products that use integrated microcavities remain rare [3, 4]. The most critical and often cited challenges of microcavities are their sensitivity to fabrication and environmental variations, and their need for precise control.

In this work, I will describe my group's efforts to mitigate these challenges in high index contrast platforms by the design of microrings. I will present microrings with improved tolerance to dimensional variations, tunable microring modulators with high extinction ratios, and modulators that break the linewidth limitations of resonant modulation. The concepts can be extended to other types of high index contrast waveguide devices, resonant modulators, and lasers. With the appropriate architectures and design approaches, microrings can realize their potential to become workhorse elements in large-scale, complex integrated photonic circuits.

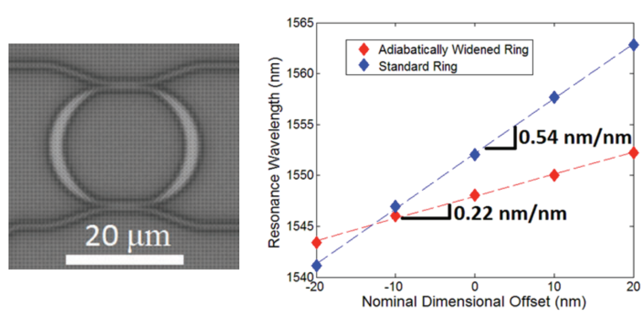
II. Improving the Dimensional Tolerance

In high index contrast platforms, such as silicon-on-insulator (SOI), microrings are sensitive to dimensional variations at the nanometer-scale [5]. Active tuning can compensate for some variability at the expense of power consumption (see Section III), but it is also possible to improve the tolerance through the passive design.

One approach is to use wide waveguides and control the mode excitation [6, 7]. By adiabatically widening a strip waveguide to a wide bend, the strip waveguide mode is transformed to the lowest order whispering gallery mode (WGM) of the wide section. The effective index of a WGM only depends on the waveguide width through the bend radius, and can be 1 to 2 orders of magnitude less sensitive to width variations than a wire waveguide mode. Adiabatically widened microrings have been used for electrical contacts [8] but have not been investigated for dimensional tolerance.

Figure 1(a) shows an optical microscope image of a microring add-drop filter with widening bends fabricated in 220 nm thick SOI with a PECVD oxide cladding with electron-beam lithography at the University of Washington [9]. The width of the bend connecting the two couplers varies parabolically from 500 nm at the coupler to a maximum of 2.2 μm. The widening bend was designed to be short while avoiding insertion losses and the excitation of higher order modes. The bend radius of the circular outer wall was 10 μm.

As a test of the approach, we designed a set of matching adiabatically widened and standard (uniform width of 500 nm) microrings, where we intentionally introduced a dimensional offset to the waveguide width. Fig. 1(b) shows the resonance shift due to the dimensional offset was 2.3 times smaller for the widened microrings than the standard rings. The spectra, free spectral range (~8.5 nm), Q factors (~1000), and extinction ratios (~15 dB) of the standard and adiabatically widened rings were similar. A reduced dimensional dependence can lower the power consumption of the post-fabrication tuning and improve the yield. The dimensional tolerance can be further improved with couplers that are less phase-sensitive.



(a) (b)

Fig. 1. (a) Optical microscope image of a fabricated adiabatically widened microring in SOI with an oxide cladding. (b) Resonance wavelength shift as a function of the nominal dimensional offset. (From [6])

III. Tunable, High-Extinction Ratio, High-Speed Microring Modulators

High extinction modulators and filters require independent and active tuning of the phase-shift and coupling coefficient to compensate for residual dimensional and thermal variations. To date, most active microrings contain a single tuning or modulation section in the ring for resonance tuning only. Indeed, most resonant modulators have extinction ratios <10 dB, lower than that of Mach-Zehnder interferometers (MZIs).

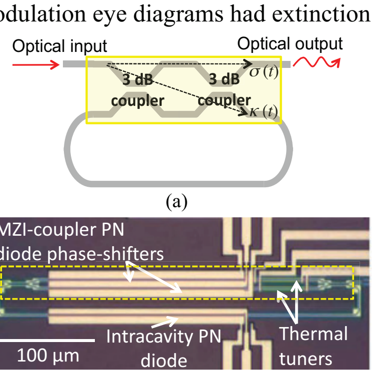
The independent tuning of the coupling coefficient and resonance wavelength can be realized using a microring with an integrated 2 x 2 MZI variable coupler (Fig. 2(a)) [10]. A common phase-shift between the top and bottom arms of the MZI-coupler tunes the resonance, while a differential phase-shift tunes the coupling coefficient.

Moreover, the modulation of the coupling coefficient, which we term "coupling modulation," leads to modulators that are ideally chirp-free and can operate at rates beyond the conventional linewidth limit [11-13]. In contrast to intracavity modulation, the eye opening increases as the linewidth decreases relative to the modulation frequency. The modulator efficiency is resonantly enhanced, because the swing in the coupling coefficient is reduced by a factor that scales with the cavity finesse [13]. Coupling modulation enables ultra-high-Q microcavities to be high-speed and efficient modulators.

As a proof-of-concept of the unique properties of coupling modulation, we fabricated the SOI MZI-microring shown in Fig. 2(b) in the IBM Silicon CMOS Integrated Nanophotonics process [14]. The PN diode phase-shifters in the MZI-coupler were modulated in push-pull, and an identical PN diode phase-shifter was included in the microring for direct comparisons between coupling and intracavity modulation. Resistive thermal tuners in the MZI were used to tune the coupling coefficient and resonance wavelength of the microring.

Figure 3(a) shows the transmission spectra of the microring, as well as the precise, independent tuning of the coupling coefficient and resonance wavelength achieved by the thermal tuners. An extinction ratio near 30 dB was reached at critical coupling. Without a bias on the PN diode phase-shifters the linewidth at critical coupling was $\Delta\nu \approx 7$ GHz, corresponding to a Q factor of about 28000 and a finesse of 14.

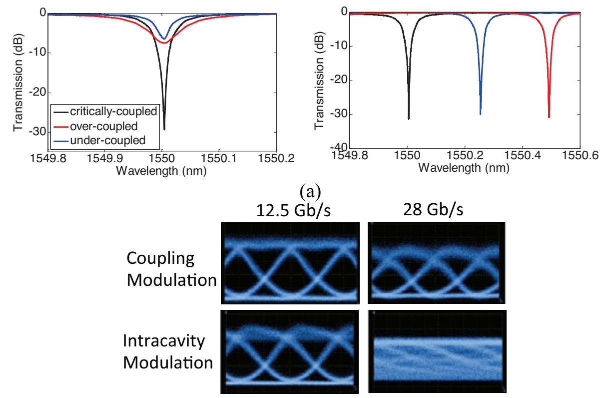
Figure 3(b) shows the eye diagrams of coupling and intracavity modulation at 12.5 Gb/s and 28 Gb/s for a NRZ PRBS 2^{31}-1 pattern. At 12.5 Gb/s, both the coupling and intracavity modulation eye diagrams had extinction ratios of



(a)

(b)

Fig. 2. (a) Schematic of a coupling modulated microring. The box marks the 2 x2 MZI-coupler. (b) The fabricated SOI MZI-microring. (From [13])



(a)

(b)

Fig. 3. (a) Measured transmission spectra as the coupling coefficient is tuned at a fixed resonance (left) and as the resonance wavelength is tuned with a fixed coupling coefficient (right). (b) Eye diagrams for coupling and intracavity modulation at 12.5 Gb/s and 28 Gb/s. (From [13])

10-13 dB. As the bit rate increased, the coupling modulation eye remained open up to 28 Gb/s, whereas the intracavity modulation eye became closed. The result shows that coupling modulation enables modulation with high extinction ratios and at rates that break the long-held cavity linewidth limit.

IV. Conclusions

The implementation and performance challenges of existing microring devices motivate a reconsideration of their design. Microcavity devices can be designed to improve their tolerance and yield without sacrificing for losses or efficiency. Breakthroughs in the device design and architectures are needed for the more widespread use of microcavities.

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