Reconfigurable Analog Photonic Networks

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Abstract—**Spurred by advances in scalable photonic system integration, ideas in photonic information processing have recently experienced a resurgence. We review the latest results in reconfigurable analog photonic networks, neuromorphic photonics, and multivariate RF photonics. These architectures could enable next-generation microwave signal processing and scientific computing.**

Networks consisting of a group of interconnected nodes can model many natural and engineered systems, including those for distributed information processing. Digital processing networks, such as multi-core processors, typically comprise nodes of complex processing capabilities and an interconnect that simply shuttles data between them. Analog processing networks, on the other hand, often employ nodes that calculate simple operations of inputs – addition, multiplication, or functions. Analog network connection strengths (a.k.a. weights) are closely tied to computational function, not just data communication. The weight profile determines overall system behavior, which is substantially more complex and varied than individual node behavior. To achieve a large repertoire of processing capabilities, analog networks rely primarily on reconfiguration of these weights. Analog networks for information processing have long been studied under the heading of neural networks. While originally inspired by biological nervous systems, neural networks are, in fact, a class of mathematical frameworks that describe reconfigurable analog network function, in much the same way that logical frameworks describe digital circuit function. This extensive knowledge of how to relate weight profiles to function can be leveraged by hardware that can be made isomorphic to a neural network framework – neuromorphic systems. Neuromorphic electronic architectures utilizing this strategy have recently attracted tremendous research interest [1].

Optics, as compared to electronics, lacks key physical requirements for implementing digital logic; however, these same physical qualities make it much better performing analog signal processing. Substantial recent investigation has been devoted to analog optical systems used as non-reconfigurable reservoir computers [2]. RF and microwave photonics (MWP) exploit the bandwidth, linearity, and tunability of optics to accomplish important, yet simple, tasks required for next-generation wireless systems [3]. Extending this performance to much more complex tasks would require models and photonic implementations of network-based information processing. Optical neural networks have been explored using free-space optics [4], but were effectively considered untenable about two decades ago because they were large, expensive, sub-GHz, and severely limited in scalability. Today, rapid advances in photonic manufacturing [5] could revolutionize large-scale photonic systems in terms of size, cost, device performance, reliability, and scalability. Here, we discuss recent advances in integrated neuromorphic photonics, photonic weight banks, and their applications to multivariate RF problems.

"Broadcast-and-weight" [6] was proposed as a protocol for implementing reconfigurable analog and neural networks using integrated photonic devices. Neuron outputs are wavelength division multiplexed (WDM) and broadcast to other neurons. At each neuron input, these WDM signals are weighted by reconfigurable, continuous-valued filters called microring (MRR) weight banks and then summed by total power detection. This electrical weighted sum then modulates the corresponding WDM carrier through a nonlinear electro-optic device [7]. The first demonstration of a broadcast-and-weight network [8] established a dynamical correspondence with a continuous-time recurrent neural network model. This correspondence allows for the application of neural network design tools to analog photonic networks, making them not merely reconfigurable, but programmable. Contemporary work in programmable RF photonics [9] focuses on linear signal processing tasks. Programmable neuromorphic photonics could address a broader array of tasks in MWP and scientific computing, such as nonlinear differential equation solving [8].

MRR weight banks are the seat of reconfigurability in integrated analog photonic networks. Their performance is therefore closely tied to the potential of these overall systems. By tuning filters on and off resonance with their respective signals, an MRR weight bank can individually weight each WDM channel. Techniques for extracting weight vectors from time-domain WDM measurements and for precise control of MRR weights were introduced in Ref. [10]. WDM channel density is limited by the ability to weight neighboring signals independently [11]. Advanced designs shown in [12] can increase scalability by a factor of three.

The accelerating demands on spectrum resources are pushing radio operations into new regimes of bandwidth, efficiency, and reconfigurability. Multi-antenna systems introduce a new dimension with which to share radio spectrum based on spatial discrimination. Digital receivers for multi-antenna systems present a formidable challenge in that every antenna needs an analog-to-digital converter (ADC), which are performance bottlenecks. After digitization, the largely redundant signals are typically distilled into one salient signal, such as the principal components (PCs) or independent components. If this distillation can be performed in the analog domain - prior to digitization - the ADC-limited receiver energy consumption

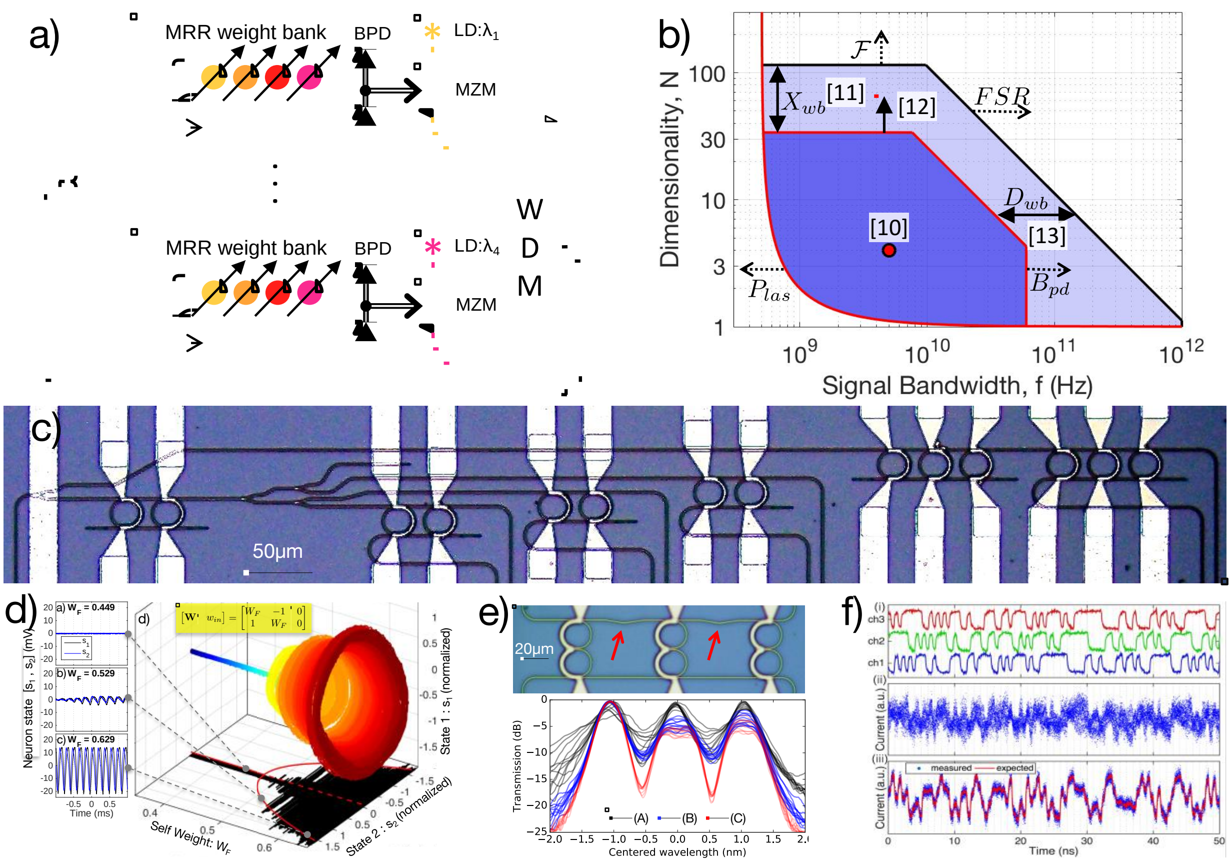

Fig. 1. a) Concept of a broadcast-and-weight network [6]. b) Regime of application for multivariate RF photonics [14]. c) Silicon waveguide implementation of a thermally reconfigurable broadcast-and-weight network; detectors and laser sources are off-chip. d) Bifurcation results of a recurrent 2-node photonic neural network [8]. e) MRR weight banks with increased tolerance to thermal cross-talk [12]. f) First principal component analysis with a MRR weight bank, before convergence (middle) and after (bottom).

would no longer trade off with number of antennas.

Multivarite RF photonics refers to the application of statistical analysis to photonic implementations of multi-channel RF signal processing. A MRR weight bank implementation of principal component analysis at 1GHz was shown in [13]. The performance limits of MRR weight banks defines the applicability regime of multivariate RF photonics, which can be compared to their electronic counterparts. Ref. [14] outlined a regime of bandwidth and number of channels where multivariate RF photonics would outperform state-of-the-art electronics.

Silicon photonic manufacturing introduces unprecedented opportunities for large-scale, analog photonic systems with wide reconfigurability. By applying neural abstractions for programming and learning interconnects, these systems could find application in new regimes of information processing where speed, adaptibility, and complexity are paramount. Further study is required to determine the specific applications where the combination of these capabilities will have greatest impact.

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