Optical Materials EXPRESS

Emerging Optical Materials, Devices and Systems for Photonic Neuromorphic Computing: introduction to special issue

ANTONIO HURTADO,[1,*] BRUNO ROMEIRA,[2] SONIA BUCKLEY,[3] ZENGGUANG CHENG,[4] AND BHAVIN J. SHASTRI[5]

[1] *Institute of Photonics, Physics Department, University of Strathclyde, 99 George Street, G1 1RD, Glasgow, Scotland, United Kingdom*
[2] *International Iberian Nanotechnology Laboratory (INL), Ultrafast Bio- and Nanophotonics Group, 4715-330, Braga, Portugal*
[3] *Applied Physics Division, National Institute of Standards and Technology (NIST), 325 Broadway, Boulder, CO 80305, USA*
[4] *State Key Laboratory of ASIC and System, School of Microelectronics, Fudan University, Shanghai 200433, China*
[5] *Dept. of Physics, Engineering Physics and Astronomy, Queen's University, 64 Bader Lane, Kingston, ON K7L 3 N6, Canada*
[*] *antonio.hurtado@strath.ac.uk*

Abstract: This is an introduction to the feature issue of *Optical Materials Express* on Emerging Optical Materials, Devices and Systems for Photonic Neuromorphic Computing.

We are very pleased to present to you this Feature Issue dedicated to highlight recent advances in the field of photonics for light-enabled neuromorphic computing and Artificial Intelligent (AI) hardware systems.

In recent years, demand for novel and increasingly powerful AI and Machine Learning (ML) systems has exploded in order to process the vast, ever-growing amounts of data generated in our society and to deliver increasingly challenging functionalities (e.g. AI assistants, autonomous vehicles, etc.). However, traditional Von Neumann computing architectures struggle to achieve the efficiency and parallelism required to recreate the complex brain-inspired neural networks that AI/ML systems typically rely on for operation. Therefore, neuromorphic (brain-like) computing approaches aimed towards novel physical realizations of neural networks have attracted increasing interest for data intense processing tasks. Whilst neuromorphic computing systems have been mainly implemented to date by electronic technologies, photonic approaches for neuromorphic information processing are receiving growing attention thanks to their unique attributes, e.g. ultrafast and energy efficient operation, high bandwidths and parallelism and low cross-talk.

Although the field of Neuromorphic Photonics is still in its infancy, it has already shown great prospects to enable a new generation of light-enabled, brain-inspired AI and computing hardware, benefitting from very high computing speeds with reduced energy budgets. This is of critical importance to lower the energy footprint of existing AI technologies whilst permitting to keep up with the growing data volumes and data processing demands in today's society. Whereas, the state-of-the-art in this fast-moving field is covered in recent review articles (see [1] for example), this Feature Issue also introduces timely Invited Opinion and Review articles providing an up-to-date reflection on the state of the art and future outlook on the field.

In this Feature Issue we present a collection of 15 articles focusing on different aspects of Photonics for Neuromorphic Computing. These range from new materials and devices, e.g. phase change materials, vertical-cavity surface emitting lasers (VCSELs), etc., novel systems and

#477577
Journal © 2022
https://doi.org/10.1364/OME.477577
Received 5 Oct 2022; published 13 Oct 2022

architectures, e.g. photonic reservoir computing, photonic accelerators, optical dendritic systems, etc., and new functionalities, e.g. synaptic spike weighting, data classification, etc.

To start, this Feature Issue includes an Invited Opinion Article by Peserico et al [2], which provides relevant insights, challenges, and prospects for novel electronic-photonic neural network accelerators. In this opinion article [2], the authors state first the great prospects of merging the advantages of photonic signal processing with electronic logic control and data storage, before reviewing the emerging electro-optic materials, functional devices, and systems packaging strategies for neuromorphic photonic computing that could offer important performance gains and fuel the ongoing AI revolution.

This Feature Issue has also timely Review Articles on different aspects of Neuromorphic Photonics Research. Firstly, an Invited Review Article by Hulser et al [3], focuses on the topic of time-delayed photonic reservoir computing providing also an in-depth analysis on the effects of the time characteristics of different time-delayed architectures on the overall performance metrics of these systems. Additionally, Skalli et al [4], provide a first comprehensive review on Neuromorphic Photonics systems based upon VCSELs, highlighting the increasing role of these key-enabling devices for novel light-enabled neuromorphic processing platforms including photonic spike-based processing systems and photonic reservoir computers. At last, an Invited review article by George Dabos et al [5] focuses on the technologies and architectures for neuromorphic photonic accelerators, ranging from bulk optics to photonic-integrated-circuits (PICs), assessing their computing efficiency. Additionally, in their review Dabos et al [5] report on the latest advances in photonic and plasmonic modulation technologies for novel weighting elements (for use in training and inference applications), introducing a novel scalable coherent crossbar layout.

The Feature Issue also counts with 11 additional research articles. These have been indexed in the Feature Issue within 6 different topical material categories, namely Materials for Integrated Optics, Nonlinear Optical Materials, Fiber Optic Materials, Laser Materials, Plasmonics and Semiconductors. For consistency we introduce here the different research articles within their respective topical categories:

Starting from the category of **Materials for Integrated Optics**, an article by Boshgazi et al. [6] proposes a photonic reservoir computer architecture acting as an alternative to virtual node-based solutions. This uses a multi-mode resonator to realize the virtual nodes required in the neural network [6]. Also, a work by Jalili et al. [7] proposes a novel method for multiplexing in optical integrated micro-ring resonator weight banks, using a synthetic frequency dimension and asymmetric flow of data in the forward and backward modes to decrease the number of devices needed to perform operations. A different article by Yael Gutiérrez et al. [8] investigates phase-change materials (PCMs) for reconfigurable and programmable photonic devices. Specifically, Gutierrez et al [8] report the use of imaging polarimetry and spectroscopic ellipsometry to reveal and directly measure the optical properties of Sb_2S_3 – a low loss PCM – in both crystalline and amorphous states.

Continuing with the category of **Nonlinear Optical Materials**, an invited paper by Skalli et al. [9] provides a comprehensive study on the performance of a scalable, parallel and autonomous photonic neural network based on a large area vertical-cavity surface-emitting laser (LA-VCSEL). In their work, Skalli et al. [9] also investigate the effect of different physical parameters, namely, injection wavelength, injection power, and bias current on the system's performance, consistency and dimensionality. Another research article by Anufriev et al. [10] proposes a bio-inspired system formed by a biomimetic sensor and an electro-optical reservoir computer, for use in non-spectroscopic sensing to discriminate and determine the constituent concentrations of a chemical mixture is proposed. The authors highlight the potentials of such a system in functionalities requiring real-time chemical composition monitoring. At last, the article by Wu et al. [11] reports on the potentials of a Ge/Si hybrid structure in a micro-ring resonator to

Optical Materials EXPRESS

implement different all-optical nonlinear activation functions (e.g. Radial basis, Relu and ELU functions) with low nonlinear threshold whilst also benefitting from CMOS compatibility and compact footprint.

Within the category of **Fiber Optic Materials**, an invited article by Ortin et al. [12] investigates an optical dendritic unit (ODU), based upon a system formed by a few-mode optical fiber. Here, the different group velocities of the fiber modes are used to define individual dendritic branches. The optical dendrites are successfully evaluated as a linear classifier in header recognition and bit counting tasks.

Additionally, in the topic of **Laser Materials,** Ortega-Piwonka et al. [13] study a neuromorphic optoelectronic excitable spike generator consisting of a resonant tunnelling diode and a nanolaser diode. The optical spikes delivered by this system are characterized in terms of their width, amplitude, response delay, distortion and jitter times. Ortega-Piwonka et al. [13] also analyse the propagation of optical spikes between such excitable optoelectronic units, outlining their potentials for future spiking neural network architectures.

In the category **Plasmonics**, Liao et al. [14] focus on the increasing role of deep learning in the design of photonic devices with high time efficiency and good design performance. In particular, Liao et al. [14] propose a deep neural network (DNN) to achieve forward prediction and inverse design for 3D chiral plasmonic metasurfaces with promising applications in bio-sensing, and further improve the training speed and performance by the transfer learning method.

The last topical category in this Feature Issue, **Semiconductors**, includes two research articles. In the first one, Robertson et al [15] demonstrate that VCSELs can act as synapses in a photonic spiking network yielding high-speed weighting and very fast weight tuning; hence reporting another step towards realizing large-scale VCSEL-based spiking photonic neuromorphic systems. The second article in this category, a work by Skontranis et al. [16] reports in theory a novel time-delayed photonic reservoir computing system using a quantum-dot (QD) spin polarized VCSEL as the nonlinear node. Skontrani et al [16] capitalise on the complex temporal dynamics of multiple energy states present in QD materials and their emission from two discrete wavebands and two polarization states, to demonstrate the enhancement of computational efficiency, when compared with traditional laser-based time-delayed reservoirs.

We sincerely hope the readership of *Optical Materials Express* will enjoy this Feature Issue on Emerging Optical Materials, Devices and Systems for Photonic Neuromorphic Computing. In our view, this gathers a timely body of work, which not only reports novel research results, but also provides new insights, outlook and prospects for new directions within this emerging and fast-moving field at the intersection of disparate topics ranging from photonics, to computer science, artificial intelligence and neuroscience.

Finally, we wish to thank all the authors, reviewers and staff members at Optica Publishing Group for their contributions and dedication to make this Feature Issue possible.

References

1. B. J. Shastri, Alexander N. Tait, and T. Ferreira de Lima, *et al.*, “Photonics for artificial intelligence and neuromorphic computing,” Nat. Photonics **15**(2), 102–114 (2021).
2. N. Peserico, T. Ferreira de Lima, P. Prucnal, and V. Sorger, “Emerging devices and packaging strategies for electronic-photonic AI accelerators: opinion,” Opt. Mater. Express **12**(4), 1347–1351 (2022).
3. T. Hülser, F. Köster, L. Jaurigue, and K. Lüdge, “Role of delay-times in delay-based photonic reservoir computing [Invited],” Opt. Mater. Express **12**(3), 1214–1231 (2022).
4. A. Skalli, J. Robertson, D. Owen-Newns, M. Hejda, X. Porte, S. Reitzenstein, A. Hurtado, and D. Brunner, “Photonic neuromorphic computing using vertical cavity semiconductor lasers,” Opt. Mater. Express **12**(6), 2395–2414 (2022).
5. G. Dabos, D. Bellas, R. Stabile, M. Moralis-Pegios, G. Giamougiannis, A. Tsakyridis, A. Totovic, E. Lidorikis, and N. Pleros, “Neuromorphic photonic technologies and architectures: scaling opportunities and performance frontiers [Invited],” Opt. Mater. Express **12**(6), 2343–2367 (2022).
6. S. Boshgazi, A. Jabbari, K. Mehrany, and M. Memarian, “Virtual reservoir computer using an optical resonator,” Opt. Mater. Express **12**(3), 1140–1153 (2022).

Optical Materials EXPRESS

7. S. Jalili, M. Memarian, and K. Mehrany, "Recycling forward and backward frequency-multiplexed modes in a waveguide coupled to phased time-perturbed microrings for low-footprint neuromorphic computing," Opt. Mater. Express **12**(3), 1198–1213 (2022).
8. Y. Gutiérrez, A. Fernández-Pérez, S. Rosales, C. Cobianu, M. Gheorghe, M. Modreanu, J. Saiz, F. Moreno, and M. Losurdo, "Polarimetry analysis and optical contrast of Sb_2S_3 phase change material," Opt. Mater. Express **12**(4), 1531–1541 (2022).
9. A. Skalli, X. Porte, N. Haghighi, S. Reitzenstein, J. Lott, and D. Brunner, "Computational metrics and parameters of an injection-locked large area semiconductor laser for neural network computing [Invited]," Opt. Mater. Express **12**(7), 2793–2804 (2022).
10. G. Anufriev, D. Furniss, M. Farries, and S. Phang, "Non-spectroscopic sensing enabled by an electro-optical reservoir computer," Opt. Mater. Express **12**(5), 1767–1783 (2022).
11. B. Wu, H. Li, W. Tong, J. Dong, and X. Zhang, "Low-threshold all-optical nonlinear activation function based on a Ge/Si hybrid structure in a microring resonator," Opt. Mater. Express **12**(3), 970–980 (2022).
12. S. Ortín, M. Soriano, I. Fischer, C. Mirasso, and A. Argyris, "Optical dendrites for spatio-temporal computing with few-mode fibers [Invited]," Opt. Mater. Express **12**(5), 1907–1919 (2022).
13. I. Ortega-Piwonka, M. Hejda, J. Alanis, J. Lourenço, A. Hurtado, J. Figueiredo, B. Romeira, and J. Javaloyes, "Spike propagation in a nanolaser-based optoelectronic neuron," Opt. Mater. Express **12**(7), 2679–2696 (2022).
14. X. Liao, L. Gui, Z. Yu, T. Zhang, and K. Xu, "Deep learning for the design of 3D chiral plasmonic metasurfaces," Opt. Mater. Express **12**(2), 758–771 (2022).
15. J. Robertson, J. Alanis, M. Hejda, and A. Hurtado, "Photonic synaptic system for MAC operations by interconnected vertical cavity surface emitting lasers," Opt. Mater. Express **12**(4), 1417–1426 (2022).
16. M. Skontranis, G. Sarantoglou, A. Bogris, and C. Mesaritakis, "Time-delayed reservoir computing based on a dual-waveband quantum-dot spin polarized vertical cavity surface-emitting laser," Opt. Mater. Express **12**(10), 4047–4060 (2022).