Automated Tuning of Ring-Assisted MZI–Based Interleaver for DWDM Systems

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Abstract: We present an RAMZI auto-tuning structure for DWDM systems, rectifying phase errors and optimizing passband alignment. Experimental results validate improved performance and operational efficiency, facilitating scalable communication infrastructures in high-performance computing systems and data centers.

1. Introduction

The synergy between silicon photonics (SiPh) and dense wavelength-division multiplexing (DWDM) technology has paved the way for link architectures that achieve ultra-high bandwidth densities and ultra-low energy consumption per bit, holding immense potential as a viable solution to alleviate the bandwidth bottleneck [1]. In DWDM systems, interleavers play a pivotal role by facilitating the subdivision and combination of different wavelength channels. They become particularly crucial in multi-free spectral range (FSR) systems [2] by effectively doubling the channel spacing with each stage of de-interleaving, thus significant reducing the inter-channel crosstalk. While basic Mach-Zehnder interferometer (MZI)–based interleavers are compact and relatively straightforward to design, they can be sensitive to fabrication/environmental perturbations, and has limited channel capacity due to fundamental dispersion. In contrast, ring-assisted MZI (RAMZI)–based interleavers incorporate ring resonators to achieve flat-top passbands [3]. This feature enhances its resilience to both perturbations and the FSR mismatch w.r.t. the DWDM source, while maintaining a compact footprint. However, the flat-top response comes with the complexity of additional rings and phase shifters, requiring a more intricate control scheme.

In this context, we introduce an RAMZI auto-tuning structure and an associated control scheme tailored to DWDM systems. This innovative solution is engineered to automatically compensate for phase errors between the ring and the MZI arm, and offer robust alignment with the DWDM source. By streamlining the optimization precess, it ensures superior performance and significantly boosts operational efficiency.

2. Interleaver Auto-Tuning Structure and Control Scheme

Fig. 1a illustrates an RAMZI with a 400 GHz FSR, designed for subdividing a 200 GHz-spacing DWDM source. To achieve a broadband flat-top response, a compact multi-mode interferometer (MMI)–based coupler with 15:85 splitting ratio is implemented for effective coupling to the ring. The effective path length of the ring, denoted as L_r, needs to be approximately twice the MZI arm length difference, ΔL. To analyze the RAMZI transmission spectrum, a tunable laser was swept across 1516–1564 nm with a 10 pm resolution, and the results are plotted in Fig. 1b. The

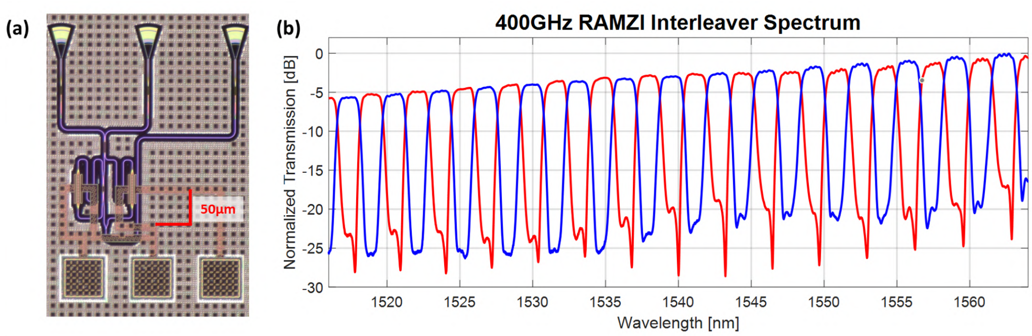

Fig. 1. **(a)** Fabricated 400 GHz MMI coupler-based RAMZI interleaver. **(b)** Measured 400 GHz RAMZI interleaver spectrum. The red and blue curves represent each interleaver output port.

transmission spectrum exhibits a flat-top response after applying 1 V to the phase shifter on the MZI arm, with an extinction ratio of 20 dB over 50 nm bandwidth for both ports. It should be noted that the unevenness in the envelope of the spectrum is primarily introduced by the grating coupler rather than the RAMZI.

To ensure the automatic compensation of phase errors for achieving the desired flat-top response, as well as the automatic alignment of the interleaver passbands/stopbands with the DWDM channels, a photodetector is necessary for generating a feedback signal, as seen in various monitored auto-tuning architectures [4–6]. However, directly tapping either one of the RAMZI output ports for photocurrent monitoring would result in a constant readout, as analyzed in [7], rendering it unusable for auto-tuning. Inspired by [7], we have devised an auto-tuning structure for our RAMZI interleaver, as depicted in Fig. 2a. The RAMZI (red box) functions as the link (de)interleaver, with a power tap integrated into its output to divert a small portion of optical power for auto-control, while the majority of the power continues on to subsequent devices, such as modulators within the transceiver. The supporting control structure (blue box) is composed of an MZI with an identical FSR to that of the RAMZI, followed by a photodetector. With the inclusion of the MZI, the resulting output current is no longer constant with the change of phase shifter voltages. Specifically, the output current will reach its maximum when the passbands of both the RAMZI and MZI are aligned with the DWDM signals, and will be minimized when their passbands offset with one another by a single channel spacing, as illustrated in Fig. 2c. Therefore, the RAMZI transmission spectrum can be optimized for both passband shape and channel alignment by either maximizing or minimizing the photocurrent.

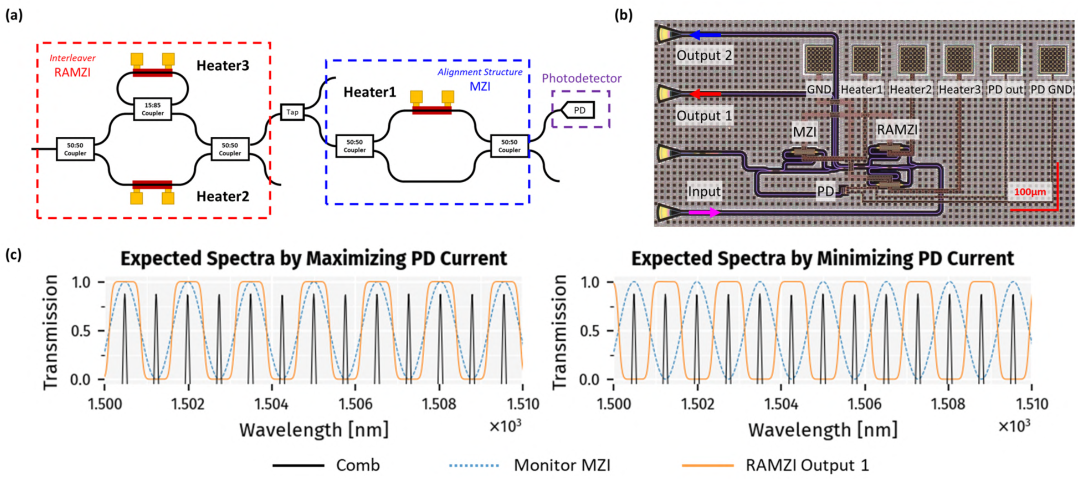

Fig. 2. **(a)** Schematic of the proposed auto-tuning structure (blue box) as an addition to the RAMZI interleaver (red box). **(b)** Fabricated RAMZI interleaver with the auto-tuning structure. **(c)** Simulation results of the optimized spectra by maximizing/minimizing PD current.

The RAMZI auto-tuning involves a total of three heaters: one in the supporting MZI (Heater1), another in the MZI arm of the RAMZI (Heater2), and the last within the ring of the RAMZI (Heater3). The optimization procedure is carried out in the following sequential steps:

1. **repeat** adjusting Heater1 **until** maximum/minimum PD reading;
2. **repeat** adjusting Heater2 **until** maximum/minimum PD reading;
3. **repeat** adjusting Heater3 **until** maximum/minimum PD reading;
4. **repeat** adjusting Heater2 and Heater3 with equal power increments **until** maximum/minimum PD reading;
5. **repeat** adjusting Heater2 and Heater3 with opposite power increments **until** maximum/minimum PD reading;
6. **repeat** steps 1 to 5 **until** no further improvement observed in PD reading;

where the adjustment to heater power at each step is performed in a binary search manner as described in [7].

3. Experiment and Results

The experimental setup for the interleaver auto-tuning is depicted in Fig. 3a. The setup consists of eight DFB lasers with a 200 GHz channel spacing, serving as the DWDM source. The DWDM channels are directed into the interleaver chip through an angled fiber array and grating couplers, combined with a broadband light source. The broadband source is primarily utilized for visualizing the interleaver spectrum and the power is controlled to be much less than the DWDM source to ensure it does not impact the auto-tuning process. The output light from the interleaver is sent to a Yokogawa optical spectrum analyzer (OSA), realizing the real-time spectrum inspection during the optimization process. It should be noted that the broadband source and the OSA serve only for visualization purposes and are not essential to the auto-tuning process. For interleaver thermal control, a DC probe is landed on the six pads, linking the interleaver structure to the power supplies. A Keysight multi-channel power supply delivers voltages for the three heaters, acting as the optimization inputs, while a Keithley high-precision power supply provides bias voltage to the photodetector, reading the output photocurrent as the optimization output. Fig. 3b shows the PD current heatmap along with the optimization paths. Dots of various colors represent the attempted initial voltages and stars represent the final voltages after auto-tuning process, all of which converge to the optimal point with minor distances caused by the precision of the measuring equipment, confirming the effectiveness and robustness of the auto-tuning method. Fig. 3c displays the initial and final interleaver spectra corresponding to the highlighted yellow path in Fig. 3b, demonstrating the optimized interleaver extinction ratio of over 20 dB and the precise alignment of the passbands with the DWDM source.

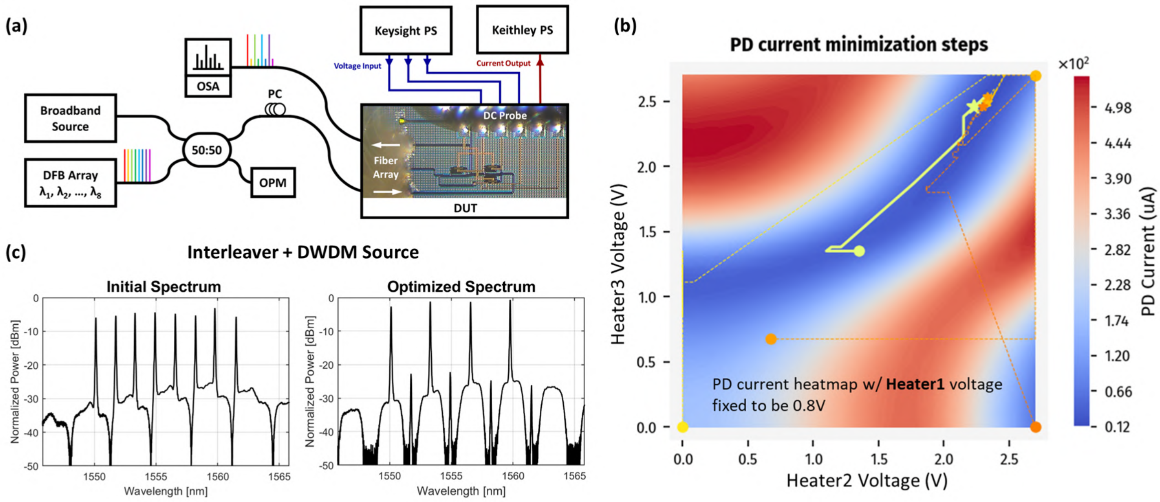

Fig. 3. **(a)** Experimental setup of the RAMZI interleaver auto-tuning test. **(b)** PD current heatmap and optimization paths plotted for a Heater1 voltage of 0.8 V, which is also the optimal Heater1 voltage found. **(c)** RAMZI interleaver spectra with DWDM source before and after the auto-tuning.

4. Conclusion

In summary, we presented a novel RAMZI auto-tuning structure and control scheme. The proposed auto-tuning structure effectively compensates for phase errors and optimizes passband alignment with DWDM signals, promoting operational efficiency and performance enhancement. This development can drive the ongoing evolution of DWDM link architectures in high-performance computing systems and data centers, fostering the realization of more efficient and scalable communication infrastructures.

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