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Balanced WDM Weight Banks for Analog Optical Processing and Networking in Silicon

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***Abstract*—We demonstrate complementary (+/–) WDM weighted addition in a bank of silicon microrings using a balanced detection technique. Weighted addition that is tunable and complementary is a key function for multivariate analog signal processing and could enable scalable analog networking approaches with silicon photonic technologies.**

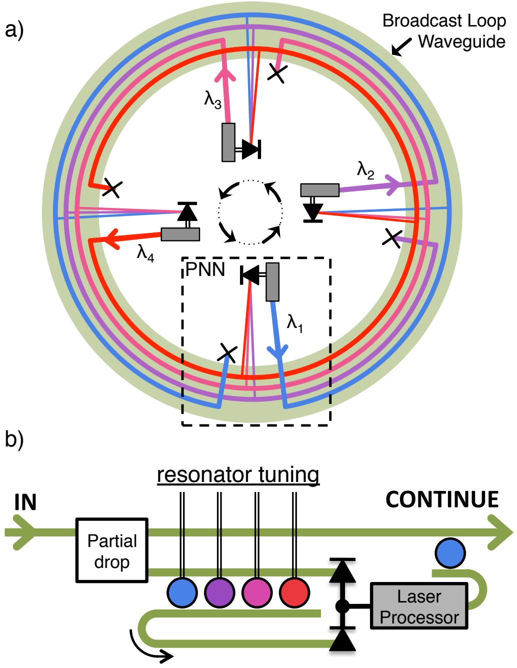

Fig. 1. a) Concept of a broadcast-and-weight network, from [3]. WDM signals are transported between processing-networking nodes (PNNs) by a loop waveguide. b) A PNN circuit. Signals on the bus are partially dropped, then a tunable filter bank independently routes channel power between opposing ports of a balanced photodetector. Continuous weight bank tuning enables effective weights from –1 to +1. Photodetectors act simultaneously as transducers and additive computational elements, solving both challenges of physical fan-in and efficient λ-conversion.

The rapid development of CMOS-compatible photonic interconnect technologies has inadvertently opened a door for unconventional circuit and system opportunities in optics. At the same time, microelectronic fields have recently renewed investigation of non-von Neumann architectures, in part, due to incipient limitations in aspects of Moore's law. In what is considered the 3rd generation of "neuromorphic" architectures, most approaches attempt to decentralize processing – a move that intimately intertwines interconnection with computing – in addition to incorporating time-resolved (in some cases analog [1]) dynamics, loosely classified as "spiking." Photonics device research has followed suit with a recent bloom of proposed forms of spiking dynamics [2]; however, few suitable optical interconnects have been proposed. In the past, neural networking ideas implemented in holograms have failed to outperform mainstream electronics at relevant problems in computing, which can largely be attributed to their incompatibility with integration and manufacturing. The state of current research is discussed in more detail in [3].

We present the first demonstration of a parallel microring resonator (MRR) filter bank for independently weighting wavelength-division multiplexed (WDM) signals and passively adding and subtracting them with standard photodetectors. Weighted addition is a generic type of analog fan-in, which describes how signals from multiple sources (e.g. multiple sensors, or other nodes in a network) are combined. The WDM version of weighted addition has immediate relevance to RF photonic problems [4], in addition to being the critical subcircuit for constructing all-analog, all-optical neuromorphic networks in an integrated photonic substrate (Fig. 1). The small fractional bandwidth of optical signals, combined with passive total-power computation of summation could offer bandwidth and interconnectivity advantages over electronic approaches to interconnects for distributed processing, in addition to unique topological opportunities via WDM (as opposed to spatial and temporal multiplexing available in electronics).

Complementary weighting is a significant challenge in optical direct detection systems where signals are represented by the power envelope, which is strictly positive; however, the ability to weight inputs over the range –1 to +1 is essential for analog processing and networking based on weighted addition. Inhibition is a fundamental component of neural communication and competitive dynamics. RF photonic circuits based on matched filtering also require some way to effect negative weights, a problem that has elicited a variety of approaches [4]. In this proceeding, we observe complementary weighting by sending resonator drop and through outputs to opposite ports of a balanced photodiode (PD). The net photocurrent is thus the difference between the total power dropped and allowed to pass through. This setup allows control of the resulting signal

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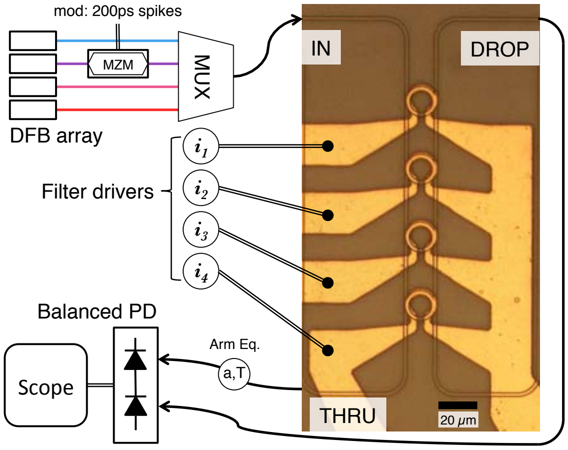

Fig. 2. Experimental setup, including optical micrograph of the 4-filter weight bank, wherein all filters drop into the same waveguide. MRR filters are tuned independently by current sources driving Ti/Au thermal tuning elements (common sink connection not shown). The input consists of four wavelength carriers, one of which is modulated by a pair of 200ps pulses, spaced by 800ps, and repeating every 3.2ns. The still-multiplexed DROP and THRU outputs of the filter bank are sent to opposite ports of a balanced photodiode (PD). The two optical outputs have fixed delay and amplitude equalization to ensure complementarity between the arms.

polarity, in addition to magnitude, using simple resonance tuning.

Silicon-on-insulator samples were fabricated through UBC SiEPIC; silicon thickness is 220nm with fully etched waveguides. Fibers are coupled to chip using focusing subwavelength grating couplers [5]. Ti/Au tuning contacts were then deposited on top of an oxide passivation layer. The device consists of two bus waveguides and four 6-8μm radius MRRs in a parallel add/drop configuration, each with a thermal tuning element (Fig. 2). Resonance quality factors are approximately 10^4, with free-spectral range of approximately 9nm for each MRR. Some resonances are split due to backscatter, which couples counterpropagating modes of the cavity. While the split passband shape can lead to signal dispersion, backscatter can be managed through fabrication parameters.

To test this device, four current sources were connected to the heating elements in the filter bank, and a spectrum analyzer was used to tune a resonance of each MRR to one of four WDM carrier wavelengths, which are spaced by 200GHz. Since there is only one drop waveguide for all of the MRRs, ascribing spectral peaks to different MRRs first required tuning them individually and recording changes. The drop and through outputs are equalized in fiber to ensure both power and delay matching between positive and negative arms, before being detected in a balanced PD. Each detector responds to the sum of weighted input signals on all wavelength channels, and the balanced PD output represents the difference between drop and through contributions. Effective weights over a complementary (+/–) range are thus attained by switching a particular channel between drop to through ports.

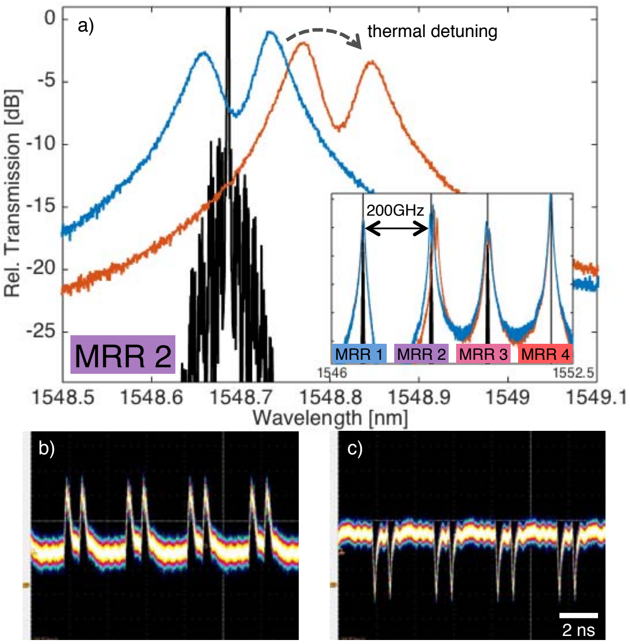

Fig. 3. a) Transmission spectra of MRR filter 2 when on resonance (blue curve) and when detuned by 0.11nm (red curve), with respect to the modulated input on a 1548.7nm carrier (black). Inset: full spectrum of the weight bank drop port showing 4 input channels. Tuning MRR 2 has little effect on the other resonance features, which are due to the other filters. b) Scope output when filter 2 is on resonance, corresponding to the blue curve in (a), indicating a positive effective weight. c) Scope output when filter 2 is detuned, corresponding to the red curve in (a), indicating a negative effective weight.

Fig. 3a shows weight tuning of a single channel in the 4-filter bank. By comparing the drop and through outputs of the bank, thermal resonance shifts can effect complementary positive (Fig. 3b) and negative (Fig. 3c) effective weights. By detuning continuously between (b) and (c), a full complementary range of effective weight values is attainable. The inset of Fig. 3a shows that the other 3 WDM channels are minimally affected, although in this experiment, other channels were unmodulated. Pulse spreading in (b) is caused by on-resonance dispersion introduced by backscatter coupling in this particular resonance, which results in the visibly split resonance. By addressing interconnect challenges of efficient parallelism and fan-in, broadcast-and-weight architectures, enabled by silicon-compatible WDM weighted addition, could open new computational domains characterized by both speed and interconnectivity.

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