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Broadband Radio-Frequency Signal Processing with Neuromorphic Photonics

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ABSTRACT

Microwave photonics and neuromorphic photonics are two parallel research areas which have simultaneously emerged at the forefront of next generation processors. These fields, while initially independent, are naturally converging to a combined silicon photonic platform. An optical processing approach yields wide bandwidth, low latency, and dense interconnection. These photonic systems are capable of supporting applications previously unfeasible. Systems such as photonic cancellers, photonic blind source separation, photonic recurrent neural networks for RF fingerprinting, and photonic neural networks for nonlinear dispersion compensation. This paper will focus on the convergence of microwave photonics and neuromorphic photonics towards an RF optimized machine learning solution. Additionally, this paper investigated the RF noise performance of neuromorphic photonic front-end. The results indicated poor RF performances, leading to the proposal of a balanced linear front-end for noise figure reduction.

Keywords: Neuromorphic Photonics, Microwave Photonics, Noise Analysis, Balanced Weight Bank

1. INTRODUCTION

Microwave Photonics (MWP) systems utilize opto-electronic devices to perform optical analog signal processing on high speed broadband radio frequency (RF) signals. These systems leverage the intrinsic wide bandwidths, tunablity, low latency, and high dynamic range of optical components to create unique processing solutions, fundamentally unattainable using RF analog electronics or digital signal processing techniques.[1] RF signals, which push the bandwidth limits of existing technological platforms become relatively narrowband when upconverted to optical frequencies. With the rise of next generation wireless communication standards the need for smart flexible broadband RF signal processing is more relevant than ever before. MWP systems are well suited to serve this demanding application space.

In parallel to the rapid development of MWP, a new field of Neuromorphic Photonics (NP) emerged. Neural networks developed on a photonic platform reap the same broadband benefits as mentioned for the MWP systems. Within the field of NP two emerging approaches are in development, spiking neural networks and analog neural networks. The former approach emulates the behavior of biological neural networks while the latter approach is an artificial neural network, which is widely used in machine learning (ML). The analog photonic neural network (PNN) offers ultra low latency, low power efficiencies, and broad bandwidths, which enables the novel capability of real-time decision making on RF signals.[2] There has been little RF analysis of analog PNNs due to the fields of MWP and NP developing in relative isolation. The analog PNN is the ideal cross-section between these research areas and merging techniques will greatly benefit the development of analog NP.

Unlike typical MWP systems, NP systems require a nonlinear processing element. While this distinction is significant, the RF performance of a PNN is dominated by the input layer, which is a linear microwave photonic system responsible for up-conversion of the RF input signal and weighted subtraction. Without optimizing, poor

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RF performance will degrade the signal integrity of the RF input and restrict the overall ML capabilities of the PNN. This paper will show the possible improvements in RF performance of the PNN when optimizing the existing PNN linear front-end from the perspective of MWP.

2. MICROWAVE AND NEUROMORPHIC PHOTONIC APPLICATIONS

This section will help illustrate the spectrum and intersections of MWP and NP systems. The following four systems target vastly different applications while sharing the same analog processing techniques and integrated silicon photonic platform. The brief highlighting of these four systems demonstrates the merging of these fields towards an optimal NP systems for broadband RF signal processing.

The first two examples, Photonic Blind Source Seperation (BSS)[3] and Microwave Photonic Cancellation (MPC),[4] are similar MWP systems which are utilized to remove the unknown mixing of interference signals with a desired signal of interest. These systems utilize silicon photonic integrated circuits with microring resonator (MRR) weight banks and balanced photodetectors to perform weighted subtraction of high-speed RF signals. The photonic BSS system uses weighted subtraction to solve an unknown mixing matrix between two statistically independent RF signals, which were combined over a wireless channel. BSS deals with signals without any priori knowledge but the signals are assumed to be zero mean and non-gaussian. The signal cancellation in BSS is guided by the variance and the kurtosis of the weighted output, by which, principle and independent component is performed. This fully integrated silicon photonic system, shown in the top left of Figure 1, performs separation of two unknown broadband RF signals over 13.8 GHz operating range.[3] The MPC, shown in the top right of Figure 1, is a special case of BSS where the condition matrix is extreme but has caveat of a priori knowledge of the interference signal. Therefore, in addition to solving a mixing matrix of weights, the two signals must also be matched with respect to phase and delay by means of a MRR linear filter. This silicon photonic system has achieved precise cancellation of 35 dB over 10 GHz of tunability.[4] BSS, MPC, and PNNs all share the need for a linear matrix of weights and subtraction, and have been developed on shared silicon platform using the same optical components. This MWP technology has reached a higher maturity than the current state-of-the-art of PNN and can be leveraged to improve analog PNN.

The second pair of systems, PNN for nonlinear dispersion compensation and Photonic RF fingerprinting, are examples of silicon NP systems targeting broadband applications. These systems expand on the functionality of the previous MWP systems by the addition of a MRR modulator utilized to apply a nonlinear transfer function. In a breakthrough experiment, Haung et. al., demonstrated a broadcast-and-weight architecture[5] implemented on a silicon photonic chip to perform fiber non-linear compensation in long haul transmission data links.[6] This clearly demonstrated the ability to perform real-time processing of high-speed signals. In parallel, silicon photonic recurrent neural networks were implemented as an analog preprocesser in series with conventional convolutional neural networks to greatly reduce the size requirements and parameters needed for the classification task, RF fingerprinting.[7] In these two stated experiments, the overall performance, compensation levels and classification accuracy respectively, was directly dependent on the RF noise performance of the PNN.[6,7]

3. RF ANALYSIS, SCALABILITY, AND BALANCED ARCHITECTURE

Unlike other optical systems, the intention for MWP is to be integrated into the front-end of an RF communication chain and therefore it is imperative that these systems be designed and evaluated with RF performance metrics at the forefront.[8] RF applications require high linearity and photonic systems will simply not be deployed within RF chains if the inclusion of the system sacrifices fails to meet RF requirements.[9] This analysis will focus on the link loss and noise figure of these systems.

3.1 Scalability / Importance of Input Layer

A photonic neuron, as shown in Figure 2, consists two subsystems: a linear front-end and a nonlinear back end. The nonlinearity is the thresholding of the weighted summation and therefore the decision making element. We are assuming these modulators will not be operated in the linear region after the input layer. If the nonlinear element of neuron responses linearly. the neuron is not being used to make a decision; back propagation and iterative design will eliminate the need for these neurons. With this assumption, only compensation of link

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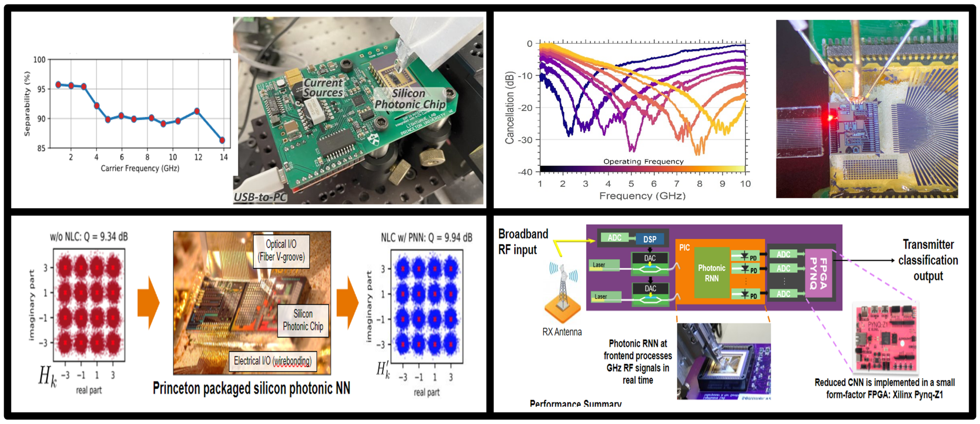

Figure 1. Photonic blind source separation results and fully integrated system[3] (Top Left), Microwave photonic canceller broadband tunable results and photonic integrated circuit[4] (Top Right), Silicon photonic–electronic neural network for fibre nonlinearity compensation[6] (Bottom Left), Photonics-inspired recurrent neural network and FPGA convolutional neural network for RF Fingerprinting[7] (Bottom Right).

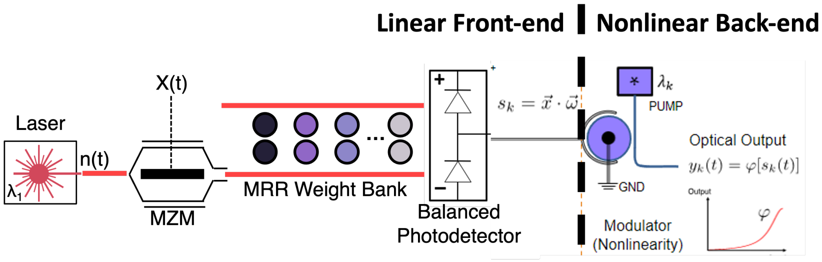

Figure 2. Systematic diagram for input layer of photonic neural network. Linear front end will be focus of analysis and will dominate RF performance of total neural network.

loss is required to further scale the depth of the PNN, which future systems can accomplish with a trans-impedance amplifier.[10] This assumption simplifies the RF analysis of the PNN link loss and noise figure to the RF performance of the linear photonic link of the input layer. The impact on SNR from this subsystem impacts the quality of decisions made by the PNN as a whole.

3.2 RF Analysis

The linear front-end of the PNN consists of a laser, modulator, optical couplers, MRR weight bank, and the balanced photodetector. In current silicon photonic platforms, the laser is off-chip and the modulator can optionally be either integrated or discrete. Currently, these systems are constructed with an externally modulated architecture but future analysis will explore the benefits of direct modulation. This analysis also assumes passive impedance matching. The RF link loss, the difference in RF power before and after the PNN front-end, is defined in eqn. 1.[8] The RF noise figure, the difference in SNR before and after the PNN front-end, is defined in eqn. 2.[8] The analysis uses component metrics available in standard academic photonic foundry fabrication runs and discrete off-the-shelf components. The shared parameters used were laser RIN of -165 dB/Hz, photodetector responsitivity, R_{pd}, of 1.09 A/W, and load resistance R_L. off-chip modulator metrics: Vpi = 3.7 V, Tmod = -3.5 dB, Gopt = -7.9 dB and on-chip modulator metrics: Vpi = 7.5 V,[11] Tmod = -4.5 dB,[11] Gopt = -5.6 dB.

$$Link\ \ Loss_{EM} = \frac{RF_{out}}{RF_{in}} = (1/4) * \left(\frac{\pi P_{in} T_{mod} R_L}{2V_\pi}\right)^2 * G_{opt}^2 * R_{pd}^2 \tag{1}$$

$$Noise\ \ Figure_{EM} = \frac{SNR_{in}}{SNR_{out}} = 1 + \frac{16V_\pi^2}{\pi^2 P_{in}^2 G_{opt}^2 R_{pd}^2 R_L^2} + \frac{16qV_\pi^2}{\pi^2 P_{in} G_{opt} R_{pd} * R_L kT} + \frac{4V_\pi^2 RIN}{\pi^2 R_L kT} \tag{2}$$

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The resulting analysis for the RF front-end is shown in 4 by the solid red curves, off-chip modulator, and solid blue curve, on-chip modulator. A black dot is plotted at 20 dBm as an estimated high-power operating point before optical power handling limits are reached. At this point the noise figure of the front-end is significantly high for both modulator choices, 35.8 dBm and 41.4 dBm, respectively. This noise figure will render the PNN not viable in many applications.

3.3 Balanced Weight Bank Architecture

Our purposed solution to the high RF noise figure of the PNN front-end is the implementation of a balanced weight bank. This system employs the techniques of a photonic canceller,[4] differential detection photonic link,[12] and the PNN front-end to achieve both weighted summation and relative intensity noise (RIN) suppression. The system, shown in Figure 3, uses a dual-output Mach-Zehnder modulator to generate complementary RF signal on two optical paths. Both optical paths have identical MRR weight banks which have inverted outputs with respect to the other optical path. Equation 3 represented the modulated optical signals following the MRR weight bank with parameters: RIN $n(t)$, signal $X(t)$, and MRR coupling α. The resultant subtraction at the balanced photodetector, shown in eqn 4, yields a two-times gain from subtraction of complementary RF signal pairs, weighting from subtraction of the two pairs, and removal of the common-mode noise, RIN. This math is simplified, in reality the noise suppression performance will be a function of amplitude matching the two pairs of optical paths as well as the strength of the RF signal.[12] Considering these two non-idealities, upwards of 30 dB of noise rejection can be achieved.[4] The cost with implementing the balanced weight bank is a two-times increase in number of resonators and control complexity.

$$\begin{array}{llll} [1]: & \alpha(X(t)+n(t)) & [3]: & (1-\alpha)(-X(t)+n(t)) \\ [2]: & (1-\alpha)(X(t)+n(t)) & [4]: & \alpha(-X(t)+n(t)) \end{array} \tag{3}$$

$$RF\ \ Output: [1+3]-[2+4] = [X(t)(2\alpha-1)+n(t)]\ -\ [X(t)(-2\alpha+1)+n(t)] = 2X(t)[2\alpha-1] \tag{4}$$

The resultant noise figure of the improved balanced weight bank PNN front-end is plotted in Figure 4. The dashed red curve, off-chip modulator, and solid blue curve, on-chip modulator. At the high-power operating point the noise figure of the front-end is significantly reduced for both modulator choices, 26.1 dBm ans 31.2 dBm, respectively. This improvement enables higher PNN ML performance and can be further improved with the addition of a low noise amplifier.

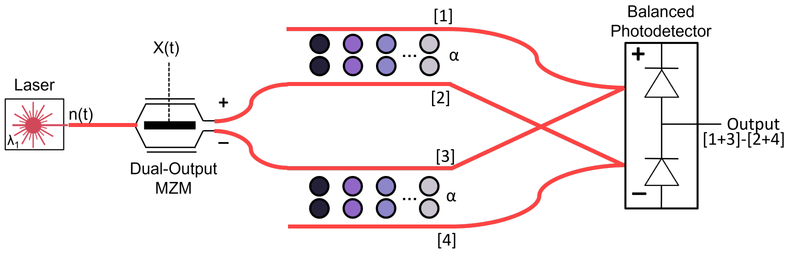

Figure 3. Schematic of balanced weight bank simultaneously responsible for weighted summation and RIN suppression.

3.4 Acknowledgments

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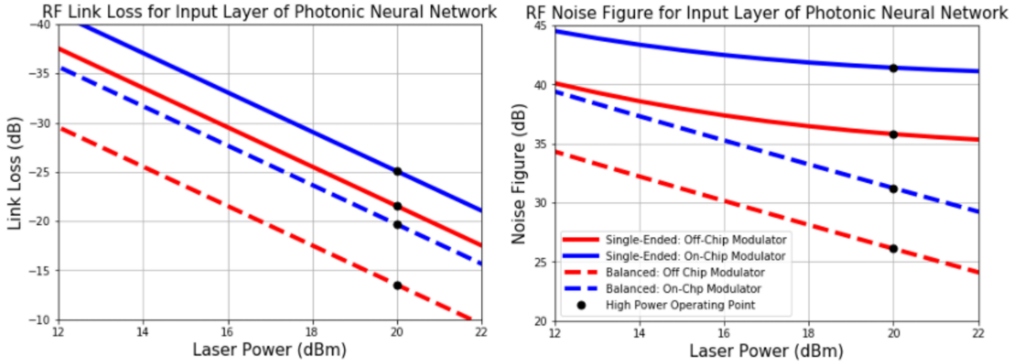

Figure 4. RF link loss (Left) and noise figure (Right) analysis for linear front end of photonic neural network. Solid Curves: Existing Single-End PNN Front-end, Dashed Curves: Balanced PNN Front-end, Red Curves: off-chip modulators, Blue Curves: on-chip modulators.

3.5 Conclusion

The success of neuromorphic photonics systems for RF signal processing depends on utilizing microwave photonics techniques, analysis, and architectures to improve existing designs. Existing photonic neural networks are unnecessarily limited due to poor microwave photonic design. This paper highlights the impact this technological platform can have on analog signal processing tasks and the currently limitations of noise figure. We introduce and proposed the solution of a balanced photonic neural network front-end and perform simulation which show drastic improvements. At a high operating optical in power the balanced weight bank architecture could improve RF noise figure of the front end by 10 dB. This improved noise performance can significantly expand the reach of neuromorphic photonics for RF signal processing applications.

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