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Energy- and Size-efficient Ultra-fast Plasmonic Circuits for Neuromorphic Computing Architectures

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Abstract

This document provides a summary of PlasmoniAC's objectives and achievements, the project overview as well as a short outline of the work performed during the project. Additionally, this report discusses the potential impact of PlasmoniAC's technology, and the dissemination activities followed by PlasmoniAC's consortium towards communicating the project's outcomes to the industrial and academic communities.

Keywords

Activity report, summary, objectives, overview, dissemination, publication.

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1 Executive Summary

This document summarizes the activities and outcomes of the project PlasmoniAC that was completed on 30/09/2023.

2 Summary of the context and overall objectives of the project

The explosive growth and effectiveness of Deep Learning based algorithms comes at a cost of exponentially increasing scale, computational power and energy requirements. Already, highly acclaimed Natural Language models (NLPs) like ChatGPT-3 are reaching daily power consumptions of up to 11 TWh, with future forecasts projecting doubling of the computing power requirements every 5-6 months. The way to the rescue was initially sought in innovative electronic AI hardware architectures, including neuromorphic and analog-in-Memory Computing (AiMC), where however the achieved efficiencies are inherently limited due to the speed and power limits of the underlying electronic interconnects. This deadlock has driven the emergence of a new field of custom Deep Learning (DL) hardware, i.e photonic accelerators, which aims to transfer the well-known high-bandwidth and low-energy interconnect credentials of photonic circuitry in the area of deep learning platforms.

Inspired by this new computing paradigm, PlasmoniAC aimed to harmonically synergize the best-in-class material platforms and photonic accelerator architectures with a novel DL framework that incorporates the idiosyncrasy of the underlying photonic components into neural network training. This unique proposition allowed PlasmoniAC prototypes to breach the energy/footprint efficiency barriers of currently available electronic accelerators and offer unprecedented energy efficiencies down to 86 fJ/ Multiply Accumulate operation (MAC) while supporting baud rates > 50 Gbaud. Moreover, driven by real application needs, the developed platform was used as a computational substrate for a variety of workloads in the areas of image identification, cybersecurity threat detection and optical channel equalization.

3 Project Overview

3.1 Project Identification

Project acronym: PlasmoniAC

Project title: Energy- and Size-efficient Ultra-fast Plasmonic Circuits for Neuromorphic Computing Architectures

Project abstract:

PlasmoniAC aimed to deploy ultra-compact and energy-efficient programmable linear plasmonic neurons targeting to bring the promise of neuromorphic photonics into a tangible reality. These would be deployed on a low-loss and low-cost Si_3N_4 (Silicon Nitride) platform using ultra-compact, low-energy and Complementary metal–oxide–semiconductor (CMOS)-compatible plasmonic computation devices for the encoding of the neuromorphic information. Aiming to enable the resolution of sophisticated tasks and applications, PlasmoniAC targeted the deployment of ultra-high speed non-linear nanophotonic and electro-optic modules. Towards this direction PlasmoniAC 's objectives included (i) the design, fabrication and characterization of standalone input and weight encoding plasmonic devices made of Barium Titanate Oxide (BTO)- , Plasmonic Organic Hybrid (POH)-, Titanium Dioxide (TiO_2)- on Si_3N_4, (ii) non-linear activation modules relying on electro-optic effects, via the combination of Silicon Germanium (SiGe) balanced photodiode and transimpedance amplifiers, as well as on purely photonic non-linear effects coming from of Indium Phosphide (InP) microdisk devices and (iii) the co-integration of the above in neuromorphic circuits for the resolution of cybersecurity tasks in a DataCenter environment, such as the identification of Distributed Denial of Service (DDoS) attacks. Finally, PlasmoniAC aimed to (iv) deliver an end-to-end neuromorphic photonic design library for the validation of neuromorphic photonic systems in inference and training tasks of Deep Learning applications.

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Web site:	http://www.plasmoniac.eu/
Logo:	plasmoniAC

3.2 Consortium Members

A consortium of 11 organizations undertakes the PlasmoniAC project. Here is a list of the partners and their acronyms.

Participant No *	Participant organization name	Acronym	Country
1	Aristotle University of Thessaloniki	AUTH	GR
2	University of Southampton	SOTON	UK
3	Swiss Federal Institute of Technology in Zurich	ETHZ	CH
4	Universite Bourgogne Franche-Comte	UBFC	FR
5	Centre National de la Recherche Nationale – Centre de Nanosciences et de Nanotechnologies (C2N)	CNRS	FR
6	Interuniversitair Micro-Elektronica Centrum	IMEC	B
7	University of IBM Research Zurich GmbH	IBM	CH
8	AMO GmbH	AMO	D
9	Mellanox Technologies	MLNX	IL
10	VPIPhotonics GmbH	VPI	D
11	Lumiphase	LUM	CH

4 Work performed from the beginning of the project to the end of the period covered by the report and main results achieved

During the project lifetime, the consortium has focused on four core action lines to meet its technical objectives.

Developing and merging the best-in-class material technologies in a single PIC computational platform. To meet its ambitious objectives PlasmoniAC extensively investigated the deployment of novel plasmonic and non-plasmonic materials including (i) BTO, POH and TiO_2 for its input data and weight modulation technology. Through executing a meticulous workplan, PlasmoniAC managed to deploy novel BTO-on- Si_3N_4modulators operating at up to 128 GBaud with an impressive voltage-length product of 4.2 Vmm, while the developmental work on TiO_2-based weighting modules concluded to low P_π of 25 mW, paving the path towards ultra-efficient plasmonic-based weighting (ii) Graphene, InP and SiGe for developing novel photodetection and non-linear activation circuitry. To this end, PlasmoniAC investigated novel zero-bias graphene photodetector with theoretical responsivities up to 1 A/W, while also deploying a new-class of opto-electronic and all-optical activation circuitry. This included, a SiGe CMOS non-linear electronic circuity that together with a photodetection stage comprised the first opto-electrical module operating both as a pre-amplifier and a programmable activation function module up to 10 Gbaud, and a InP micro-disk nano laser diode operating as an all-optical activation function with input power requirements as low as 11.5 uW. (iv) Hafnium oxide (HfO2) based memristive elements for non-volatile weighting, demonstrating the first photonic weighting structure controlled through a memristive element, while offering up to 23 different states. (v) Si_3N_4 for deploying a loss optimized interconnect substrate for synergizing its best-in class materials.

Design and deploy optimized photonic accelerator architectures. Through its execution, PlasmoniAC delved deep into the development of novel photonic accelerator architectures, evolving its GA envisioned coherent linear neuron architecture into a fully-fledged Photonic (Crossbar) Xbar design, that drew inspiration from the successful development of electronic XBar arrays. This development allowed PlasmoniAC to further its initial trainable parameter targets and highlighted a pathway towards high-scale, high-weight update linear accelerators. Specifically, PlasmoniAC's Xbar designed to offer up to 30 dB lower insertion loss when targeting 64×64 matrix radices, versus the previously prominent photonic accelerator approach, validating its credentials as a viable alternative for next-generation photonic accelerators.

Bridging the gap between Deep Learning and photonic hardware. From its conception PlasmoniAC aimed to bridge the gap between the currently deployed rigid Deep Learning framework with the idiosyncrasy of the underlying analog photonic components, a far cry of the mature and predictable digital electronic counterparts. This vision allowed PlasmoniAC to develop a new Deep Learning framework, capable of integrating in the Neural Network (NN) training process the performance degrading factors of photonic accelerators, including among other, quantization noise, shot noise, relative intensity noise and limited bandwidth. This framework was successfully deployed in both software models of Photonic Neural Networks and experimentally validated in PlasmoniAC prototypes, revealing significant accuracy and or bandwidth relaxation benefits. Finally, PlasmoniAC successfully merged its innovative Deep Learning framework with an established photonic circuitry simulation suite (VPI), migrating its models and algorithms in a powerful VPI-PyTorch co-simulation suite, capable of rapid prototyping.

Prototyping and application benchmarking. In view of both safeguarding the deployment of PlasmoniAC's photonic neuromorphic architectures in tangible integrated prototypes and benchmarking its architectures in different plasmo-photonic integration platforms, PlasmoniAC laid out a four-folded development roadmap that encompassed the development of four generations of photonic accelerator prototypes that concluded to a 4x4 Xbar prototype using SiGe Electro Absorption Modulators (EAMs) for up to 50 Gbaud operation and a POH-based design that will include Phase Change Materials for its weighting module. Finally, PlasmoniAC assessed the performance of its photonic NN architectures and fabricated prototypes, through the experimental deployment of a wide range of DL datasets for: (i) image recognition e.g., MNIST, CIFAR-10, (ii) application specific NN-classifiers for cybersecurity network traffic monitoring *i.e.* DDoS reconnaissance attack identification and optical communication i.e. NN-assisted channel equalization.

Activities related to the development and integration of the BTO modulators and graphene PDs led to the founding of two respective start-up companies by IBM and AMO respectively, aiming to commercialize the related technologies. In addition, AUTH's and MLNX (NVIDIA)'s pioneering work in the fields of photonic accelerators and network cybersecurity led to the submission of a total of 4 US patents.
In total the multi-disciplinary research of PlasmoniAC has led to over 20 journal articles and appearance in 50 conferences proceedings including 20 invited talks. Finally, PlasmoniAC successfully co-organized two workshops in "Neuromorphic Photonics", that attracted worldwide attention from both academia and industry while also promoting collaboration between relevant EU Horizon programs.

5 Progress beyond the state of the art, results until the end of the project and potential impacts

PlasmoniAC's cross-cutting workplan, extending from material technology to photonic accelerator architectures and related applications, enabled impressive beyond the state-of-the-art advancements in multiple fronts. Specifically, PlasmoniAC's thorough investigation of BTO material properties and its deployment over a low-loss Si_3N_4 photonic substrate paved the way towards next generation >100 Gbaud optical modulator and extended the portfolio of its spin-off consortium member Lumiphase. On the photonic accelerator front, PlasmoniAC demarcated from the previously prominent unitary Mach-Zehnder Interferometer (MZI)-mesh based architectures, enabling for the first time bijective mapping of the weight matrix in a coherent architecture and leading to 3 related submitted patents. The experimental implementation of this architectural vision during PlasmoniAC, allowed it to reach performance metrics close or even higher to the projects target, i.e. 86 fJ/MAC and 1.33 TMAC/sec/mm^2, significantly outperforming electronic counterparts in energy efficiency metrics. Finally, on the network security front PlasmoniAC introduced a radical architectural approach that targeted both a novel framework to identify incoming network cybersecurity threats and a concept of a next generation photonic converged accelerator for smart Network Interface cards (NICs). This approach led to the submission of a new patent for DDoS detection and the first demonstration of DDoS reconnaissance attack identification at 50 Gbaud.

6 Dissemination

6.1 Organization of #2 workshops on Neuromorphic photonics

PlasmoniAC consortium in collaboration with other H2020 EU projects co-organized tow highly appealing workshops in the field of neuromorphic photonics. The organization committee comprised of several individual project partners.

Specifically, the “1st Workshop on Neuromorphic photonics” was held online during the COVID-19 pandemic period (6-7 December 2021) and was organized in the frame of the H2020 EU projects PLASMONIAC (http://www.plasmoniac.eu/), NEBULA (http://nebula-h2020.eu/) and NEOTERIC (https://neoterich2020.eu/). A total of 15 invited talks were given from distinguished academic and industry experts. A parallel young researcher poster session was held during the last day of the event, with the participants in the whole workshop surpassing 100, with more than 70 connected at the same time. The proceeding of the workshop in both pdf and video format are accessible on-line through AUTH’s file sharing platform, allowing the distillation of the acquired knowledge across the photonic scientific community. The site of the workshop where more relevant information is accessible online at: http://plasmoniac.eu/workshops/home.html.

The ”2nd Workshop on Neuromorphic photonics” was held on-site (12-14 July 2023) in the University of West Attica and was organized in the frame of the H2020 EU projects PLASMONIAC (http://www.plasmoniac.eu/), PROMETHEUS (https://prometheus-he.eu/) and NEOTERIC (https://neoterich2020.eu/). A total of 20 invited talks were given from distinguished academic and industry renowned speakers from all over the globe, that covered the subject in different aspects presenting the latest achievements in the fields of neuromorphic photonic engineering and optical neural networks. The site with the workshop details can be retrieved by: https://rncp.eu/workshop/.

6.2 PlasmoniAC publications

PlasmoniAC’s achievements were disseminated in prestigious workshops, journals and conferences:

Dissemination activities

- <u>Workshops/Symposia/Booths</u>

[1] N. Pleros, “Plasmonics in CMOS foundries: a new toolkit for PICs”, PIC International Conference, Nov. 2020 (online)

[2] G. Dabos, A. Totovic and N. Pleros "Neuromorphic Photonic Architectures" DATE Conference 2020, Grenoble (online)

[3] M. Lemme, “2D Materials for Artificial Intelligence Systems - Eyes, Ears, Nose and Brain?”, Graphene Canada 2020

[4] G. Rinke, “Wafer Scale Integration of Graphene - 2D Experimental Pilot Line at AMO”, Graphene4US 2020.

[5] Z. Wang, “Wafer Scale Integration of Graphene”, GO2021.

[6] A. Tsakyridis, “Universal Linear Optics in Neuromorphic Photonics”, ECOC, Basel 2022

[7] M. Moralis-Pegios, “Silicon Photonics for Data Center interconnects and security applications”, ECOC Basel 2022

[8] M. Moralis-Pegios, “High-speed Silicon Photonic neuromorphic computing enabled by hardware-aware deep learning methods”, Mini-symposium “Photonic Neuromorphic Computing” AOP, Guimaraes 2022

[9] M. Moralis-Pegios, “Compute with Light: Architectures, Technologies and Training Models for Neuromorphic Photonic Circuits”, 1st workshop on Neuromorphic Photonics 2022

[10] G. Giamougiannis, “Universal linear optics for neuromorphic computing”, EPFL-Swiss photonics 2023

[11] M. Moralis-Pegios, “High-speed Silicon Photonic neuromorphic computing enhanced by hardware-aware deep learning methods”, 2nd workshop on Neuromorphic Photonics 2022

- <u>Invited Talks</u>

[1] B.J. Offrein, "Integrated Photonics for Neuromorphic Computing, PIC International", Brussels 8-11-2021 (Invited)

[2] B.J. Offrein, "Neuromorphic Computing on integrated Photonic Circuits, Group IV Photonics", 7-12-2021 (Invited)

[3] B.J. Offrein, J. Geler-Kremer, J. Weiss, R. Dangel, P. Stark, A. Sharma, S. Abel and F. Horst, "Volatile and non-volatile optical weights in photonic neuromorphic computing", CLEO2021, 10-5-2021 (Invited)

[4] G Dabos, G Mourgias-Alexandris, A Totovic, M Kirtas, N Passalis, A Tefas, N Pleros, "End-to-end deep learning with neuromorphic photonics", SPIE Photonics West OPTO 2021.

[5] N. Pleros and A. Tefas, "", IEEE Photonics Summer Topicals, July 2021 (online)

[6] N. Pleros et.al, "Compute with Light: Architectures, Technologies and Training Models for Neuromorphic Photonic Circuits" ECOC 2021

[7] M. Moralis-Pegios et. al., "Coherent Photonic neuromorphic computing for high-speed Deep Learning applications", SPIE Photonics West 2022

[8] M. Moralis-Pegios et al., "Photonic Neuromorphic Computing: Architectures, Technologies, and Training Models," 2022 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 2022, pp. 01-03.

[9] M. Lemme "Two-Dimensional Materials for Nanolectronics and Photonics", IU.NET Days, Modena, Italy, September 10-11, 2020

[10] M. Lemme "Graphen und weitere zweidimensionale Materialien aus der Nanotechnologie", Rotary Club Aachen, 22.09.2020

[11] M. Lemme "A European Experimental Pilot Line for Wafer-scale Integration of Graphene and 2D Materials", Pacific Rim Meeting on Electrochemical and Solid State Science, PRIME, Hawaii, USA, October 4-9, 2020

[12] M. Lemme "Two-dimensional Materials and Devices: Promising Concepts for Emerging IT Applications", International Conference on Solid-State Devices and Materials, SSDM, Toyama, Japan, September 27-30, 2020

[13] M. Lemme "Anwendungspotenziale zweidimensionaler Materialien in der Mikro- und Nanotechnologie", 8. GMM-Workshop und BMBF-Workshop des VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V., Bochum, September 15-16, 2020

[14] M. Lemme, "2D Materials for Artificial Intelligence Systems - Eyes, Ears, Nose and Brain?", Graphene Canada 2020

[15] G. Rinke, "Wafer Scale Integration of Graphene - 2D Experimental Pilot Line at AMO", Graphene4US 2020.

[16] Z. Wang, "Wafer Scale Integration of Graphene", GO2021.

[17] M. Lemme, "European Experimental Pilot Line for 2-Dimensional Materials", NIL Industrial Day 2021.

[18] M. Lemme, "2-Dimensional Materials for Silicon Integration", 2021 NSF Workshop on CMOS+X Technologies.

[19] A. Tsakyridis et. al., "Accelerating linear operations with light", IEEE Photonics Summer Topicals, July 2023

[20] A. Totovic, A. Tsakyridis, G. Giamougiannis, M. Moralis-Pegios, G. Dabos, G. Mourgias-Alexandris, N. Pleros, "On-Chip > 100 TMAC/sec Neuromorphic Photonics Turning into Reality", (Invited), IEEE Photonics in Switching conf., Sept. 2021

[21] A. Tsakyridis, G. Giamougiannis, A. R. Totovic, M. Moralis-Pegios, N. Pleros, "Fidelity-Restorable Universal Linear Optics and Neuromorphic Photonics", (Invited), Conf. on Lasers and Electro-Optics (CLEO) 2022, San Jose, CA, USA, May 2022

- <u>Conference Proceedings</u>

[1] B.J. Offrein, Jacqueline Geler-Kremer, Jonas Weiss, Roger Dangel, Pascal Stark, Ankita Sharma, Stefan Abel, Folkert Horst, "Prospects for photonic implementations of neuromorphic devices and systems", IEDM 2020 (Invited)

[2] B.J. Offrein, "Ferroelectric Phase Shifters in Silicon Photonics for novel Types of Optical Computing", MRS Fall Meeting, 2020

[3] B.J. Offrein, "Opportunities for integrated optics in neuromorphic computing", PIC International II, 2020

[4] P. Stark, B.J. Offrein, "Opportunities for analog signal processing in the electrical and the optical domain", WS5, ECOC 2020

[5] G. Dabos, A. Totovic, N. Passalis, A. Tefas, and N. Pleros, "Femtojoule Technology Roadmap for TeraMAC Neuromorphic Photonic Accelerators", IEEE Photonic Conference 2020 (IPC2020)

[6] B.J. Offrein, "Analog optical accelerators for neuromorphic computing", Cadence Photonics Summit, 2020

[7] G. Mourgias-Alexandris, N. Passalis, G. Dabos, A. Totovic, A. Tefas, and N. Pleros, "Time-series classification with an all-optical recurrent neuron", ECOC 2020, Brussels, 6-10 December 2020

[8] G. Mourgias-Alexandris, G. Dabos, N. Passalis, A. Tefas, A. Totovic, and N. Pleros, "All-optical recurrent neural network with sigmoid activation function", in Optical Fiber Communication Conference (OFC) 2020, OSA Technical Digest (Optical Society of America, 2020), paper W3A.5

[9] G. Mourgias-Alexandris, A. Totovic, N. Passalis, G. Dabos, A. Tefas, and N. Pleros "Neuromorphic computing through photonic integrated circuits", Proc. SPIE 11284, Smart Photonic and Optoelectronic Integrated Circuits XXII, 1128403 (26 February 2020); https://doi.org/10.1117/12.2543781

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[11] N. Passalis, G. Mourgias-Alexandris, N. Pleros and A. Tefas, "Adaptive Initialization for Recurrent Photonic Networks using Sigmoidal Activations" 2020 IEEE International Symposium on Circuits and Systems (ISCAS), Sevilla, 2020, pp. 1-5, doi: 10.1109/ISCAS45731.2020.9181106

[12] George Dabos, George Mourgias-Alexandris, Angelina Totović, Nikolaos Passalis, Anastasios Tefas and Nikos Pleros, "Photonic Recurrent Neural Networks with Gating Circuit" CLEO 2020 OSA (Virtual Conference)

[13] N. Passalis, M. Kirtas. G. Mourgias-Alexandris, G. Dabos, N. Pleros and A. Tefas, "Training noise-resilient recurrent photonic networks for financial time series analysis", in EUSIPCO 2020

[14] George Mourgias-Alexandris et al, "A Silicon Photonic Coherent Neuron with 10GMAC/sec processing line-rate", OFC 2021.

[15] B.J. Offrein, Integrated Photonics for Neuromorphic Computing, PIC International, Brussels 8-11-2021 (Invited)

[16] B.J. Offrein, Neuromorphic Computing on integrated Photonic Circuits, Group IV Photonics, 7-12-2021 (Invited)

[17] B.J. Offrein, J. Geler-Kremer, J. Weiss, R. Dangel, P. Stark, A. Sharma, S. Abel and F. Horst, Volatile and non-volatile optical weights in photonic neuromorphic computing, CLEO2021, 10-5-2021 (Invited)

[18] B.J. Offrein, Photonic Integrated Circuits for Neural Network Inference and Training, OFC2021 in Symposium The Role of Machine Learning in Optical Systems and The Role of Optics in Machine Learning Systems (Invited)

[19] P. Stark, J. Weiss, R. Dangel, F. Horst, J. Geler-Kremer and B.J. Offrein, High-Performance Neuromorphic Computing Based on Photonic Technologies (Invited)

[20] A. Messner, et. al, "100 Gbit/s NRZ Data Modulation in Plasmonic Racetrack Modulators on the Silicon Photonic Platform", ECOC 2020, doi: 10.3929/ethz-b-000459799.

[21] M. Kohli et. al, “Highly Efficient Grating Coupler for Silicon Nitride Photonics with Large Fabrication Tolerance”, OSA Advanced Photonics Congress 2021.

[22] G. Giamougiannis et. al, “Silicon-integrated coherent neurons with 32GMAC/sec/axon compute line-rates using EAM-based input and weighting cells”, ECOC 2021.

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[28] A. Tsakyridis, G. Giamougiannis, M. Moralis-Pegios, G. Mourgias-Alexandris, A. R. Totovic, G. Dabos, M. Kirtas, N. Passalis, A. Tefas, D. Kalavrouziotis, D. Syrivelis, P. Bakopoulos, E. Mentovich, N. Pleros, “DDOS attack identification via a silicon photonic Deep Neural Network with 50 GHz input and weight update”, Optical Fiber Comm. Conf (OFC) 2023, San Diego, CA, USA, Mar. 2023

[29] C. Pappas, S. Kovaios, M. Moralis-Pegios, A. Tsakyridis, G. Giamougiannis, J. Van Kerrebrouck, G. Coudyzer, X. Yin and N. Pleros, “Programmable tanh- and ReLU-like Optoelectronic Activation Functions for Neuromorphic Photonic Circuits”, Optical Fiber Comm. Conf (OFC) 2023, San Diego, CA, USA, Mar. 2023

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[3] G. Mourgias-Alexandris et al., "Neuromorphic Photonics With Coherent Linear Neurons Using Dual-IQ Modulation Cells," in Journal of Lightwave Technology, vol. 38, no. 4, pp. 811-819, 15 Feb.15, 2020, doi: 10.1109/JLT.2019.2949133.

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[8] J. Faneca et. al, “Towards low loss non-volatile phase change materials in mid index waveguides”, 10.1088/2634-4386/ac156e, http://arxiv.org/abs/2101.11127.

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