Review article

Thomas Ferreira de Lima, Alexander N. Tait, Armin Mehrabian, Mitchell A. Nahmias, Chaoran Huang, Hsuan-Tung Peng, Bicky A. Marquez, Mario Miscuglio, Tarek El-Ghazawi, Volker J. Sorger, Bhavin J. Shastri* and Paul R. Prucnal

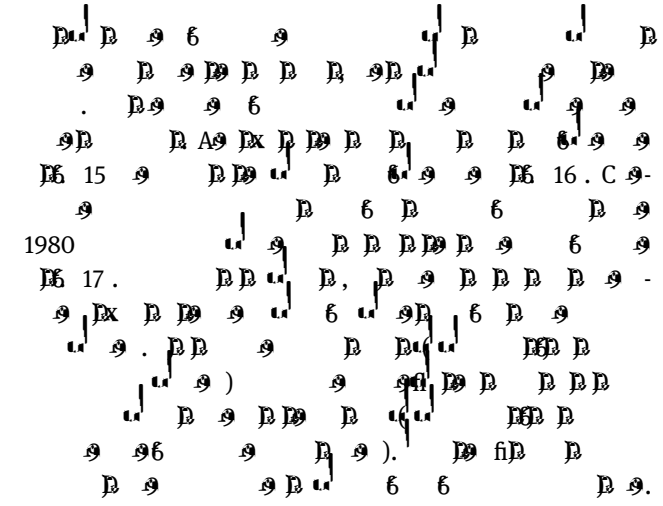
Primer on silicon neuromorphic photonic processors: architecture and compiler

https://doi.org/10.1515/nanoph-2020-0172
Received March 6, 2020; accepted June 10, 2020; published online August 10, 2020

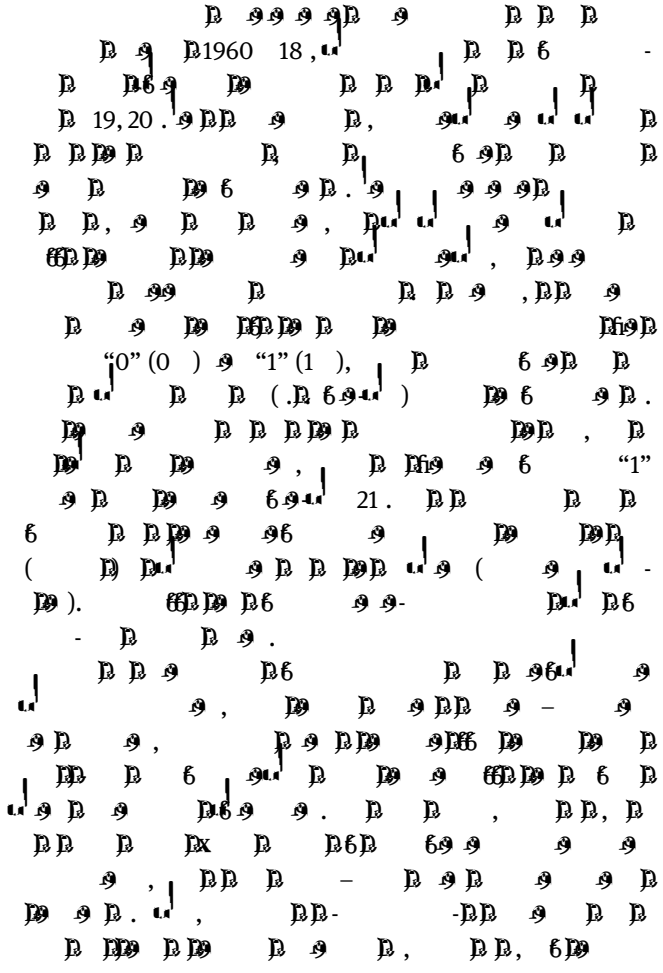
Abstract:

[illegible]

3 Photonic information processing



3.1 Previous decades



quantum silicon photonics, photonic reservoir computing, RF photonics.

3.3.1 Quantum silicon photonics

110 , 111 , 112 . 113, 114 115 .

B 116 . D . A 846.3( )-249 5 642.2(95) -2.

5 Neuromorphic processor architecture

79 , C , fi . B , fi . , ‘fix’ . , (D) - , , , (DAC) - - (ADC).

5.1 Processor firmware specifications

A 4, (- ,) (,) (,). - . A ( ) , , , , fl , , - .

Command &
Control .

5.2.2 Command & control circuit

A Command & Control , C. 117, 118 . 119 114 , 120 . DC / C, reconfiguration . C 10,000 .

5.2.3 Reconfiguration circuit – interfacing with the real world

(C) , 79 . C ,

, - 𝄢 𝄢 𝄢 𝄢 𝄢 𝄢
𝄢 𝄢 𝄢 𝄢 𝄢

133, 134 -290/ 6397. 59 5 97 -37 7.2( )-410(218)-242.118(.9(8.222)-217.2( )-3 2.8

135 . 7) 107 , 45 (x7). 131 , 132 (8).

energy ef*f*iciency (energy/MAC), throughput per unit area i.e. compute density (MACs/s/mm^2), speed (MVM/s), and latency (s),

100), (
100) 143 .

, -
. ,
- ,
: (1) -
,
143 , (2)
,
, .
,

[16] P. Ambs, “Optical computing: a 60-year adventure,” Adv. Opt. Technol., vol. 2010, pp. 22–25, 2010 [Online]. https://doi.org/10.1155/2010/372652.
[17] T. E. Bell, “Optical computing: a field in flux,” IEEE Spectr., vol. 23, no. 8, pp. 34–57, 1986.
[18] O. A. Reimann and W. F. Kosonocky, “Progress in optical computer research,” IEEE Spectr., vol. 2, no. 3, pp. 181–195, 1965.
[19] R. W. Keyes, “What makes a good computer device?,” Science, vol. 230, no. 4722, pp. 138–144, 1985 [Online]. Available at: http://science.sciencemag.org/content/230/4722/138.
[20] R. W. Keyes, “Optical logic-in the light of computer technology,” Opt. Acta Int. J. Opt., vol. 32, no. 5, pp. 525–535, 1985.
[21] J. W. Goodman, “Fan-in and fan-out with optical interconnections,” Opt. Acta Int. J. Opt., vol. 32, no. 12, pp. 1489–1496, 1985 [Online].
[22] R. Amin, R. Maiti, Y. Gui, et al., Broadband sub- ghz ito plasmonic Mach–Zehnder modulator on silicon photonics, 2019.
[23] J. W. Goodman, Introduction to Fourier optics. San Francisco, USA: McGraw-Hill, 1968.
[24] L. J. Cutrona, E. N. Leith, L. J. Porcello, and W. E. Vivian, “On the application of coherent optical processing techniques to synthetic-aperture radar,” Proc. IEEE, vol. 54, no. 8, pp. 1026–1032, 1966.
[25] J. Misra and I. Saha,(with)-261.5(oehndh480TD(ƴTj/F21Tf.46240TD(Artiƴ)Tj/F071Tf150840TD()Tj/F21Tf.56190TD[cical)-260.2neurcalr:l

[52] C. Mesaritakis, V. Papataxiarhis, and D. Syvridis, "Micro ring resonators as building blocks for an all-optical high-speed reservoir-computing bit-pattern-recognition system," J. Opt. Soc. Am. B, vol. 30, no. 11, pp. 3048–3055, 2013 [Online]. Available at: http://josab.osa.org/abstract.cfm?URI=josab-30-11-3048.

[53] J. Capmany, J. Mora, I. Gasulla, J. Sancho, J. Lloret, and S. Sales, "Microwave photonic signal processing," J. Lightwave Technol., vol. 31, no. 4, pp. 571–586, 2013.

[54] A. Farsaei, Y. Wang, R. Molavi, et al., "A review of wireless-photonic systems: Design methodologies and topologies, constraints, challenges, and innovations in electronics and photonics," Opt. Commun., 2016 [Online]. Available at: http://www.sciencedirect.com/science/article/pii/S0030401816300748, https://doi.org/10.1364/iprsn.2016.jtu4a.14.

[55] W. Liu, M. Li, R. S. Guzzon, et al., "A fully reconfigurable photonic integrated signal processor," Nat. Photon., vol. 10, no. 3, pp. 190–195, 2016.

[56] Y. Liu, A. Choudhary, D. Marpaung, and B. J. Eggleton, "Gigahertz

computing," IEEE J. Sel. Top. Quantum Electron., vol. 19, no. 5, pp. 1–12, 2013.
[81] 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., vol. 8, no. 2, pp. 228–299, 2016 [Online]. Available at: http://aop.osa.org/abstract.cfm?URI=aop-8-2-228.
[82] A. Hurtado, K. Schires, I. Henning, and M. Adams, "Investigation of vertical cavity surface emitting laser dynamics for neuromorphic photonic systems," Appl. Phys. Lett., vol. 100, no. 10, p. 103703, 2012.
[83] F. Selmi, R. Braive, G. Beaudoin, I. Sagnes, R. Kuszelewicz, and S. Barbay, "Relative refractory period in an excitable semiconductor laser," Phys. Rev. Lett., vol. 112, p. 183902, 2014 [Online].
[84] B. Romeira, R. Avó, J. M. L. Figueiredo, S. Barland, and J. Javaloyes, "Regenerative memory in time-delayed neuromorphic photonic resonators," Sci. Rep., vol. 6, p. 19510, 2016 [Online].
[85] M. A. Nahmias, A. N. Tait, L. Tolias, et al., "An integrated analog O/E/O link for multi-channel laser neurons," Appl. Phys. Lett., vol. 108, no. 15, p. 151106, 2016 [Online]. Available at: http://scitation.aip.org/content/aip/journal/apl/108/15/10.1063/1.4945368.
[86] H. T. Peng, M. A. Nahmias, T. F. de Lima, A. N. Tait, B. J. Shastri, and P. Prucnal, "Neuromorphic photonic integrated circuits," IEEE J. Sel. Top. Quantum Electron., vol. 24, no. 6, pp. 1–15, 2018.
[87] H. Peng, G. Angelatos, T. F. de Lima, et al., "Temporal information

[112] K.-L. Du, A. Lai, K. Cheng, and M. Swamy, "Neural methods for antenna array signal processing: a review," Sig. Process., vol. 82, no. 4, pp. 547–561, 2002 [Online]. Available at: http://www.sciencedirect.com/science/article/pii/S0165168401001852.

[113] A. N. Tait, P. Y. Ma, T. F. de Lima, et al., "Demonstration of multivariate photonics: blind dimensionality reduction with integrated photonics," J. Lightwave Technol., vol. 37, no. 24, pp. 5996–6006, 2019.

[114] P. Y. Ma, A. N. Tait, T. F. de Lima, C. Huang, B. J. Shastri, and P. R. Prucnal, "Photonic independent component analysis using an on-chip microring weight bank," Opt. Express, vol. 28, no. 2, pp. 1827–1844, 2020 [Online]. Available at: http://www.opticsexpress.org/abstract.cfm?URI=oe-28-2-1827.

[115] A. N. Tait, T. F. de Lima, P. Y. Ma, M. P. Chang, M. A. Nahmias, B. J. Shastri, P. Mittal, and P. R. Prucnal, "Blind source separation in the physical layer," in 2018 52nd Annual Conference on Information Sciences and Systems (CISS), 2018, pp. 1–6.

[116] E. Gordon, "Design and control of a photonic neural network applied to high-bandwidth classification," Undergraduate Thesis, Princeton University, 2017.

[117] 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, vol. 24, no. 8, pp. 8895–8906, 2016 [Online]. Available at: http://www.opticsexpress.org/abstract.cfm?URI=oe-24-8-8895.

[118] A. N. Tait, H. Jayatilleka, T. F. D. Lima, P. Y. Ma, M. A. Nahmias, B. J. Shastri, et al., "Feedback control for microring weight banks," Opt. Express, vol. 26, no. 20, pp. 26422–26443, 2018 [Online]. Available at: http://www.opticsexpress.org/abstract.cfm?URI=oe-26-20-26422.

[119] P. Y. Ma, A. N. Tait, T. F. de Lima, S. Abbaslou, B. J. Shastri, and P. R. Prucnal, "Photonic principal component analysis using an on-chip microring weight bank," Opt. Express, vol. 27, no. 13, pp. 18329–18342, 2019 [Online]. Available at: http://www.opticsexpress.org/abstract.cfm?URI=oe-27-13-18329.

[120] C. Ríos, N. Youngblood, Z. Cheng, et al., "In-memory computing on a photonic platform," Sci. Adv., vol. 5, no. 2, pp. 1–10, 2019.

[121] G. Indiveri and S.-C. Liu, "Memory and information processing in neuromorphic systems," Proc. IEEE, vol. 103, no. 8, pp. 1379–1397, 2015.

[122] Lumerical solutions." [Online]. Available at: https://www.lumerical.com/.

[123] L. Alloatti, M. Wade, V. Stojanovic, M. Popovic, and R. J. Ram, "Photonics design tool for advanced cmos nodes," IET Optoelectron., vol. 9, no. 4, pp. 163–167, 2015.

[124] W. Bogaerts and L. Chrostowski, "Silicon photonics circuit design: methods, tools and challenges," Laser Photon. Rev., vol. 12, no. 4, p. 1700237, 2018.

[125] Omnisim omni-directional photonic simulations." [Online]. Available at: https://www.photond.com/products/omnisim.htm.

[126] E. Ghillino, E. Virgillito, P. V. Mena, et al., "The synopsys software environment to design and simulate photonic integrated circuits: a case study for 400g transmission," in 2018 20th International Conference on Transparent Optical Networks (ICTON)

[145] M. R. Mahmoodi and D. Strukov, "An ultra-low energy internally analog, externally digital vector-matrix multiplier based on nor flash memory technology," in 2018 55th ACM/ESDA/IEEE design automation conference (DAC), 2018, pp. 1–6.
[146] A. N. Tait, "Silicon photonic neural networks," Ph.D. dissertation, Princeton University, 2018 [Online]. Available at: https://dataspace.princeton.edu/jspui/handle/88435/dsp01vh53wz43k.
[147] J. Schrauwen, D. V. Thourhout, and R. Baets, "Trimming of silicon ring resonator by electron beam induced compaction and strain," Opt. Express, vol. 16, no. 6, pp. 3738–3743, 2008 [Online]. Available at: http://www.opticsexpress.org/abstract.cfm?URI=oe-16-6-3738.
[148] A. H. Atabaki, A. A. Eftekhar, M. Askari, and A. Adibi, "Accurate post-fabrication trimming of ultra-compact resonators on silicon," Opt. Express, vol. 21, no. 12, pp. 14139–14145, 2013 [Online]. Available at: http://www.opticsexpress.org/abstract.cfm?URI=oe-21-12-14139.
[149] S. S. Djordjevic, K. Shang, B. Guan, et al., "CMOS-compatible, athermal silicon ring modulators clad with titanium dioxide," Opt. Express, vol. 21, no. 12, pp. 13958–13968, 2013.
[150] K. Padmaraju and K. Bergman, "Resolving the thermal challenges for silicon microring resonator devices," Nanophotonics, vol. 3, no. 4–5, pp. 269–281, 2014.
[151] A. V. Krishnamoorthy, X. Zheng, G. Li, et al., "Exploiting CMOS manufacturing to reduce tuning requirements for resonant optical devices," IEEE Photon. J., vol. 3, no. 3, pp. 567–579, 2011.
[152] Z. Su, E. S. Hosseini, E. Timurdogan, et al., "Reduced wafer-scale frequency variation in adiabatic microring resonators," in OFC 2014. IEEE, 2014, pp. 1–3.
[153] A. Mekis, S. Gloeckner, G. Masini, et al., "A grating-coupler-enabled cmos photonics platform," IEEE J. Sel. Top. Quantum Electron., vol. 17, no. 3, pp. 597–608, 2011.
[154] W. Bogaerts, S. K. Selvaraja, P. Dumon, et al., "Silicon-on-insulator spectral filters fabricated with cmos technology," IEEE J. Sel. Top. Quantum Electron., vol. 16, no. 1, pp. 33–44, 2010.
[155] S. Assefa, F. Xia, and Y. A. Vlasov, "Reinventing germanium avalanche photodetector for nanophotonic on-chip optical interconnects," Nat. Lett., vol. 464, pp. 80–84, 2010.
[156] S. Agarwal, T.-T. Quach, O. Parekh, et al., "Energy scaling advantages of resistive memory crossbar based computation and its application to sparse coding," Front. Neurosci., vol. 9, p. 484, 2016 [Online]. Available at: https://www.frontiersin.org/article/10.3389/fnins.2015.00484.
[157] M. Glick, L. C. Kimmerling, and R. C. Pfahl, "A roadmap for integrated photonics," Opt. Photon. News, vol. 29, no. 3, pp. 36–41, 2018.