Silicon Photonic Neural Networks

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Abstract

Microelectronic computers have encountered challenges in meeting all of today's demands for information processing. Meeting these demands will require the development of unconventional computers employing alternative processing models and new device physics. Neural network models have come to dominate modern machine learning algorithms, and specialized electronic hardware has been developed to implement them more efficiently. A silicon photonic integration industry promises to bring manufacturing ecosystems normally reserved for microelectronics to photonics. Photonic devices have already found simple analog signal processing niches where electronics cannot provide sufficient bandwidth and reconfigurability. In order to solve more complex information processing problems, they will have to adopt a processing model that generalizes and scales.

Neuromorphic photonics aims to map physical models of optoelectronic systems to abstract models of neural networks. It represents a new opportunity for machine information processing on sub-nanosecond timescales, with application to intelligent RF signal processing, mathematical programming, and real-time control. The strategy of neuromorphic engineering is to externalize the risk of developing computational theory alongside hardware. The strategy of remaining compatible with silicon photonics externalizes the risk of platform development. We demonstrate small neuromorphic photonic systems after developing the requisite new protocols, methods, and strategies for experimental proof-of-concept. The microring weight bank is introduced as the novel device that configures connection strengths between neurons.

The primary result of this thesis is a move from neuron-like photonic devices to complete networks of photonic neurons. This dissertation focuses on one kind of neuromorphic photonic network that is fully compatible with contemporary silicon photonic foundries. We give sufficient background on silicon photonics and neural networks at a level intended to introduce researchers from one field to the other. We describe design principles of silicon photonic neural networks and then derive scalability limits and power scaling relationships

that connect performance to platform. Example benchmark tasks that demonstrate key processing capabilities are studied. Finally, we argue that the recurrent silicon photonic neural network is a good baseline against which to compare other implementations of neuromorphic photonics.

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Journal Articles

[1] A. N. Tait, T. Ferreira de Lima, E. Zhou, A. X. Wu, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal. **Neuromorphic photonic networks using silicon photonic weight banks**. *Scientific Reports*, 7(1):7430 Aug. 2017.

[2] A. N. Tait, A. X. Wu, E. Zhou, T. Ferreira de Lima, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal. **Microring weight banks**. *J. Selected Topics in Quantum Elec.*, 22(6), Nov. 2016.

[3] A. N. Tait, T. Ferreira de Lima, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal. **Multi-channel control for microring weight banks**. *Opt. Express*, 24(8):8895–8906, Apr. 2016.

[4] A. N. Tait, T. Ferreira de Lima, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal. **Continuous calibration of microring weights for analog optical networks**. *IEEE Photonics Technol. Lett.*, 28(8):887–890, Apr. 2016.

[5] A. N. Tait, J. Chang, B. J. Shastri, M. A. Nahmias, P. R. Prucnal. **Demonstration of WDM weighted addition for principal component analysis**. *Opt. Express*, 23(10), May 2015.

[6] A. N. Tait, M. A. Nahmias, B. J. Shastri, P. R. Prucnal. **Broadcast-and-weight: an integrated network for scalable photonic spike processing**. *J. Lightwave Technol.*, 32(21), Nov. 2014.

[7] A. N. Tait, B. J. Shastri, M. P. Fok, M. A. Nahmias, and P. R. Prucnal. **The DREAM: An integrated photonic thresholder**. *J. Lightwave Technol.*, 31(8), Apr. 2013.

Book chapters

[8] A. N. Tait, M. A. Nahmias, Y. Tian, B. J. Shastri, and P. R. Prucnal. "**Photonic neuromorphic signal processing and computing**". in *Nanophotonic Information Physics*, M. Naruse ed. pp. 183–222. Springer, Berlin/Heidelberg Dec, 2013.

Refereed Conference Proceedings

[9] A. N. Tait, T. Ferreira de Lima, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal. **Reconfigurable analog photonic networks**. in *IEEE Photonics Conference (IPC)*, pp. 267–268, Oct. 2017.

[10] A. N. Tait, A. X. Wu, T. Ferreira de Lima, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal. **Microring weight bank designs with improved channel density and tolerance**. in *IEEE Photonics Conference (IPC)*, pp. 101–102, Oct. 2017.

[11] A. N. Tait, T. Ferreira de Lima, M. P. Chang, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal. **Application regime and distortion metric for multivariate RF photonics**. in *IEEE Optical Interconnects Conference (OI)*, pp. 25–26, Jun. 2017.

[12] A. N. Tait, T. Ferreira de Lima, E. Zhou, A. X. Wu, M. P. Chang, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal. **Silicon microring weight banks for multivariate RF photonics**. in *OSA Conference on Lasers and Electro-Optics (CLEO)*, p. SM1O.6, May 2017.

[13] A. N. Tait, E. Zhou, A. X. Wu, M. A. Nahmias, T. Ferreira de Lima, B. J. Shastri, and P. R. Prucnal. **Demonstration of a silicon photonic neural network**. in *IEEE Photonics Society Summer Topical Meeting Series (SUM)*, pp. 72–73, Jul. 2016.

[14] A. N. Tait, A. X. Wu, E. Zhou, T. Ferreira de Lima, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal. **Multi-channel microring weight bank control for reconfigurable analog photonic networks**. in *IEEE Optical Interconnects Conference (OI)*, p. WC4, May 2016.

[15] A. N. Tait, M. A. Nahmias, T. Ferreira de Lima, B. J. Shastri, A. X. Wu, E. Zhou, E. C. Blow, and P. R. Prucnal. **Continuous control of microring weight banks**. in *IEEE Photonics Conference (IPC)*, pp. 411–412, Oct. 2015.

[16] A. N. Tait, M. A. Nahmias, B. J. Shastri, M. P. Chang, A. X. Wu, E. Zhou, E. C. Blow, T. Ferreira de Lima, B. Wu, and P. R. Prucnal. **Balanced WDM weight banks for analog optical processing and networking in silicon**. in *IEEE Photonics Society Summer Topical Meeting Series (SUM)*, p. MC2.3, Jul. 2015.

[17] A. N. Taitand P. R. Prucnal. **Applications of wavelength-fan-in for high-performance distributed processing systems**. in *IEEE/ACM International Symposium on Nanoscale Architectures (NANOARCH)*, pp. 177–178, Jul. 2014.

[18] A. N. Tait, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal. **Broadcast-and-weight interconnects for integrated distributed processing systems**. in *IEEE Optical Interconnects Conference (OI)*, pp. 108–109, May 2014.

[19] A. N. Tait, M. A. Nahmias, M. P. Fok, and P. R. Prucnal. **A dual resonator enhanced asymmetric Mach-Zehnder: Ultrafast passive thresholder for silicon-on-insulator**. in *International Conference on Optical MEMS and Nanophotonics (OMN)*, pp. 212–213, Aug. 2012.

Textbook

[1] P. R. Prucnal and B. J. Shastri. "**Neuromorphic Photonics**". CRC Press, May, 2017. (Contributor to)

Relevant Co-authored Journal Articles

[1] T. Ferreira de Lima, B. J. Shastri, A. N. Tait, M. A. Nahmias, and P. R. Prucnal. **Progress in Neuromorphic Photonics**. *Nanophotonics*, 6(3):577–599, Mar. 2017.

[2] P. R. Prucnal, B. J. Shastri, T. Ferreira de Lima, M. A. Nahmias, and A. N. Tait. **Recent progress in semiconductor excitable lasers for photonic spike processing**. *Adv. Opt. Photon.*, 8(2):228–299, Jun. 2016.

[3] T. Ferreira de Lima, A. N. Tait, M. A. Nahmias, B. J. Shastri, and P. R. Prucnal. **Scalable wideband principal component analysis via microwave photonics**. *IEEE Photonics Journal*, 8(2):1–9, Apr. 2016.

[4] M. A. Nahmias, A. N. Tait, L. Tolias, M. P. Chang, T. Ferreira de Lima, B. J. Shastri, and P. R. Prucnal. **An integrated analog O/E/O link for multi-channel laser neurons**. *Applied Physics Letters*, 108(15), Apr. 2016.

[5] R. Toole, A. N. Tait, T. Ferreira de Lima, M. A. Nahmias, B. J. Shastri, P. R. Prucnal, and M. P. Fok. **Photonic implementation of spike-timing-dependent plasticity and learning algorithms of biological neural systems**. *J. Lightwave Technol.*, 34(2):470–476, Jan. 2016.

[6] B. J. Shastri, M. A. Nahmias, A. N. Tait, A. W. Rodriguez, B. Wu, and P. R. Prucnal. **Spike processing with a graphene excitable laser**. *Sci. Rep.*, 5:19126, Dec. 2015.

[7] M. A. Nahmias, A. N. Tait, B. J. Shastri, T. Ferreira de Lima, and P. R. Prucnal. **Excitable laser processing network node in hybrid silicon: analysis and simulation**. *Opt. Express*, 23(20):26800–26813, Oct. 2015.

[8] B. J. Shastri, M. A. Nahmias, A. N. Tait, B. Wu, and P. R. Prucnal. **SIMPEL: Circuit model for photonic spike processing laser neurons**. *Opt. Express*, 23(6):8029–8044, Mar. 2015.

[9] B. J. Shastri, M. A. Nahmias, A. N. Tait, and P. R. Prucnal. **Simulations of a graphene excitable laser for spike processing**. *Optical and Quantum Electronics*, 46(10):1353–1358, Feb. 2014.

[10] M. A. Nahmias, B. J. Shastri, A. N. Tait, and P. R. Prucnal. **A leaky integrate-and-fire laser neuron for ultrafast cognitive computing**. *J. Selected Topics in Quantum Elec.*, 19(5), Sep. 2013.

[11] M. P. Fok, H. Deming, M. A. Nahmias, N. Rafidi, D. Rosenbluth, A. N. Tait, Y. Tian, and P. R. Prucnal. **Signal feature recognition based on lightwave neuromorphic signal processing**. *Opt. Lett.*, 36(1):19–21, Jan. 2011.

Relevant Undergraduate Independent Work Reports (available upon request)

[1] E. Gordon. **Design and control of a photonic neural network applied to high-bandwidth classification**. undergraduate thesis [Adviser: Prucnal], Princeton University, 2017.

[2] E. Zhou. **Silicon photonic neural networks**. undergraduate thesis [Adviser: Prucnal], Princeton University, 2016.

[3] A. X. Wu. **Advanced designs of silicon microring resonators (MRR) in wavelength division multiplexing (WDM) weight banks**. undergraduate thesis [Adviser: Prucnal], Princeton University, 2016.

[4] L. Tolias. **Quadratic optimization with integrated photonics**. undergraduate thesis [Advisor: Prucnal], Princeton University, 2016.

[5] A. N. Tait. **Network analysis of a multichannel photonic neuron**. ELE 454 term paper [Teacher: Prucnal], Princeton University, May 2010.

Chapter 1

Introduction

Computing today is in many ways the same as it was in the 1960s: digital microelectronics implementing a centralized processing unit (CPU) architecture. Throughout this time, their performance improved exponentially according to what is known as Moore's law. There have always been predictions that Moore's law is ending. Nevertheless, microelectronics have managed to maintain an exponential rate of improvement through the development of new technologies and architectures, such as multi-core architectures, graphical processing units (GPUs), and field-programmable gate arrays (FPGAs). Today, there are a growing number of computational problems that seem well out of reach, even when extrapolating for microelectronic performance advances. Conventional computers are here to stay; however, recent years have seen a resurgence in unconventional computing approaches, ranging from neuromorphic electronics to radio frequency (RF) photonics.

This thesis proposes silicon photonic neural networks as a complement to digital microelectronic computing. Photonics do not possess the same physical properties of metal interconnects and complementary metal-oxide-semiconductor (CMOS) transistors. It is unquestionable that photonics, specifically fiber optics, is preferable for high-bandwidth communication over long distances. Motivated by successes in optical communication in the 1960s and 1980s, some began to ask if optics could be used to process information[1], as