Coherent interactions in microring weight banks and impact on channel density

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***Abstract*—We experimentally observe and simulate coherent inter-resonator effects specific to microring weight banks. An analysis based on this effect results in quantitative performance limits of weight banks, a key subcircuit for multivariate analog signal processing and scalable analog interconnect approaches in silicon photonics.**

The rapid development throughout photonic integration and manufacturing fields open up possibilities for a wide variety of large scale interconnect systems on-chip. Analog optical interconnects have long been recognized for their potential to address bottlenecks in unconventional, distributed, and/or neuromorphic processors, wherein many simultaneous and continuously tunable connections are required. However, the enormous cost to develop scalable and/or integrated application-specific photonic signal processing platforms, in concert with incredible advances in digital signal processing techniques, presented practical barriers to past research and development in this area. However, microring resonators (MRRs)–which are common photonic circuit elements ubiquitous in wavelength-division multiplexed (WDM) systems–could bring analog signal processing opportunities to silicon integrated photonic circuits (Fig. 1).

While weighted addition is a generic type of analog fan-in, the WDM approach to weighted addition offers bandwidth and interconnectivity advantages over electronic approaches to interconnects for distributed processing due to its passive total-power computation of summation and the small fractional bandwidth of optical signals. Additionally, weighted addition via WDM has relevance in RF photonic problems and is a critical subcircuit for constructing all-analog, all-optical neuromorphic networks [1]. Recently, a parallel microring resonator (MRR) filter bank has demonstrated independently weighting wavelength-division multiplexed (WDM) signals and passively adding and subtracting them with standard photodetectors [2]. In addition to offering a continuous range of complementary weights from -1 to +1, the ideal WDM weight bank is able to switch WDM channels completely independently from one another. However, the N-channel generalization of a non-ideal weight bank is complex.

Standard analyses of WDM channel density limits are driven by a metric of inter-channel cross-talk [3]. This metric degrades with channel density, so a cross-talk specification sets the density limit. Unlike MRR demultiplexer circuits, weight banks have only two output ports detected by a balanced photodetector (PD). However, if WDM channels are still multiplexed when detected, the notion of inter-channel cross-talk does not have a clear meaning. With increasing channel density, a new limiting metric is called for. An ideal tunable weight bank in the single-channel case possesses a range of tuning states that include directing an incident optical signal completely to a through port (positive weight), completely to a drop port (negative weight), or to any intermediate ratio of both. If a real weight incurs some loss, its weight range becomes a subset of the ideal, and comparing the usable range to the ideal range yields a ratio that quantifies the real device's ability to perform tunable optical weighting.

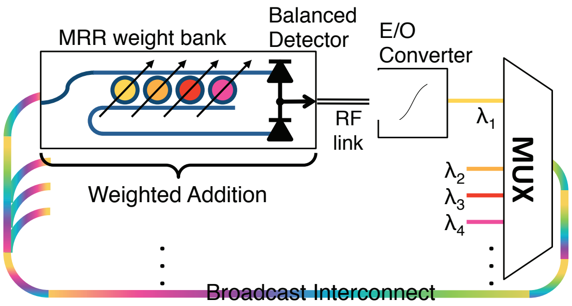

Fig. 1. A proposed analog photonic processor with a WDM broadcast interconnect and weighted connections controlled by microring resonators (MRR) [2].

In this work, we extend a similar metric describing weight tunability range to the two-channel case in order to quantify WDM channel density limits in MRR weight banks. Furthermore, device modeling in the dense spacing regime is potentially complicated by coherent feedback between MRRs that are parallel-coupled to two bus WGs. Optical signals that are partially dropped by multiple MRRs can make round trips and self-interfere. If a given tuning parameter can affect multiple weight values, then the bank's weight range can not be linearly separated into any composition of non-ideal single-channel weight ranges. Experimentally, we find that the optical phase of bus WGs can have a significant impact on channel density limits.

Samples were fabricated on silicon-on-insulator wafers at the Washington Nanofabrication Fabrication through the UBC

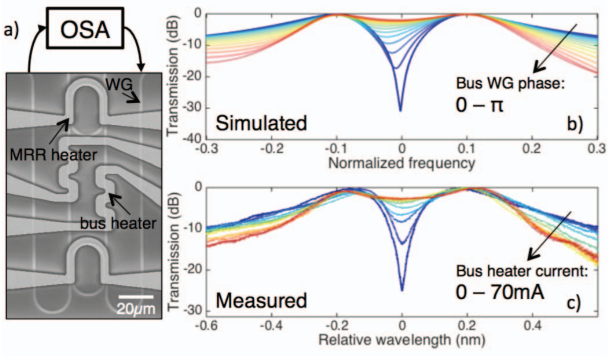

Fig. 2. Experimental verification of coherent interaction between MRR weights in silicon. Coherent effects that depend on bus WG phase are expected to dominate the dense WDM channel spacing regime. a) 2-channel weight bank featuring 2 bus WGs b) coherent interaction effects due to bus tuning as predicted by parametric simulator and c) verified by measured transmission

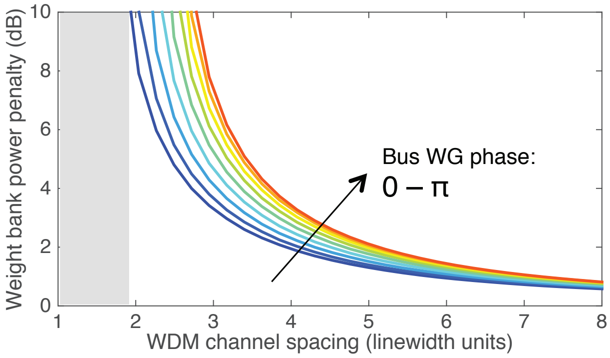

Fig. 3. Simulation of excess power penalty caused by inability to differentiate neighboring channels. Both the density wall and power-density tradeoff depend significantly on bus WG phase.

SiEPIC rapid prototyping group. Silicon thickness is 220nm. 500nm wide WGs were patterned by Ebeam lithography and fully etched to the buried oxide. The weight bank circuit consists of two bus WGs with MRRs in a parallel add/drop configuration. Ti-gold heating contacts were then deposited on top of an oxide passivation layer. The 2-channel weight bank designed to examine coherent interaction effects contains two racetrack resonators with perimeters of 80.0 and 80.1μm. Individual Q-factors are 7,750. Additional heaters are pattened over each bus WG, which are 60μm long (Fig. 2a).

To test this device, the sample is mounted on a temperature-controlled alignment stage, where ohmic heating in these contacts can tune a MRR's resonant wavelength. The chip is coupled to a fiber array using focusing subwavelength grating coupler arrays [4]. An optical transmission spectrum analyzer (OSA) measures the transfer functions from in to drop ports. We first used the MRR heaters to adjust two resonances to a 0.4nm separation (2 filter linewidths). We then tuned bus heaters non-uniformly between 0 and 70mA, such that the data traces were taken at intervals approximately uniform in electrical power.

Current is applied equally to each bus heater to prevent creating an asymmetric temperature profile across the device. This approach ensures that both resonators are made to shift together, maintaining their spacing at 2 linewidths. Differences in phase between bus WGs would be difficult to study with this technique, but are not expected to have an impact on resonator-like coherent interaction effects. Simulation accurately matches the measured effect (Fig. 2b,c).

Fig. 2b,c shows that bus tuning significantly affects the dip between filters, whose depth ranges from –2.7dB to –25.0dB relative to peak transmission. The steepness of rolloff regions are also slightly affected. The measurements closely match corresponding simulations in which the effective bus phases were parameterized and swept uniformly, shown in Fig 2c. A parametric simulator based on generalized matrix transmission theory [5] makes accurate predictions about weight banks in the dense channel regime. From an intuitive standpoint, it seems that this coherent effect that depends on bus phase could have an impact on channel density. If the goal is to be able to set the weight of neighboring WDM channels independently, then it would be disadvantageous to have the responses blur into a single peak like the red traces in Fig. 2b,c. On the other hand, it may be possible to take advantage of the deep isolation between peaks represented by the blue traces.

Further directions would include quantifying the degree to which weights can be set independently and use the simulator to study how this metric is affected by channel spacing and MRR interaction. Using a power penalty metric that is based on tuning *range* of a device with strong coherent feedback requires many evaluations of a complex model. A custom simulator incorporating parametric programming concepts with generalized transmission theory is introduced to efficiently simulate the tunability power penalty metric vs. system parameters. This simulation engine is used to find the power penalty in a sweep over channel spacing and bus WG phase (Fig. 3). From this plot, we observe that as filter peaks merge together, all frequencies are coupled to the drop port. The power penalty decreases smoothly as channel spacing is increased above the absolute cutoff, representing a system design tradeoff between WDM channel spacing and power penalty and providing guidelines on future weight bank designs. At 3dB penalty, we find that the minimum channel spacing falls between 3.41–4.61 linewidths, which for a MRR with finesse 200, corresponds to 43–59 channels. Analyses that incorporate coherent interactions on the bus WGs will be an essential engineering tool.

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