Microring Weight Bank Designs with Improved Channel Density and Tolerance

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***Abstract*—Microring weight banks enable reconfiguration in analog photonic networks and multi-channel RF front-ends. We demonstrate 2-ring weight banks and show that they are tolerant to fabrication and thermal effects. Weights consisting of two microrings can potentially increase channel capacity by a factor of 2.72-fold.**

Microring resonator (MRR) weight banks could enable novel signal processing approaches in integrated photonics. The accelerating demands on spectrum resources are pushing radio operations into new regimes of bandwidth, efficiency, and reconfigurability. Multivarite RF photonics is the application of wavelength-division multiplexed (WDM) multi-channel photonic devices to RF signal processing [1]. When WDM signals are detected, the electronic output represents their sum. In analog and/or neural networks, reconfiguration is performed by changing weight values. In these systems, N distinct wavelengths of light carry N signals from N antennas or N analog network elements [2]. Recent acceleration of high-performance, CMOS-compatible photonic integrated circuit (PIC) platforms promise to greatly expand the possibilities for large scale systems.

MRR weight banks allow for reconfigurable functionality in analog photonic networks to be integrated on a silicon photonic chip. By tuning filters on and off resonance with their respective signals, an MRR weight bank can individually weight each WDM channel. MRR weight banks are the key photonic subcircuit associated with interconnection and network configuration in integrated analog photonic networks and multivariate RF photonics. Their scaling potential is therefore closely tied to the performance limits of these overall systems, which must be better understood to allow the construction of larger systems.

In conventional analyses of MRR devices for multiplexing, demultiplexing, and modulating WDM signals, the tradeoff that limits channel spacing is inter-channel cross-talk [3]. As shown in Ref. [4], this analysis can not be applied to MRR weight banks. Weight banks have a metric of effective insertion loss that trades off with channel density, and this tradeoff depends on phase accumulated on the bus waveguides between MRR weights (Fig. 1). Multi-MRR coherent interactions are especially relevant when resonances are closely spaced, so it is essential to account for them in channel density analysis. In a 1-pole bank, a channel partially coupled through a neighboring MRR – instead of causing inter-channel cross-talk – can return through the opposite bus waveguide to complete a coherent feedback path involving multiple MRRs [5]. 2-pole banks instead have coherent feedforward paths that behave like interferometers.

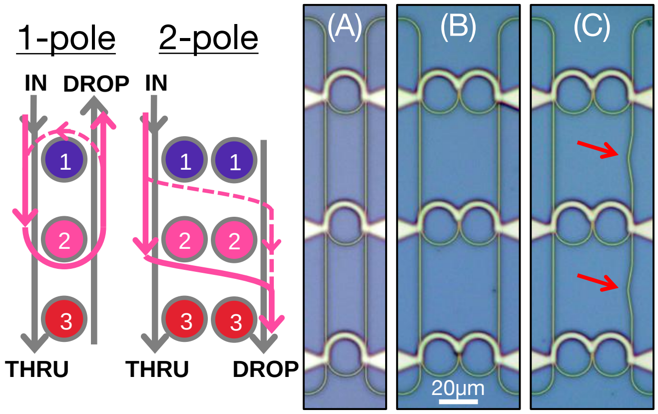

Fig. 1. 1-pole weight banks showing coherent feedback path when a wavelenth channel (pink) couples through a neighboring MRR. 2-pole weight banks showing coherent *feedforward* path when a wavelenth channel (pink) couples through a neighboring MRR. Device A: fabricated 1-pole weight bank with 3 weights. Device B-C: fabricated 2-pole weight bank with 3 weights. Device C also contains a bus length difference in order to alter the interference condition. Due to their symmetry, tuning MRR resonances will heat bus waveguides equally, changing their summed length, but keeping the length difference consistent.

Here, we demonstrate 2-pole MRR weight banks and analyze their impact on WDM weight bank channel scaling limits, tunability, and fabrication tolerance. Using the simulation tools developed in [4], we estimate a factor of 2.72× improvement in channel scalability as compared to 1-pole weight banks. The advantages of 2-pole banks stem from steeper filter rolloff but also, crucially, their interferometer-like interaction between neighboring weights, which depends on a phase difference in two bus waveguides, rather than a phase sum. Therefore, this interaction can be controlled lithograpically and does not change with tuning.

Experiment Silicon-on-insulator samples have silicon thickness is 220nm with fully etched waveguides. Ti/Au tuning contacts were then deposited on top of an oxide passivation layer. The sample, mounted on a temperature controlled alignment stage, is coupled to fiber through focusing sub-wavelength grating couplers [6]. The weight bank consists of two bus waveguides and four (pairs) of 10-10.3μm radius MRRs in a parallel add/drop configuration, each with a thermal tuning element (Fig. 1A-C). Device A is a 1-pole bank. Device B is 2-pole. Device C is also 2-pole, but with a lithographically defined bus waveguide length difference.

The procedure for assessing how MRR tuning affects the bus phase condition is as follows. Initially, the resonances are distributed based on fabrication variation. Analyzing their peak locations with a spectrum analyzer, the resonances are tuned to a separation of 1.0 nm. Then, all rings are tuned collectively such that their center wavelengths traverse 3.0 nm, while their separation from one another remains constant at 1.0 nm. In this way, thermal cross-talk affects the bus waveguides as the MRRs are tuned.

Fig. 2 shows the results of tracking and tuning each weight bank. Inter-resonator interference can be observed in the dips between peaks. For device A (black), the dips between resonance peaks varies strongly as a function of tuning. The 2-pole devices B (blue) and C (red) maintain a constant transmission profile. This is because thermal cross-talk from MRRs to bus WGs cancel out, making the interference condition stay relatively constant with dynamic tuning. Device C, which introduced a bus path length difference exhibits deeper isolation between filters. This means that the interference can be *designed* in order to hit an optimal interference point, which is advantageous for independent weighting of neighboring channels.

Scaling analysis Ref. [4] introduced a channel density metric and parametric simulator for studying microring performance. The limit of WDM channels depends both on resonator finesse and a cross-weight interference factor, where $\delta\omega_{3dB}$ is the channel density in linewidth units where effective insertion loss is 50%. This limit was found to be between $3.41 < \delta\omega_{3dB} < 4.61$ for 1-pole MRR weight banks, depending on the inter-weight interference phase. Since this phase condition changes with tuning and fabrication variation, it cannot be controlled. Therefore, the worst-case performance is always the case.

Using the same parametric simulator, we perform simulations of the weight bank penalty for 2-pole banks, to be printed in a later paper. We find that $1.69 < \delta\omega_{3dB} < 2.45$. With 1-pole banks, we have here shown that the worst-case scenario must be assumed, whereas 2-pole banks can be fabricated with best-case performance, tolerant to variation and tuning. Therefore, this weight bank design represents a factor of $2.72\times$. Supposing state-of-the-art resonator finesse of 540, this translates to an improvement from 117 to 320 channels.

In order to set the weight values of MRR weight banks, model-based calibration techniques have been shown [7]. The advanced modeling techniques used in [4] were posited to be necessary for controlling the weight of densely multiplexed banks. While these advanced simulation tools are used for the purpose of studying density limits here, they are not practical for controlling large systems. Their computational requirements are prohibitive even for a single bank with 10s of channels. Larger silicon photonic neural networks with potentially 1000s of MRR weights could be controlled by a co-integrated CMOS chip; however, these are even less powerful than a desktop computer. With 2-pole weight banks, full modeling of all interference paths may not be necessary because the shape of filters is repeatable. This means that simplified control models could potentially be used, making weight control of DWDM 2-pole weight banks possible with simple CMOS control chips.

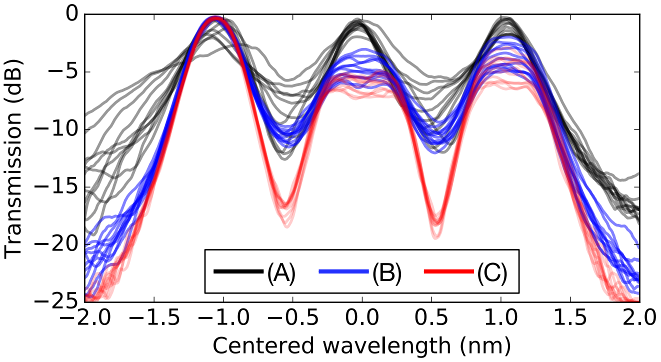

Fig. 2. Transmission data measured while tuning MRRs together. After tuning to a common spacing of 1.0 nm, resonances are swept in concert over 11 points totalling a span of 3.0 nm. The x-axis shows the relative wavelengh offset from the center of the profile as it is tuned. 1-pole device A (black) varies strongly with common-mode tuning, while 2-pole devices B-C retain a constant profile. Furthermore, device C (red) exhibits a deeper dip between peaks, indicating that weights are more isolated as a result of the fabricated bus length difference.

We have compared in experiment 1-pole and 2-pole silicon MRR weight banks. As opposed to other WDM devices based on MRRs, weight banks are sensitive to coherent interactions between neighboring filters, and the character of this interaction is fundamentally different for odd-pole and even-pole filters. By tuning banks of 3 weights together to effectively change sweep their interference conditions, we have shown that 1-pole weight banks are not at all tolerant to tuning-related thermal cross-talk, while 2-pole weight banks are. Furthermore, we showed that the interference condition of 2-pole banks can be controlled lithographically in order to exploit these interference effects for greater isolation between channels.

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