Microring Modulation-and-Weight Banks

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Abstract: For photonic neural networks, we propose a novel microring bank with carrier-effect and thermal dual-tunability, which can 1) combine modulating and weighting for saved space, 2) improve tuning efficiency, and 3) inherit WDM-enabled scalability.

Photonic neural networks have promised superior bandwidth, efficiency, and latency performance. However, the demonstrated network size falls far short as opposed to its electrical counterparts, primarily due to the large footprint of the integrated components. Multiply and accumulation (MAC) is the essential operation on a photonic chip, and it is realized by a series of integrated devices that independently perform the electrical-to-optical (EO) conversion, optical weighted summation, and optical-to-electrical (OE) conversion. Precisely, in addition to photodetectors handling the OE conversion, an array of Mach-Zehnder interferometers (MZI) or Microring resonators (MRR) modulate input signals onto their corresponding laser lights [1]. Then, subsequently cascaded meshes of MZIs or bank of MRRs apply weighting onto the modulated lights and sum them up [2].

Comparing MZI and MRR, the former has a larger size since longer waveguides are required for sufficient light interaction. Meanwhile, MRR leverages the merit of a resonator to have a similar interaction at reduced physical geometry, and the concurrent wavelength selectivity further allows multiple MRRs to share the same waveguide for further reduced footprint and improved scalability. With that, the modulation (EO conversion) and weighted summation are performed on separate but very similar devices (both are MRR-based), taking more than double the chip area. Besides, the wavelength selectivity necessitates the alignment of the MRRs for modulating and weighting, which can be practically difficult due to fabrication variations.

In this paper, we demonstrated that a single microring resonator can handle functionalities of both the EO conversion and the weighting. The ring waveguide is doped as a PN junction to allow input signal modulation by carrier depletion effect, and a metal heater on top of the ring enables the weighting through the thermal-optical effect. These two sets of tuning mechanisms are naturally aligned as based on the same ring resonator. Additionally, we observed more energy-efficient weighting than the previous separate arrangement, as the tuning curve is steeper. Besides, we can inherit the benefits of WDM combability to have multiple such MRRs in a single bank to facilitate the construction of large-scale networks.

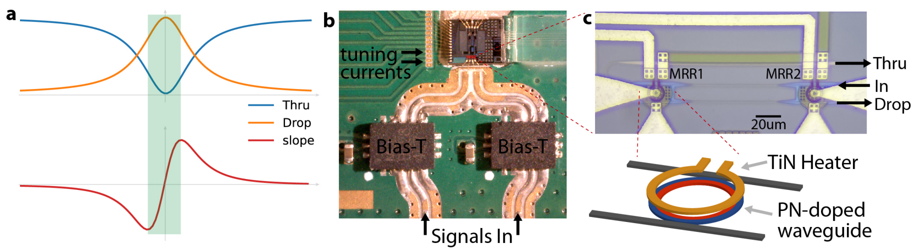

Fig. 1. Principle of the proposed modulation-and-weight bank (a) Theoretical transmission profile of a ring resonator and the slope (b) Packaged chip (c) MRR bank layout

Conventional microring modulator has P-type and N-type doped waveguide area that introduce carrier effect to allow input voltage across the junction to vary the refraction index (RI) of the waveguide, and so does the resonance frequency. Therefore, if one laser has a frequency located near the transmission profile of the MRR, this slight change of RI can convert to intensity variation. Notably, the sensitivity of such conversion is proportional to the slope, which continuously varies as against the detuning from the resonance peak, as shown in 1. Therefore, if another tuning mechanism can change the relative location between the laser frequency and the transmission profile, regarding a constant input signal amplitude, the optical modulation depth can be varied accordingly. This additional tuning mechanism can be readily achieved by making a metal heater right on top of the ring waveguide and leveraging the thermal-optical effect to allow wide-range control of the detuning.

As indicated in Fig. 1a, the slope changes drastically near the center of the resonance frequency, allowing a tiny amount of detuning for sufficient signal weighting outcome. Assuming a Lorentzian-shaped profile, merely 10 percent of detuning from the resonance can achieve the peak slopes. In contrast, rings in conventional weight banks must be detuned more than eight times larger to cover more than 90 percent range of the same amount of weighting. This reduced detuning range translates to reduced energy, contributing to a more efficient way of weighting. Since these revised MRRs still work as standard ring resonators, multiple MRRs with slightly different radii can be put on the same bus waveguide and work without interference, permitting the incorporation of multiple MRRs in such a wavelength-division-multiplexing fashion. The conventional MRR weight bank connects its Thru and Drop port to a balanced photodetector (BPD) to obtain both positive and negative weights. In this MRR modulation-and-weight bank, opposite weights can be obtained when tuned to opposite sides from the resonance peak. Therefore, the balanced detection is not necessary but can double the output amplitude since the Drop and the Thru transmission slope are nearly identical but with opposite signs.

As a proof-of-principle demonstration, we taped out such an MRR modulation-and-weight bank composed of two MRRs with radii corresponding to 7 μm and 7.0106 μm, respectively. As shown in Fig. 1b, Each has four electrical pads connecting to its heater and PN-doped waveguide. A co-packaged current source (Analog Device LTC2662) provides programmable tuning currents for the metal heaters. We also added RF connectors with optimized PCB traces to connectorize the PN junction, allowing high-speed signal input from an arbitrary waveform generator (Keysight M8196a) to the MRRs. The Drop and Thru ports of this MRR bank are connected to an off-shelf BPD (Thorlabs PDB780CAC) for OE conversion.

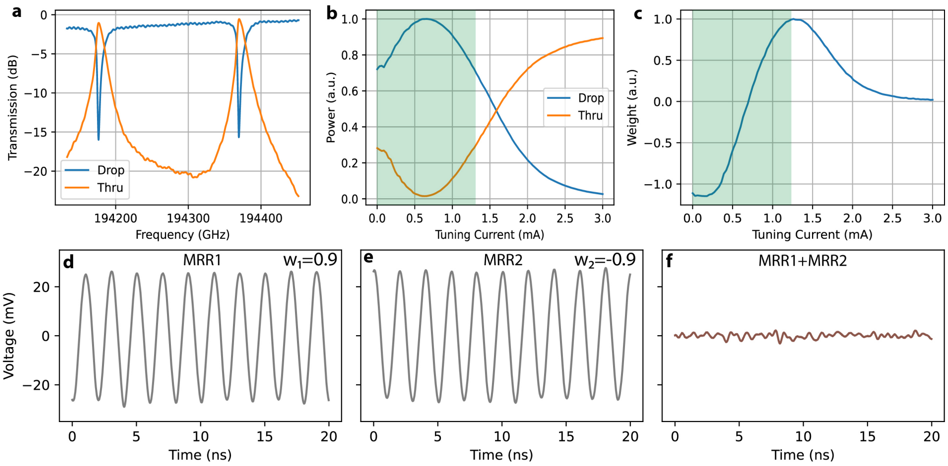

Fig. 2. Experimental results. (a) Spectrum of the tested MRR bank. (b) Output power and (c) Weight in against tuning current. (d) Output weighted signal when only MRR1 is modulated with input signals and tuned to a weight of 0.9. (e) Similar to (d) but on MRR2 and weight equal to -0.9. (f) Weighted addition when both MRRs are modulated and weighted.

Testing on the MRR with a resonance of 194382 GHz (the right one in Fig. 2a), we use a laser with a frequency tuned to 194367 GHz and feed to the In port of the MRR bank. Fig. 2b illustrates the output optical power from the Drop and Thru ports in against the tuning current. We then applied a 500 MHz sinusoid signal to the PN junction and used a scope to record the output waveform from the BPD while varying the tuning current. The corresponding weights are shown in Fig. 2c. As indicated by the results, for such an MRR, changing the heating current from 0 mA to 1.22 mA can vary the weight from the most negative to the most positive. Given the metal heaters have a resistance of about 330 Ohms, it translates to a maximal tuning power of 0.5 mW, which is 20 times smaller than the tuning power of a conventional MRR weight bank [3]. Then, we applied identical signals to the two MRRs, and Fig. 2e and e show the output waveform when only one of the two MRRs was applied with the signals. Fig. 2e shows when the two MRRs were tuned to opposite weights, where the two signals are supposed to cancel each other. The root-mean-square deviation of the result shown in Fig. 2f is about 0.914 mV, indicating good accuracy and linearity of this MRR bank.

With less than half of the footprint, 5% of the power consumption, and WDM-compatible scalability, we anticipate this MRR bank can facilitate the future needs of the increased scale of future photonic neural networks.

References

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