Demonstration of Multi-Channel Feedback Control for On-Chip Microring Weight Banks

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Abstract: We demonstrate a multi-channel feedback control for microring weight banks and achieve a record-high accuracy and precision. With the simplified procedures, the feedback control becomes more practical for configuring large-scale photonic networks.

1. Introduction

Recently, there has been much research on photonic processors to accelerate information processing. Benefiting from the high-bandwidth optical interconnect, photonic processors can break the bandwidth and speed limitation of conventional electronic processors. Most importantly, the aggregate bandwidth of photonic processors can scale up simply by adopting additional channels at different wavelengths (i.e., wavelength-division multiplexing (WDM)). On-chip micro-ring resonator (MRR) weight banks, consisting of parallel-coupled MRR, are capable of weighting individual WDM channels over a continuous range of -1 to 1 [1]. Due to the adaptive parallelism and reconfiguration, MRR weight banks are promising candidates for reconfigurable elements in neuromorphic photonics, large-scale reconfigurable systems and microwave photonics [2–4]. These applications rely on the ability of commanding weights on multi-channels accurately. However, the fabrication variations and thermal sensitivity make the MRR weight bank control very challenging.

Our prior work demonstrated feedback weight control by monitoring the photoabsorption-induced changes in resistance across in-ring photoconductive heaters. An effective 5.1 bits of accuracy is achieved on two WDM channels. In this work, we demonstrate multi-channel weight control (up to 4 channels) and achieve a record-high accuracy and precision for all the controlled channels. In addition, we simplify the control procedures which now only requires one electrical SourceMeter per MRR and one photo-detector (which can be integrated on chip, and therefore avoiding the need to tap the optical signal off chip) for the weight bank. The high-performance multi-channel weight control and simplified control procedures suggest that the scheme can be practically applied to control large-scale reconfigurable photonic networks.

2. Silicon MRR weight banks and weight control setup

Fig. 1(a) shows the design of the MRR weight bank and the experimental setup for feedback weight control. The silicon weight banks in this work are fabricated on a silicon-on-insulator (SOI) wafer with silicon thickness of 220 nm and buried oxide thickness of 2 μm. The MRR weight bank consists of four MRRs coupled with two bus waveguides (500 nm width) in a add/drop configuration. The four MRRs have the radii of 8.0, 8.1, 8.2, 8.3 μm. The slight difference in radii is introduced to avoid resonance collision. The gap between the ring and bus waveguide is 200 nm. The input signals are obtained from four WDM laser sources combined by an arrayed waveguide grating coupler. The combined signals are shown in Fig. 1(b) together with the transmission spectrum of the MRR weight bank. The output signal is detected by a power meter off chip. The light is coupled in and out of the chip with TE focusing grating couplers. For the purpose of feedback, in-ring photoconductive heaters are implemented with a 10 μm wide N-doped section patterned to follow each MRR, outside of which heavy N++ doping is used to make ohmic contacts. The N-doped heater is used to actuate the weight by thermally tuning the MRR resonance, and to sense the MRR transmission from photoabsorption-induced changes in the heater resistance. The DC pads are wire-bonded to a chip carrier that is connected to the SourceMeters to thermally tune individual MRRs and sense the heater resistances. Wire bonding allows a stable contact between the SourceMeters and the heaters, leading to a precise measurement of the heater resistance.

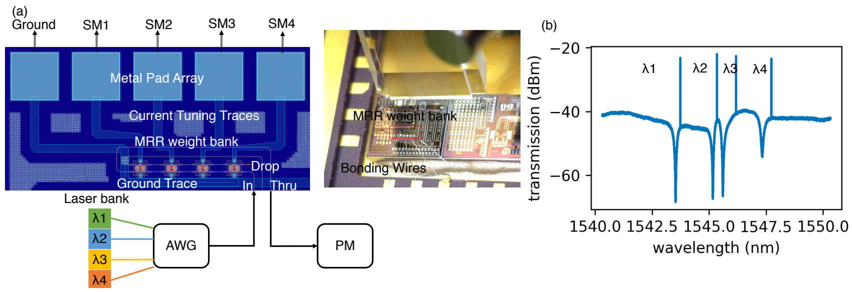

Fig. 1. (a) Device design and experimental setup. SM: SourceMeter; AWG: arrayed waveguide grating, PM: power meter (b) Input signals and the transmission spectrum of the MRR weightbank

3. Multi-channel feedback weight control

We perform the feedback weight control detailed in Ref. [5]. In short, the SourceMeter delivers a current to each MRR to change the frequency offset between its resonance and the neighboring lasers. The frequency offset determines the optical power in the MRR. The light is partially absorbed by the N-doped heater, which results in carrier generation and in turn, reduces the resistance of the N-doped heater. The light induced conductivity change (i.e. photoresponse) is approximately quadratic to MRR transmission [6]. Therefore, the MRR transmission spectrum can be estimated by measuring the resistance difference with and without optical signal using the SourceMeter. Obtaining the relation between the photoresponce and the actuated current enables a feedback loop for the weight control: a binary search algorithm can be performed to search for a target transmission.

For multi-channel weight control, the estimation of the quadratic relationship between the photoresponse and the MRR transmission is not accurate, especially when weight bank channels are partially overlapped in spectrum. The spectral overlapping is difficult to be controlled due to the fabrication variance. Therefore, an edge transmission correction is needed to correct the function between photoresponse and MRR transmission by directly measuring the actual weights under different photoresponse, The correction is critical for multi-channel weight control. In Ref. [5], the actual weight measurement is conducted simultaneously for two channels by using scope-based decomposition of the 2×2 weight matrix. This approach requires external measurement equipment for AC signal generation and detection including pattern generator and sampling scope. In addition, scaling this approach to a large number of channels can be challenging: the photodetector will saturate when the channel number increases, which in turn reduces the accuracy of weight decomposition.

Here, we adopt a simplified edge transmission correlation using only a power meter. The correlation is conducted on the 4 channels sequentially. Only the channel under evaluation is turned on. The MRRs paired with the other three channels are set to the estimated resonance according to the previous calibration results. The relationship between the photoresponse and the MRR transmission is re-evaluated by measuring the optical power under different photoresponse.

4. Results

To assess the weight control performance, we measured weights (Fig. 2(a)) and calculate the offset between a given measured weight and command weight (Fig. 2(b)) as a function of command weights for a given channel. This is performed as the other 3 channels are combinedly swept across their range of operation to study the crosstalk in the multi-channel scenario. The accuracy (mean deviation from the command weights) and precision (non-repeatable standard deviation around this mean) are evaluated across all the weights combinations (worse scenario). A record-high accuracy and precision are achieved in all the four channels (summarized in Table 1).

The improvement in accuracy and precision over our previous work [5] is attributed to more accurate measurement of both the photoresponse (via wire bonding) and the transmission edge (by directly measuring the optical power using power meters).

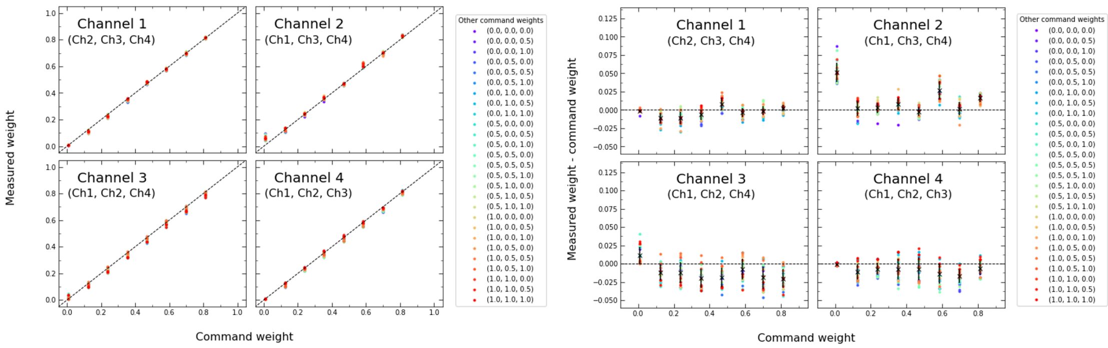

Fig. 2. (a) Measured weights (a) and offset between a given measured weight and command weight as a function of command weights for a given channel. For a given datapoint, the tuples in the legend contain the command weight values for the other channels in the order displayed below the plot label. The dashed lines in (a) represent the ideal target weights. The black crosses in (b) denote the mean offset from the ideal weight (reproducible offset). The black vertical lines in (b) show the standard deviation of the measured weight (non-reproducible offset).

Channel	1	2	3	4
Accuracy (bits)	7.2	5.5	6.0	6.6
Precision (bits)	7.2	6.8	6.2	6.5

Table 1. Accuracy and Precision measurement

5. Conclusion

In conclusion, we have experimentally demonstrated, a continuous, multi-channel control of a microring weight bank with a record-high accuracy and precision. The results, obtained with the simplified control procedures, suggests that the feedback weight control can be practically used to control large-scale reconfigurable photonic networks.

6. Acknowlegement

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References

1. A. N. Tait, A. X. Wu, T. F. De Lima, E. Zhou, B. J. Shastri, M. A. Nahmias, and P. R. Prucnal, “Microring weight banks,” IEEE Journal of Selected Topics in Quantum Electronics **22**, 312–325 (2016).
2. W. Liu, M. Li, R. S. Guzzon, E. J. Norberg, J. S. Parker, M. Lu, L. A. Coldren, and J. Yao, “A fully reconfigurable photonic integrated signal processor,” Nature Photonics **10**, 190 (2016).
3. N. C. Harris, D. Bunandar, M. Pant, G. R. Steinbrecher, J. Mower, M. Prabhu, T. Baehr-Jones, M. Hochberg, and D. Englund, “Large-scale quantum photonic circuits in silicon,” Nanophotonics **5**, 456–468 (2016).
4. P. R. Prucnal and B. J. Shastri, *Neuromorphic photonics* (CRC Press, 2017).
5. A. N. Tait, H. Jayatilleka, T. F. De Lima, P. Y. Ma, M. A. Nahmias, B. J. Shastri, S. Shekhar, L. Chrostowski, and P. R. Prucnal, “Feedback control for microring weight banks,” Optics express **26**, 26422–26443 (2018).
6. H. Jayatilleka, K. Murray, M. Á. Guillén-Torres, M. Caverley, R. Hu, N. A. Jaeger, L. Chrostowski, and S. Shekhar, “Wavelength tuning and stabilization of microring-based filters using silicon in-resonator photoconductive heaters,” Optics express **23**, 25084–25097 (2015).