Silicon microring weight banks for multivariate RF photonics

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***Abstract*—Microring weight banks enable novel analog processing approaches in integrated photonics. Incorporating multivariate statistical techniques, microring weight banks can implement wideband, analog dimensionality reduction. We demonstrate principal component analysis of three 1GHz signals performed in a silicon microring weight bank.**

Analog photonic circuits have demonstrated superior performance in simple radio-frequency (RF) processing tasks [1]. In an RF photonic receiver, the input RF signal modulates the intensity of an optical carrier wave (i.e. electrical-to-optical (E/O) conversion) which is then detected to yield the output RF signal (i.e. optical-to-electrical (O/E) conversion). Between E/O modulation and O/E detection, the optical signal is processed with tunable optical components.

Multi-antenna systems introduce a new dimension with which to share radio spectrum based on spatial discrimination. Signals received by phased-array antennas have a high degree of redundancy, so they are typically combined in such a way to distill the most salient information. Central to this is the concept of *dimensionality reduction*, in which information across many channels is fused in an intelligent way to extract a smaller number of information-rich signals. Dimensionality reduction relies on learning the optimal combination of inputs based on statistical analysis. For example, principal component analysis (PCA) is a linear multivariate signal processing task that finds a statistically optimal 1D representation of higher-dimensional data.

Digital receivers for multi-antenna systems present a formidable challenge in that every antenna needs an analog-to-digital converter, which are performance bottlenecks. With any digital approach, the rate of data to be digitized increases in proportion to the number of antennas. Wideband dimensionality reduction in the analog domain – prior to digitization – would be able to avoid performance tradeoffs between bandwidth, energy use, and number of antennas.

Multivarite RF photonics refers to the application of statistical analysis to photonic implementations of multi-channel RF signal processing. In a multivariate RF photonic receiver, N distinct wavelengths of light carry N signals from N antennas (Fig. 1) or by N delay taps of an FIR filter. When WDM signals are detected, the electronic output represents their sum. Using this analog, parallel, and physical dimensionality reduction, power is not related to bandwidth, unlike the case with digital floating-point based addition. The ability of photonics

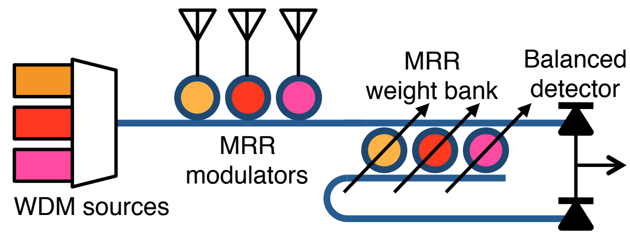

Fig. 1: Microring resonator (MRR) implementation of a WDM weight bank. Tuning MRRs through the resonance edges splits a continuous amount of optical power between drop and through ports. A balanced photodetector (PD) yields the sum and difference of weighted signals.

to implement vector multiplication and addition results in a potential to transform the performance tradeoffs of wideband, multi-antenna systems.

Systems for optical information processing have, in the past, faced challenges competing with the scalability of mainstream electronics, yet the rapid development of CMOS-compromise to bring the manufacturing economies of integration to photonic processing systems. A photonic device called a microring (MRR) weight bank can implement fully reconfigurable WDM vector operations and are completely compatible with emerging photonic platforms. The MRR weight bank is therefore a critical subcircuit for multivariate RF photonics.

Prior work on MRR weight banks showed weight control over a range from –1 to +1 in a single MRR [2]. In [3], a more sophisticated calibration model of thermal and optical effects was developed to allow accurate and simultaneous calibration of a bank of MRR weights. In previous work, 2-channel simultaneous control was shown for pairs of weights in a 4-channel bank [3]; however, visualizing simultaneous operation in >2 dimensions presents a challenge.

In this paper, we demonstrate 3-channel functionality of a silicon MRR weight bank in finding the first principal component of a 3-dimensional, 1GHz signal. Silicon-on-insulator samples were fabricated through UBC SiEPIC; silicon thickness is 220nm with fully etched waveguides [4]. 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 10-10.3μm radius MRRs in a parallel

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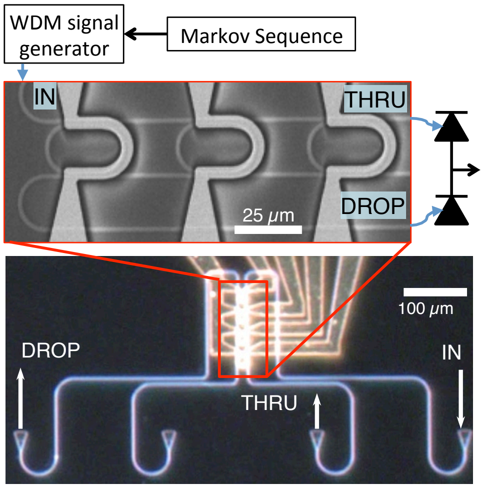

Fig. 2: Experimental setup and device under test. A signal generator in fiber produces WDM channels that are partially correlated. A thermally tuned MRR weight bank applies analog weights reconfigurably to each WDM channel. Complementary drop/thru outputs are detected by a balanced PD to yield the weighted sum. The device is coupled to fiber with grating couplers.

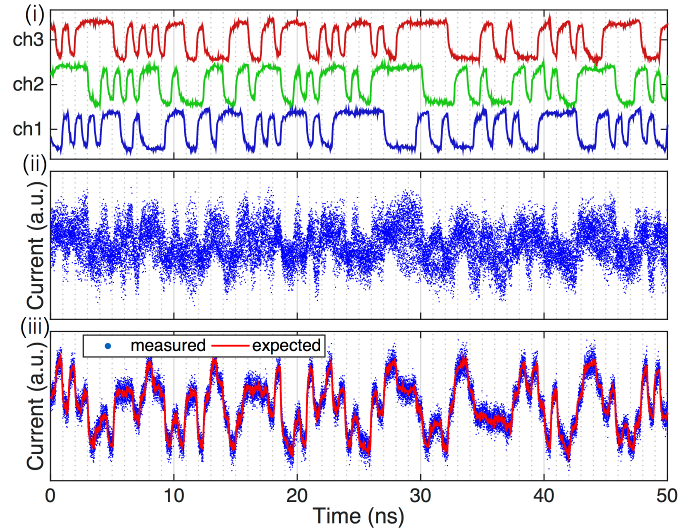

Fig. 3: First principal component analysis (PCA) on a three-dimensional signal. (i) The three input signals are partially-correlated 2Gbps binary patterns, generated by methods detailed in [6]. (ii) Initial output signal over 20 trials, resulting in a variety of initial outputs. Weights are initialized randomly on each trial. (iii) Converged output signal over 20 trials after 30 Hebbian iterations (blue points), compared with the expected first principal component of the inputs (red curve), as calculated with a CPU-based PCA function. The plot shows good correspondence between the converged output and real principal component, for all initializations.

add/drop configuration, each with a thermal tuning element (Fig. 2). The WDM signal generator described in [6] produces multiwavelength inputs that are time-delayed versions of a single modulating signal. When the generating signal is a binary Markov sequence wherin subsequent bits are correlated, then the WDM signal generator produces partially correlated WDM signals. Partially corellated signals contain redundant information are therefore amenable to PCA [6].

The MRR weight bank is calibrated with a non-Markov pseudo-random bit sequence. This ensures that each channel is decorrelated, enabling simultaneous weight measurement [3]. Then, the generating sequence is switched to a 1Gbps Markov sequence with positive correlation between subsequent bits. These inputs are recorded and plotted in Fig. 3(i). Weights are initialized randomly over 20 trials, pictured in Fig. 3(ii). The expected first PCA signal is computed offline based on stored inputs. A common technique to converge on the first principal component is the Hebbian rule, in which weights are updated in the direction of the correlation between stored inputs and their measured weighted sum. The outputs after 30 Hebbian iterations over all trials are plotted in blue in Fig. 3(iii) and compared to the expected principal component (red curve).

The convergence of the PCA algorithm depends on the ability to accurately command multiple weights in a feedforward way. Fig. 3 shows successful convergence of the algorithm and demonstrates that microring resonators are a viable pathway to achieving precise weighted addition. Other multivariate analyses might be applied to broaden the applicability of MRR weight banks to RF photonic systems. For example, all-optical computation of input-output correlations could enable online convergence to the principal components without knowledge of the input signals [7]. Further work could aim to increase the number of controlled channels per MRR weight bank, and explore the ultrafast behavior of weighted addition-based analog optical networks [8] and their RF signal processing applications. Furthermore, calculation of fourth-order statistics could enable independent component analysis, which is a core function of blind signal separation [9]. As explored in [10], the channel limit for programmable WDM weighted addition is approximately $N \leq 148$ when using resonators available on conventional silicon photonics platforms. The scaling prospects offered by MRR weight banks greatly expands the potential impacts of the proposed project for blind source separation in large antenna arrays.

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