Silicon Photonic Weight Bank Control of Integrated Analog Network Dynamics

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***Abstract*—Analog interconnection networks are configured setting connection weights. Microring weight banks are a key device for making such networks in silicon photonic circuits. We demonstrate a small analog network in silicon using a single node with simple dynamics, showing dynamics parameterized by microring weight banks.**

I. INTRODUCTION

Recent times have seen massive amounts of progress in systems using photonics integrated technology, specifically in silicon photonics, where the aim is to bring more efficient interconnects to the chip level. At the same time, recent research in unconventional electronics decentralizes signal processing, creating an even larger demand for efficient interconnect performance. The potential for optics to play a role in an unconventional processing has re-ignited investigation of laser devices that exhibit similar dynamics to biological neurons [1]. Utilization of analog physical dynamics represents a key step towards attaining the efficiency and functionality exhibited by biophysical information processors [2]; however, research on neural-inspired dynamics in photonics has focused largely on single lasers. Networks that can be implemented in silicon are a crucial aspect of neuron-inspired photonics.

We experimentally demonstrate optoelectronic dynamics controlled by a thermally-tuned silicon photonic microring (MRR) weight bank. MRR weight banks enable continuous and complementary (+/–) weighting of wavelength-division multiplexed (WDM) signals. By adjusting the weights of a MRR bank, we are able to control the shape of the non-linearities that the system is outputting, demonstrating control of complex dynamics in a small analog network in silicon with a single node. While time-delayed electro-optic oscilators as demonstrated possess an extremely rich repertoire of behaviors, they have relatively little ability to be configured to network-based models [3]. Ultimately, larger networks of MRR weight banks could support a highly configurable and high-bandwidth photonic processing network, called broadcast-and-weight [4] (Fig. 1).

Broadcast-and-weight leverages recent advances in photonic integrated circuit technology to address interconnect challenges faced by distributed processing. In a neural network, each node receives multiple signals through a tunable function of weighted additon, and performs a nonlinear function. The single output signal is then sent to multiple receiver neurons. In this schema, a single waveguide can carry multiple signals, allowing for great efficiency. The broadcast loops allows each neuron to interact with others connected within the same loop. In our on-chip interconnect protocol called broadcast-and-weight, the output of each neuron has a unique wavelength, and is at the same time made available to every other neuron in the system. WDM effectively channelizes available bandwidth without spatial or holographic multiplexing and avoids coherent interference effects during fan-in. High-bandwidth optical channels are compatible with recently proposed laser neuron devices [1], which could access a picosecond computational domain that impacts application areas where both complexity and speed are paramount (e.g. adaptive control, real-time embedded system analysis, and cognitive RF processing).

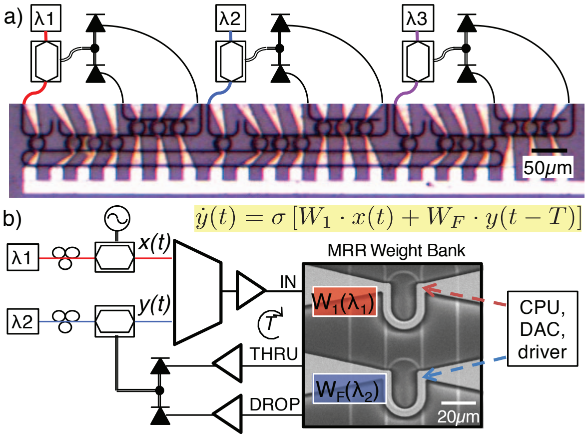

Fig. 1. a) Concept of a small broadcast-and-weight circuit connected through an integrated loop network with microring weight banks. Each neuron receives, through a feedback loop, a combination of its own output and the output of the other neurons in the system in additional to an input signal as the input. b) Current experimental setup for a single neuron. Nonlinearities are achieved through MZMs. A two-channel MRR weight bank adjust the shape of the input signal, which is later recombined with the original signal. The equation models the dynamics for a single neuron.

Our experimental setup is shown in figure 1b. Samples were fabricated on 220nm thick silicon-on-insulator wafers through UBC SiEPIC [5]; waveguides are fully-etched, 500nm wide, and oxide-clad. Ti/Pt/Au heating contacts were then deposited to provide thermo-optic MRR resonance tuning. The weight bank device consists of two bus waveguides and two MRRs in a parallel add/drop configuration. The weight bank

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is calibrated using a method shown in [6] in order to obtain an accurate estimate of the weight values.

WDM signals are directly inputted into the MRR weight bank. Mach-Zehnder modulators are used to introduce nonlinear effects into the system. The signals are added together in the balanced photodetector, and this output signal is multiplexed with an input signal, creating a feedback loop in the system. MRR weights are calibrated for optimal results. Thermal tuning is applied to the weight banks to vary the degree of nonlinearity produced by the system.

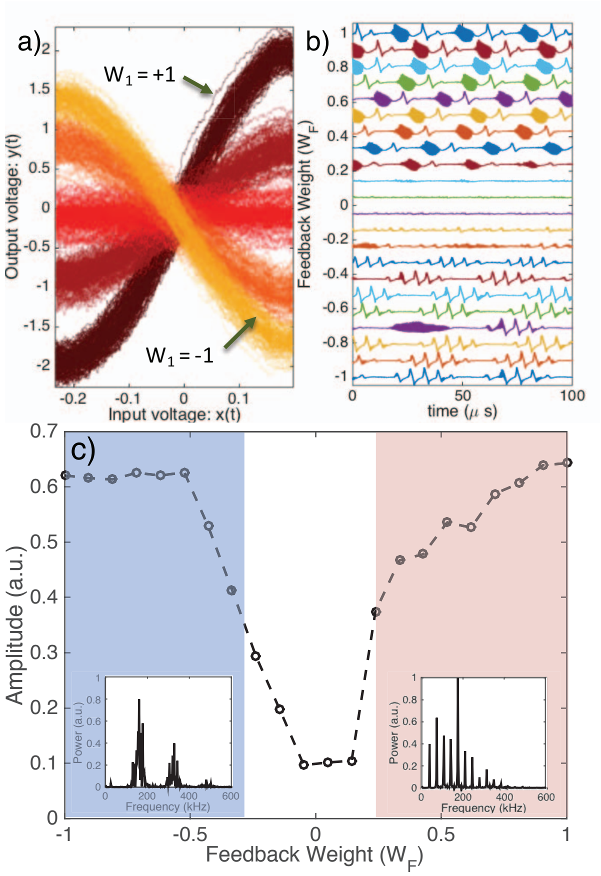

Fig. 2. a) Results obtained from using negative and positive weights on MRRs to change shape of output function. b) Voltage activation levels for each weight. As can be seen, activation was not symmetrical between negative and positive weights of the same value. c) Shaded areas represent different dynamics, achieved from different weights. Insets: Fourier transforms of selected data in (b), corresponding to different dynamics in positive and negative weight regimes.

The dynamics of a single neuron node with a self connection can be represented by

$$\frac{dy(t)}{dt} = \sigma(W_1 \cdot x(t) + W_F \cdot y(t - T)) \tag{1}$$

where y is the output, T is the feedback delay, $W_1 x(t)$ is the input signal multiplied by a weight, and $\sigma(\cdot)$ is a saturation function [7].

In figure 2 we show the experiment results of using weights to vary degrees of nonlinearity in a neural system. As can be seen from 2a, measured nonlinear functions are both positive and negative. It can be seen that the slope of the nonlinear function varies directly with the weight applied to the system; strong positive weights produce strongly positive correlated nonlinear functions, and vice versa. It is important to note that the function is able to produce negative outputs with a single degree of freedom, when most systems take several.

Fig. 2b demonstrates the complexities in the system in the positive and negative weights. As can be seen, the effects of the weights applied centered around zero are not symmetrical. In general, positive weights tend to produce higher voltage levels than do negative weights. Blue and red regions correspond to bifurcations in the dynamics of the system, where it changes from stable to oscillitory. Inset electrical signal spectra taken at points in either regime show the different types of oscillation that occur with a strong positive vs. strong negative feedback weight.

Finally, Fig. 2c further displays the complexities of the system. Typically, in a system such as this one with a single continuous value node, the only expected bifurcation is between stability and bistability; in this system, we see two bifurcations, created by a stable zone and then the effects of the positive and negative weights, introducing oscillating limit cycles in both unstable regions. This effect is produced by the delay. As shown in (1), by introducing a long time delay of t that is long when compared to the bandwidth of the system, the result is extremely complicated dynamics. It is important to note that the limit cycles are different the regions of bifurcation caused by the positive and negative weights (figures 2b and 2c); this is further evidence of the complicated dynamics achieved.

We have demonstrated control of nonlinear dynamics in photonic systems introduced by modulators using microring weight banks. This modulator approach represents a alternative to laser dynamics which is compatible with silicon photonic technology. Although off chip light sources are required, existing techniques already exist for efficient packaging of off chip laser systems due to the universality and convenience of these sources in silicon photonics. In addition, this approach is potentially scalable due to the ease of adding more nodes and more weights, leading to more complex behaviors and additional degrees of freedom present in the system. The proposed system represents the simplest circuit with this approach, yet is a large step toward creating entire networks based on the same principles.

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