Crosstalk-Resilient Wavelength Locking for Si Micro-Ring-Resonator-Based Ultra-Dense WDM Receivers

Seung-Jae Yang*, Yongjin Ji*, Dae-Won Rho, Jae-Ho Lee, and Woo-Young Choi
Department of Electrical and Electronic Engineering, Yonsei University, South Korea
**Authors contributed equally to this work*
Email:wchoi@yonsei.ac.kr

Abstract: We present a crosstalk-resilient wavelength locking technique for realizing micro-ring resonator (MRR)-based WDM receivers having ultra-dense channel spacing. The crosstalk between adjacent MRRs is suppressed by custom-designed electronic circuits, and a new wavelength locking technique is used that searches and maintains the target wavelength for each MRR even under severe crosstalk conditions. The technique is experimentally verified with a Si photonic 4 λ × 28 Gb/s WDM receiver having 250 pm (31.2 GHz) channel spacing.

1. Introduction

The growing demands for AI/ML computation necessitate high-throughput, energy-efficient solutions for scale-up and scale-out interconnects within large-scale data centers. Interconnect solutions based on Si photonics are being widely deployed, and in order to further enhance the bandwidth density, the wavelength-division multiplexing (WDM) technique is actively pursued, in which micro-ring resonators (MRRs) are used in WDM receivers as wavelength-domain filters with their wavelength-dependent transmission characteristics and small footprints [1-3].

With MRRs, reducing channel spacing allows a larger number of WDM channels within the given free-spectral range (FSR), resulting in increased total throughput. However, with reduced channel spacing, optical signals from neighboring channels can cause crosstalk, degrading the received signal. Approaches such as increasing the MRR quality factor or utilizing high-order ring structures can mitigate this limitation [4], but at the expense of reduced received data bandwidth or increased complexity, respectively. We have addressed this problem by electrically canceling the MRR crosstalk with a custom-designed receiver IC [5]. Although this approach can successfully suppress crosstalk between closely spaced WDM channels, locking the MRR resonance wavelength to the desired value for each WDM channel against any external perturbation presents a significant challenge. In this paper, we present a new technique to address this issue.

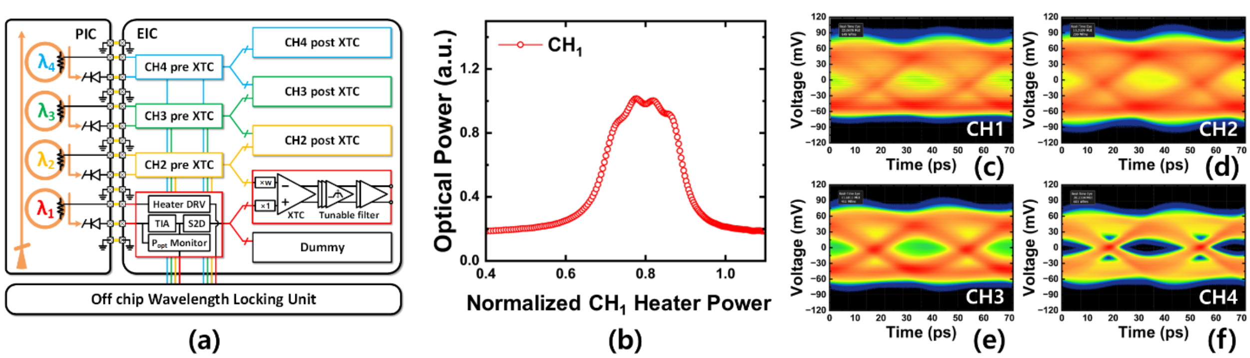

Fig. 1. (a) Top block diagram of WDM receiver with crosstalk cancellation and wavelength locking unit, (b) measured drop-port optical power of CH_1 MRR for 250 pm channel spacing with varying CH_1 on-chip heater power normalized to the value corresponding to 1 V heater voltage, and (c)-(f) measured 28 Gb/s eye diagrams of 4 channels at 250 pm channel spacing with temperature variation.

Fig. 1(a) shows the block diagram of the 4-channel WDM receiver with the crosstalk cancellation and wavelength locking unit. Fig. 1(b) shows the drop-port optical power of CH_1 corresponding to λ_1 channel in Fig. 1(a) when the WDM channel spacing is 250 pm, as the power supplied to the CH_1 on-chip heater is scanned while all four wavelength input signals are introduced to the receiver. As can be seen in the figure, it is not possible to clearly identify four distinctive peaks corresponding to four input wavelengths due to the relatively small channel spacing compared to the transmission bandwidth of the MRR. Although initial matching of each MRR with the target wavelength is achieved by sequentially turning one laser on at a time, it is not possible to lock this condition against any external perturbation. Fig. 1(c)-(f) show the measured 28 Gb/s WDM receiver eye diagrams when the ambient temperature changes sinusoidally by 5°C.

2. Proposed Wavelength Locking Method

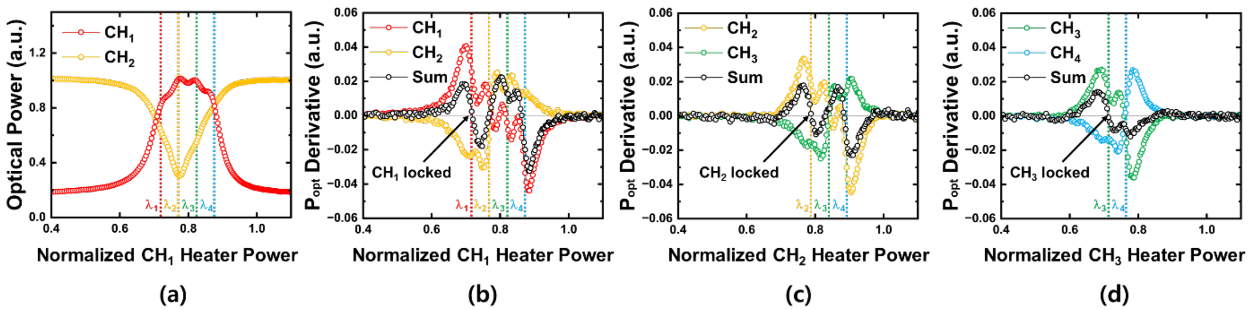

Fig. 2. (a) Measured CH_1 and CH_2 drop-port powers with CH_1 heater power sweep. (b) Derivatives of CH_1 and CH_2 drop-port powers and their sum with CH_1 heater power sweep. (c) Derivatives of CH_2 and CH_3 drop-port powers and their sum with CH_2 heater power sweep. (d) Derivatives of CH_3 and CH_4 drop-port powers with their sum with CH_3 heater power sweep.

In order to solve the above problem, we utilize the sum of derivatives of the monitored drop-port optical powers of two adjacent MRRs. Fig. 2(a) shows the measured drop-port optical powers for CH_1 and CH_2 during the CH_1 on-chip heater power sweep for WDM channel spacing of 250 pm. The dashed lines indicate desired heater powers corresponding to the four channel wavelengths. A key observation is that the monitored drop-port optical power for CH_2 shows a dip, which occurs when the CH_1 resonance wavelength is aligned with λ_2. At this alignment point, most of the λ_2 optical power is dropped into CH_1. The conventional peak-searching method utilizes the derivative of the monitored optical power from a single channel and determines zero-crossing points of the derivative as desired points [6]. However, as demonstrated in Fig. 2(b), the CH_1 monitored power derivative fails to cross zero at λ_1. This occurs because while the desired signal contribution reaches zero at this point, crosstalk from CH_2 introduces a non-zero derivative component, disrupting accurate wavelength identification. By leveraging the fact that this crosstalk is also reflected in the CH_2 monitored optical power, the sum of derivatives from CH_1 and CH_2 exhibits a zero-crossing at the CH_1 signal wavelength, as indicated by the red-dashed line in Fig. 2(b). Therefore, while the conventional peak-searching method relying solely on the CH_1 derivative fails to identify the CH_1 wavelength, the proposed derivative sum method successfully compensates for the crosstalk effects by summing the derivatives and accurately identifies the desired operating point. The MRRs for other channels are also locked using the derivative sum method. The CH_2 wavelength is determined based on CH_2 and CH_3 derivatives during CH_2 heater power sweep, as shown in Fig. 2(c), and CH_3 wavelength is determined based on CH_3 and CH_4 derivatives, as shown in Fig. 2(d). For CH_4, since there is no crosstalk from subsequent channels, only the CH_4 derivative needs to be monitored, making this equivalent to a single-channel derivative method.

3. Measurement Results

Fig. 3(a) shows the chip photograph of the implemented 4-channel WDM optical receiver. The photonic integrated chip (PIC) and electrical integrated chip (EIC) are wire-bonded and mounted on a PCB. The EIC includes an optical power monitor that converts optical power to voltage, which is fed into an external wavelength locking unit. This unit controls the heater driver on the EIC to tune the resonance wavelengths of MRRs in the PIC based on the derivative sum method. The measurement setup is illustrated in Fig. 3(b). Four continuous-wave optical signals are coupled into separate fibers and pass through polarization controllers before and after the Mach-Zehnder modulators (MZMs) to match the polarization with the MZM and grating coupler, respectively. The four signals are combined, amplified by an erbium-doped fiber amplifier (EDFA), and coupled into the PIC via a grating coupler. The two MZMs were alternately configured to modulate the target channel and crosstalk channels for comprehensive testing.

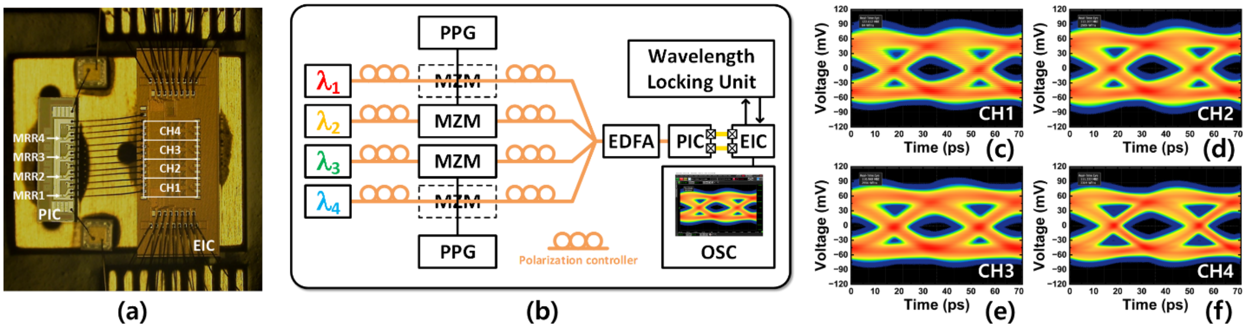

Fig. 3. (a) Integrated chip photo, (b) measurement setup, and (c-f) measured 28 Gb/s eye diagrams of 4 channels at 250 pm channel spacing with the proposed wavelength locking with temperature variation.

Experimental validation of the proposed derivative sum method was performed using 28 Gb/s PRBS15 optical signals with -3 dBm optical power per channel. Fig. 3(c)-(f) demonstrate the effectiveness of the wavelength locking system through eye diagrams measured for 250 pm (31.2 GHz) channel spacing during a sinusoidal 5°C stage temperature variation. These measurements were obtained with the crosstalk cancellation technique from [5] already implemented. With wavelength locking enabled, the system maintained robust eye quality and achieved an aggregate throughput of 112 Gb/s. We achieved a spectral density of 0.89 b/s/Hz, calculated by dividing the data rate of 28 Gb/s by the channel spacing of 31.2 GHz. A higher spectral density enables increased aggregate throughput within a given FSR. This work represents a more than fivefold improvement over the previously published maximum spectral density of 0.16 b/s/Hz, achieved with a data rate of 16 Gb/s and a channel spacing of 100 GHz [2]. This performance can be scaled to over 1.3 Tb/s with 48 channels having 250 pm channel spacing within 12.29 nm FSR, showing a great potential for ultra-dense WDM Si photonic interconnect systems.

4. Conclusion

This work demonstrates a crosstalk-resilient wavelength locking method that enables ultra-dense WDM operation with 4 λ × 28 Gb/s at 250 pm (31.2 GHz) channel spacing. The proposed derivative sum approach overcomes the limitations of conventional peak-searching methods by utilizing the differential response of adjacent channel monitored optical powers. Combined with our crosstalk cancellation technique, the system ensures robust eye quality even under external thermal stress. This work achieved the highest spectral density of 0.89 b/s/Hz for IM/DD systems.

5. Acknowledgements

This work was supported by Institute of Information & communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (No.RS-2023-00222171). The EDA tool was supported by the IC Design Education Center (IDEC), Korea.

6 References

[1] C. S. Levy et al., "8-λ × 50 Gbps/λ Heterogeneously Integrated Si-Ph DWDM Transmitter," *IEEE Journal of Solid-State Circuits*, vol. 59, no. 3, pp. 690-703, 2024.

[2] Y. Wang et al., "Silicon photonics chip I/O for ultra high-bandwidth and energy-efficient die-to-die connectivity." *IEEE Custom Integrated Circuits Conference (CICC)*, Denver, USA, 2024.

[3] A. Rizzo et al., "Massively scalable Kerr comb-driven silicon photonic link" *Nature Photonics*, vol. 17, pp. 781-790, 2023.

[4] Zhang, Lei, *et al*. "Cascading second-order microring resonators for a box-like filter response." *Journal of Lightwave Technology* vol. 35, no. 24, pp. 5347-5360, December 2017.

[5] S. -J. Yang et al., "A Si Photonic WDM Receiver with Micro-Ring Resonator Crosstalk Cancellation," TH.01.03, SC3, *European Conference on Optical Communication (ECOC)*, Copenhagen, Denmark, 2025.

[6] H. -K. Kim *et al*., "A 4-λ × 28-Gb/s/λ Silicon Ring-Resonator-Based WDM Receiver With a Reconfigurable Temperature Controller," in *Journal of Lightwave Technology*, vol. 42, no. 7, pp. 2296-2302, 1 April 2024.