Project Acronym: **Fun-COMP**

Project Title: **Functionally scaled computing technology:** From novel devices to non-von Neumann architectures and algorithms for a connected intelligent world

WP5

Dissemination and Exploitation

(WP Leader UOXF)

Deliverable D5.10: Open Technology Workshop

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Partner(s) responsible: UOXF

Contributors: UOXF (H Bhaskaran, W Zhou), UNEXE (C D Wright), WWU (Wolfram Pernice) plus external speakers

Dissemination level: PU[1]

[1] CO: Confidential, only for members of the Fun-COMP consortium (including the Commission Services); PU: Public.

Open Technology Workshop

The Fun-COMP project brings together partners with expertise spanning a wide range of scientific and technical disciplines. To help ensure that such expertise is shared between partners, and to help to increase public awareness in the science and technology underpinning Fun-COMP and related technologies, a number of cross-disciplinary training and dissemination workshops will be held during the course of the project.

The first such training event was held at the University of Oxford on March 18th 2019 (note that this was formally delayed from month-9 - as in original DoW - to month-12 to make coincident with project progress meeting) and has been reported in Deliverable D5.7

The second training event was also held at the University of Oxford, on August 22nd 2019, and focused on integrated photonics systems. This event, which we entitled "Conversations on the Future of Integrated Photonics and Computing", was reported in Deliverable D5.8.

The third event – a Technology Workshop – had the aim of presenting research results and identifying future research challenges in the general area of photonic computing. The consortium originally planned to hold this as an in-person event in Month-26 of the project. However, due to the impact of covid-19 pandemic, the decision was taken (by the project GA) to delay this event to October 2021 and move to an online meeting hosted by Oxford (and held shortly after the E\PCOS 2021 conference).

Thus, the workshop was duly held and configured as the second in our series of "Conversations on the Future of Integrated Photonics and Computing". The format consisted of the delivery of keynote presentations by leading industrial and academic figures in the field, the presentation of contributed posters, and, importantly, panel discussions highlighting challenges and opportunities for photonic computing technologies.

The keynote speakers were:

1. Dr Nick Harris, founder and CEO of Lightmatter Inc (see https://lightmatter.co/). Lightmatter have developed a photonic coprocessor that can be fully integrated with conventional electronic systems, and Nick highlighted some of the major challenges that had to be overcome in this endeavour.

2. Prof Demetri Psaltis, EPFL (see https://www.epfl.ch/labs/lo/) who gave us an intriguing insight into past and future developments in optical neural networks.

A number of contributed posters were also presented, including those listed below:

- Electrical switching of the mainstream PCMs, Wen Zhou & Harish Bhaskaran, Department of Materials, University of Oxford
- Approximate Vector-Matrix Multiplication Using Low Rank Matrix Factorization, Samarth Aggarwal, Johannes Feldman & Harish Bhaskaran, University of Oxford
- Harnessing Optoelectronic Noises in a Photonic Generative Adversarial Network, Changming Wu[1], Xiaoxuan Yang[2], Heshan Yu[3], Ruoming Peng[1], Ichiro Takeuchi[3], Yiran Chen[2], Mo Li[1], [1]Department of Electrical and Computer Engineering, University of Washington, USA, [2]Department of Electrical and Computer Engineering, Duke University, USA, [3]Department of Materials Science and Engineering, University of Maryland, USA

- Out-of-the-box nonlinearity for optical neuromorphic computing readout systems, Chonghuai Ma, Floris Laporte, Stijn Sackesyn, Joni Dambre and Peter Bienstman, Ghent University
- Low-Latency Quadratic Programming with Neuromorphic Photonics, Thomas Ferreira de Lima, Lightwave Lab, Princeton University, USA

The workshop was open to all Fun-COMP partners, including young PhD and post-doc scientists for partner laboratories, as well as a number of invited external delegates from industry and academia (total number of attendees was 55).

Copies of the poster presentations are available on the public pages of Fun-COMP website (www. fun-comp.org).

A copy of this deliverable is also available on the public pages of the Fun-COMP website via the *News* then *Public project deliverables* pages, i.e. via the link https://fun-comp.org/news/public-project-deliverables/

Technical aspects and findings of the workshop are reported below.

Meeting Report: Conversations in Oxford – Future of Integrated Photonics in Computing Oxford UK, 5th October 2021.

https://conversationsinphotonics.web.ox.ac.uk/home

With inputs from Paul Prucnal, Wolfram Pernice, David Wright, Harish Bhaskaran, Bhavin Shastri, Francesca Parmigiani, Abu Sebastian, Alessio Lugnan, Nick Harris, Demetri Psaltis, Oliver Graydon, Carlos Rios, Xing Lin, Xuan Li

Current State of the Art

- **Computing density can be drastically improved using photonic cores.** Compared to electronics, photonic computing provides additional degrees of freedom in phase, polarisation, intensity and wavelength. While so far these properties have not been fully harnessed, developing components that do so has the potential to drastically increase the computing density. An important question from a research perspective then becomes: what innovations in photonics can be transferred over to neuromorphic computing using light?
  An additional challenge identified by the consortium is the miniaturisation of light sources as well as the development of compact and stable optoelectronic modulators and tuneable lasers which can fit within conventional printed circuit boards. These should also be integrable with photonic devices. Naturally, this needs to be executed by cost-effective electro-optic implementations. An example is the integration of a frequency comb, with wavelength multiplexers and demultiplexers. This approach can drastically improve the computation bandwidth.

- **Photonics in computing will be driven by solving industry-relevant problems**, e.g., heat and power consumption concerns. Photonic computing using passive components does not generate heat considerably or consume energy beyond passive losses on the chip (e. g. absorption, scattering). In this regard, on-chip photonic computing could replace the same function that was previously implemented by electronics (but more power-hungry). Although this does not provide a complete solution for computing, it involves photonics to solve some hard problems experienced by electronics, which can potentially bring more photonics aspects into the industry. Such an expected trend is similar to the development of fiber-optics communication.

- **Packaging of photonics:** Packaging of photonic circuits is an important challenge particularly in computing. Photonic wire bonding can allow multiple computing chips to be effectively interfaced on the same package. This approach is contingent on achieving the required alignment tolerances drift-mitigation strategies and scalable fabrication methods. Photonic wire bonding is identified by the consortium as a viable route in interfacing chips and a flexible and reliable solution for large-scale photonic integrated systems.

Challenges and emerging research trends

- **On-chip light source:** The development of cost-effective and compact on-chip light sources was identified as a priority by the consortium. Using an optical fibre to drive the chip is not ideal. There needs to be an alternative on-chip light source. Some challenges in using lasers in particular their low quantum efficiency (about 20%), time delay, temperature sensitivity and power consumption. Lasers integrated on a packaged chip are even more unstable because of temperature instabilities and low thermal transport during operation. Moreover, the time delay increases significantly. Multiwavelength sources are also identified as a strong demand. Accordingly, feedback circuits and stabilisation systems are necessary to ensure stable spectra and low output power fluctuations over the multiwavelength range.

- **Co-existence of free-space and integrated systems**: From the scaling-up point of view, free-space photonics can be scaled up favourably in terms of parallel pixels. Integrated photonics is currently challenging to scale up. However, integrated photonics offers a lot of advantages in terms of mobility and stability, making them more adaptive to versatile applications. Therefore, in terms of applications, it is identified that integrated photonic circuits are better suited for general applications where flexibility is required while free-space systems are better suited for task-specific applications such as image processing. A challenge is how to integrate free-space optical computing systems on-chip and take advantage of their scalability, large data throughput in parallel.

- **Optical memories for foundry**: Currently, several research groups have the backend process to fabricate optical memories based on the phase-change materials onto foundry supplied photonic chips. This backend process is limited by its three-dimensional chip designs which cannot be effectively processed. The solution to the backend process limitation might involve foundries to set standards and qualification procedures to adapt to photonic memories. An additional challenge faced by the integration of PCMs and photonics or with electrical heaters is the cyclability which needs to be between 10^10 and 10^12 cycles. Nonetheless, the cyclability requirement is also application-dependent. In terms of memory density, current optical memories have not met the requirement of moving 50TB per second in & out of the weight banks.

Scaling down to several nm and accessing it optically and electrically maybe the future trend. Recent work on integrated plasmonics and phase change materials may be a promising route.

Knowledge gaps and Opportunities

- **On-chip multiwavelength source:** Current frequency combs have significant limitations in terms of drift and power isolation. Considerable effort is needed to develop multiwavelength laser sources that can be integrated onto silicon photonic technologies. It will be very stable for emission spectrally and power. And need to keep resonant devices locked to different frequencies, analysis to be done on chip of minimum stabilisation energy.

- **Benefiting more from the multiple degrees of freedom of photonics:** One advantage of photonics is the multiple degrees of freedom that can be harnessed. For example, phase, mode, polarisations, wavelength, etc., have been exploited in telecommunications. It would be great to use these optical dimensions in photonic computing. Wavelength division multiplexing has been used to increase compute density. But it becomes costlier to utilize more dimensions and how this can be implemented efficiently is not clear.

- **Interface between electronics and photonics:** Electronics are still needed around an optical core and peripheral photonic components. Photonics can take computation load of the linear part of computations, which may account for 90% of the operations. Photonics take pull this load and relax the requirements from electronics. Digital electronics and SRAM are still needed and are unlikely to be fully replaced. There is still 10% part remaining on the digital domain, which is critical to speed. Converting signals and processing signals at the same time remains as one of the major challenges and bottlenecks in computing. It is also a hard problem to extract a clock when converting from the optical to the electronic domain and vice versa.

- **Reproducibility:** Free-space optical computing systems can be scaling up. However, reproducibility can become a problem if photonic computing is performed with free-space system. Errors can accumulate when the size of the system is large. Correcting these errors layer by layer using the backpropagation method is sophisticated. Way of integrating the free-space system to enhance its reliability is not clear.

- **Standardization with new materials:** In large factories like TSMC, integration with phase change materials is still difficult. Also, in foundry MPWs, photonic elements such as memories employing phase change materials are still not available in standard processing. Qualifications and investigations on the properties of these materials for foundries are yet to be done.

In summary, the meeting concluded that innovations are needed in integrated photonics both piecewise in individual devices but also in the integration and scaling to larger architectures. In particular, the miniaturization of light sources, frequency combs while maintaining low cost is an important milestone ahead. Photonic wire bonding technology eases the problem of tedious alignment and minimizes the drift issue over time, however the development of cost and time effective inter and intra chip photonic wire bonding technologies remains a challenge.

Phase change materials enable important functions and are uniquely suited to enable in-memory photonic computing. However, there are clear challenges concerning standardization of photonic components, clarifying to what extent photonics can replace electronics, and how to synergistically integrate photonics and electronics. The challenges are further specified as: improving the scalability and stability of photonics, pushing forward the co-integration of photonics with CMOS, as well as optimizing optoelectronic interfaces. The solutions to these challenges will require collaborations between individual research groups and support from foundries. While the committee focuses on looking for specific applications where photonics is the only solution or where electronics fail due to bandwidth or speed limitations, it is emphasized that more general applications should not be overlooked. Academia should need to take a step back and investigate knowledge gaps such as exploring the utilization of all degrees of freedom of photonics in a cost-effective manner, and the compatibility of photonic platforms in new computation models. The committee has reached a consensus that demonstrating photonic-electronic hybrid approaches for industry-relevant problems is a crucial step at the current stage to build up confidence in integrated photonics and establish an ecosystem with sustainable trained talents and budget input.

Conversations in Photonics 2021 - Attendees List

Samarth	Aggarwal	University of Oxford	UK
Harish	Bhaskaran	University of Oxford	UK
Peter	Bienstman	UGent	Belgium
Simon	Bilodeau	Princeton University	USA
Eric	Blow	University of Princeton	USA
Matt	Brookes	Dstl	UK
Alfredo	de Rossi	Thales	France
Eli	Doris	Princeton University	USA
Tobias	Edison	University of Oxford	UK
Evangelos	Eleftheriou	Axelera AI	The Netherlands
Nick	Farmakidis	University of Oxford	UK
Johannes	Feldman	Salience Labs	UK
Thomas	Ferreira de Lima	Princeton University	United States
Santiago	Garcia-Cuevas Carrillo	University of Exeter	UK
Oliver	Graydon	Nature Photonics	United Kingdom
Nicholas	Harris	Lightmatter	USA
Yuhan	He	University of Oxford	UK
Juejun	Hu	MIT	USA
Chaoran	Huang	Chinese University of Hong Kong	Hong Kong
Kairan	Huang	University of Oxford	UK
Aashu	Jha	Princeton University	USA
Ahmed	Khaled	Queen's University	Canada
Jason	Lee	University of Oxford	UK
Yuhang	Lee	University of Oxford	UK
Mo	Li	University of Washington	USA
Y	Li	University of Oxford	UK
Xing	Lin	Tsinghua University- EE	China
Alessio	Lugnan	Ugent - Imec	Belgium

Chonghuai	Ma	Ghent Univercity- imec	Belgium
Tara	Milne	University of Oxford	UK
Francesca	Parmigiani	MICROSOFT RESEARCH CAMBRIDGE	United Kingdom
Hsuan-Tung	Peng	Princeton University	USA
Wolfram	Pernice	Universität Heidelberg	Germany
Paul	Prucnal	Princeton University	USA
Demetri	Psaltis	EPFL	Switzerland
Carlos	Rios	University of Maryland	USA
Abu	Sebastian	IBM Research - Zurich	Switzerland
Bhavin	Shastri	Princeton University	USA
Joe	Shields	University of Exeter	UK
Yu	Shu	University of Oxford	UK
Anat	Siddharth	EPFL	Switzerland
Eugene	Soh	University of Oxford	UK
James	Tan	University of Oxford	UK
Håvard	Toftevaag	University of Oxford	UK
Mengyun	Wang	University of Oxford	UK
David	Wright	University of Exeter	UK
Changming	Wu	University of Washington	USA
Fei	Xia	LKB	USA
Lei	Xu	Princeton University	USA
Nathan	Youngblood	University of Pittsburgh	USA
Barry	Yu	University of Oxford	UK
Weipeng	Zhang	Princeton University	USA
Yi	Zhang	University of Oxford	UK
Wen	Zhou	University of Oxford	UK