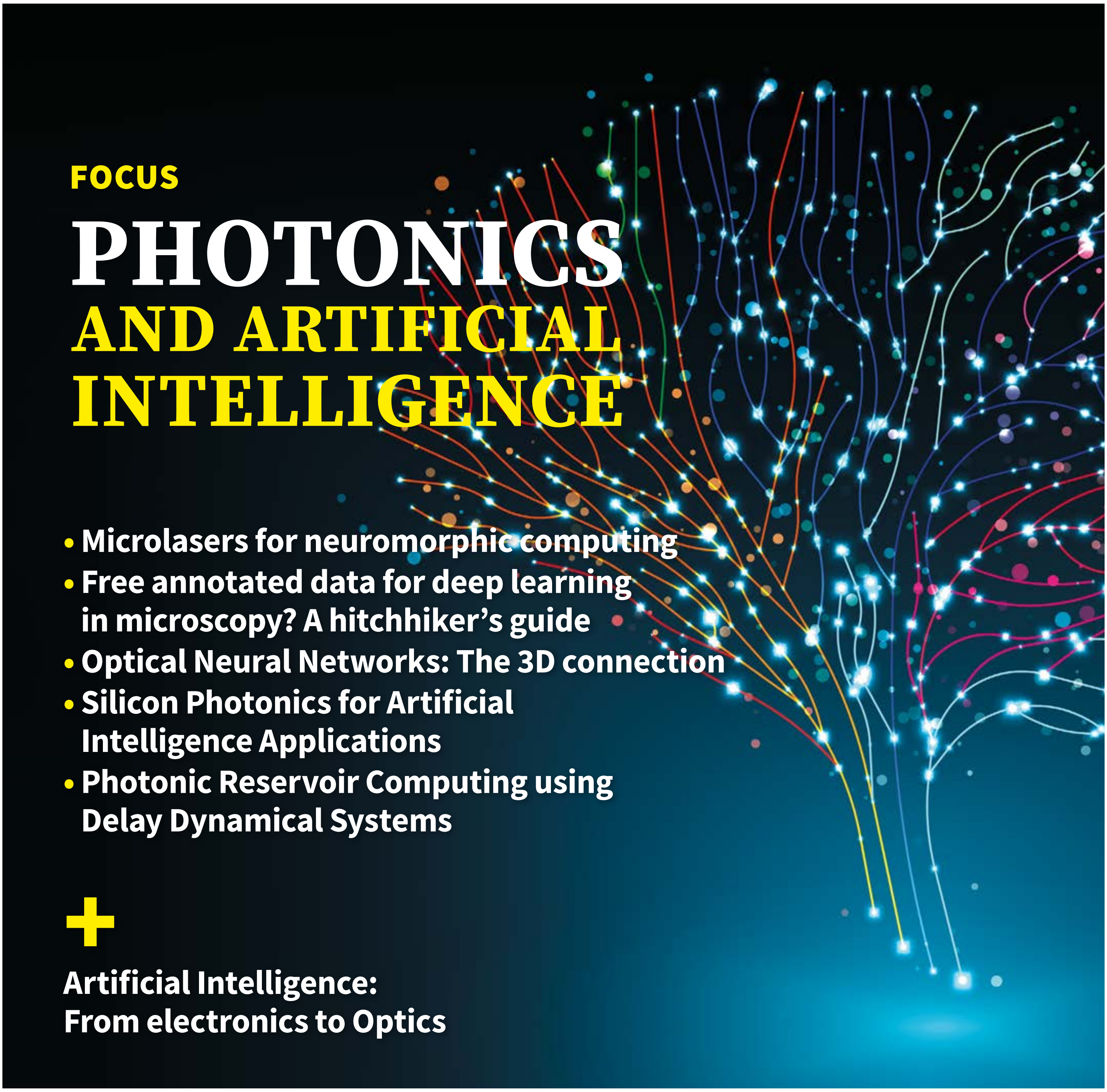
Photoniques

N°104

LIGHT AND APPLICATIONS | EOS & SFO JOINT ISSUE



FOCUS

PHOTONICS AND ARTIFICIAL INTELLIGENCE

- Microlasers for neuromorphic computing
- Free annotated data for deep learning in microscopy? A hitchhiker's guide
- Optical Neural Networks: The 3D connection
- Silicon Photonics for Artificial Intelligence Applications
- Photonic Reservoir Computing using Delay Dynamical Systems

+

Artificial Intelligence: From electronics to Optics

France/EU : 19 € | Rest of the World : 25 €

Photoniques

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33 rue Croulebarbe,
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2 avenue Augustin Fresnel
91127 Palaiseau Cedex, France
mariam.mellot@institutoptique.fr
Tél. : +33 (0)1 64 53 31 82

Publishing Director
Jean-Paul Duraud, General Secretary of the French Physical Society

Editorial Staff
Editor-in-Chief
Nicolas Bonod
nicolas.bonod@edpsciences.org

Journal Manager
Florence Anglézio
florence.anglezio@edpsciences.org

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EDP Sciences,
17 avenue du Hoggar,
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Editorial

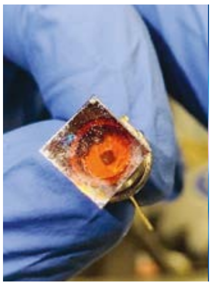
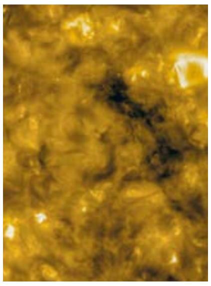
NICOLAS BONOD
Editor-in-Chief

Photonics and AI: from the software to the hardware

Advances during the 19th century in optical microscopy, together with the discovery of silver nitrate staining of nerve cells, allowed Santiago Ramón y Cajal to prove in the 1880s that nerve cells are single entities transfering impulses through nerve synapses. This discovery forged a solid link between neural networks and optics. The 20th century saw the rise of artificial neural networks with pioneering works by McCulloch & Pitts in the 1940s followed by the development of perceptrons by Frank Rosenblatt in the 1950s. While artificial intelligence has now become ubiquitous in a wide range of scientific fields thanks to the development of deep learning, photonics has retained this privileged link with artificial intelligence: not only are deep learning techniques revolutionizing many areas of optics such as imaging or inverse design, but photonics is now addressing the development of all-optical artificial neural networks. Photonic technologies aim at creating a new paradigm in computing and data processing by designing optical processors no longer based on von Neumann's architecture, as computing has been for the last 70 years, but on neuroinspired architectures. This issue of *Photoniques* is thus dedicated to one of the greatest scientific challenges of the 21st century and shows us how photonics will be at the centre of future breakthroughs in computing and data processing.

The finalization of this issue was marked by the announcement of the 2020 Nobel Prize Laureates. The Physics Prize celebrates theoretical advances in the formation of black holes (Roger Penrose) and the discovery of a super-massive black hole at the centre of our galaxy (Reinhard Genzel, Andrea Ghez). This latter prize builds on an impressive list of Nobel prizes related to optics or rewarding discoveries made possible thanks to optical techniques and technologies. The observation of this super-massive black hole has been made possible by the combination of several optical techniques such as interferometry and adaptive optics to compensate in real-time atmospheric turbulences. The implementation of these techniques in telescopes, including the European Southern Observatory's Very Large Telescope, has allowed precise tracking of stellar orbits from which the presence of black holes are deduced.

As we can see, optical techniques and technologies are solidly to the fore in the greatest scientific adventures of this 21st century, from the exploration of the universe by our giant telescopes to the design of optical perceptrons that will revolutionize tomorrow's computing. *Photoniques* will have so many topics to report on due to the exciting scientific adventures of photonics in the 21st century.

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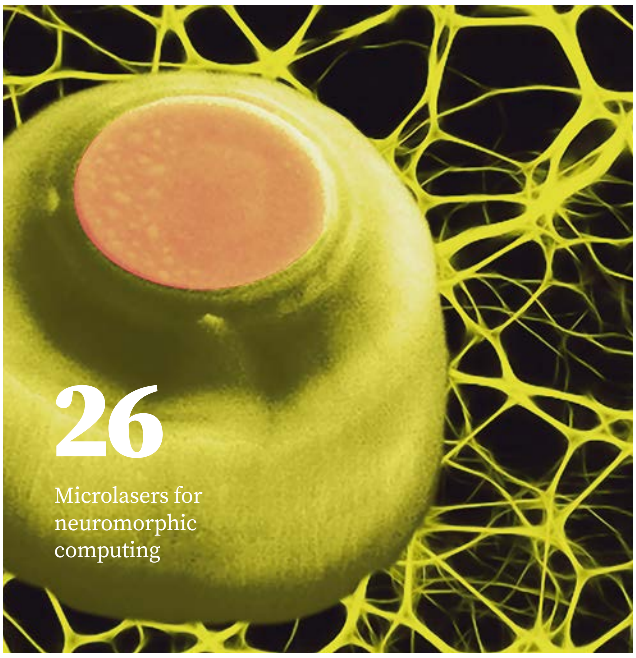
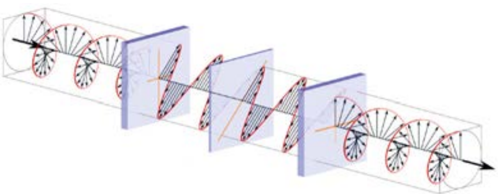




Advertisers

EOS/SFO forewords

PHILIPPE ADAM
President of the French Optical Society

GILLES PAULIAT
President of the European Optical Society

Six months since our last issue of our magazine in English. What's up since then?
The period leading up to the holidays was intense; it was mainly devoted to managing the agendas in order to ensure the continuity of the SFO's activities and to interface them with our communities, at the national and European level, in order to avoid possible "traffic jams" in the events agendas, caused by multiple postponements all around. Now after rescheduling our activities, we hope to come back to a normal situation... as far as the COVID will let us serenely work in the upcoming months!
An important issue since that time is the change at the head of the European Optical Society. First, SFO would like to thank Umberto MICHINEL for his strong involvement and supporting activities for the benefit of the European optical community. Secondly, SFO would like to warmly congratulate Gilles PAULIAT for his election at the head of EOS. Of course, SFO and Gilles PAULIAT know each other very well over the years. It is a great pleasure to cross his path again: we have common plans for the years to come and a lot of exciting tasks to achieve. One of them is the organisation of the EOS Annual Meeting in France in 2021. SFO and EOS will work closely together.
Maybe another workshop to take care of in this somewhat disturbed period: the overall landscape could be a bit unstable; we are all aware about the consequences of the pandemic situation on our activities. A bit of concern is for the PhD students who should achieve their works in a fixed period. We will do our best to help them, at the national and maybe international level.
At the scientific level, I am happy the current issue is devoted to AI. The links with photonics are clear and the summary is quite promising, important as such for scientific knowledge and future developments, but crucial as well for many applications with strong social impacts: diagnosis and processing, population protection and crisis management, global resilience enhancement ... I am really looking forward to reading this magazine.
Now back to school time. It will be surely chugging along and the balances to work in serenity have to be implemented. So good luck to you all!

The present health condition worldwide strongly affects our social and working relationships. Our learned societies had to learn how to serve the optics and photonics communities under these news constraints.
Initially EOS planned to celebrate the European Optical Society (EOS) Annual international conference and industrial exhibition, EOSAM, under the warm sun of Porto, on 7-11 September 2020, organized together with the Portuguese Society for Optics and photonics, SPOF. However, to ensure the safety of our attendees, EOS made the difficult decision to move the onsite event into online. The organizers, all presenters made a considerable effort to provide high quality presentations. During EOSAM, 12 topical meetings, 4 plenary live sessions and a special project session were held, including the esteemed Emmy Noether distinction awarded by the European Physical Society to Hatice Altug. With more than 300 live attendees during the plenary talks and more than 350 replay views of sessions, this first time ever online event in the history of EOS was a great success.
The situation thus prompted us to learn new ways for remote working with some positive facets: from an ecological point of view of course but also because the possibility to pause and play videos gives additional insight in the scientific content. Once the crisis is over, we should continue to use these tools to strengthen our ties. Do not hesitate to contact and share your ideas with your learned societies in which you are the real players.
From this year on, EOSAM becomes a yearly event. It moves around Europe to better interact with the local communities and create a unique experience for the attendees. Next EOSAM will be held in Paris on 6-10 September 2021. EOS will organize it jointly with the French Optical Society, SFO. Save already the date to contribute to EOSAM2021, to meet in-person and to make this event our next big common success!
Apart from meetings, we have many other ways to keep in touch and stimulate the imagination. "Photoniques" is the journal of the French Optical Society. This special SFO/EOS issue about "Photonics and Artificial intelligence" is a nice way of sharing our thoughts. Let's invent the world of tomorrow.
I wish you an insightful reading.

AGENDA

■ **OPTIQUE Dijon 2021,**
5 au 9 juillet 2021
Congress of the SFO
Congrexpo - Dijon - France

ATTENDEE REGISTRATION IS NOW OPEN

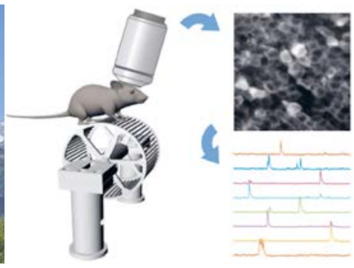
RESERVATION IN THE INDUSTRIAL EXHIBITION IS NOW OPEN

OPTIQUE Dijon 2021 covers a wide range from the fundamental to the applied research, industrial developments and pedagogical innovations. An exhibition area for photonics industry, including start-ups, will be set up at the heart of the congress. This congress provides fertile ground for beneficial exchanges between the actors of optics and photonics.

Professor Gérard Mourou, Nobel Prize in Physics 2018, will deliver the keynote opening plenary speech in this congress. OPTIQUE Dijon also includes plenary sessions led by guest speakers renowned internationally for their expertise, several thematic conferences and poster sessions.

■ **PHOTONICS EXCELLENCE DAYS 2020,**
November 26 - 2020
Proposing of the SFO
IOGS - PALAISEAU

All the events of the SFO:
www.sfoptique.org/agenda/



SCHOOL IN LES HOUCHES, 25–30 APRIL 2021

ALL-OPTICAL INTERROGATION OF NEURONAL NETWORKS IN VIVO

Thanks to the development of optogenetics, activity of neural networks can be recorded and modulated using optical methods. Thereby, these methods have become major tools for studying the neural mechanisms underlying perception, memory and behavior in animal models.
In this school, we will describe the different fluorescence microscopy techniques that have been developed and used to record neuronal activity in vivo, as well as the methods that enable modulating activity according to precise spatio-temporal patterns. We will first discuss the theoretical bases of these methods, and then we will present recent advances that have improved their speed, depth of penetration, field of view (2D and 3D), and applicability to the awake animal, both in head-fixed and unconstrained configurations. We will also give an overview of the palette of optogenetic tools available and the associated targeted labeling technologies. Finally, we will discuss the methods for analysis of raw functional signals, showing the wealth of information that these experiments can provide. The school is designed for students and researchers in neurophysiology using optical methods and for physicists participating in their development.

CONTACT
Cathie VENTALON et Laurent BOURDIEU From IBENS – The ENS Institute of Biology
Schedule – Submission campaign : November 26th, 2020 – February 1st, 2021
For more Information: https://www.sfoptique.org – section "Écoles thématiques de la SFO"

FREEFORM OPTICS: ISSUES & CHALLENGES IS NOW OPEN

5th edition of days of the SFO "Club Calcul Optique"
19–20 november 2020 • IOGS – Institut d'Optique Graduate School • Palaiseau – France

The SFO "Club Calcul Optique" is organizing its 5th edition of days of discussion around the issues and challenges of "freeform" optics, a technology that is now spreading very quickly in the world of photonics and our daily lives. The 2020 edition of these days will bring together many academic and industrial players involved in the design, production, metrology, and integration of freeform optical components.

CONTACT
Yan CORNIL (LIGHTTEC)
Yvan SORTAIS (Group of Industrial Photonics – CHARLES FABRY Laboratory - IOGS)
For more Information: https://www.sfoptique.org – section "Conférences des clubs SFO"

AGENDA

- **Photonics West,**
March 6-11, 2021,
San Francisco, United States
If you want to exhibit on the French Pavilion, contact us: agautret@photonics-bretagne.com

Mathieu Jacquemet joins Photonics Bretagne's team

Last February, our local Campus obtained a label of Excellence and a national funding "PIA: Teaching & Innovation Territory" of 4,2M€ over 5 years. One major aim of the project is to match student skills and company needs by improving or setting up new training. In this objective, Photonics Bretagne welcomed on the 1st of September Mathieu Jacquemet, who is in charge of structuring, promoting and developing continuing and initial training (including work-study) in photonics in Brittany, by making the link between companies and schools (Lycée Le Dantec, IUT de Lannion, ENSSAT…). His technical expertise within Quantel (Lumibird) during more than 10 years and his experience in the field of training with a strong taste for the transmission of knowledge will be major assets to carry out his mission.

A new Photonics Bretagne's board

The General Assembly of Photonics Bretagne was held on the 17th of September. On this occasion, a new board was elected for a 3-year term. The new President, Patrice Le Boudec (Idil Fibres Optiques) succeeds Benoit Cadier (iXblue), now Vice-President such as Hugues Tariel (Diafir) and Thierry Georges (Oxxius). 8 other board members have also joined to drive the association for the next period: Samuel Poulain (Le Verre Fluoré), Jean-François Morizur (CAILabs), Jean-Claude Keromnes (Kerdry), Sébastien Grot (Lumibird), Pascal Besnard (ENSSAT), Mehdi Alouini (Institut Foton), Estelle Keraval (Anticipa), and Tiphaine Leduc (Bretagne Développement Innovation). Delighted to see such a great panel involved in the development and strategy of the association!

FULL SUCCESS FOR FRENCH PHOTONICS DAYS

Organised by Photonics France, SupOptique Alumni and Photonics Bretagne on the 17th and 18th of September, the French Photonics Days was a great success with a fully booked event (limited to 100 people due to the COVID19 situation) on the topic of Specialty optical fibres and future applications. With a high level scientific content including more than 20 speakers leaded by 2 invited talks (Gérard Mourou, Nobel Prize winner 2018 in Physics on intense lasers and Hervé Lefèvre scientific director of iXblue who presented the last development of fiber gyroscopes), the conference gathered the whole French community interested in fibers and associated components/subsystems (fiber lasers, sensors, transmission…). An inspiring round table and an eagerly awaited networking was much appreciated by the audience while respecting strict safety procedures. The Brittany region, Cote d'Armor department and the Lannion district well known for its world-class photonic ecosystem including companies, research centers and schools, were delighted to sponsor and welcome such a great event in the magnificent coastal city of Perros-Guirec and its amazing sea view congress center.

WELCOME TO OUR 12 NEW MEMBERS

HYTECH IMAGING, ECAT-ID, ORPHIE, PIXEL SUR MER, EINEA, i2S, O++, BIOTECH SANTE BRETAGNE, INSTITUT FEMTO-ST, INSTITUT DES NANOTECHNOLOGIES DE LYON, CORIA, ZOOPOLE DEVELOPPEMENT have joined the association last September. Photonics Bretagne is proud to keep increasing its network that gathers now 116 members!

Evolution of the China mission

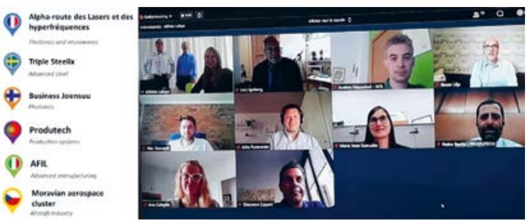
The 2020 edition of the Laser World of Photonics China exhibition was held in Shanghai over July 3^{th}-5^{th} in a quite special context. The tradeshow brought together 819 exhibitors and 57,135 visitors.

Due to the Covid-19 pandemic, member companies of the ALPHA-RLH cluster could not physically attend. Therefore, Balthazar Boyer, the cluster's China delegate, who coordinates participation at this event, offered to member's distributors to represent them on the ALPHA-RLH booth. This formula has proven to be appreciated and effective, allowing distributors of Aurea Technology, i2S, Novae Laser, Photonis and Spark Lasers to promote their innovative products and technologies.
The China mission, led by Balthazar Boyer, allows several members of the cluster to benefit from a tailor-made support on the Chinese market, which represents a huge potential in terms of business, particularly for industrial laser sources and optical systems.

With 10 years of experience, the China mission is now opening up to other French clusters, in accordance with the Alliance of Photonics Competitiveness Clusters which has been set up in the context of the Phase IV (2019-2022) of the « Pôles de compétitivité » French policy. This is the case with OPTITEC cluster (Provence-Alpes-Côte d'Azur region), whose member NewTec Scientific has recently joined the mission.

EUROPEAN PROJECT PIMAP+

SUPPORTING SME INTERNATIONALIZATION HAS BEEN LAUNCHED!



Gathering six European clusters, PIMAP+ aims to strengthen cross-sectoral cooperation in the fields of photonics, advanced manufacturing, metalworking and aerospace industry. After two years dedicated to international market analysis and the establishment of first contacts during strand 1 in USA and Canada, the next stage will focus on accelerating access to international markets for SMEs. In addition to the American market, Asian market will be a focal point through China and Japan.
As the coordinator, ALPHA-RLH has organized a virtual kick-off-meeting on September 21^{st}. Partners have decided to target one key international fair in each country of concern. Multi-days visits will support development of partnerships, business agreements and B-to-B cooperation.
A call for interest will be published at the beginning of 2021 to select SMEs interested to join business missions in each targeted country. If you are a SME interested in joining the international activities, please contact Alithéa Lafaye: a.lafaye@alpha-rlh.com

Welcome to Lauriane!

Lauriane Brucci is currently enrolled at the IAE Aix-Marseille Graduate School of Management to achieve her last year of master's degree. In few months, she will graduate a MSc Management specialized in international business. As an apprentice, she will be joining ALPHA-RLH starting mid-December 2020 until end of September 2021. She will be involved in international project development in line with the cluster's objectives, in peculiar regarding a new mission in Ohio (USA).

A new international support offer!

ALPHA-RLH is a resolutely international-oriented cluster and this since its inception. Indeed, due to its core business in the field of deep-tech innovation, opening up to the American and Chinese markets was a necessity. Today, its offer is progressively expanding towards Canada and Japan, notably thanks to the European PIMAP+ (Photonics for advanced manufacturing) project. In addition to this collective support offer, ALPHA-RLH, with the arrival of Lauriane, will market starting 2021 an individualized support package based on predefined specifications: search for partners, distributors, market research, participation in European events or workshop or trade fair, location study.

UPCOMING INTERNATIONAL EVENTS

- **European Microwave Week (EuMW)**
  January 10-15, 2021
  in Utrecht (The Netherlands)
- **Photonics West**
  March 6-11, 2021
  in San Francisco (USA)

Briefly

Systematic in figures:
€3.18 billion for R&D
625 innovation projects
Over **620 listed products** and services, built on collaborative R&D

KICKOFF OF THE EUROPEAN COSME PROJECT FOODPACKLAB STRAND 2!

Being a top priority of the Paris Region area, agrotch is a driving sector of the Deep Tech ecosystem. Indeed, the Optics and Photonics Hub of Systematic is involved in the FoodPackLab project (COSME programme strand 2) started end of September at last ! Quick reminder : it aims at fostering cross-border and cross-sectorial collaboration of clusters and business networks in the strategic field of food security by supporting the implementation, testing and European partnerships.
https://foodpacklab.eu/

Global Summit by Hello Tomorrow

Global summit gathering will be gathering 1000 corporates, 300 Incubators & accelerators, 300 Investors, 400 Researchers and Tech, 200 International media. Join us on our virtual booth and meet DT4G startups! Online event 16th-20th November.
https://www.deeptechforgood.eu/

INDUSTRY 4.0: THE RISE OF DEEP TECH

March 11th, Systematic Paris Region, as a key leading ecosystem in Deep Tech organized an event in the international Deep Tech Week; Industry 4.0: the rise of deep tech. DTG4 start-ups were most welcome to participate and to demonstrate during our event.

AGENDA

■ **WHAT'S ON? at DAMAE Medical**
November 19th 2020, come and visit our member to discover, among others, their innovative solution LC-OCT (Line-field Confocal Optical Coherence Tomography) that gives access to cellular resolution imaging of inner microstructures of the skin up to the dermis, immediately and non-invasively:
https://damae-medical.com/

DeepTech4Good programme closes October 31th!

DeepTech4Good is an Acceleration Programme, financed under the Horizon 2020 framework, committed to help Deep Tech startups accelerate their development and scale up at European level. 4 application domains: Health & Well-being, Industry 4.0, Smart Mobility, Smart City. DeepTech4Good is led by 4 innovation hubs from Germany, France, Austria and Spain, working together to identify high potential Deep Tech startups.
This European project, coordinated by Systematic, also aimed at attracting private and public finance. Indeed, a board of private investors took part in start-up fundraising challenges to evaluate the applications and the pitch sessions during the 6 events organized throughout the project.

START EUROPE CAMPFIRE

March 10th, **Paris Campfire** launched the new wave of projects form the Startup Europe initiative of European Commission, Directorate-General for Communications Networks, Content and Technology. The Campfire was animated by consortium leaders and project partners, to share project objectives, highlight the opportunities and network the community partners for the projects to increase synergies and have more impact collectively.

#DeepTech4Good

SME-CORPORATE MEETINGS EVENT

The last event of this program, hold on July 16, led to a great business meeting with 6 major corporations presenting their use cases and 26 SMEs presenting their technologies. 45 one-to-one business meetings were organized with corporates and SMEs and will be followed-up during the project, 6 business meetings were planned outside the framework of this event due to agenda conflicts or too numerous demands and 3 on-site visites were also planned with Siemens.

Want to join the Optics & Photonics Hub of Systematic? Don't wait any longer and contact:
Lola Courtillat, Hub Coordinator:
lola.courtillat@systematic-paris-region.org

French Photonics Days - Do you have the fibre of innovation?

Special optical fibres and future applications

Great success of this second edition of the 17 & 18 September organised by Photonics France, SupOptique Alumni and Photonics Bretagne under the Breton sun with 100 participants (maximum gauge due to COVID19). Round-table, conferences and networking moments followed one another for a very positive result.
A more detailed report will be available in the next issue of Photonics, as the French Photonics Days has just come to an end at the time of writing.

NEW STUDY OF FRENCH PHOTONICS

The last study of the French photonics industry is finished! Based on 2018 data, this new map shows that there are in France 1051 companies producing photonic components and systems for all applications with an annual growth in the number of companies of 5%. Their total turnover is 19 billion euros in 2018. 73,000 employees work in these companies in technical skills, R&D, production, marketing, sales and management.
It is very interesting to compare the growth in turnover and workforce with the French global industry between 2018 and our last study in 2013. During this period, the growth in turnover in photonics is 6 times greater than that of the industry in France ! The most important application sectors are core components and materials, health and wellbeing, environment, energy and lighting, telecommunications and quantum information, and defense and security.
Find the cartography on our website www.photonics-france.org.

New members

Photonics France has now 170 members! Welcome to : Centrale Supélec ; Institut Femto-ST ; Scintil Photonics ; Institut Foton and Micro-Mécanique

NEW PREMISES

Photonics France is pleased to announce its change of address! Find us now at 60 avenue Daumesnil, 75012 Paris. Near the Gare de Lyon railway station, a meeting room is always available for our members or non-members, accessible under conditions. Do not hesitate to contact us for more information…

AGENDA

T4 2020 Q4 forecast planning: on your diaries!

Photonics France offers numerous events, animations and partnerships throughout the year, accompanied by sponsoring actions at affordable rates. Discover our provisional schedule for the last quarter of 2020 and the first half of 2021 and book your dates now!

- Meeting « Normalization & Corporate Social Responsibility »
  Paris - 3 November 2020
- Discovery Meeting of Photonics France
  Paris - 10 November 2020
- « Forum de la Photonique » partnership
  26 November 2020
- Photonics Online Meetings #2
  3 December 2020
- ASD Days partnership
  11 December 2020
- SPIE Astronomical Telescopes + Inst. partnership
  San Diego - 13-18 December 2020
- 3rd edition of the JSO
  Grenoble - 03-04 February 2021
  New dates
- Photonics West exhibition partnership
  San Francisco - 06-11 March 2021
  New dates
- TechInnov partnership,
  Paris - March 11, 2021
- Global Industrie partnership
  Lyon - 16-19 March 2021
  New dates
- Photonics Online Meetings #3
  TBC - 11 May 2021
- Laser World of Photonics Pavilion,
  Munich - 21-24 June 2021
- Congress + General Assembly of Photonics France
  TBC - June 3, 2021

Would you like to become a sponsor of one of our events? Please contact us.

TO CONTACT PHOTONICS FRANCE
Phone: 01 79 35 56 16
contact@photonics-france.org
www.photonics-france.org

Dual-use fact-finding mission to the United Arab Emirates

KETs4Dual-Use (K4DU) partnership has carried out its second fact-finding mission to the United Arab Emirates (UAE) between 13 and 15 January 2020.
The country ranks among the top 15 defense spenders in the world and the defense expenditure as a proportion of GDP has remained comparatively high in recent years in response to various threats and events in the region. UAE's 2016 defense expenditures stood at approximately $23.4 billion, while it is projected that the country's defense expenditure will grow at a compound annual growth rate (CAGR) of 6.5% to value $31.8 billion by 2021.
In November 2019 the UAE authorities launched EDGE, a government-owned company that supports the country position as a global player in advanced technology and monitoring the threat of hybrid warfare while streamlining the local defense industry. With combined annual revenue of $5 billion, EDGE employs more than 12,000 individuals, and it consolidates 25 national subsidiaries in the field of defense, focusing on five principal areas: platforms and systems, missiles and weapons, cyber defense, electronic warfare and intelligence and mission support.
K4DU delegates have held meetings with Tawazun Holding as well as Emirates Defense Companies Council (EDCC) representatives in order to discuss how European dual-use SMEs could contribute to EDGE initiatives as well as future collaboration opportunities, notably in form of participation at the UAE flagship defense exhibitions UMEX and IDEX.

The agenda also included meetings with ATOS UAE office, with focus on possible involvement of European dual-use SMEs in the local supply chains, as well as with French and Danish military attachés.
This fact-finding mission has enabled the K4DU partnership to establish initial contacts with the UAE defense & security ecosystem, which will be further pursued during the UMEX exhibition (February 2020) and EXPO 2020 hosted by Dubai (October 2020 – April 2021).

CONTACT :
Regina Zainetdinova - European & international Affairs
regina.zainetdinova@pole-optitec.com

Dual-use fact-finding mission to the United States and Canada

KETs4Dual-Use (K4DU) partnership has carried out its first fact-finding mission to the United States of America (USA) & Canada between 14 and 18 October 2019.
The North America region with the USA and Canada is clearly one of the priority destinations for the consortium given the size of its defense & security market. The USA remains the country with the highest annual military expenditure in the world, which amounted to $649 billion, representing 36% of world military expenditure. Canada, together with the USA, represents 90% of total spending in the Americas. Although its defense spending is significantly lower ($21,6 billion), it represents an entry door to the US market in many ways, as the partners learned during the trip.
During the first part of the trip to Washington, K4DU partnership joined forces with the Alliance partnership. The two delegations participated in the Annual Meeting & Exposition of the US Army and met with the US National Defense Industry Association (NDIA). The K4DU delegates also met with the Regulatory Affairs team of the International Society for Optics & Photonics (SPIE) in order to discuss the current dual-use technologies landscape in the US and collaboration possibilities with US entities, notably from a regulatory perspective.
After a two-day stay in Washington, the K4DU delegation proceeded to Ottawa where they participated in the SME Day organised by Canadian Association of Defense and Security Industries (CADSI).
The last destination was Montréal. Hosted by Québec's Ministry of Economy and Innovation and photonics cluster Optonique, the delegates met with various stakeholders of the Quebec's ecosystem active in the defense and security domain such as Department of Canada's Defense Ministry in charge of innovation programme IDEaS, Centre for Technology Transfer in Optics-Photonics Optech, Pan-Canadian Cluster in Cybersecurity In-Sec-M, Accelerator Innovitech, ITC Research and Innovation Hub PROMPT, Québec's Aerospace Cluster Aero Montréal, Aerospace Research and Innovation Hub of Québec CRIAQ, National Institute of Optics, Quebec's Electronic System Industry (ISEQ) and companies such as IBM, Excelitas and Cysca Technologies.
This fact-finding mission has enabled the K4DU partnership to establish initial contact with US & Canadian associations in order to discuss possibilities of future collaboration and to identify opportunities for creating partnership synergies between SME members.
All presentations from the meetings and contacts of aforementioned organisations are available on request.

CONTACT:
Mr Ziga Valic
Head of EU & International Affairs
Ziga.valic@pole-optitec.com
+32 471 71 22 18

Dual-use fact-finding mission to Singapore

KETs4Dual-Use (K4DU) partnership has carried out its third - and last - fact-finding mission to Singapore between 10 and 12 February 2020. The delegation arrived to Singapore at the moment when authorities raised the "Disease Outbreak Response System Condition" (DORSCON) due to the COVID-19 virus from yellow to orange (level 3 out of 4). The delegates were therefore able to witness in person an impeccable organisation and processes put in place by the authorities, which enabled them to heavily reduce the impact of COVID-19.

Singapore has the largest defense expenditure in the South East Asian region and has allocated $15.5 billion for defense expenditure and $4.9 billion for homeland security expenditure in 2019. It procures the majority of its defense equipment from foreign companies, with its defense imports driven by the country's policy of utilizing technology to improve the efficiency of its armed forces. Significant imports include arms, ships, missile systems, and armored vehicles. Historically, the largest supplier of arms to Singapore was the United States, however, countries such as France and Germany have made substantial inroads into the country's defense industry. The majority of Singapore's defense budget is therefore allocated for capital expenditure, due to the country's concentration on the acquisition of advanced technology in order to enhance the capabilities of its relatively small armed forces. Ministry of Defense (MINDEF) is increasingly moving towards commercial-off-the-shelf products and systems for better cost management/control and for longer through-life support.

K4DU delegates have held meetings with Jumpster and the French Chamber of Commerce in Singapore in order to discuss future collaboration and business development between European and Singapore SMEs. They were also received by the European Union delegation in Singapore. A longstanding partner of OPTITEC, Lux Photonics Consortium, has also organised visits of their members LightHaus Photonics and Advanced Micro Foundry. Given the occasion, the delegation also attended Singapore Air Show.

This fact-finding mission has enabled the K4DU partnership to establish initial contacts with the Singapore defense & security ecosystem, which will be further pursued during a visit with a delegation of companies in 2021.

CONTACT : Mr Ziga Valic - Director EU & International Affairs
Ziga.valic@pole-optitec.com • +32 471 71 22 18

MoU OPTITEC-LUX

Following the optical-photonic economic mission held in Singapore in 2018, a Memorandum of Understanding (MoU) was signed between OPTITEC and its Singaporean counterpart Lux Photonics Consortium. Preliminary discussions on collaboration between the two organizations were launched during the visit of the French delegation to Singapore in October 2018, followed by the official signing of the MoU in March 2019.

Lux Photonics Consortium is the main entity representing the optics-photonics sector in Singapore. This is an initiative of the Nanyang University of Technology (NTU) and the National University of Singapore (NUS), which is supported by the National Research Foundation under the Office of the Prime Minister.

2018 was the year of Innovation France-Singapore, where the importance of Singapore was emphasized as an economic partner. This highly urbanized city-state, located at the southern tip of the Malaysian Peninsula, is a true global business hub and strategic deployment point in Southeast Asia.

With its dynamic optical-photonic ecosystem and a well-established legal framework, it is the ideal location for French players to deploy their dynamic business skills in the South-East Asia area, with easy access to the Chinese market.

This MoU is a framework for members of two organizations to weave and strengthen economic relationships in order to move towards lasting collaboration.

CONTACT: Mr Ziga Valic - Head of EU & International Affairs
Ziga.valic@pole-optitec.com • +32 471 71 22 18

OPTITEC signs the Memorandum of Understanding with Optonique-Québec

At the Laser World of Photonics, held in Munich from June 24 to 27, 2019, a Memorandum of Understanding (MoU) was signed by Marc Ricci, the Director-General of the OPTITEC division and his Québec counterpart, Marie-Christine Ferland, the Director-General of the Optonic Optics-Photonics Center of Excellence.

The Canadian province of Québec boasts a long history in the industry optics-photonics. The ecosystem is made up of more than 168 industrial companies and more than 21 research centres and clusters.

It generates a turnover of more than $800 million, exports nearly 85% of its production and has more than 7,500 employees. More than a quarter of Canada's photonic optics economy is Québec.

Optonique aims to mobilize and federate all the players in the optics-photonics sector in Québec to promote their technologies and know-how at the provincial, national and international levels. Its mission is to energize and represent the optical-photonic ecosystem of Québec, to increase its capacity to carry out structuring projects and to foster its potential for innovation, creativity and competitiveness.

This MoU represents a framework for members of two organizations to integrate and consolidate economic relations in order to move towards lasting collaboration.

Canada is also a target country for the European EU KETs4Dual-Use project managed by OPTITEC. An exploratory mission to Canada and the US will be organized by the consortium in autumn 2019.

More information on Optonics:
https://optoni.ca/

CONTACT:
Mr Ziga Valic
Head of EU & International Affairs
Ziga.valic@pole-optitec.com
+32 471 71 22 18

Moving forward connecting people
and enabling business opportunities

By now everyone had hoped to be back in full speed, meeting up with business partners and attending conferences and exhibitions. Unfortunately, the pandemic is not under control. Exhibitions are still being postponed or cancelled, travel restrictions are still not fully lifted, and physical meetings continue to be a health concern. Still, even in these uncertain times, EPIC has grown exponentially, achieving yet another milestone of now having over 600 members, and moving forward to becoming the largest industry association in the world.

So how come EPIC is doing so well, in a time where there are so many challenges. One of the reasons is for sure its capability to adopt to a changing environment. Roy McBride, Managing Director at Power Photonic made a nice statement about this: "It's great to see how innovative and effective EPIC has been in rising to the challenge of COVID-19. I'm proud to be a member of EPIC!" And it is true that EPIC has stepped up to these challenges. Not only continuing with webinars, but finding new ways of online events, like meetings on managing remote teams, working with social media, but especially with the online technology meetings.

In the beginning of 2020 EPIC's YouTube channel had reached a few hundred views on its videos. Now, thousands of people view the video every week. #EPICgoesLIVE has been an amazing journey for EPIC. The EPIC Online Technology Meetings have resonanced through the industry, attracting more and more viewers and subscribers every day. Robert Gehlhaar, Senior Researcher at IMEC said: "I would like to thank the EPIC team for putting all the meetings together and sharing them online. It's a great initiative and large resource to build future projects."

So, moving to the digital environment has paid off, with applications for memberships coming in, so business can engage with the EPIC network. This summer, EPIC reached a new milestone of having over 600 members. Member 600 is a "typical" EPIC Member: still small, but rapidly growing and ambitious! Carlos Lee, Director General of EPIC stated: "We are so proud to have QiOVA become our 600th member and I am grateful to all the companies that support us on this enlightening journey".

EPIC was created in 2003 to promote a sustainable photonics industry and especially in these times it is crucial to stay innovative and to stay connected. This fall, EPIC launched a new member service: EPIC Member New Product Launch. Traditionally, new products are released in conjunction with a major exhibition. With most shows being cancelled, EPIC felt it was time to start a new revolution, engaging relevant journalists, end-users, clients, and the complete EPIC network to help members successfully launch new products. The EPIC Member New Product Launch will be a combination of an online meeting with qualified attendees, and a live launch on YouTube for everyone to see. So, if you are an EPIC member and you are planning for a significant new product to be released, be sure to reach out by sending an email to info@epic-assoc.com.

QiOVA, a laser equipment supplier from Andrézieux-Bouthéon, France received the award for becoming the 600th EPIC Member

AGENDA

Upcoming EPIC Online Technology Meetings
EPIC events are renowned for excellent networking, creating new connections and strengthen existing ones. Connecting EPIC members means building trust within the photonics industry

EPIC Online Technology Meeting on Photonics for Dermatology and Aesthetic Applications
05 October 2020, 15:00 CEST

EPIC Online Technology Meeting on Laser Glass Processing
12 October 2020, 15:00 CEST

EPIC Online Technology Meeting on Additive and Advanced Metal Manufacturing
19 October 2020, 15:00 CEST

EPIC Online Technology Meeting on Free Space Optical Communication and LiFi
26 October 2020, 15:00 CET

EPIC Online Technology Meeting on Photonic Systems for High-end Research
02 November 2020, 15:00 CET

EPIC Online Technology Meeting on Water Quality Monitoring and Purification (in cooperation with IUVA)
09 November 2020, 15:00 CET

EPIC Online Technology Meeting on 3D Sensing
23 November 2020, 15:00 CET

EPIC Online Technology Meeting on Photonics for Improved Pharma Processes
30 November 2020, 15:00 CET

EPIC Online Technology Meeting on Industrial Laser Manufacturing for Naval and Aeronautic Applications
14 December 2020, 15:00 CET

FIND OUT ABOUT UPCOMING EPIC EVENTS ON
www.epic-assoc.com/epic-events

At a glance

Paris-Saclay university, of which the Institut d'Optique is a founding member, is ranked 14th institution worldwide by the Shanghai international academic ranking (August 2020).

Prof. Philippe Bouyer, appointed Director of Innovation and Corporate Relations

Since August 28, Philippe Bouyer has been appointed Director of Innovation and Corporate Relations. His mission is to develop the institution's innovation strategy and to stimulate partnerships with the economic world in synergy with education (particularly the Entrepreneurship study track of SupOptique).

AGENDA

■ **EVENT:**
Nov. 26: **European Photonics Career Fair, the professional networking event for jobs in photonics.**
Institut d'Optique, 2 av. Augustin Fresnel, 91120 Palaiseau

■ **NEXT SESSIONS FOR CONTINUING EDUCATION**
Nov.4 to 6: **Optronics Systems (Advanced)**
Nov. 24 to 27 and Dec 8 to 11: **Optics basics**
Dec.1 to 3: **Optics without calculation (Basics)**
Dec. 14 to 16: **Low Light Level Vision and Photon Counting Imaging (Advanced – Specialized)**

Continuing education catalog:
fc.institutoptique.fr

Contact:
fc@institutoptique.fr

CONTACT INSTITUT D'OPTIQUE GRADUATE SCHOOL:
Kenza.Cherkaoui@institutoptique.fr
www.institutoptique.fr

Institut d'Optique Graduate School

The Institut d'Optique Graduate School, as a world leader in teaching, research and innovation in photonics has, over time, become a key player in its economic and academic sector. With an intense research activity in line with its teaching themes, the Master of Science in engineering program (diplôme d'ingénieur SupOptique) has become one of the most prominent and successful tracks for photonics R&D scientists worldwide. Research rapidly translates its breakthroughs into teaching programs that remain in close collaboration with laboratories.

A new thematic focus for the Master of Science in engineering program: Quantum science and engineering (QSE)

This proximity between research and teaching allows for teaching innovation.
The SupOptique schooling offers students highly visible and professionally valuable thematic paths in several fields from the most fundamental to the most applied, related to the sciences and technologies of light. The first to be launched is the **Quantum science and engineering (QSE) thematic focus.** Part of a complete 3-year curriculum, it covers all aspects of quantum physics and engineering: theoretical studies, technological processing, applied devices, experimental implementation, etc.
Graduate are ready to take up the major scientific and industrial challenges brought by the shift towards quantum technologies:

- building quantum computers
- developing the building blocks of future communication networks based on single photons and quantum cryptography
- mastering quantum technologies for sensors with ultimate sensitivity.

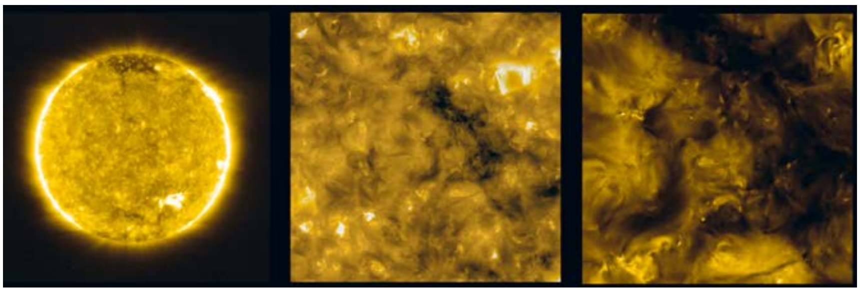
MORE INFORMATION: https://bit.ly/3mnF4Cv

EXCEPTIONAL IMAGE CAPTURE FOR THE SOLAR ORBITER MISSION

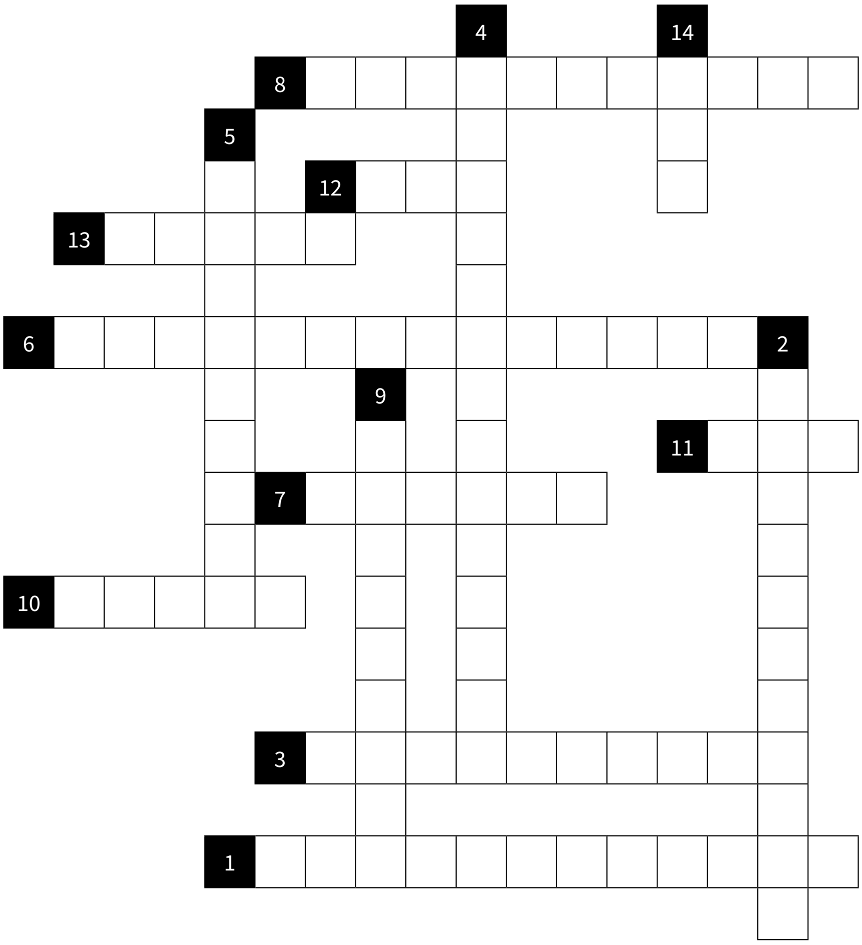
Achieving high quality images in the extreme ultraviolet is a real challenge and requires optical components at the cutting edge of today's technology. Drawing on 40 years of expertise, the Charles Fabry laboratory (Institut d'Optique and CNRS) has designed and manufactured mirrors with unequalled performances for the telescopes of the Solar Orbiter space mission.
These mirrors are among the most perfect optical surfaces embedded in space instruments. Multilayer interference coatings based on a new combination of materials (aluminum/molybdenum/silicon carbide) have enabled a new world record in efficiency to be achieved.

MORE INFORMATION: https://bit.ly/3c4rL5k

First images from FSI (left) and HRI (middle and right) at a wavelength of 17.4 nm captured on May 30, 2020.



CROSSWORD PUZZLE
ON OPTICAL DEVICES



1 Splits and analyzes the spectrum
2 Brilliant device used by physicist, chemist and biologist
3 May be confocal or widefield, brightfield or darkfield, *etc.*
4 To characterize short pulses
5 May be very large and very remote
6 Michelson, Mach-Zender, Fabry-Perot, *etc.*
7 For capturing images
8 For measuring the optical activity
9 Building block of integrated optics
10 Coherent light source
11 For wavefront engineering (acronym)
12 Used by ophthalmologists (acronym)
13 Tiny electromechanical devices (acronym)
14 The fastest modulator (acronym)

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Physics Nobel prize 2020
& breakthroughs in optical instrumentation

The Nobel prize in physics is awarded to Roger Penrose for the theoretical advances on the formation of black holes and to Reinhard Genzel and Andrea Ghez for the discovery of an extremely massive object on the centre of our galaxy. *Photoniques* interviews Frank Eisenhauer, lead scientist of the GRAVITY project, to reflect on the key role optical instrumentation had von the discovery of the massive black hole at the center of the Milky Way.

Can you describe the main discovery rewarded by this Nobel Prize.

This Nobel prize is for the discovery of black holes, one of the most exotic phenomena in the universe. As shown by the Nobel Laureate Roger Penrose, Einstein's theory of general relativity can lead to the formation of a compact object, from which not even light can escape: a black hole. The Nobel prize to Reinhard Genzel and Andrea Ghez awards the experimental proof that these theoretical objects actually exist, and that such a black hole resides in the center of our Galaxy.

What were the main steps to achieve this amazing discovery?

This research started 30 years ago. Motivated by earlier observations of so-called quasars, massive black holes were thought to reside in the centers of all large galaxies, and as such also in our own Galaxy, the Milky Way. But our black hole was well hiding, and it was up to Reinhard Genzel, Andrea Ghez and their colleagues to uncover the dark object by following the motion of stars, and ultimately demonstrating its black hole nature by precisely measuring the full orbit of a nearby star.

What are the main optical techniques involved in this discovery?

There are three main techniques. The first one are large format infrared detectors, the second is the overcoming of atmospheric perturbation with speckle interferometry, adaptive optics and laser guide stars, the third is infrared / optical interferometry.

What are the main breakthroughs in optical instrumentation needed to demonstrate the presence of a super massive black hole?

The Galactic Center is hidden behind interstellar dust and is invisible at optical wavelengths. So the first step was to establish infrared astronomy in the beginning of the 1990s. This was the time when large-format detector arrays became available for observing at infrared wavelengths. Developing and using infrared cameras and spectrometers at the largest telescopes at that time, Reinhard Genzel and Andrea Ghez could peer through the interstellar dust and see the stars moving at excessively high speeds, indicating the presence of the black hole. The second big technology step was to overcome the image blurring from Earth's atmosphere by real-time control of the wavefront, a technique called adaptive optics. You measure each milli-second the wavefront distortion with a so-called wavefront sensor and compensate this distortion with a deformable mirror. Following a decade-long development, the teams brought adaptive optics to 8-10 meter telescopes in Hawaii and Chile in the early 2000s. This new technique allowed Reinhard Genzel and Andrea Ghez to trace the full orbit of a star, thereby pinning down the extreme mass of the dark central object, and leaving no other plausible explanation than a black hole. Integral field spectroscopy, a technique to measure simultaneously the spectrum for every pixel of an image, brought the third dimension to the orbit measurements. Adaptive optics needs a bright star close to the object of interest to run the control loop a thousand times per second. To look at fainter stars, you need to create your own artificial bright star by projecting a high-power laser onto the stratosphere. The latest breakthrough is the development of optical infrared interferometry and the GRAVITY instrument. This instrument combines the four telescopes of the European Southern Observatory to a 130-meter diameter telescope, delivering yet 20 times sharper images than possible with a single telescope and adaptive optics. The exquisite precision of interferometry is now also testing the theoretical basis for black holes, Einstein's theory of general relativity, and has detected the gravitational redshift and the Schwarzschild precession in the orbit of the star.

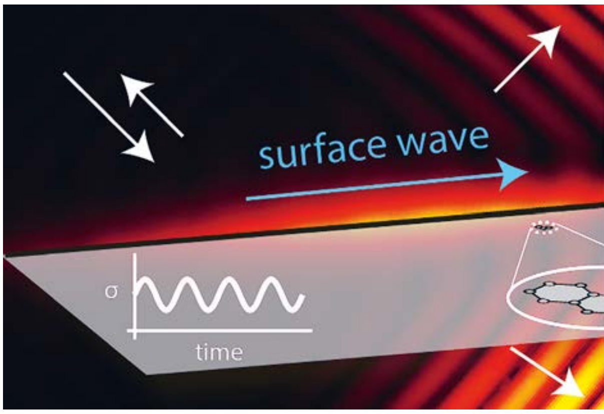
DR GUY PERRIN'S* POINT OF VIEW AND PERSPECTIVE

Breakthroughs in photonics and optical techniques were absolutely indispensable for these astronomical achievements. They come from the culture of astronomers who don't only implement off-the-shelf components on optical benches but develop systems and co-develop technologies to go beyond the state-of-the-art. During these 30 years, astronomers have developed instruments, for example adaptive optics systems with laser guide stars; It is a really complex system with the detection, the correction of atmospheric aberrations, the extreme quality of the optical system not to lose the high image quality brought by adaptive optics, and to sample them exactly as needed, and on top of that, the ability of dispersing light. So you see that it is a very complex system, it's like an orchestra where you have a collection of soloists. **Everything works at the same time, at the edge of what each component can do, so that at the end you can get this fantastic discovery.** There's a long path of instrumentation and development that leads to this discovery.

*Astronomer at Paris Observatory/LESIA (France), Co-Investigator of GRAVITY, head of the French contribution

Temporal Wood Anomalies: Smoothing the Path to the Near-Field

When Robert Wood noticed in 1902 an anomalous diffraction efficiency in the light reflected off a metallic grating, little was known about surface waves. Surface waves can confine electromagnetic radiation to volumes far smaller than its free-space wavelength, a fundamental limit for conventional optical elements. This enables the achievement of enormous electromagnetic energy densities, and the miniaturisation of optical components. However, this extreme confinement also forbids them to be excited from free space on a flat surface. This implies a need for gratings and other near-field couplers to impart incoming light the necessary in-plane momentum. The engineering of these spatial inhomogeneities requires nanofabrication, which typically increases costs, introduces losses, and hinders reconfigurability. Now a team led by researchers at Imperial College London have proposed an alternative route for free-space radiation to couple to surface modes: instead of coupling radiation to surface waves via spatial inhomogeneities of a surface, they suggested using temporal variations of its properties, such as periodic modulations of the charge carrier density of the medium: in other words, a *temporal Wood anomaly*. With the recent advent of ultrathin, highly tunable materials such as graphene and ITO, and active elements in microwaves and RF, temporal Wood anomalies may soon pave a new path towards the near-field, enabling complete device reconfigurability, and challenging the very need for nanofabrication in nanophotonics.



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THE POLARIZATION OF LIGHT CAN DRIVE THE PHOTOLUMINESCENCE FROM HYBRID PLASMONIC NANOSOURCES

In microscale optoelectronics, the possibility to precisely control the spatial distribution of the active medium allows for the optimization of systems and devices. At the nanoscale, this issue still constitutes a challenge. In particular, in hybrid plasmonic nano-emitters based on the combination between quantum emitters and localized plasmonic modes, the nanoscale control of the emitters' position would open up new doors to drive light emission from weak to strong coupling. An international consortium led by the L2n Laboratory of the University of Technology of Troyes has reported on this control that has been achieved *via* surface plasmon-triggered two-photon polymerization of a photosensitive formulation containing nano-emitters. By using different geometries of gold nanoparticles and different modes of plasmon excitation, nano-emitter-containing active medium has been structured selectively with different degrees of symmetry in the close vicinity of the metal nanoparticles.

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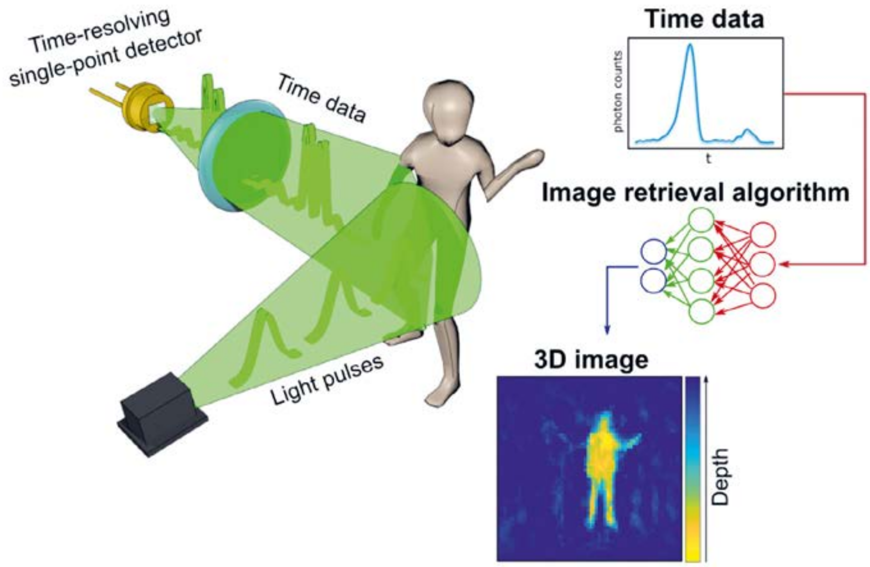
Obtaining images from temporal data

Obtaining an image is simple when a camera, formed by a sensor array and collection optics, is used. Alternatively, one can use a single-pixel sensor and form an image by structuring the illuminating source. Either way, to form an image one clearly requires using some form of spatial sensing. In a recent work [1], researchers from the University of Glasgow and collaborators at TU Delft and the Politecnico di Milano have shown that it is possible to obtain images without any form of spatial sensing, by using time-resolving sensors and deep learning. Under their approach, the system illuminates the scene with pulses of light, while the sensor records the arrival time of the reflected photons. This data is arranged in the form of a time histogram that is then analysed by a deep neural network that provides an estimate of the scene in three-dimensions. Although the researchers have proven the ability of the system to image multiple people walking in a room and to retrieve the shape of different geometric objects, the key of the imaging with temporal data is that every sensor with time-resolving capabilities is potentially an imaging device, which can transform commercial-of-the-shelf devices, such as radio or acoustic sensors, into cameras.



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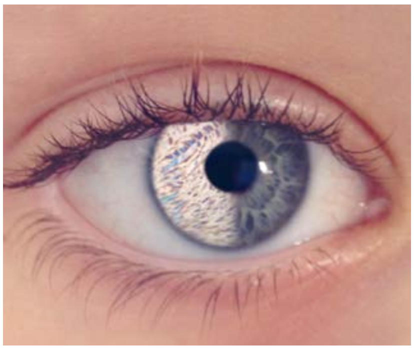
Alex Turpin, Gabriella Musarra, Valentin Kapitany, Francesco Tonolini, Ashley Lyons, Ilya Starshynov, Federica Villa, Enrico Conca, Francesco Fioranelli, Roderick Murray-Smith, and Daniele Faccio, "Spatial images from temporal data," Optica **7**, 900-905 (2020). https://doi.org/10.1364/OPTICA.392465

IS CORNEA REALLY TRANSPARENT?



Most natural and synthetic materials are non-crystalline at the mesoscopic scale. Polycrystalline or amorphous (disordered) phases with heterogeneities at scales ranging from a few tens of nanometers to a few tens of microns usually scatter visible light, and they become opaque beyond a certain thickness. Heterogeneous yet transparent non-crystalline materials can be found in living organisms, many of them based on a collagen scaffold (*e.g.*, the eye cornea). Synthetic materials combining transparency and biomimetic mechanical response can also be produced by self-assembly. However, the physical origin of transparency in natural and artificial biopolymer materials is still poorly understood. Researchers at the Paris Laboratory of Condensed Matter Chemistry (Sorbonne Université, Collège de France, CNRS), Institut Langevin (ESPCI Paris-PSL, CNRS) and Soft Matter Science and Engineering (ESPCI Paris-PSL, Sorbonne Université, CNRS) have found a gap of transparency in synthetic fibrillar collagen matrices within a very narrow range of concentration. By studying the relation between the three-dimensional fibrillar network quantitatively, and the optical and mechanical properties of the macroscopic matrices, the authors show that transparency results from structural partial order inhibiting light scattering, while preserving mechanical stability, stiffness and nonlinearity. The potential to produce by self-assembly biopolymer hydrogels with such striking optical properties opens an interesting route in the study of photonic materials. Moreover, the similarities between synthetic collagen matrices and natural corneas provide new elements in the understanding of the appearance of transparency in natural materials.

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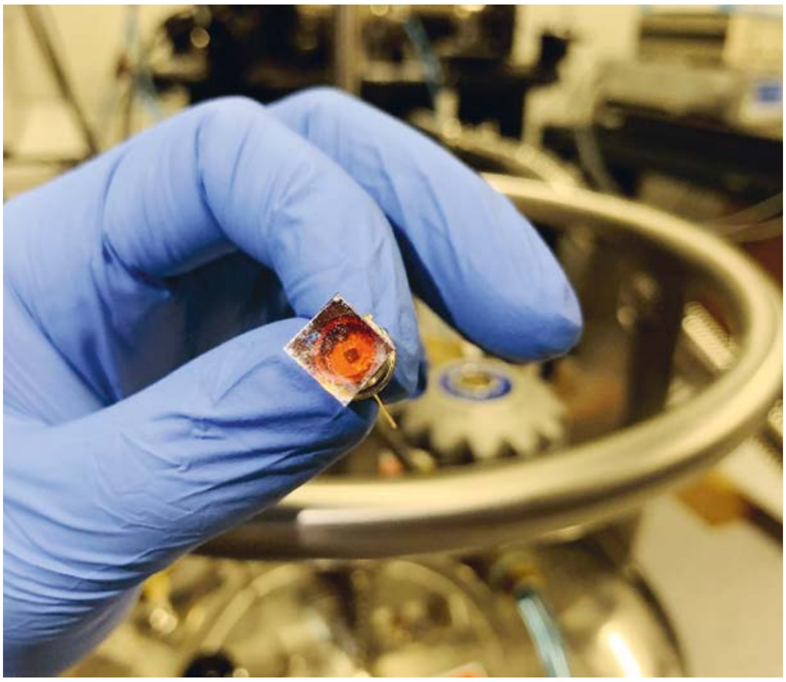
A new broadband light source for compact spectroscopy and imaging in the SWIR

Broadband optical emitters in the visible have revolutionized low power consumption lighting technology. It is now widely accepted that imaging and optical sensing is expected to go well beyond taking pictures, by exploiting a broader spectral range into the infrared, particularly the short-wave infrared (SWIR).

Augmented reality, 3D-, multispectral- automotive-, biomedical- imaging, as well as food quality and recycling monitoring are just some of the applications that require low-cost optoelectronic technologies in the SWIR. For spectroscopy and multispectral imaging in the SWIR, the necessity for broadband emission has imposed the use of halogen lamps, a bulky, inefficient and hard-to-miniaturize light source.

Researchers from ICFO report the first broadband solid-state SWIR light emitter technology that is based on low-cost, solution processed, thin film technology based on colloidal quantum dots. Alternative efforts to address this challenge had been based on phosphor based materials relying on atomic optical transitions of elements (transition metals or rare Earth) incorporated into inorganic glasses. However due to fundamental limitations those have failed to provide efficient broadband optical emission in the SWIR. Now, the authors have engineered tandem multibandgap colloidal quantum dot stacks that where designed to provide broadband emission, operating as a phosphor downconverter layer with unprecedentedly broad spectrum, high efficiency and high optical output power. Furthermore, by leveraging the conductive nature of the QD stack they demonstrate the first broadband SWIR active LED. The practical relevance of the technology is further demonstrated in real-case studies for the identification of plastics, food and chemicals employing infrared optical spectroscopy.



The QD nanophosphor thin film layer on a plastic substrate glued atop a commercial visible LED that emits broadband SWIR light. [Acknowledgment: Photo taken By Alina Hirschmann]

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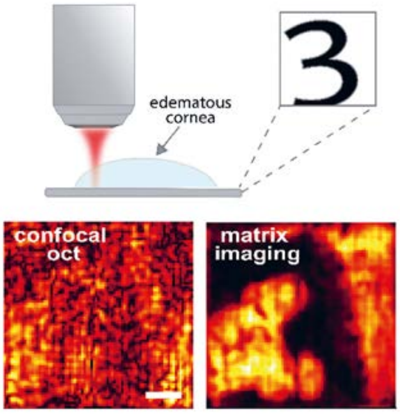
https://doi.org/10.1002/adma.202003830

TOWARDS DIGITAL TRANSPARENCY OF BIOLOGICAL TISSUES



Imaging of a resolution target through a highly opaque monkey cornea. Matrix imaging (right) reveals details of the resolution target that were totally hidden by the edematous cornea in confocal microscopy (left) because of aberrations and multiple scattering.

Researchers at the Langevin Institute in Paris have proposed a computational matrix imaging method for making biological tissues transparent in optical microscopy. More specifically, this method aims at overcoming the aberration issues and multiple scattering phenomena that prevent conventional microscopes from imaging biological tissues in depth (i.e beyond a few hundred microns). While, in the past, adaptive focusing methods, inspired by astronomy, have been able to overcome low-order aberrations, these approaches are effective only over a few microns, deep in biological tissues.

Here, from non-invasive reflection measurements, the authors manage to retrieve the transmission matrix that connects any point inside the tissues with each sensor of a camera outside. This matrix is the key for imaging. It allows a fine compensation of all the aberrations that light undergoes during its travel through the medium. It also allows the filtering of the multiple scattering noise which generally strongly alters the contrast in optical microscopy. More broadly, this approach can be extended to any type of wave. Applications range from biomedical diagnosis in optical microscopy and ultrasound imaging to the detection of cracks in industrial materials.

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Mie shaping nonlinear disorder

Changing the colour of coherent light is of great importance for many applications in photonics. Methods for nonlinear frequency conversion often rely on quadratic nonlinear crystals, which have large nonlinearities, wide transparency windows (infra-red to visible) and high-damage thresholds. In bulk crystals, the efficient nonlinear conversion can be achieved through phase matching. At the micro- and the nanoscale, the nonlinear conversion is enhanced by leveraging on resonant interactions. A drawback of both approaches, however, is to provide wavelength-specific performances and narrowband applications. Increasing the complexity of the crystalline structure, for instance by introducing disorder, enables a widely tunable frequency conversion and usually do not require high-quality materials.

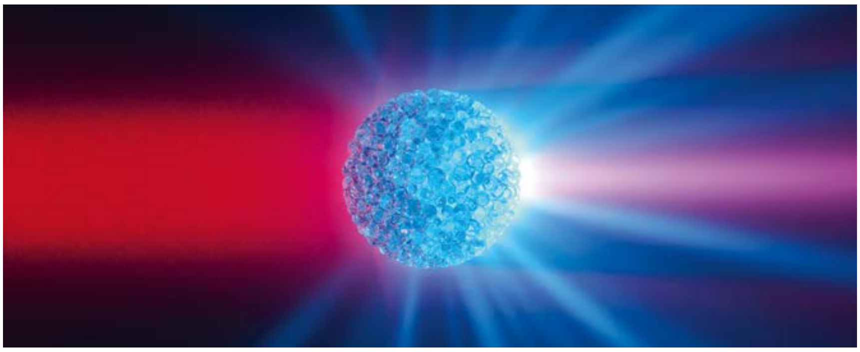

Image credit: Jolanda Müller

A team of researchers at ETH Zurich has developed a nonlinear photonic microstructure that combines resonances and disorder to obtain enhanced second-harmonic generation on a large bandwidth. They implement random quasi-phase-matching in three-dimensional Mie resonant microspheres realized by the bottom-up assembly of barium titanate nanocrystals. In these microspheres, the Mie resonances drive and enhance the second-harmonic generation, while the disorder keep the phase-matching conditions relaxed. The second harmonic grows continuously with the size of the microsphere and is as efficient as a crystal of the same size by using 70% less material. The microspheres can be adapted to achieve frequency conversion from the infrared to the near-ultraviolet ranges, are low cost and scalable to large surface areas.

REFERENCE

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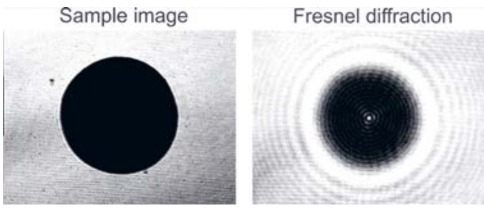
LINK TO THE FREELY ACCESSIBLE VERSION:
https://go.nature.com/31lUbn6

REPRODUCING THE FRESNEL-ARAGO EXPERIMENT TO ILLUSTRATE PHYSICAL OPTICS

Jérôme WENGER*, Benoît ROGEZ, Thomas CHAIGNE, Brian STOUT
Aix Marseille Univ, CNRS, Centrale Marseille, Institut Fresnel, Marseille, France
* jerome.wenger@fresnel.fr



Is there a bright spot in the shadow of an opaque disk? Nearly 200 years ago, Augustin Fresnel and François Arago's remarkable answer to this question validated the wave theory of light and inaugurated the modern theories of diffraction. Today, their renowned experiment can be easily reproduced using lasers and cameras. Far beyond its historical interest, the experiment is a versatile platform to illustrate the main concepts of optical physics, including diffraction, interference, speckle, and Fourier optics.

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INTRODUCTION: A BRIEF HISTORICAL BACKGROUND ABOUT FRESNEL-ARAGO EXPERIMENT

At the beginning of the 19th century, Newton's corpuscular theory of light was hard pressed to explain Thomas Young's observations of interference fringes by light passing through double slits. Consequently, in 1818, the French Academy of Sciences launched a contest to reward an improved understanding of the properties of light. Augustin Fresnel authored one of two reports submitted to the Academy of Sciences [1]. Fresnel's essay notably developed a means to describe light diffraction using a wave theory of light based on Huygen's principal. The prize committee was principally composed of a renowned generation of scientists who favoured Newton's particle theory. Amongst their ranks was Siméon Poisson who thought he had debunked Fresnel's theory when he remarked that it predicts a bright spot at the centre of the shadow of an opaque disk, which he held to be clearly false [3]. Fresnel realized however that shadows in everyday life generally lack the spatial

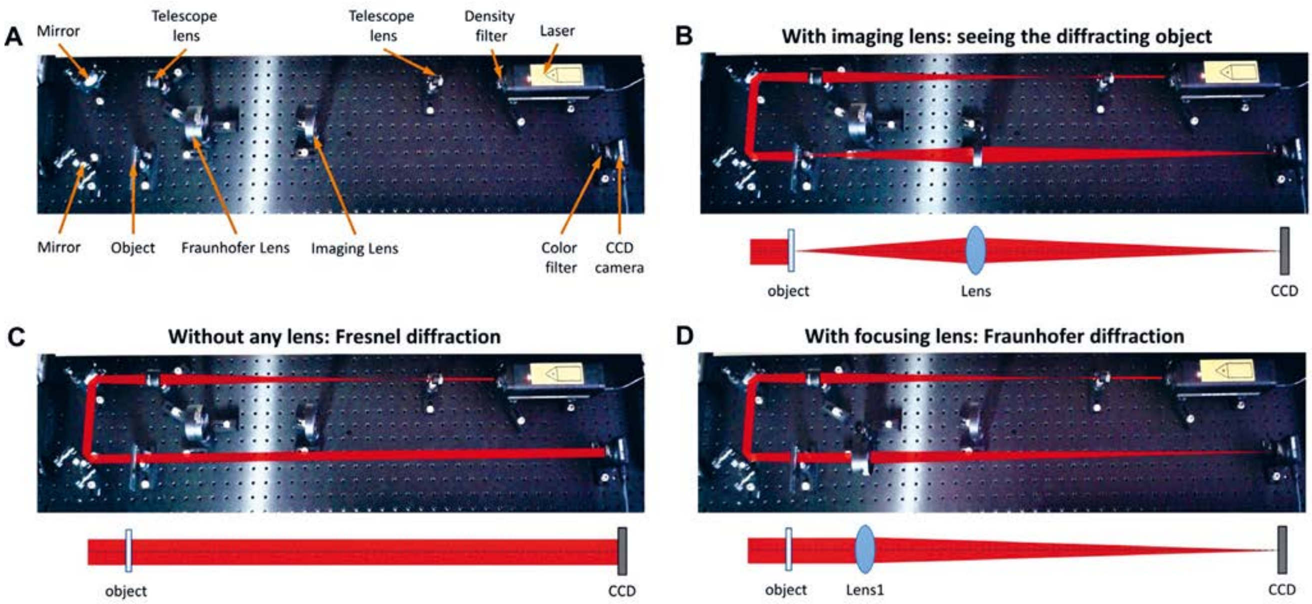

Figure 1.
Experimental demonstration setup (A), with its different operation modes for imaging the sample (B), direct Fresnel diffraction (C) and Fraunhofer diffraction (D).

coherence and geometry required for such an observation. Fresnel, together with the committee president, François Arago, put Poisson's prediction to the test, and Arago announced to the world that there is indeed a bright spot in the shadow of a disk! It is difficult for scientific revolutions to be hailed overnight, and when the French Academy awarded Fresnel its prize in 1819, the official report highlighted the accuracy of the agreement between theory and experiment, while the word "wave" was mentioned only once. Fresnel's wave theory was almost immediately included in curriculums however, and its successes were of such magnitude that within only a few short years, the notion of light as particle emissions was relegated to the realm of historical anecdote until its spectacular revival by Einstein nearly a century later. Fresnel's prize marked only the beginning of the physical optics adventure, and several decades of discovery, mathematics and scientific revolution had to pass before Fresnel's intuitions and hypotheses were all firmly vindicated. In modern times, Fresnel's theory of light diffraction is now understood as an approximation to more complete theories, but its practicality is such that its use is still widespread.

Now, more than 200 years later, using lasers and cameras, we can easily reproduce this historical experiment which played such a crucial role in our understanding of the properties of light.

EXPERIMENTAL SETUP

This modernized version of the Fresnel-Arago experiment is built on a 120 × 30 cm^2 breadboard for ease in handling (Fig. 1A). The light source is a 0.8 mW compact HeNe laser at 632.8 nm, whose output is further attenuated, by a neutral density filter, down to 0.2 mW. This power provides adequate visualization of the light beam while being low enough to ensure correct eye safety without requiring any specific laser safety equipment for the teacher or the students.

The laser beam is laterally expanded 16× using a telescope made of two lenses in order to reach a beam diameter of around 10 mm enabling correct visualization. The sample is placed directly on the laser beam path, held by two clips (Thorlabs FH2) which provide a versatile approach to move the sample during the live demonstrations. The camera is a USB-powered monochrome CMOS device (Thorlabs DCC1545M) whose sensor is placed in the light beam with no further optics. In order to operate under ordinary light conditions, the camera is equipped with a 610 nm long pass color filter to block most of the visible light from the room while transmitting the red laser light.

Fresnel diffraction by the sample object at finite distance is viewed directly on the camera (Fig. 1C). A supplementary biconvex lens of 200 mm focal length on a flippable mount can be used to image the sample on the camera (Fig. 1B). Additionally, another lens can be added to observe large distance Fraunhofer diffraction patterns (Fig. 1D). In this latter case, the lens is positioned so that the camera lies in the image focal plane of the lens. We used a 750 mm focal length, again on a 90° flip lens mount to allow inserting and removing the lens so as not to require optical alignment during demonstrations. Further details about the optical setups, including complete references of the components used can be found in Ref. [2].

Fresnel, together with the committee president, François Arago, put Poisson's prediction to the test, and Arago announced to the world that there is indeed a bright spot in the shadow of a disk!

EXPERIMENTS TO BE PERFORMED

The demonstration setup allows to visually demonstrate major concepts of physical optics: diffraction, interferences, speckle, Fourier optics... Table 1 summarizes the main experiments that can be performed. Online videos on the Youtube channel of Institut Fresnel [3] show some examples of experiments recorded live. A principal common feature is to frequently switch from directly visualizing the sample (using the imaging lens, Fig. 1B) to observing the diffraction shadow (removing the imaging lens to be in Fresnel diffraction conditions, see Fig. 1C). Below, we briefly describe the different experiments and the sample preparation, focusing on simple methods that anyone can reproduce without specific tools.

The Fresnel-Arago diffraction experiment aims at observing the central bright spot in the shadow of an opaque disk. To fabricate the opaque disks, we deposited small dots of water-soluble black paint on a clean microscope glass slide using a thin brush or the tip of a needle. It takes a bit of trial and error to find the right consistency of the water–diluted black paint (paint for model making works well), but once the right consistency is achieved, nearly circular droplets of diameters from 0.5 to 2 mm are readily obtained. For the experiments, different disk diameters can be compared, showing that larger disks produce smaller Fresnel-Arago spots. Putting the disk

Table 1.
Demonstration experiments and main concepts illustrated with this setup.

PHYSICAL OPTICS CONCEPT	TEASING TEXT FOR STUDENTS
Diffraction by a disk: Fresnel-Arago spot	This demonstration reproduces the historical Fresnel-Arago experiment and explores the shadow of an opaque disk, answering the question: is there light in the center of a shadow from a black disk?
Diffraction by a hole: the Airy disk	What is the shadow of a single hole milled in an opaque screen? The most studied case of diffraction is illustrated here experimentally using simple optical elements.
Young's double slits interferences	Can adding light to light create shadow? This demonstration shows that this can indeed be the case, reproducing Young's historical double slit interferences experiment, which is now the most studied interference configuration.
Random interferences and Speckle	What is the shadow of multiple scatterers illuminated by a coherent laser beam? This demonstration illustrates the principle of speckle formation by multiple random interferences.
Strioscopy and Fourier optics	Mastering optics allows you to filter an image even before it reaches the camera! This demonstration illustrates the principle of strioscopy, which is a specific application of Fourier optics.

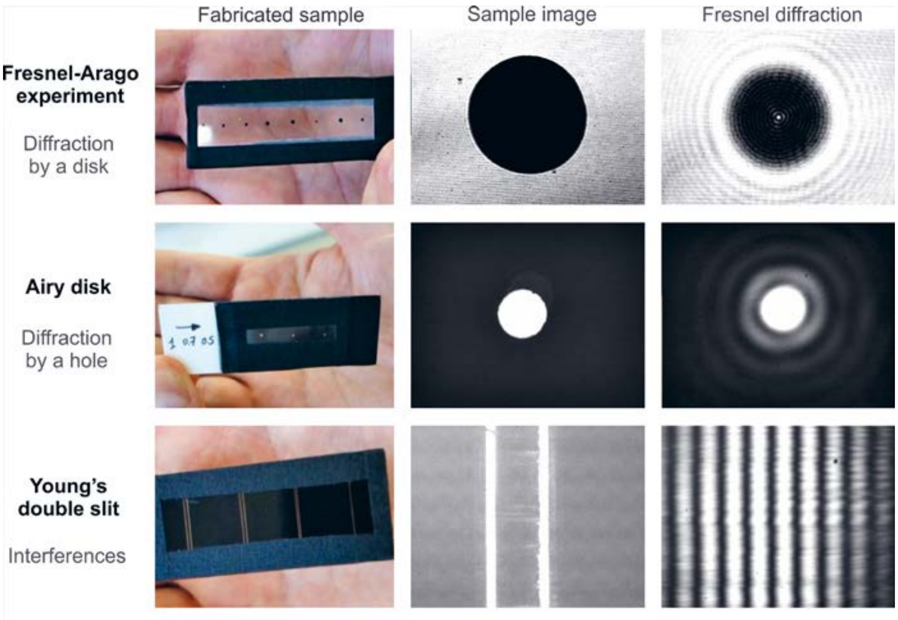

Figure 2. Examples of samples and experimental results for three selected demonstrations.

sample on a rail and moving it away from the camera gives nice results. This simple experiment allows one to travel through disk's shadow and observe the growth of the Fresnel diffraction pattern.

The same setup allows one to visualize the diffraction by a single hole; by far the most studied example of diffraction. To fabricate this sample, a thin plastic sheet was painted in black to make an opaque screen. Circular holes of diameters from 0.5 to 2 mm were then drilled manually using drill bits bought at a local hardware store. The effect of different hole diameters on the diffraction pattern can be illustrated. The Airy diffraction pattern is readily visible, and is important to discuss the resolution in optical microscopy. By moving the sample closer to the camera (~1–2 cm), we can also observe dark regions at the centre of the bright spot, showcasing spectacular additional diffraction patterns.

Young's double slit interferences are also frequently used to discuss the interference phenomenon. To fabricate the single and double slits, a cleaned microscope glass slide was covered with black spray paint. Next, the paint layer was scratched using the tip of a needle guided by a ruler. Nearly parallel slits can easily be obtained this way, with an interslit distance below 1 mm. This experiment illustrates how interferences lead to some regions having increased light intensity while in others it falls to nearly zero. Students can also see how changing the distance between slits affects the inter-fringe separation: narrower inter-slit distances yielding larger separation between fringes.

Supplementary experiments involve speckle formation and random interferences. Here, the sample consists of butterfly scales randomly deposited on a glass microscope slide, although virtually any multiple scattering media would produce similar conceptual results. In this experiment the sample is placed on the rail just in front of the camera (visualizing the shadow from each individual scatterer) then translating the sample to increase the sample-camera distance, the shadows of each scatterer progressively interfere until a complete random interference pattern (speckle) is obtained.

For the strioscopy experiment, the sample is a prepared microscope slide (slice of rat intestine in our case). The image is formed on the camera, then (keeping the imaging lens) a black disk (the same as for Fresnel-Arago experiment) is inserted in the lens back focal plane (200 mm away from the lens) to block the ballistic transmitted light and filter high spatial frequencies. As a consequence, the image contrast is inverted, and fine details stand out more prominently. This illustration of Fourier optics demonstrates how image formation is affected by the optical system, without involving computer processing.

CONCLUSION

The reproduction of a famous experiment of the early 19th century turns out to be a rich and versatile platform to illustrate and demonstrate the main concepts of optical physics. Diffraction, interferences, speckle, image formation, Fourier optics and strioscopy can be shown in a didactic manner. Using modern optical elements, building this system and performing these experiments is nowadays quite easy [2]. Additionally, short videos illustrating the experiments described here can be found on the Youtube channel of Institut Fresnel. With a supplementary discussion of the coherence concept in optics, we hope that this modern homage will help to stimulate the next generation of young engineers, scientists and teachers.

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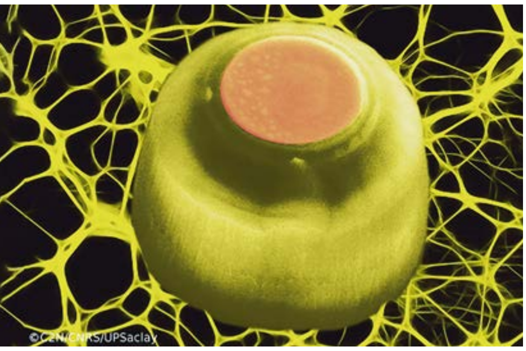
MICRO-LASERS FOR NEUROMORPHIC COMPUTING

Venkata Anirudh PAMMI[1], Sylvain BARBAY[1,*]
[1] Centre de Nanosciences et de Nanotechnologies, CNRS, Université Paris Saclay, Palaiseau, France
* sylvain.barbay@c2n.upsaclay.fr



Spiking micro-lasers are interesting neuromorphic building blocks to realize all-optical spiking neural networks. Optical spike-based computing offers speed and parallelism of optical technologies combined with a sparse way of representing information in spikes, thus with a potential for efficient brain-inspired computing. This article reviews some of the latest advances in this field using single and coupled semiconductor excitable micro-lasers.

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Neuromorphic photonics aims at drawing inspiration from the brain to design efficient computing hardware using a photonic substrate. The interest in this field stems from the potential gain in speed and parallelism due to the use of optical technologies while reducing the energy consumption compared to standard Von Neumann architectures. Amongst the numerous neuromorphic photonic platforms, excitable micro-lasers display many properties present in biological neurons and are thus appealing to implement fast and efficient brain-inspired functionalities. Starting from the building block, the optical neuron, one of the major objectives is to design photonic neural networks which are interconnected excitable nodes with controllable weights, implementing learning capabilities. These building blocks can also be used in new computing frameworks such as liquid state machines [1] and photonic processing accelerators, using spike-based computing strategies [2] replacing the binary logic paradigm: while in standard computers information is encoded in a voltage level representing either the binary value 0 or 1, in the brain information is encoded in 'spikes' which are short electrical pulses emitting by neurons. Spiking is a fundamental property of biological neurons which is a generic property found in many physical systems and is also called excitability (insert).

Excitability in optics can be obtained in different experimental systems. A particularly attracting configuration is the case of the semiconductor laser with saturable absorber (see insert). A laser with saturable absorber contains, in addition to a gain medium, an absorptive medium whose absorption saturates with the intracavity laser intensity. This type of laser can be self-pulsing above the laser threshold and reveals an excitable behaviour below threshold; the rest state is then the laser off state. When the laser is subjected to perturbations above the excitable threshold, it emits calibrated optical pulses which can be of hundreds of picosecond duration or less. The difficulty is to integrate in a laser both the gain and the saturable absorber medium, because basically both require opposite pumping conditions. We have been able to design and fabricate such a semiconductor micro-laser, opening the way to optical neurons behaving similarly to biological ones, but with the important differences that optical neurons respond on timescales more than one million times shorter than their living counterpart [3].

Another important property of neurons is their absolute refractory period: neurons cannot spike at arbitrary high frequencies; there is a minimal time difference between two spikes. There is also a relative refractory period which corresponds to an intermediate situation where a neuron produces an attenuated spike in response to a second stimulus after having spiked once. This means that neurons have a memory of their past state. In semiconductor optics, the relative refractory period is very short, less than one nanosecond. The refractory periods are fundamental for unidirectional transport of information in the axon, as will be explained below.

Because excitability is the result of a dynamical process, the neuron responds to any above threshold stimulus with the same calibrated pulse but with a different latency time, which depends on the input perturbation strength: the weaker the perturbation, the larger is the delay in the response. This mechanism introduces a natural coding scheme into spikes of input perturbation amplitudes, the temporal coding: information on the input amplitude of a stimulus is reflected into the temporal delay of the produced spike. This coding mechanism is an alternative coding scheme to the simpler rate coding scheme which encodes the input amplitude in the rate of spikes. However, it has been proven that this former coding can only explain the fast image recognition capability of the brain. It is therefore an important mechanism for any spike-based, biologically plausible computing architecture. In the optical neuron, spike latency ranging from few hundreds of picoseconds to several nanoseconds have been measured in response to short optical input stimuli.

Equipped with excitable response, refractory period and spike latency, the optical neuron can respond to stimuli and encode information into spikes. It can act as a nonlinear gate but it cannot compute on its own. The computing ability comes from a fourth important ingredient, the temporal summation. Neurons can integrate sub-threshold stimuli over time: they are 'leaky-integrators'. As a consequence, a neuron receiving delayed stimuli from different sources will be able to spike if the stimuli are close and not if they are far away: they can detect coincidences [4]. This simple property has huge consequences since it mathematically leads to the property of universal computing: networks of coincidence detector neurons can approximate any function. They constitute the third generation of neural networks and are believed to be more powerful in terms of the number of nodes needed for a specific computing with respect to other kinds of neural networks.

COMPUTING WITH COUPLED NEUROMORPHIC MICRO-LASERS

Even though a single optical neuron can realize simple computing tasks, coupling several such neurons is necessary to scale up the computational power [5]. A simple yet non-trivial coupling scheme is self-coupling or autapse, where the laser response is coupled back to itself *via* a time delayed feedback. This configuration is motivated from biology since autapses are found in the mammalian brain and it is hypothesized that they linked to the memory capacity. From a physical point of view, having such structures in neural networks can enable complex dynamics and present ways to store information.

An all-optical autapse is built by reflecting back the response of the laser

We have been able to design and fabricate such a semiconductor microlaser, opening the way to optical neurons behaving similarly to biological ones, but with the important differences that optical neurons respond on timescales more than one million times shorter than their living counterpart [3].

using *e.g.* a distant mirror placed several tens of centimeters away, forming an external cavity with a feedback time on the order of tens of nanoseconds. If the system is fed with a single optical perturbation above the excitable threshold, it will generate a train of spikes whose repetition period corresponds to the sum of spike latency and cavity round-trip time. Additional input perturbations can be sent to the system to add or remove spike trains and change the timing of existing spike trains. This demonstrates an all-optical buffer for spikes which can be controlled with single optical pulses. In the short term (~ tens to hundreds of external cavity round-trips) after the initial excitation, the individual spike trains seem independent and do not interact with each other. This implies that the information can be stored in the inter-spike intervals and can be preserved for hundreds of nanoseconds. This is sufficient to act as a working memory, *i.e.* an intermediate storage with limited capacity, a central concept in neuroscience. However, if the spike trains evolve for longer durations, we observe that the inter-spike intervals equalize: any time coded information is lost in the long term. This equalization can be seen as a computational process similar to that in an associative memory. Associative or Content Addressable memory is a type of memory with a computing ability. It accepts an input which can be partial information and retrieves the stored memory closest to it. This is exactly what happens in the case of the optical autapse. If the system is fed with one time-equalized spike train, it responds with this state. If it is fed with a nearby state (corresponding for instance to a given, non periodic,

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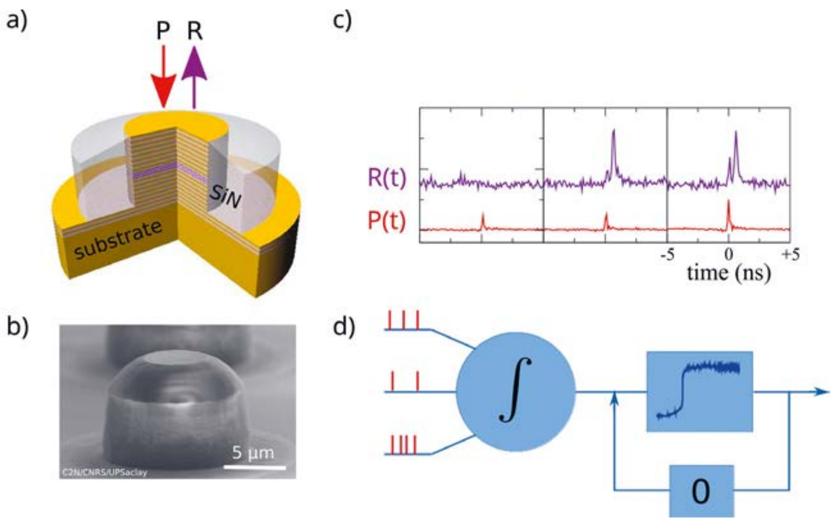

Excitable semiconductor micro-laser: an excitable semiconductor micro-laser is depicted in a) with a SEM micrograph in b). It comprises two Distributed Bragg Reflectors and an active zone composed of quantum wells (for gain and saturable absorption) and is encapsulated in a SiN layer to prevent oxidation and for better heat management. The micro-laser is optically pumped (not shown) and subjected to pulsed perturbations (P). In the excitable regime, the 'rest' state of the system corresponds to the laser off state (below laser threshold). Small perturbations do not change the state of the neuron. However, when a perturbation above the so-called excitable threshold is sent to the micro-laser, an 'action potential' is generated in the form of a response pulse R (a spike). Importantly, as can be seen in c), the shape of the generated pulse does not depend on the input perturbation as long as it is above the excitable threshold: the neuron acts as a "all-or-none" system and has thus a highly nonlinear response. Other major properties of the neuron are represented schematically in the diagram d): the optical neuron can sum input stimuli in the form of spikes from different sources, the integrated signal is compared to a threshold and a spike is emitted if the threshold is reached. The neuron then recovers to its quiet state. The recovery is not instantaneous and takes some time: this is referred to as the refractory periods of the neuron. Also, the response spike is generated with a dynamical delay which depends on the integrated perturbation strength.

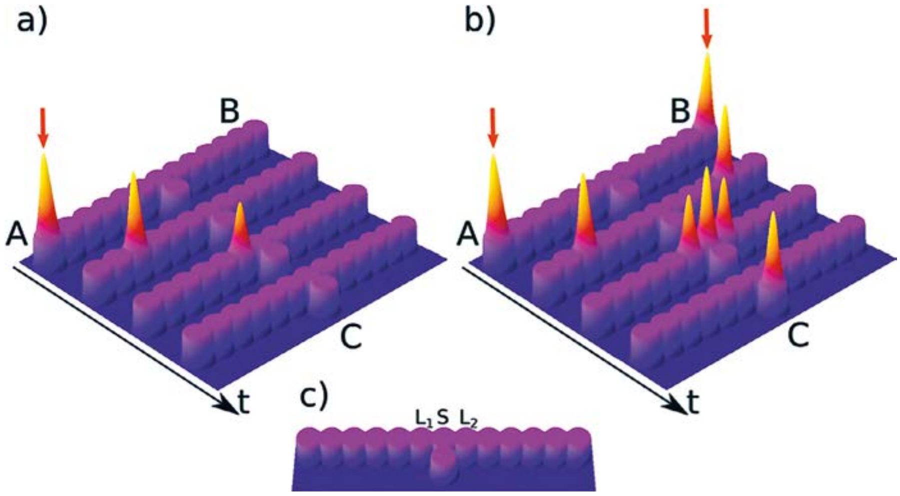

Figure 1.
Temporal AND logic gate. The micropillars are represented by small touching cylinders in c). All the nodes are in the excitable regime and receive the same level of pump except nodes L_1 and L_2 which are pumped less. In a) node A is initially excited by an external perturbation. The response spike propagates along the gate but fails to excite node S. Thus, no output is detected at the exit node C. In b) both nodes A and B receive an input at the same time. The excitations propagate towards each other and are summed in S resulting in a spike at the output node C.

timing configuration of spikes), it will converge to the closest state in memory. Notably, this functionality is implemented here thanks to a single neuron, while it usually needs many nodes and connections such as in Hopfield networks.

A second scheme consists of several evanescently coupled optical neurons. In this scheme the lasers are placed physically close together so that their emission modes overlap, resulting in the coupling of optical field from one laser to its neighbour. Suppose there is a chain of N coupled lasers in their rest state in the excitable regime (see Fig. 1). If a perturbation excites a spike in the first laser and if the coupling is large enough, this excitation will propagate along the chain much like in the axon in biological neurons, giving rise to a lossless saltatory propagation. The propagation is unidirectional: when one laser inside the chain emits a spike, the optical field leaks symmetrically in both its nearest neighbours. But one of the neighbours is inevitably in its refractory period and does not respond to this spike whereas the other node does. Excitability is a highly nonlinear process and these propagating pulses have special properties. Unlike linear waves that propagate and interfere when they meet, excitable spikes usually collapse when they meet. Using this property and recalling that the excitable threshold depends on the pump amongst other things, a temporal AND gate can be built. The temporal AND gate shown in Fig. 1 only fires when it receives two (or more) inputs within a certain time window such that the sum of the individual inputs exceeds a threshold. The nodes L_1 and L_2 shown in Fig. 1c receive a lower level of pump as compared to the other nodes, allowing to realize this functionality. In Fig. 1a, only node A is excited by an input signal. This signal propagates till the node L_1 where the excitable response is lower because of the decreased pump. The lower response fails to excite the summation node S and consequently no response is detected at node C. However, if both nodes A and B are excited at the same time as in Fig. 1b, the node S sums the two sub-threshold excitations and emits a spike at node C. The same kind of coincidence detection circuitry is found in some animals (*e.g.* in the Barn owl) for determining the direction of sound stimuli. Elaborating on this effect and using the propagation delays enabled by the spike propagation, more advanced circuits can be designed allowing to distinguish between spike trains with different interspike intervals and detect a definite temporal pattern sequence.

In conclusion, spiking micro-lasers constitute good candidates to design fast and scalable neuromorphic circuits for spike-based processing. Coupled to artificial synapses such as built from phase change materials, spiking lasers have recently been shown to provide learning capabilities too [6]. Besides their interest in analog computing, spiking micro-lasers also enable to study biologically plausible architectures that can benefit from the advances in neurosciences.

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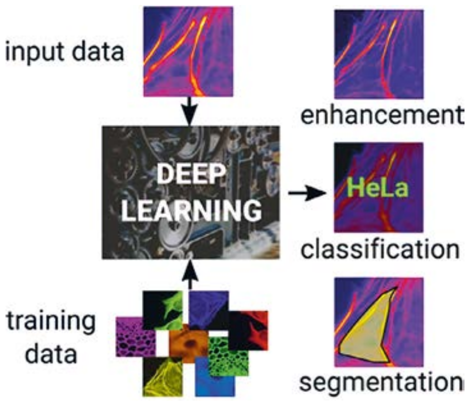
FREE ANNOTATED DATA FOR DEEP LEARNING IN MICROSCOPY? A HITCHHIKER'S GUIDE

Adrian SHAJKOFCI[1,2], Michael LIEBLING[1,3*]
[1] Idiap Research Institute, Rue Marconi 19, 1920 Martigny, Switzerland
[2] École Polytechnique Fédérale de Lausanne (EPFL), Route Cantonale, 1015 Lausanne, Switzerland
[3] University of California, Santa Barbara, CA 93106-9010, USA
*michael.liebling@idiap.ch



In microscopy, the time burden and cost of acquiring and annotating large datasets that many deep learning models take as a prerequisite, often appears to make these methods impractical. Can this requirement for annotated data be relaxed? Is it possible to borrow the knowledge gathered from datasets in other application fields and leverage it for microscopy? Here, we aim to provide an overview of methods that have recently emerged to successfully train learning-based methods in bio-microscopy.

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Optical microscopy, despite being an invaluable tool in biology and medicine to observe and quantify cellular function, organ development, or disease mechanisms, requires constant trade-offs between spatial, temporal, and spectral resolution, invasiveness, acquisition time, and post-processing effort. As for other imaging fields, learning-based techniques are having a major impact in microscopy, where their potential to improve resolution, reduce invasiveness, or increase the speed of microscopy acquisitions has recently been demonstrated. Yet despite the ever-increasing computational power, it is often the lack of labeled training data that is the limiting factor for wide adoption. Annotating data is often a lengthy and expensive task, since it involves tedious work, generally by skilled experts. Annotation can be especially challenging in the case of three-dimensional images, common in microscopy, despite the development tools dedicated to this task. While the acquisition and annotation of volumetric data is common in some medical settings and for certain modalities because of their wide use for healthcare applications (*e.g.* magnetic resonance imaging (MRI), annotated by trained radiologists), microscopy applications often lack similarly large and high-quality annotated volumetric datasets.

For many applications in biology, the time burden, cost, or physical feasibility of acquiring and annotating datasets for deep learning models de novo is simply out of the question. Can this requirement for annotated data be relaxed? Is it possible to borrow the knowledge gathered from datasets in other application fields, such as e-commerce or computer gaming, and leverage it for bio-microscopy? Specifically, could annotated datasets be generated from realistic synthetic models of tridimensional objects? Or could more abstract prior knowledge about the data be used to enhance the resolution? Here, we aim to provide an overview of some solutions that have emerged to tackle the problem of gathering sufficient annotated data to train learning-based methods in bio-microscopy. We have grouped the approaches in four broad categories: developing manual annotation strategies, learning from annotated images from other domains, building annotations from simulations, and using self-annotated data. This quest for annotated data is summarized in Figure 1.

OVERVIEW OF DATA ANNOTATION STRATEGIES FOR DEEP LEARNING METHODS IN BIOMICROSCOPY

LEARNING FROM LARGE TRAINING DATASETS

Image segmentation is a common computer vision task in which each pixel of an image is assigned a label corresponding to the object it belongs to. In microscopy, it is used, for example, to delineate, identify, and count cells. Learning-based segmentation methods require a training data set composed of images together with masks that correspond to the objects and their coordinates in the images. This annotation is usually performed manually and can be tedious. Other fields have integrated the task of annotating images into security forms on the web (to exclude robots from accessing content) or into entertaining game puzzles, such as to entice the public to provide quality annotations. Sullivan *et al.* have proposed to annotate microscopy data by a similar approach, as part of a multiplayer computer game named Eve Online [1]. Using the publicly available data set from the Cell Atlas of the Human Protein Atlas (HPA), they obtained, over one year, nearly 33 million classifications of subcellular localization patterns of immunostained proteins in 20 different organelles and cellular structures. The results were successfully used as a training dataset for a segmentation Deep neural network (DNN).

LEARNING FROM OTHER DOMAINS

Training a machine learning algorithm by re-using computer vision data sets that were originally intended for other tasks is at the core of transfer learning. This approach can overcome the lack of annotated data in one field (such as microscopy) if annotated data exist in a different field. A wide variety of annotated image datasets are available, such as ImageNet, MS-COCO or Places, which contain foremost scenes depicting everyday objects and situations. In addition to allowing access to a large number of examples, learning from natural-scene images can help avoid learning on images that contain unwanted aberrations, such as blur and low-light noise commonly found in microscopy images. It becomes essential when developing methods that aim at removing aberrations, for example when using a DNN pipeline for deconvolution or denoising of microscopy images, since the ground truth of natural-scene photographs is more readily accessible that fine structures that challenge the resolution limits of the most powerful microscopes.

In most cases of transfer learning, pre-trained models are used as feature extractors, as the input of an unsupervised classifier such as support vector machines (SVM), or are fine-tuned with job-specific training data. However, there are some applications where transfer learning can be used without fine-tuning, specifically, when the feature space can be mapped identically in both domains. For image deconvolution and depth estimation, a description of the Point Spread Function (PSF) is a pre-requisite and accurately determining PSF parameters is therefore essential. Recently, we formulated the problem of retrieving the physical PSF parameters of an optical microscope as a regression task for which we trained a DNN. Interestingly, when learning from data that consist of textured images, even if they are different from the end-use application, the trained model remains just as accurate as when it is trained on microscopy images [2]. The ability to train on generic data also helps prevent over-fitting the trained model to a specialized and narrow data set, which would make the model less suitable to be used in other situations. It also suggests the possibility of generalizing the trained network to other data types, provided that the new data and the data used for training share a common feature space.

LEARNING FROM SIMULATED DATA SETS

Generating annotated data from simulations is another effective approach to produce large and reliable training data sets. In some computer vision applications, such as autonomous car driving, data from simulated computer graphics 3D environments have been effectively used to train segmentation methods. Examples of such datasets include the Flying chairs dataset, or the GTA5 dataset derived from a computer game.

Generally, the accuracy of DNNs trained only on simulated data is poor, due to the extreme complexity of natural scenes that can hardly be reproduced with simple simulations.

In microscopy, image complexity remains fairly low in some modalities such as single-molecule localization microscopy (SMLM), where features consist of dots. The image processing task, for which DNNs have been used, consists in converting images of random subsets of activated fluorophores, obtained over many consecutive diffraction-limited frames, into a high-precision point cloud. Data simulation of a realistic diffraction-limited ground truth is achievable, for example, by filtering the expected objects by the optical PSF and take into account a realistic noise model [3]. Such approaches have allowed recent DNN methods such as [4] to recover densely overlapping PSFs of multiple emitters over a large axial range and output a list of their 3D positions. The corresponding training data set were created by simulating a large number of images using randomly generated 3D patterns and the phase mask that governs the PSFs modelled on the physical implementation of the microscope. In order for the simulations to work as a sole training data, one possible way is to restrict the parameter space (*i.e.* the output of the network) by closely modeling the data generation model to the physical properties of the optical system ([2], [4]).

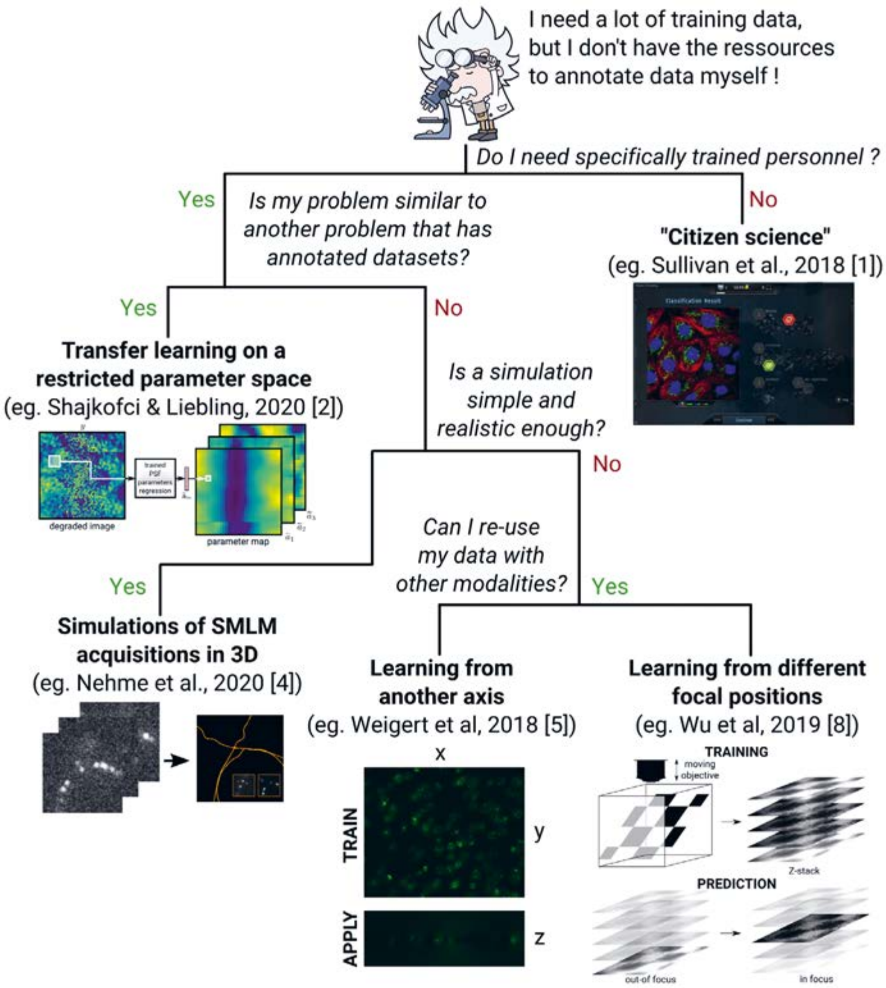

Figure 1.
The quest for less painful annotation: overview of questions and methods. The illustrations were made by AS and adapted from the original papers.

LEARNING FROM THE INPUT IMAGE ITSELF

DNNs are also used for image enhancement such as deblurring (going from a blurry image to a sharper image), denoising (going from a noisy to a clean image), and for super-resolution (going from a low-resolution image to a higher-resolution image). These networks are traditionally trained on pairs of clean and distorted images. In microscopy, where the raw images often already reach the physical limits due to diffraction, a higher-resolution ground-truth image is simply not accessible. To cope with this problem, it is sometimes possible to use approaches that exploit particular features of the data, such as its isotropy or the availability of complementary imaging modalities.

Weigert *et al.* [5] proposed a pipeline aimed at restoring images using semi-synthetic training data. Specifically, it restores the axial resolution of volumetric images lost due to the axial elongation of the optical PSF and the low axial sampling rate. By assuming that similar features are to be expected regardless of sample orientation, the method leverages the fact that these features can be much better resolved in lateral views than in depth, hence the training to improve depth-resolution is done based on the latter images. Nevertheless, for many other applications, access to higher quality images or synthetic data is not available. To overcome this limitation, Krull *et al.* [6] developed a self-supervised training method for denoising based on the assumption that the noise is independent from pixel to pixel and that the true intensity of a pixel can be predicted from the local image context since it is not locally independent. The method involves a noise model whose probability distribution is learned from the training data and a network is trained to discriminate the underlying image from the noise. As a training set, a very small dataset of noisy images of the same type can be used. This method is virtually equivalent to training a DNN for every specific noise distribution.

A similar training scheme was also used in [7, 8], where the authors trained a generative adversarial network (GAN)-based DNN to transform an acquired low-resolution image into a high-resolution image using matched pairs of experimentally acquired images after registration and alignment. In [7], these pairs came from images of the same object using a confocal microscope and a STED microscope. In [8], the authors used a similar DNN to generate images that look as if they had been taken from another focal plane by training from images acquired at different heights in the sample. For both applications, the authors caution that the network must be (re)-trained for each specific image modality or experimental setup, as the methods do not produce ideal results otherwise. The application of such methods therefore remains somewhat limited to cases where the type of images and microscope settings are known beforehand and where a high number of similar images can be acquired, which could be particularly relevant for time-lapse imaging, high-resolution 3D stacks, or imaging of histological samples prepared under controlled and standardized conditions.

CONCLUSIONS

Deep learning technologies have enabled multiple applications that are transforming our day-to-day routines, including the way we approach microscopy. While limitations such as network capacity (can networks learn to predict from the wide variety of data types common in microscopy?), generalization (can a network trained on one type of data be used to handle other types of data?), and overfitting (is the network limited to predicting only what it has already seen?) are some pressing issues that the field is facing, the lack of good quality training data is likely the single most important aspect that affects accuracy and effectiveness of tasks such as enhancement, classification or segmentation. The most promising methods to overcome the scarcity of training data appear to leverage prior knowledge of the physical objects and image formation process [4], [5], [2], or of the noise distribution [6].

Even if we are still a long way from a blind pipeline that will enhance, classify or segment biological data without tedious annotation work, good knowledge of the problem and assumptions about the data allow scientist to already reap the benefits of deep learning tools by crafting adapted training sets without having to produce or wait for the availability of large annotated sets.

ACKNOWLEDGEMENT

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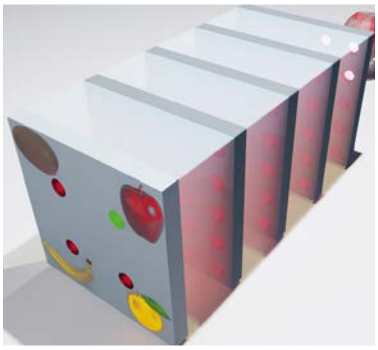
OPTICAL NEURAL NETWORKS: THE 3D CONNECTION

Niyazi Ulas DINC[1], Demetri PSALTIS[1], Daniel BRUNNER[2,*]
[1] Optics Laboratory, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
[2] FEMTO-ST/Optics Department, UMR CNRS 6174, Université Bourgogne Franche-Comté, 25030 Besançon Cedex, France
* **daniel.brunner@femto-st.fr**



We motivate a canonical strategy for integrating photonic neural networks (NN) by leveraging 3D printing. Our belief is that a NN's parallel and dense connectivity is not scalable without 3D integration. 3D additive fabrication complemented with photonic signal transduction can dramatically augment the current capabilities of 2D CMOS and integrated photonics. Here we review some of our recent advances made towards such an architecture.

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Several decades passed between the introduction and the large-scale exploration of neural networks (NN). Since the proposal of simple NNs in 1943 [1], the field has gone through multiple cycles of euphoria and challenges until reaching today's large-scale interest and exploitation [2]. Readily available high-performance computing systems now allow emulating powerful (deep) NN architectures whose connections are optimized based on computationally expensive learning concepts such as gradient back-propagation. As a consequence, NN currently excel on previously unseen scales, but at the same time the constraints of today's CMOS-based computing threatens to limit the reach of this revolution.

As illustrated by their name, the initial objective of NN, *cf.* Fig. 1(A), was providing a 'logical calculus of the ideas immanent in nervous activity' [1], and as such their composition mirrors a most rudimentary aspect of the mammalian neo-cortex: nodes are densely linked into a network with connections much like synapses, dendrites and axons connecting biological neurons. However, this is only possible in the context of a global structural property of the neocortex in which neurons, and even more so connections, are distributed across a 3D volume, *cf.* Fig. 1(B). The majority of cortical neurons are arranged in planes located inside the grey matter that wraps around the brain, and stacks of neurons form short-range connections (labelled a in Fig. 1(B)) which travers the grey matter's volume. Crucially, grey matter encloses white matter, and inside this volume the brain's long-range (connections (labelled b and c in Fig. 1(B)) connections are located. 3D connections are therefore a canonical feature of brain architecture. The scale and connectivity of the human brain's network would otherwise simply not fit inside the human skull. The brain therefore provides a very good primer for exploiting 3D circuit topology. Even though the 3D topology of brains emerged from evolutionary development, science and engineering can deliberately combine advantageous strategies and concepts. Combining the 3D network topology of biological brains with photonic signal transduction is a highly appealing strategy for next generation NN computing.

In this paper, we elaborate the potential of 3D printing technology for integrated photonic NN chips. Such additive fabrication enables true 3D integration and naturally complements the mostly 2D lithography that struggles to implement parallel NN connections with a scalable strategy.

Photonics offers fundamental energy, speed and latency advantages when establishing the communication between NN neurons along the staggering amount of network connections. 3D printing is a potential path for 3D integration of optically interconnected Si or other electro-optic chips.

CANONICAL 3D PHOTONIC NEURAL NETWORK ARCHITECTURE

Physically realizing dense connections for the large number of neurons (typically >1000 units) contained in each NN layer results in a formidable challenge. A parallel NN processor needs to provide a dedicated physical link for each connection, which is difficult since the amount of possible connections scales quadratically with the number of neurons. A connection's defining property is its strength, and its physical implementation for example by memristors, micro-rings or holographic memory always occupies some basic unit of area *i.e.* volume. Integration in 2D results in a quadratic scaling of the circuit's area with a network's size [3], *cf.* Fig. 2(A). In a 3D implementation weights can be stacked, for example, in planes, and for the simplest organization [3], both, the number of required planes and memory-elements per plane scale linearly with the number of neurons. This mitigates the size-scalability roadblock and 3D routing may well be a fundamental prerequisite for scalable and parallel NN chips. Realizing such 3D circuits electronically is challenging due to the capacitive coupling and the associated energy dissipation when sending information along signalling wires.

In order to overcome these challenges we investigated a canonical photonic NN architecture where neurons in the form of nonlinear components are arranged in 2D sheets, while connections are integrated in 3D printed photonic circuits, *cf.* Fig. 2(B). We do not constrain the nature of photonic neurons or the 3D routing strategy. All-optical as well as electro-optical components acting as neurons are possible, and the 3D photonic interconnect can be realized by refractive index modifications in a 3D medium, multiple stacks of diffractive-optics planes [4] as well as complex 3D circuitry of photonic waveguides [3].

3D NANO-PRINTING TECHNOLOGY

Additive manufacturing (AM) has been a popular method for prototyping ever since it was developed in the 1980s as it does not require special tooling or molds. However, its true advantage over most conventional manufacturing methods is AM's ability to produce 3D parts of great complexity, which is unfeasible or even impossible with subtractive or 2D lithographic methods. Among various AM techniques, two-photon polymerization

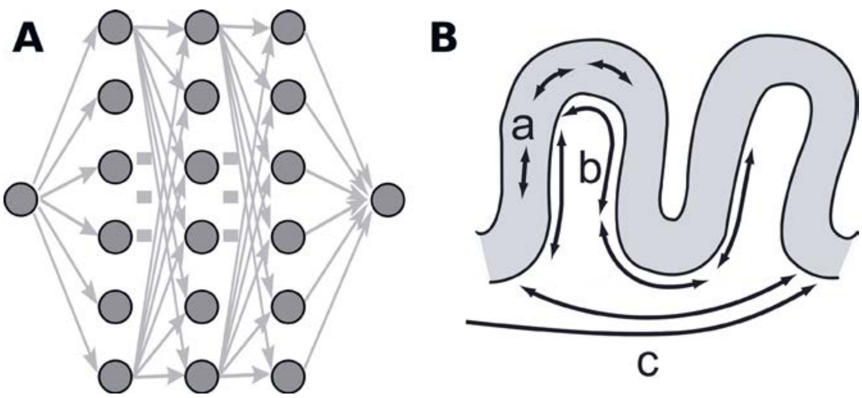
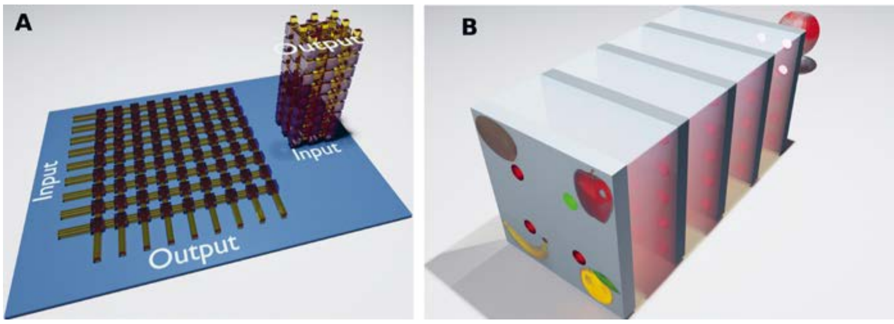


Figure 1.
(A) In a Neural Network (NN) typically millions of connections link simple nonlinear neurons which are arranged in layers. (B) In the brain short, medium and long range (a, b, c, respectively) neural connections are established in the volume of white and grey matter. Adapted from Schüz, *et al.*, Encyclopedia of Neuroscience 2009.



(TPP) is of special interest since it provides sub-micron feature sizes in materials that are transparent in the optical domain with refractive index values close to those of glass. TPP utilizes femtosecond lasers to expose and polymerize photoresists. The two-photon process is of significance as it enables feature sizes below the Abbe diffraction limit thanks to the polymerization's quadratic dependence on exposure intensity. One-photon processes in turn yield larger polymerized voxels due to a linear dependence of polymerization on exposure intensity. Control of the light intensity threshold for polymerization and quenching effects further contribute to sub-diffraction resolution. TPP exposure-dose can be controlled through scanning speed and laser intensity, which provides control over the degree of photoresist's polymerization and hence over the local refractive index. This enables the possibility of printing graded-index (GRIN) elements [5]. 3D direct-laser writing systems offer robust, commercial TPP setups where complex optical elements can be printed (*cf.* Fig. 3) at different resolutions by selecting among different resin-objective pairs. In subsequent sections, we present different optical elements that were fabricated by a Nanoscribe 3D printer.

Figure 2.
(A) Realizing the connections in 2D interconnects is not scalable, and 3D integration is essential for parallel NN integration. (B) In our canonical 2D/3D photonic NN, neurons are arranged in 2D while connections are established in the 3D volume between layers of neurons, where the NN correctly identifies an apple.

For the concepts presented in this paper, the most important feature of AM/TPP is the ability to access independently each voxel in the fabrication volume, which enables holographic as well as wave-guide based photonic connections. From the holography point of view it is key to go beyond $1/M^2$, which is the efficiency relation where M is the number of multiplexed holograms [6]. This fundamental limitation holds for any optical holographic material where recording is accomplished by means of multiple optical exposures [7] due to the superposition of multiple holograms following a recording sequence that is designed to use the dynamic range of the index modulation equally. Crucially, efficiency could be improved to 1/M if the hologram were constructed voxel-by-voxel or in a multilayered fashion. TPP makes it practical to adopt both options. In addition, the ability to access each point in the volume enables the fabrication of complex 3D-routed waveguides that define the optical signal's path in 3D, reminiscent of the dendrites and axons in the brain.

3D DISCRETE-WAVEGUIDE INTERCONNECTS

As previously introduced, connections between biological neurons are made by dedicated 'wires' formed by axons connected to dendrites *via*

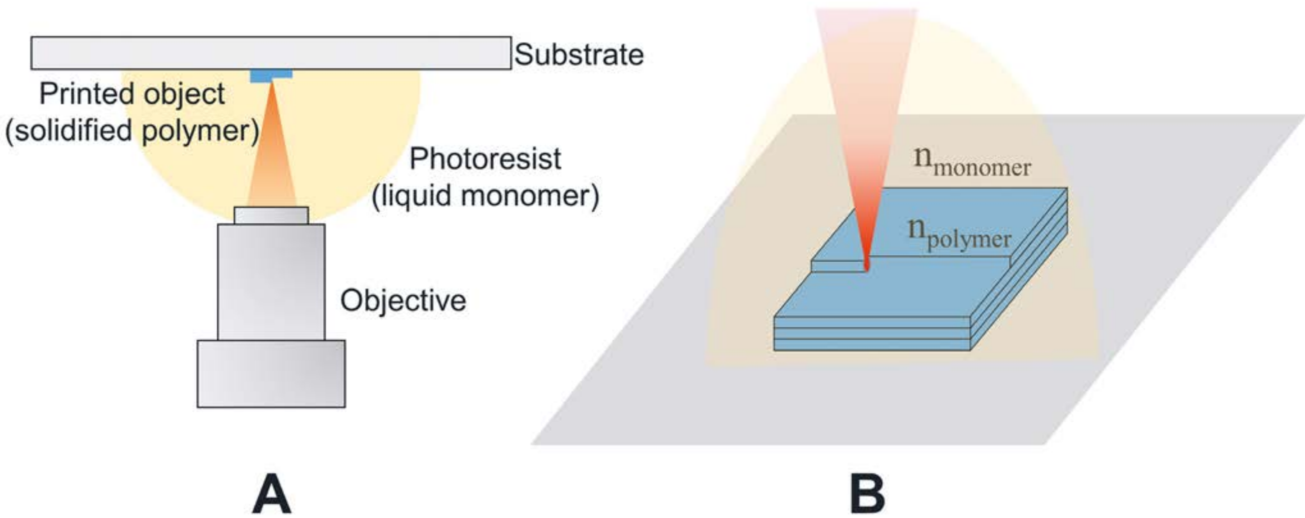


Figure 3.
(A) 3D printing scheme with the objective focusing the femtosecond laser pulse into the photoresist. (B) Layer-by-layer printing process.

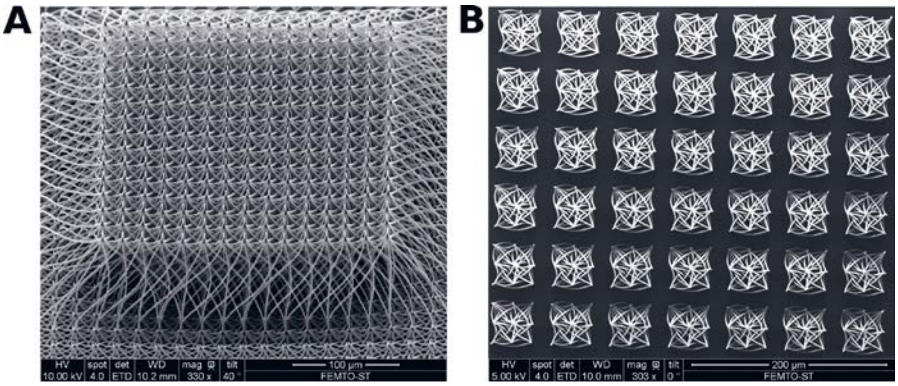


Figure 4.
SEM micrographs of 3D printed waveguides [3] realizing parallel interconnects with high connectivity (A) and according to Haar filters (B).

synapses, and the photonic equivalent of such spatially discrete links is the optical waveguide. An optical waveguide utilizes the principle of total internal reflection, where a medium with a higher refractive index is surrounded by a medium with a lower refractive index. Recently Moughames *et al.* [3] 3D printed such optical waveguides using a Nanoscribe 3D printer and connections in the form of optical splitters realized the dense connectivity between neurons.

Different connection topologies were demonstrated. Arranging 1 to 81 splitters in an 15×15 input waveguide array, *cf.* Fig. 4(A), demonstrated a 3D printed dense interconnect for 225 neurons in an area of only 300×300 µm^2. Inspired by convolutional NNs, the same authors realized Boolean Haar filters arranged in a 7×7 array, see Fig. 4(B). Such arrays can filter images containing 21×21 pixels in parallel, which in principle is sufficient for realizing a convolutional layer applied to the MNIST handwritten digit dataset. Most importantly the area of both 3D interconnects scales linearly with the number of inputs.

GRADIENT INDEX CONTINUOUS INTERCONNECTS

Multilayered diffractive optical elements, *cf.* Fig. 5, can also perform interconnection tasks utilizing the 3D *via* optical volume elements (OVEs). OVEs can be designed by utilizing a nonlinear optimization scheme, learning tomography (LT), which calculates the topography of either multilayered or GRIN volume elements to approximate desired mappings. Figure 5(A,B) shows an demonstration by Dinc *et al.*, which acts as an angular multiplexer (lantern) that maps plane waves with different incidence angles to linearly polarized multimode fiber modes [4]. It provides an interconnect between single mode fibers stacked with different angles and a multimode fiber to map each single mode fiber input/output to a specific mode of multimode fiber, hence performs mode-division multiplexing. Another example of LT computed OVEs realizing Haar filters such as demonstrated in [3] are shown in Fig. 5(C,D).

POSSIBILITIES FOR PHOTONIC NEURONS

The function of a NN neuron is the summation of its inputs followed by a nonlinear transformation. Summation of the individual fields impinging on a neuron can be realized in photonics by the superposition of optical fields. Unfortunately, nonlinearity is since many years the Achilles-heel of photonics compared to electronics. However, modern photonic devices have significantly lowered the energy consumption which can now be below 100 fJ per nonlinear transformation [8]. Many standard nonlinear photonic components have potentially high modulation bandwidths, fast response

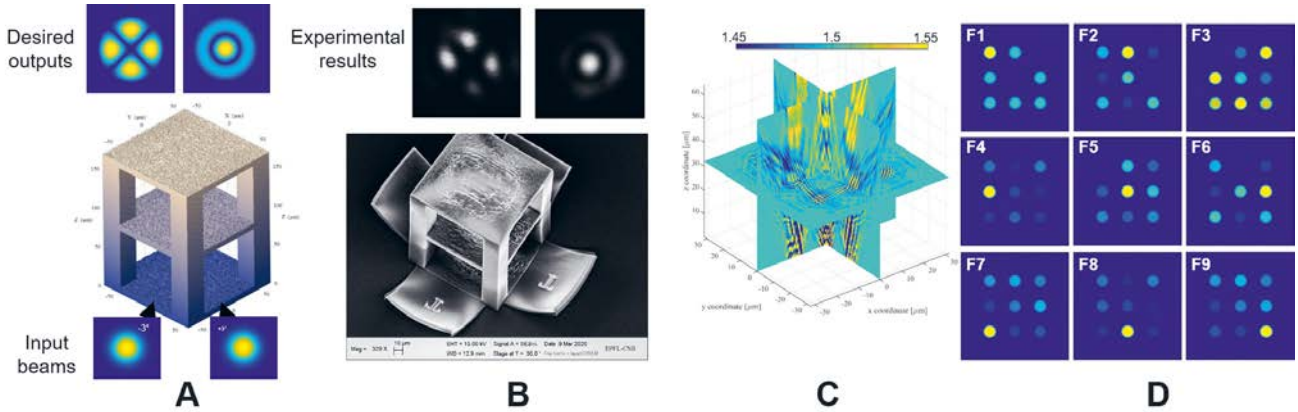


Figure 5.
(A) 3D rendering of the OVE in [4] with the ideal input and output pairs; (B) SEM image of the printed structure and the corresponding experimental results. (C) XY, YZ and XZ cut planes of a GRIN OVE, optimized for Haar filtering. The colorbar shows RI variation. (D) Corresponding output fields obtained by simulating the propagation of inputs through the optimized GRIN volume. All field plots have a window size of 32x32 µm^2 and color code shows the normalized amplitude for each.

times and can directly be interfaced with fully parallel as well as dense 3D photonic interconnects. Photonic neurons combined with our 2D/3D canonical NN architecture therefore offer new concepts for addressing the long-standing challenges of parallelism and connection density for high-speed NN computers.

In order to make most efficient use of the footprint and circuit volume, photonic neurons need to be arranged in a 2D array. Furthermore, neurons that accept multi-mode fields as their input could potentially be beneficial as this relaxes design constraints and allows for high-density integration of 3D photonic waveguides without a cladding. Finally, any optical transformation is associated with losses and the 3D photonic interconnect is no exception; neurons including optical amplification would mitigate such losses. At this stage, we can imagine all-optical, electro-optical as well as plasmonic neurons, and the most promising concept will certainly have to strike a balance between speed, efficiency, flexibility and potentially amplification.

OUTLOOK

The viability of integrating photonic circuits suited for NN interconnects in 3D has recently been demonstrated in principle [3, 4]. Ultimately, scalability is key for computing hardware, which implies that stacking 2D neurons and 3D interconnects into deep photonic NNs requires optical losses to be counterbalanced by amplification without resulting in an unsustainable thermal energy deposition inside the integrated photonic circuit.

However, the computational power of a NN relies on more than simply establishing specific connections in parallel. The nonlinearity of its neurons is a fundamental requirement for solving complex tasks, and here significant room for improvement exists. Another defining feature of NN is the optimization of their connections during training. New, ideally in-situ optimization strategies are in urgent demand. In combination with plasticity such as non-volatile memristive effects, these concepts would significantly reduce the complexity of potential auxiliary support circuits as well as of the 3D interconnect itself.

ACKNOWLEDGMENT

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SILICON PHOTONICS FOR ARTIFICIAL INTELLIGENCE APPLICATIONS

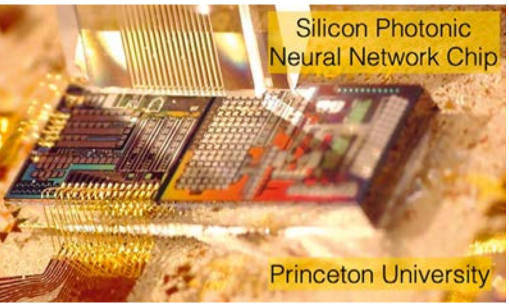
Bicky A. MARQUEZ[1,*], Matthew J. FILIPOVICH[1], Emma R. HOWARD[1], Viraj BANGARI[1], Zhimu GUO[1], Hugh D. MORISON[1], Thomas FERREIRA DE LIMA[2], Alexander N. TAIT[2,3], Paul R. PRUCNAL[2], Bhavin J. SHASTRI [1,2]

[1] Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, ON KL7 3N6, Canada

[2] Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA

[3] Applied Physics Division, National Institute of Standards and Technology, Boulder, CO 80305, USA

*bama@queensu.ca



Artificial intelligence enabled by neural networks has enabled applications in many fields (*e.g.* medicine, finance, autonomous vehicles). Software implementations of neural networks on conventional computers are limited in speed and energy efficiency. Neuromorphic engineering aims to build processors in which hardware mimic neurons and synapses in brain for distributed and parallel processing. Neuromorphic engineering enabled by silicon photonics can offer sub-nanosecond latencies, and can extend the domain of artificial intelligence applications to high-performance computing and ultrafast learning. We discuss current progress and challenges on these demonstrations to scale to practical systems for training and inference.

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Analog computing has recently been considered a potential avenue to decrease energy and time requirements for executing algorithms such as deep neural networks. Analog special-purpose hardware requires the manufacturing of machines to physically model each individual component of such networks. This proves to be a significant challenge as current deep networks scale up to thousands or even billions of neurons to solve complex artificial intelligence (AI) tasks. To enable the use of analog machines to map brain circuitry, the functions of biological neurons must be modelled. The most common neural models are spiking artificial neurons and perceptrons. While spiking artificial neurons are biologically realistic, the field of AI is currently perceptron-based [1].

Perceptrons implement multiply-accumulate (MAC) operations. MAC operations serve to quantify the number of multiplications and additions required to run deep networks. A perceptron of M inputs can perform M MAC operations per time step. Multiple MAC operations can be executed in parallel to implement any type of artificial neural network (ANN). MACs are currently the most burdensome hardware bottleneck in ANNs; for instance, the deep network AlexNet requires 724 million MACs to solve ImageNet [2].

The photonic platform is currently one of the most promising technologies to tackle the expensive calculations performed by deep networks. Silicon photonics offers high-scalability, high-bandwidth, low-footprint, and low-energy consumption [3]. The high-bandwidth and multiwavelength parallel properties of light allow for optical information processing at a high data rate. The ability of neuromorphic photonic systems to provide substantial improvement in our computing capabilities is moving ever closer, with, potentially, PetaMac/second/mm^2 processing speeds.

In this article, we describe a photonic scheme that can perform parallel MAC operations on-chip and introduce two photonic platforms that allow for

AI hardware acceleration: i) a special-purpose photonic architecture for executing the direct feedback alignment (DFA) algorithm for neural network training [6], and ii) an implementation of a Long-Short Term Memory (LSTM) neural network [7]. Both proposed designs offer fundamental speed and bandwidth advantages over digital electronic implementations.

BACKGROUND: NEUROSCIENCE AND COMPUTATION

Digital computers are typically computing systems that perform logical and mathematical operations with high accuracy. Nowadays, such complex systems significantly outweigh human capabilities for calculation and memory. Nevertheless, if we were to compare a human agent with a digital machine, we would see that there are many abstractions that should be made to perform one-to-one comparisons. Such abstractions assume that human cognitive processes are completely procedural and follow standard logic. However, most human cognitive acts do not follow a set of well-defined instructions. Therefore, a one-to-one mapping between human and digital computers might not be suitable.

Analog neuromorphic computing approaches might be more suited to mimic human brain processes. The goal is to create a one-to-one mapping between the neural system and the analog machine, where each biological quantity is modelled by an equivalent analog artificial model. For an architecture such as the human brain, this could be a demanding requirement. The human brain contains approximately 100 billion neurons and 100 trillion synaptic interconnections that must be represented in an artificial machine. However, a subset of the brain circuitry can still be represented in an artificial machine to simulate some of the human cognitive processes.

Recently, most significant advances in the field of AI have been achieved using a perceptron, shown in Fig. 1, as the artificial model of the neuron. The output y of the neuron represents the signals sent from the axon of a biological neuron and is mathematically described by

$$y = f(W \cdot x + b).$$

The x_i inputs transmit the information to the neuron through the weights W_i which correspond to the strength of the synapses. The summation of all weighted inputs and their transformation *via* activation function f are associated with the physiological role of the neuron's cell body. The bias b represents an extra variable that remains in the system even if the other inputs are absent.

ANNs are built using perceptrons as neural primitives such that the synaptic connections are either positive or negative to mimic excitatory and inhibitory neural behaviour. A nonlinear activation function can be used to define activated and deactivated behaviours in artificial neurons. ANNs can be categorized as either feed forward (where connections between neurons do not form a cycle) or recurrent neural networks (where cycles exist).

Attempts to build fast and efficient perceptron-based ANNs have been

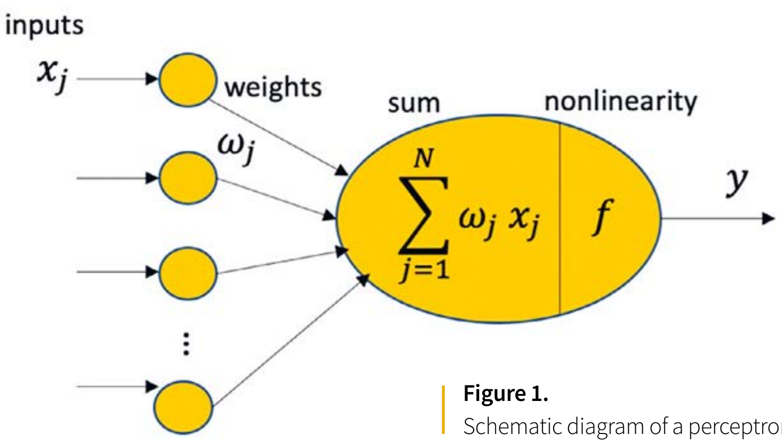


Figure 1.
Schematic diagram of a perceptron.

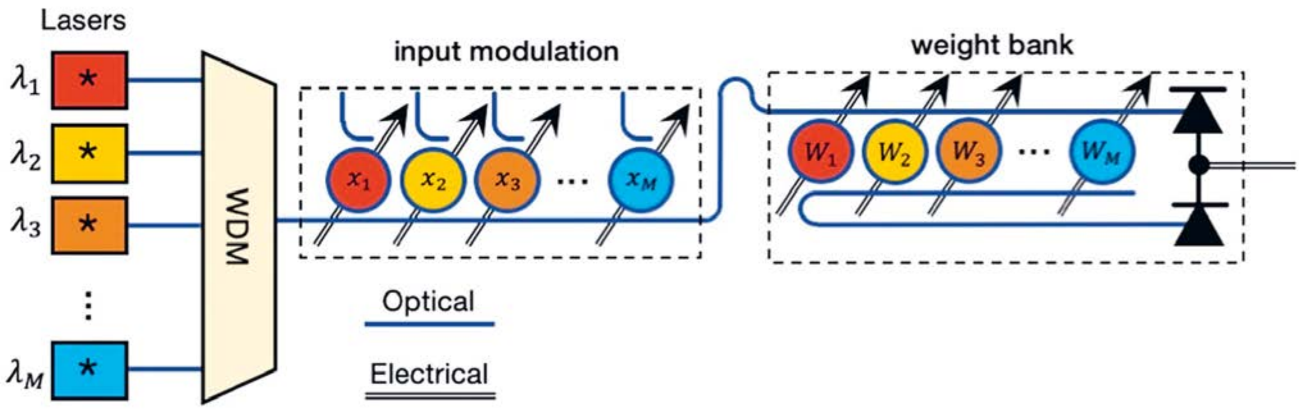


Figure 2.
Add-drop MRR weight bank with a balanced photodetector implementing *M* element-wise multipliers to perform *N* MAC operations in parallel.

reported throughout recent years. An interesting computing acceleration technique consists in using hardware units to perform MAC operations at high speeds. A MAC unit performs multiplications and accumulation processes: (a+$w.x$). Multiple MAC operations can be run in parallel to perform complex operations such as convolutions and digital filters. MACs are typically used in implementations of ANNs in digital electronics [4]. Nevertheless, the serialization of the summands to perform weighted addition makes this process inefficient; consequently, chip designers are looking for alternative solutions such as full parallelism. One of the most promising technologies for this purpose is based on the photonic platform.

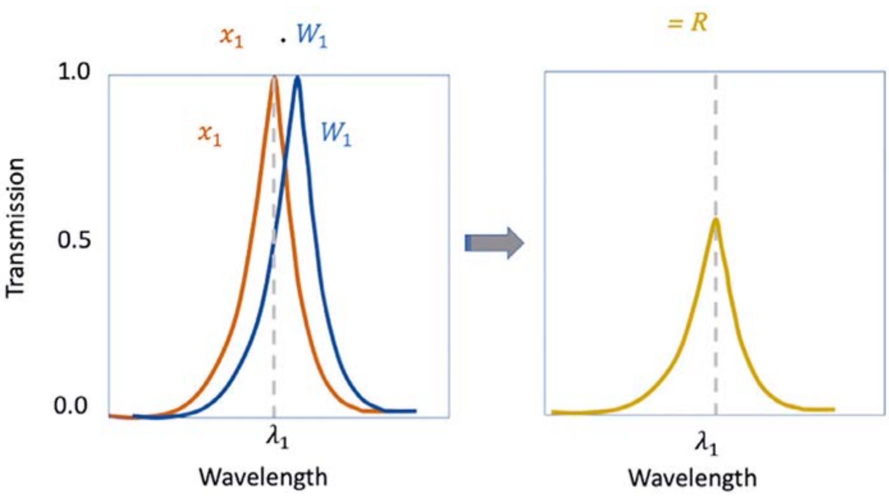
PHOTONIC PERCEPTRON AND MAC OPERATIONS

A scalable photonic architecture that implements parallel MACs can be achieved using on-chip wavelength division multiplexing (WDM) techniques [8]. This design uses microring resonators (MRRs) [9], *i.e.* photonic synapses, to encode input values and weights onto multiple wavelength signals. Tuning a given MRR on and off resonance changes the transmission of each signal through the respective filter, effectively multiplying the signal with a desired weight. An advantage of using MRRs is the ability to tune the weight values using a variety of different methods: thermally, electro-optically, or through light absorption such as phase-change or graphene materials. In this work, tuning is performed by thermally modifying the refractive index of the MRR waveguide. The application of voltage values to the heater allows us to map real-valued numbers to the device.

Figure 3.
(a) Transmission versus wavelength curves of two different MRRs (MRR(x_1), MRR(W_1) performing element-wise optical multiplications, and (b) the product of such multiplication.

An array of M MRRs can emulate the weighted addition of a single neuron if add-drop MRRs and a balanced photodetector are incorporated into the model, as shown in Fig. 2. In this illustration we show how to perform M MAC operations in parallel in photonics. Input values to the neuron can be mapped to voltage values V_i that tune each individual MRR(x_i). Each voltage value has a one-to-one correspondence with an MRR transmission profile T_i, and the same principle holds for weight values. The experimental implementation of this method requires the use of M lasers with different wavelengths λ_i (with $i=1,\dots,M$) that represent M channels.

Two MRRs with different on and off resonance configurations at the same wavelength λ_1 will therefore perform element-wise multiplications, as shown in Fig. 3. Here, we show an illustration of the multiplication



between two transmission elements x_1 and W_1, yielding the resulting value R. In Fig. 3(a), the element x_1 is tuned to have the maximum optical transmission, whereas W_1 is tuned to half the maximum. To implement x_1, MRR(x_1) is set on-resonance with λ_1 and MRR(W_1) is tuned to be half off-resonance with the same wavelength. They represent real-valued numbers 1 and 0.5, respectively. The result of such multiplication, shown in Fig. 3(b), is $R = 0.5$. A similar process is followed with the remaining sets (MRR(x_i), MRR(W_i)) for $i > 1$. Once the weighted-addition is performed using a balanced photodetector, an on-chip nonlinear function can be added by using a microring modulator.

Based on this scheme, we can design systems to solve many complex AI tasks. In the following sections, we will describe how to efficiently implement ANN training and inference on photonic chips.

> Benefiting from the speed and energy advantages of photonics over traditional digital computers, the DFA training algorithm can be implemented *in situ* on silicon photonic hardware

APPLICATIONS

To implement ANNs on photonic chips, we stack N element-wise multipliers that perform weighted additions, as shown in Fig. 4. The $N \times M$ input values received from digital-to-analog converters (DACs) modulate the intensities of a group of M lasers with identical powers but unique wavelengths. These modulated inputs are sent into an array of photonic $N \times M$ weight banks (uploaded from the DACs), which then perform the multiplications for each channel. This architecture is a general representation of the multiwavelength platform as it can be used for inference, as demonstrated in [8], as well as *in situ* training.

ON-CHIP NEURAL NETWORK TRAINING

Benefiting from the speed and energy advantages of photonics over traditional digital computers, the DFA training algorithm can be implemented *in situ* on silicon photonic hardware [6]. The DFA algorithm is a supervised learning algorithm for training ANNs, where the error is propagated through fixed random feedback connections directly from the output layer to the hidden layer. The DFA algorithm has been used to train ANNs using the MNIST, Cifar-10, and Cifar-100 datasets, and yields comparable performance to the popular backpropagation training

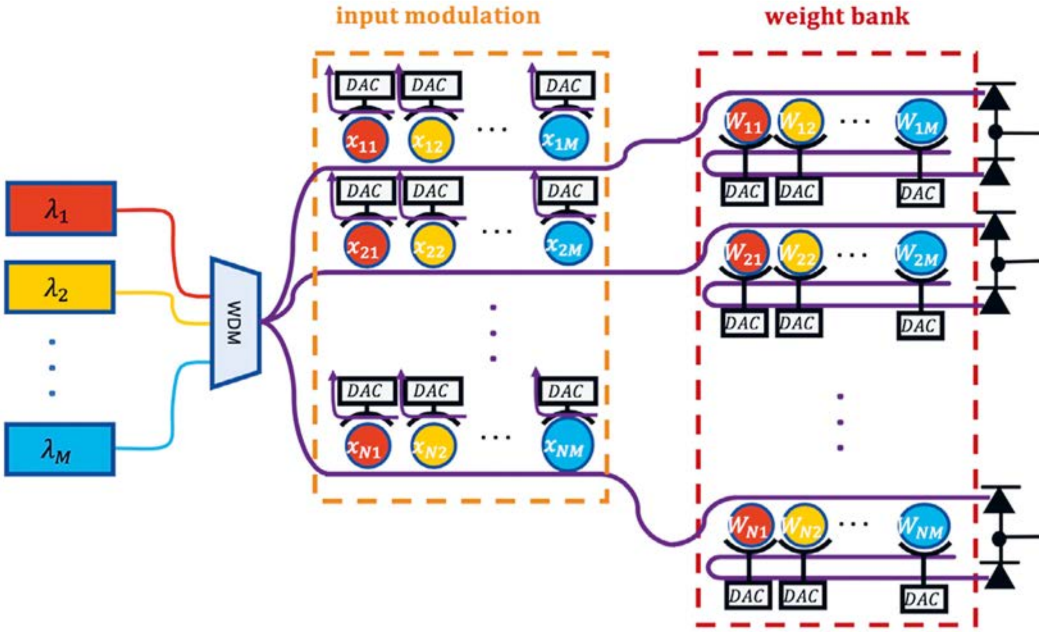


Figure 4. The input and kernel values modulate the MRRs via electrical currents proportional to those values.

algorithm [10]. A DFA photonic integrated circuit can be designed with two connected blocks with $M = 10$ and $N = 100$. This design could perform 2000 MACs per pass, enabling weight updates between two layers of 1000 neurons in 1000 passes.

LONG-SHORT TERM MEMORY NEURAL NETWORK

Similar to the DFA circuit, LSTM networks [11] can also be implemented using the multiwavelength photonic architecture [7]. An LSTM network is a recurrent architecture that offers advantages for time-series processing. Neuromorphic photonic LSTMs offer a solution to the growing demand for high-speed, high-bandwidth neural networks in time-series applications, including video processing, autonomous driving, and optical communications. The performance of the photonic LSTM for inference tasks was tested by applying the network to a simple univariate time series data problem in simulation. The simulation of this task demonstrates that even very small photonic LSTM networks performing up to 64 MACs per pass can be highly effective at performing inference tasks time series data.

CONCLUSION

Neuromorphic photonics promises exciting developments for the future of AI. In an effort to extend the bounds of digital computers for AI applications, the high bandwidth operation and full programmability of analog photonic integrated circuits can facilitate ultrafast learning and inference of ANNs. Current implementations of photonic machines face complex technical challenges that many research groups and companies have begun addressing, including the control of the processing unit and efficient memory access. Successful solutions to these problems could enable the widescale adoption of photonic processors to tackle practical AI applications.

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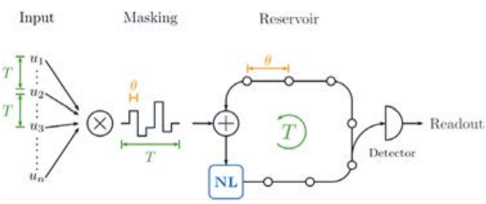
PHOTONIC RESERVOIR COMPUTING USING DELAY DYNAMICAL SYSTEMS

Piotr ANTONIK[1], Serge MASSAR[2,*], Guy VAN DER SANDE[3]
[1] LMOPS EA 4423 Laboratory & Chair in Photonics, Centrale-Supélec & Université de Lorraine, 2 rue Edouard Belin, Metz, France
[2] Laboratoire d'Information Quantique, CP224, Université libre de Bruxelles, Av. F. D. Roosevelt 50, Bruxelles, Belgium
[3] Applied Physics Research Group, Vrije Universiteit Brussel, Pleinlaan 2, Brussels, Belgium
*** smassar@ulb.ac.be**



The recent progress in artificial intelligence has spurred renewed interest in hardware implementations of neural networks. Reservoir computing is a powerful, highly versatile machine learning algorithm well suited for experimental implementations. The simplest high-performance architecture is based on delay dynamical systems. We illustrate its power through a series of photonic examples, including the first all optical reservoir computer and reservoir computers based on lasers with delayed feedback. We also show how reservoirs can be used to emulate dynamical systems. We discuss the perspectives of photonic reservoir computing.

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NEURAL NETWORKS

The next decades will see dramatic evolutions in information processing technology. The exponential improvements of computers known as Moore's law is expected to end. Therefore, in order for performance to continue to improve, one will have to devise computing systems based on entirely new architectures and/or components. One of the most promising approaches is to take inspiration from the biological brain. The brain is able to do remarkable computations, whose underlying algorithm we do not understand, with very low footprint and energy consumption. The brain's architecture is completely different from the von Neumann architecture used in digital computers. It is based on a very large number (10^{10}) of slow (ms time scale) neurons, massively connected together, working in parallel. Thus, an alternative exists.

During the last decades artificial intelligence has made dramatic progress. It enables computers to equal or surpass humans at tasks such as image recognition or game playing. These algorithms are most often based on artificial neural network (*i.e.* brain inspired). They can be viewed as a group of interconnected nonlinear nodes (neurons) on which input signals are applied.

Because such artificial neural networks are fundamentally analog systems, one expects that significant savings in energy consumption and footprint could be achieved by implementing them in analog, rather than digital, hardware. This old dream is attracting renewed interest. Photonics is a promising area in which to realize such analog neural networks. Indeed, photonics allows one to implement high-performance systems and can in principle allow for much higher speed of operation than electronics, with a high degree of multiplexing. Photonic information processing systems would find a natural area of application in telecommunications. It is still too early to know if such promises will be realised. In the following, we sketch some recent work on photonic

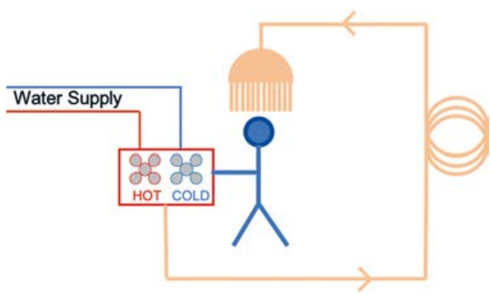


Figure 1.
Schematic of a delay dynamical system. The nonlinear node is the sensory and motor system of the person under the shower. The delay is induced by the pipes between the faucets and the shower.

neural networks based on the reservoir computing paradigm.

RESERVOIR COMPUTING

In general, it is very difficult to optimize all the links (inputs to neurons, interconnections between neurons, neurons to output) in a neural network. Indeed, the most general neural networks are recurrent networks, *i.e.* networks that have feedback loops. But training recurrent networks is hard, because, as one changes the interconnection weights of a recurrent network, one may suddenly enter new dynamical regimes. The system may start oscillating or become chaotic. Such changes completely modify the behaviour of the network and severely impair its information processing capability. Training mechanisms cannot cope with such brutal changes. Therefore, most neural networks use simpler architectures. For instance the deep learning neural networks behind the recent dramatic progress in artificial intelligence are based on feed forward networks without any recurrences.

Reservoir computing [1] uses recurrent networks, but in a way that circumvents the above problems. In this approach, the interconnections between neurons are fixed and chosen randomly. This network of connected neurons, called the Reservoir, is driven by a time-dependent signal. The strength of the connection between neurons is adjusted by a global scaling to a regime where the network will respond deterministically, but in a nonlinear way, to the input signal. The only part of the reservoir computer that is trained is the output layer, *i.e.* the connection between the reservoir and the output neurons. This training is easy because there is no feedback between the output and the reservoir. For instance, one can drive the reservoir with a speech signal, and train an output neuron to have a high level (corresponding to 1) if a certain word is pronounced, and to have a low level (corresponding to 0) otherwise. This approach is not as powerful as the deep networks mentioned above and is no longer the state of the art in machine learning. But it does have very good performance on tasks such as speech recognition, time series prediction, *etc.*

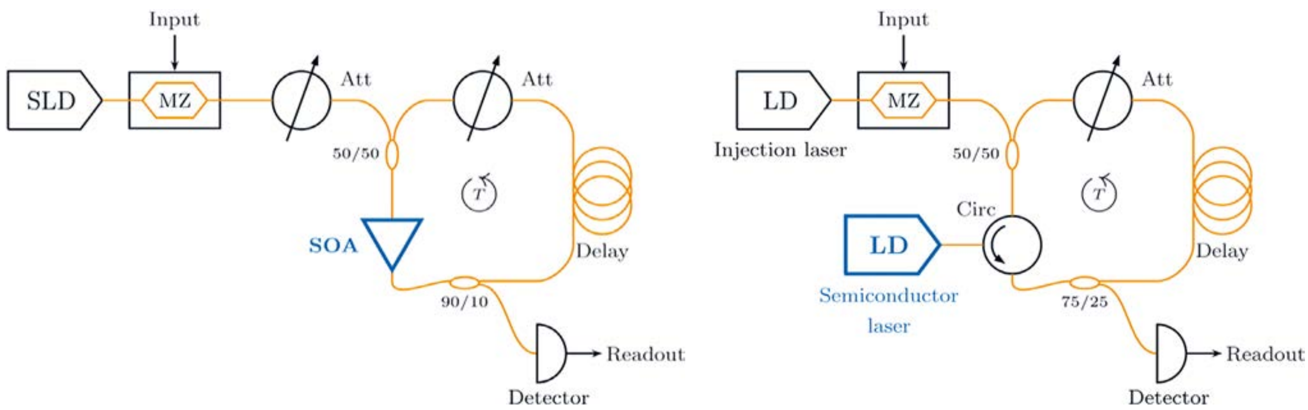
Reservoir computing is a flexible approach. The fact that the networks can be chosen randomly means that there is no need to use biologically realistic neurons. Most high dimensional dynamical systems should work, provided the strength of the nonlinearity can be tuned to bring the system slightly below the threshold for spontaneous oscillations or chaos. This flexibility makes reservoir computing particularly well suited for experimental study.

DELAY DYNAMICAL SYSTEMS

Delay dynamical systems can be found in biology, chemistry, physics, engineering. A simple example is the regulation of the temperature in a shower, see Fig. 1. Imagine you are taking a shower, and the water is too cold. You turn the hot water faucet. There is a delay between your action on the faucet, due to the length of pipe between the faucet and the shower, and the change in temperature of the water. If you have turned the faucet too far, the water may become burning hot after that delay. So you switch off the hot water faucet. Now, it is freezing cold. If you continue, you may oscillate indefinitely between a too hot and a too cold shower, without ever reaching the right temperature.

This is a typical example of a delay dynamical system. Your action on the system at time t depends on its state at an earlier time t-T (here T is the delay induced by the pipes). As the example shows, such systems can have highly complex dynamics. They can exhibit oscillations and even chaos. Furthermore, they are very high dimensional systems, since the state of the system at time t depends on all the past history between t and t-T.

Figure 2.
All-optical reservoir computers based on delay dynamical systems. Left, schematic of the first all-optical reservoir computer [3] operating in incoherent light. Right, schematic of a reservoir computer based on a semiconductor laser with delayed feedback [4]. In both experiments the masked input is encoded using a Lithium Niobate Mach-Zehnder intensity modulator (MZ). Fiber optics components are in orange. The nonlinear node which is essential for in reservoir computers is represented in blue. Super-luminescent Light Emitting Diode (SLD), Attenuator (Att), Semiconductor Optical Amplifier (SOA), Laser Diode (LD).



Delay dynamical systems are rather easy to implement and study experimentally, because they require only a delay loop and a nonlinear node through which the feedback acts. In the example, the delay is the pipe, and the nonlinear node is the combination of your sensory and motor system.

DELAY SYSTEMS AS RESERVOIRS

The rich dynamics, high dimensionality, and ease of experimental implementation make delay dynamical systems good candidates for reservoir computers. How does one transform a delay dynamical system into a reservoir? The answer is to divide the delay loop of length $L=vT$ (with v the speed of propagation around the loop) into N intervals of length L/N and duration $\theta=T/N$, and consider each interval as a ``neuron” [2]. In this way, we create a large number N of neurons (typically N ranges between a dozen to several hundreds). We then drive the delay system with the input signal u to which we apply a sample and hold procedure so that the input is held constant during a delay T.

However, this procedure is not sufficient, because all the N neurons would be identical, all having the same behaviour. To solve this issue, a masking procedure is applied: the input u is multiplied by a mask m(t) which is periodic of period T. In this way, each neuron is multiplied by a different value of the mask, and therefore exhibits different dynamics. The Table of Content Graphics represents schematically the masking procedure and the neurons distributed along the delay loop.

In order to further improve performance it is necessary to couple the neurons together. Two solutions have been proposed. The first is to introduce a low pass filter in the delay loop with time constant comprised between T and θ. The second is to slightly desynchronize the time during which the input is held constant and the round-trip time T.

The output of the reservoir is obtained by measuring the system during a time T, thereby collecting the states of the N neurons. The output is a linear combination of these N states, with the weights of the linear combination adjusted through a training procedure.

ALL-OPTICAL RESERVOIR COMPUTER

These principles were used to build the first all optical reservoir computer [3]. It consists of a fibre optics delay dynamical system operating in the telecommunication C-band, see Fig. 2. This first system operated using incoherent light. An electronic signal corresponding to the time dependent input multiplied by the input mask is generated electronically and drives an intensity modulator thereby producing a time dependent input optical signal whose intensity is adjusted with a variable attenuator and which is then is injected into the fiber loop. The delay dynamical system consists of a Semiconductor Optical Amplifier (SOA), a variable optical attenuator, and a fiber spool that acts as delay line. The SOA operating near saturation acts as nonlinear node. The cavity operates below the lasing threshold. A tap coupler followed by a readout photodiode is used to measure the neurons. The round trip time of the delay system was $T=7.9$ µs, corresponding to the time needed to process one input. The number of internal nodes, *i.e.* neurons, was varied between N=50 to 200. The output of the reservoir was computed off-line on a digital computer. The system was used for a telecommunication inspired task, the equalization of a nonlinear communication channel, and for a simple speech recognition task, the recognition of isolated spoken digits.

RESERVOIR COMPUTER BASED ON SEMICONDUCTOR LASER WITH DELAYED FEEDBACK

Semiconductor lasers are the most common type of lasers, with a wide range of applications such as telecommunication, material processing, etc. Semiconductor lasers submitted to optical feedback have a rich dynamic which has been intensively studied. In reference [4] the nonlinear response of a semiconductor laser subject to feedback was used as reservoir, see Fig. 2. The external input was injected as a modulated optical field and the output layer was implemented off-line after detection. The optical feedback loop had a delay of $T=77.6$ ns. It was used to classify spoken

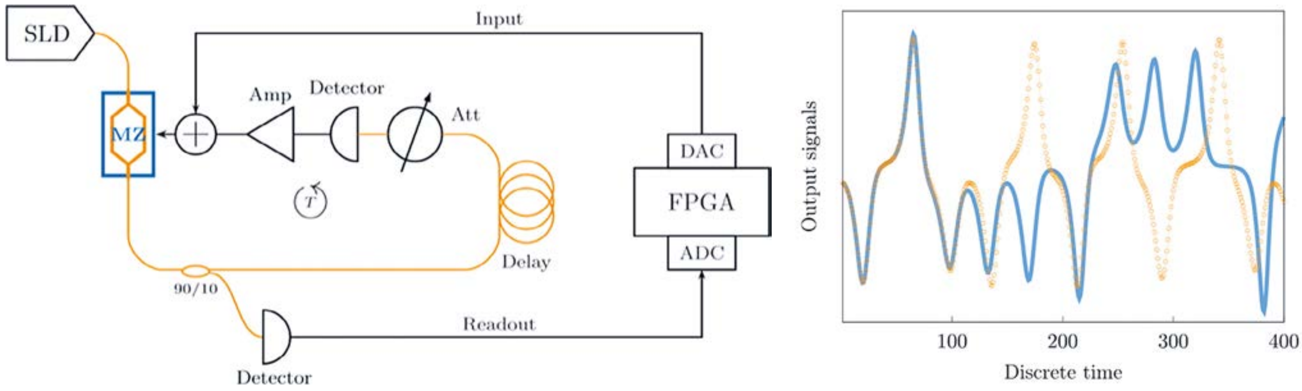


Figure 3.
Reservoir computer used to emulate a chaotic system (adapted with permission from [6]). The optoelectronic reservoir is schematized on the left. Fiber optics components are in orange, electronic components are in black. The nonlinear node is a Mach-Zehnder modulator. The output is computed online using a Field-Programmable Gate Arrays (FPGA) coupled to an Analog-to-Digital Converter (ADC) and a Digital-to-Analog Converter (DAC), and then reinjected as input into the reservoir. Right, output of the reservoir when used to predict the trajectory of the Lorenz system. Initially (up to approximately t=100) the reservoir output (in orange) follows faithfully the trajectory of the Lorenz system. Afterwards the trajectories diverge, but stay similar to the trajectories of the Lorenz system.

digits and to forecast chaotic time series. Subsequent work focused on increasing the speed of such systems and integrating them on a Photonic Integrated Circuit (PIC). Recently a compact and robust chip based reservoir was demonstrated by integrating a semiconductor laser and a 5.4 cm delay line (corresponding to a time delay of T=1.2 ns) on an InP photonic chip [5]. This reservoir accommodates N=23 neurons and showed good performance on tasks.

USING RESERVOIRS TO EMULATE DYNAMICAL SYSTEMS

Let us imagine you would like to predict future samples of a time series, such as the evolution of the stock market, or the output of a dynamical system. Reservoir computing provides a very powerful way to achieve this goal [1]. All you need is a record of the time series during a sufficiently long period of time. First, you drive the reservoir with the recorded time series and train the reservoir to predict the time series one-time step ahead. When you reach the end of the recorded time series, you feed the one-time step ahead prediction back into the reservoir as input signal. In this way the reservoir becomes an autonomous system that can predict the time series a second time step ahead. Continuing like this, you will predict the long-time behaviour of the time series. Due to noise and limited precision your prediction will diverge after some time from the true time series, but it will be similar to the original time series. The reservoir, with its output feedback as input, is now emulating the dynamical system you were trying to predict. This remarkable behaviour has been studied theoretically [1] and experimentally [6], see Fig. 3.

CONCLUSION

Reservoir computing, because of its versatility and ease of implementation, has allowed experimental implementations of neural networks with performances comparable to digital implementations. The architecture based on delay dynamical systems is behind much of this progress, as it simplifies the experimental system which consist only of a delay line and a non-linear node. However, such implementations have an inherent limitation, because all neurons are processed sequentially, which slows down overall operations. An important current objective is to develop architectures in which all neurons are processed simultaneously. Increasing speed, decreasing footprint, broadening the scope to other types of neural networks, are other important goals. Whether such analog neural electronic or photonic networks will find applications remains to be experienced. Today they are very exciting research topics, at the boundary between technology and artificial intelligence.

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ARTIFICIAL INTELLIGENCE: FROM ELECTRONICS TO OPTICS

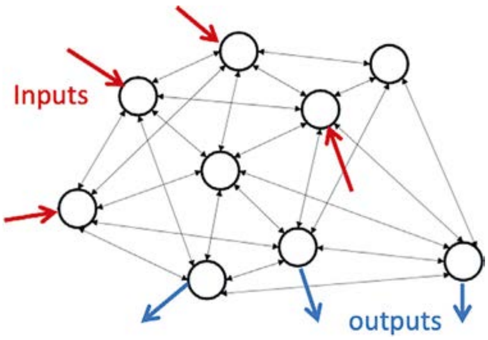
Sylvain GIGAN[1,3,*], Florent KRZAKALA[2,3], Laurent DAUDET[3], Igor CARRON[3]

[1] Laboratoire Kastler Brossel, ENS-Université PSL, CNRS, Sorbonne Université, Collège de France, Paris, France

[2] Laboratoire de Physique de l'École Normale Supérieure, ENS, Université PSL, CNRS, Sorbonne Université, Université de Paris, Paris, France

[3] LightOn, 2 rue de la Bourse, Paris, France

***sylvain.gigan@lkb.ens.fr**



Machine Learning and big data are currently revolutionizing our way of life, in particular with the recent emergence of deep learning. Powered by CPU and GPU, they are currently hardware limited and extremely energy intensive. Photonics, either integrated or in free space, offers a very promising alternative for realizing optically machine learning tasks at high speed and low consumption. We here review the history and current state of the art of optical computing and optical machine learning.

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Since the dawn of micro-electronics and the emergence of lasers, both optics and electronics platforms have been competing for information processing and transmission. While electronics has been overwhelmingly dominating computing for the last 50 years thanks to Moore's law, optics and photonics have been increasingly dominant for communications, from long distance communications with optical fibers to optical interconnects in data centers. Machine Learning, that also originated in the 1950s, has seen tremendous developments in the last decade. The emergence of deep neural networks has become the *de facto* standard for big data analysis and many of the tasks that we today consider normal: from voice recognition to translation, image analysis to future self-driving cars. However, machine learning's progress requires exponentially increasing resources, be it in memory, raw computing power, or energy consumption. We introduce in this article the basics of neural networks, and see how this new architecture shatters the *status quo* and provides optics a new opportunity to shine in computing, whether in free space or in integrated photonics circuits.

EXPECTED CONTENTS

Optical computing. Classical computing, such as the one running on our PC, is based on the so-called Von-Neuman architecture laid out in the 1940s, where a program is stored in a memory, and instructions are read and executed on a processor, while input and output are exchanged in the memory through a communication bus. This architecture has been basically unchanged since its inception, and only improved thanks to the progress of microelectronics and nanolithography, allowing the feature sizes of components to shrink to 7 or less nanometers nowadays. This has consequently diminished tremendously the Ohmic losses and the energy consumption to a few pJ/operation, and allowed the increase of the operating clock frequencies of the components to reach several GHz. Thus, component density has driven the number of transistors on a processor to several tens of billions, while driving its cost down. This is the well-known Moore's law, leading to the observation that a good desktop PC nowadays has a processing power of several TeraFlops (10^{12} floating point operations per second).

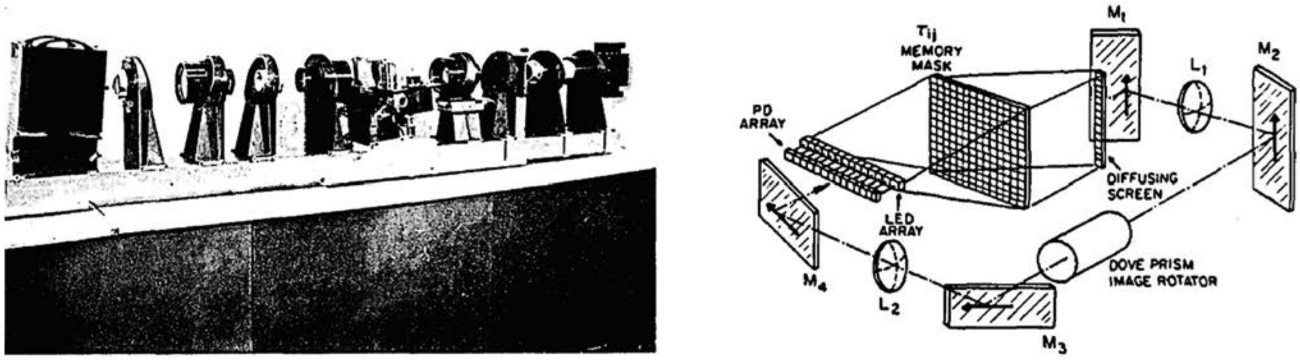
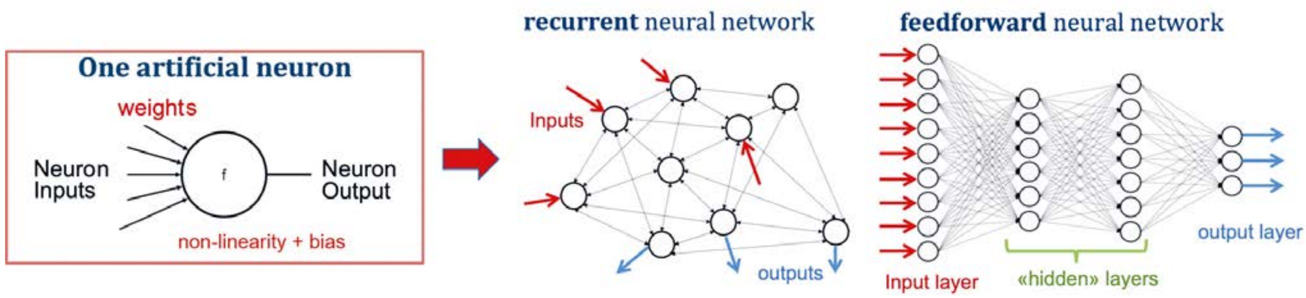


Figure 1.
Some historical examples of optical computing. Left: the 1972 Tilted Plane Optical processor used for synthetic Aperture Radar all optical image processing (from Kosma *et al.* Applied Optics 11.8 (1972): 1766-1777), right, a vector-matrix-multiplier with optical feedback (from Psaltis *et al.* Optics Letters **10.2** (1985): 98-100) Reprinted with permission from © The Optical Society.

Optics has several advantages compared to electronics: its intrinsic parallelism, its almost unlimited bandwidth, the ability of simple transformation by simple propagation (such as a Fourier Transform) compared to electrons [1]. Thus, optics has from the very start been considered as a viable alternative for analog computing. In the eighties, the emergence of optical non-linearities, semi-conductor lasers and optical memories has given hope that optics may be used to build an all-purpose computing platform. Alas, the progress in optics failed to match Moore's law exponential pace, and the hope of building such an all-purpose optical computer was abandoned in the nineties [2]. Still, optics found numerous applications in storage, and of course in telecommunications, both in long-distance with optical fibers, and more recently in interconnects.

Neural networks. In parallel, a computing paradigm, resolutely different from conventional programming, emerged also in the 1950's: Artificial neural networks or ANN, on which all modern artificial intelligence is based. It is (loosely) inspired from the structure and behaviour of the brain, where neurons are connected to each other in very complex networks, and where the response of a neuron can be triggered in a complex and non-linear way by the electric influx it receives from many other neurons. Artificial neural networks are similarly made of "neurons" or nodes, that integrate signals from other neurons, with various weights, and emit a resulting signal based on a non-linear activation function. This signal is, in turns, fed to a number of other neurons. The network also includes input and output neurons, that either receive or send information to and from the outside world. Just like the brain, a neural network can be made to "learn", *i.e.* be optimized for a given task, by adjusting its weights, for instance being fed at the input with images, being able to classify them into categories. The analogy with the brain stops there: while the brain counts approximately 80 billions neurons and 100 trillions connections, ANNs have to be limited to much less neurons and weights, and to much simpler architectures, in order to make the training of the network possible. Several typical architectures have been developed over the last decades, to maximize efficiency on a given task, while keeping the training of the neural network computationally tractable. Most of the time, neurons are organized in layers of various sizes (number of neurons) and connectivity. It ranges from the simplest networks, such as the perceptron (a single layer linking N inputs to a single output) which was one of the earliest ANN, to multi-layered feedforward neural networks (where neurons are organized in successive layers and information is passed from

Figure 2.
Structure of an artificial neural network. Left: an artificial "neuron" comprising several inputs value, and one or many outputs, result of the non-linear combinations of the inputs. Center and left: two popular ANN architectures.

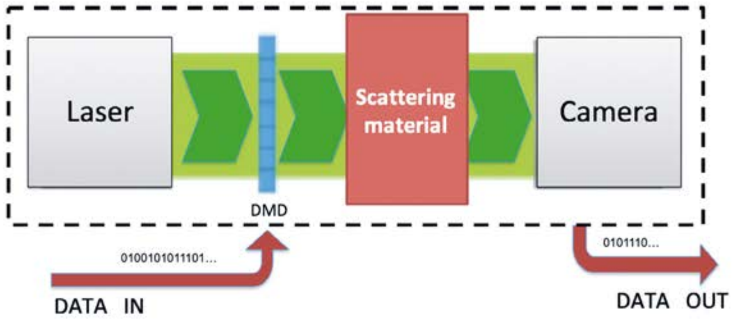


layer to layer) to recurrent networks (where information can flow backwards and be fed back to previous layers). The connections from a layer to the next can be very sparse, in particular convolutional layers, or dense (all-to-all connected). The performance of ANNs depends on its structure, for instance a perceptron is good for simple linear classification, but more complex tasks require more complex network structures.

Deep learning. While artificial intelligence saw good progresses, until the early 2000s, its overall performance for day-to-day tasks remained modest and did not find any clear real-life applications. This changed tremendously in the last two decades, thanks to the emergence of a powerful architecture: Deep learning, and its corollary networks, known as Deep Neural networks. Deep Neural networks are layered networks with a large number of "hidden" layers. Pioneers such as Yann Lecun, Yoshua Bengio and Geoffrey Hinton, have shown that deep neural networks have an ability to solve highly complex problems [3]: in essence, while the first layers can pre-process the input information (for instance contours in images, or words in text), deeper layers can gradually distil more abstract concepts, such as identifying an object, or extracting the sense of a text. Nowadays, deep learning has demonstrated unprecedented performance at tasks that we only recently believed would be forever out of reach of machines, from beating the best player at the game of Go, to self-driving cars, to language translation, to give just a few salient examples. Such deep networks have grown to unbelievable sizes, up to tens of billions of parameters (weights) to be trained. Thus, a key-enabling concept that has allowed deep learning to scale to large size is the ability to train such large network efficiently: the back-propagation algorithm, a concept perfectly matched to deep architectures, where the network can be trained layer by layer from the last to the first with a gradient-descent algorithm. Thanks to these, machine learning has entered the ability to make sense of complex and very large size information; this is sometimes coined as "big data".

GPU and CPUs. The rise of deep learning and big data has been mostly powered by Moore's law, allowing training and inference of very large neural networks. An important factor driving deep learning is the transition to Graphic Processing Units (GPU). Initially designed for computer graphics, these specialized processors were optimized for parallel processing of large vectors and matrices. For neural networks, where training and inference require a vast number of such multiplications, GPUs turned out to be much more powerful than CPUs (Central Processor Unit) and are now ubiquitous - incidentally, NVIDIA, the leader in GPU for deep learning, has now a capitalization that is on par with Intel. However, GPU and CPU are still enormously power-hungry: it has been shown that training a single neural network can use as much energy as 5 cars over their lifetime, and more globally, big data and data centers already account for an estimated 4% of our energy, and it may grow to over half of our energy consumption in the next decade, if nothing changes. Meanwhile, Moore's law is officially stalling: nanolithography and transistors are reaching their physical limits, progresses in consumption and speed are getting much slower [4]. Worse, the implementation of neural networks on both CPU and GPU suffers from the so-called "Von Neumann bottleneck": the bus transferring data between memory and computing units ultimately limits performance.

The dawn of optical Machine Learning. To overcome this fundamental problem, some non-conventional computing hardware has been introduced, called "neuromorphic", where circuits are directly emulating the connectivity and functions of a neural network, instead of a program on a CPU or GPU. This approach, that broadly belongs to non-von-Neumann architectures, should be much more energy efficient, and fast. Of all the possible implementations of neuromorphic computing, Optics and Photonics stands out, with unique advantages. First, light can propagate virtually without loss or heating, whether in free space, in many materials, or in integrated waveguides. This propagation



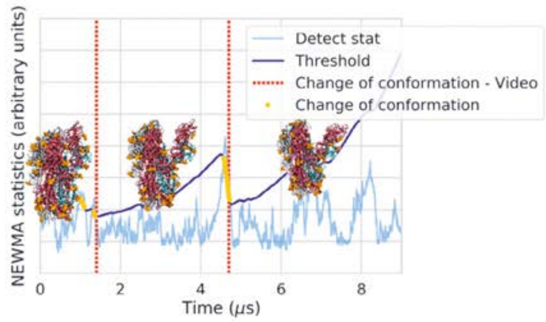


Figure 3.
LightOn's optical processor. Left: scheme of the random projections principle, information is encoded on a spatial light modulator, then a random matrix multiplication is achieved by passing through a disordered material, and the result is read of a camera sensor. Right: example of an advanced machine learning task, here the automatic detection of conformational change of a large molecule in molecular dynamic calculations (here on SARS-Cov2 molecule, responsible for the COVID-19 disease) [5].

can be used to emulate the connectivity between two neural layers, but also convolutions, etc. Photons do not naturally interact, meaning it is possible to multiplex information, and power consumption is independent of the operating frequency. Finally, thanks to tremendous progress in optoelectronics, detectors (from fast photodiodes to CMOS cameras), modulators (from fast integrated electro-optics modulators to spatial light modulators), and source (lasers), are extremely efficient and can be mass-produced. The semiconductor industry naturally provides the backbone to produce photonic integrated circuits. In short, optics has several key-advantages to implement neural networks in a nearly ideal way. Still, optics faces several challenges, in particular the difficulty to achieve non-linearities in hidden layers, or the challenge to scale and tune networks with integrated optics, preventing the possibility, to date, to provide a true versatile platform for deep learning. Yet, optics can provide a very solid alternative in specialized implementations, from ultrafast small scale networks, to convolutions and pre-processing in imaging, to reservoir computing (a type of RNN with fixed weights). After pioneering works in the 80s and 90s, many impressive advances have been reported in academia in the last decade, and industry also shown a renewed interest, whether within big companies or through start-up creations.

An example, LightOn. As an illustration of how optics can benefit machine learning, LightOn (the company we co-founded in 2016) proposed a solution to perform optical machine learning, based on our experience in free-space light propagation in complex media. In essence, we currently provide very large-scale random matrix multiplication (corresponding to a dense all-to-all connectivity) between millions of inputs (spatial light modulator pixels) and millions of outputs (camera pixels). Able to operate at several kHz, it corresponds to doing several Peta-Operations per second (typical of supercomputers), with a matrix size that could not even be stored in the memory of a conventional computer, and with a consumption of a few tens of Watts. While apparently very specific, the operation we propose can be useful in many data processing applications, from inference to training [5], or even molecular dynamics (see Fig. 3). In fact, these random multiplications can be seen as universal compression engines, with performance guarantees that are well matched to the very statistical nature of modern machine learning. Of course, this is just one approach to optical machine learning, and other approaches, either based on free space or integrated optics, fixed or tunable weights, linear or non-linear effects, shallow or deep, also proposes various solutions to accelerate machine learning and support its future growth.

CONCLUSION

In conclusion, we have presented an historic perspective of optical computing and shown that, after having failed at proposing an all-purpose computing platform in the 20th century, optics and photonics have more recently emerged as very appealing solutions for hybrid hardware implementation of neural networks, able to sustain the growth in computing power and supersede electronics, beyond Moore's law. Optical neural networks have recently rebooted the interest in optical computing, and we believe it is just the beginning.

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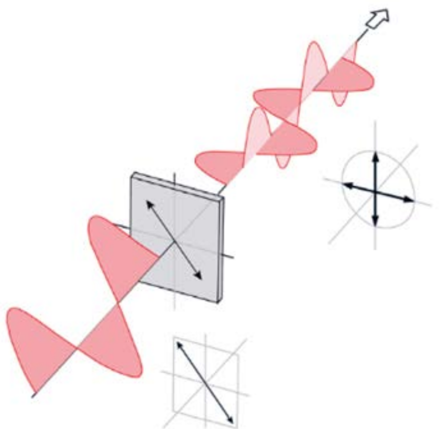
WAVEPLATES: PHYSICAL PRINCIPLES, USES AND PURCHASE TIPS

Xavier ZAMBRANA-PUYALTO
Istituto Italiano di Tecnologia – Via Morego 30, Genova 16163, Italy – **xavislow@protonmail.com**



Waveplates are optical elements that are mainly used to tailor the polarization of collimated optical beams. Their use is as spread as that of the polarization of light. As a result, the market offers an overwhelming amount of options. Here we explain how to navigate through this sea of possibilities.

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Image adapted from http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/quarwv.html

Light beams are electromagnetic (EM) fields fulfilling Maxwell equations. For non-relativistic applications, they can be described with an electric and a magnetic field. The magnetic field of light tends to be negligible compared to the electric field, and in the remaining of the article it will be neglected. The electric field is a three dimensional vector function, which is described as a function of space and time, *i.e.* $\mathbf{E}(\mathbf{r},t)=(E_1(\mathbf{r},t), E_2(\mathbf{r},t), E_3(\mathbf{r},t))$. Yet for many optical applications, in particular in all of those where the light beam is collimated, the electric field can be described within the paraxial approximation. In this approximation, and assuming a monochromatic response, $\mathbf{E}(\mathbf{r},t)$ can be expressed as a transverse scalar function times a unitary two-dimensional vector, *i.e.* $\mathbf{E}(\mathbf{r},t)=E(x,y)\exp(ik_z z-i\omega t)\mathbf{u}$, where $\mathbf{u}=u_x\mathbf{x}+u_y\mathbf{y}$ is referred to as the polarization vector.

Within the paraxial regime, the polarization vector $\mathbf{u}$ and the transverse spatial pattern of the beam $E(x,y)$ can be modified independently. Let us emphasize that this is not the case for non-paraxial or tightly focused beams. That is why, within the paraxial approximation, modifying $E(x,y)$ does not affect the polarization vector $\mathbf{u}$, and modifying the polarization vector

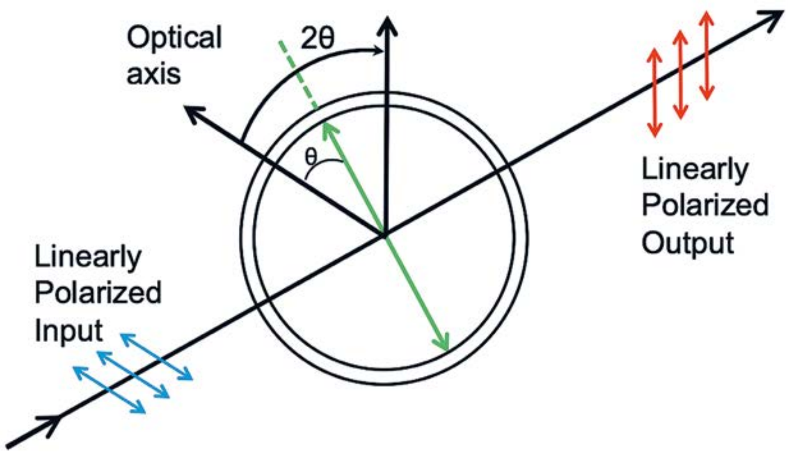

Figure 1.
A linearly polarized collimated beam propagates through a half-wave plate. The optical axis of the waveplate forms an angle θ with the polarization of the incoming beam. As a result, the polarization of the output beams is rotated by an angle 2θ with respect to the input beam. Image adapted from [5].

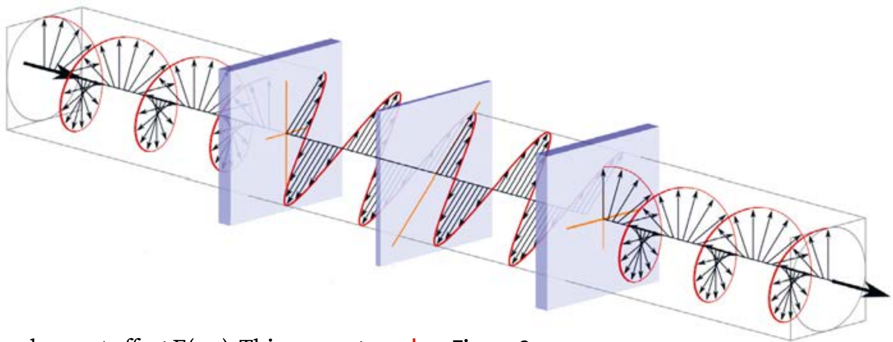

Figure 2.
A circularly polarized beam is transformed into a linearly polarized beam and back to a circularly polarized beam by two quarter-wave plates. Image adapted from [6].

u does not affect E(x,y). This property is widely used in optical experiments. Whereas E(x,y) can be modified with many different methods, *e.g.* waveguides, spatial filters, holograms [1], SLMs [2], *etc.*, **u** is mostly tailored by linear polarizers and waveplates. The operations carried out by linear polarizers and waveplates are fundamentally different: while waveplates carry out unitary transformations, *i.e.* they do not modify |E(x,y)|, linear polarizers act as projectors and they can modify E(x,y) [3]. In this article, we will focus our attention on waveplates.

Let's consider a monochromatic paraxial beam $\mathbf{E_{in}}(\mathbf{r},t)=E(x,y)\exp(ik_z z-i\omega t)(u_x\mathbf{x}+u_y\mathbf{y})$ with $|\mathbf{u}|^2=1$. When $\mathbf{E_{in}}$ goes through a piece of homogeneous and isotropic material of thickness *d*, it is known that the beam picks up a phase [4]. That is, at the exit of the material, $\mathbf{E_{out}}=\mathbf{E}_{in}\exp(-inkd)$, where *n* is the index of refraction of the material, and *k* the wavenumber of the beam. The phase picked up by the beam is the same for the two polarization components (**x** and **y**), and it is proportional to both the thickness of the material *d*, as well as its index of refraction *n*. Now, let us imagine that the index of refraction of this material of thickness *d* was such that it was n_x/n_y for the **x**/**y** polarization components. In that case, $\mathbf{E_{out}}=E(x,y)\exp(ik_z z-i\omega t)\ (u_x^{out}\mathbf{x}+u_y^{out}\mathbf{y})$, with $u_{out}^{x/y}=\exp(-in_{x/y}\,kd)u_{x/y}$. As a result, $u_x/u_y\neq u_x^{out}/u_y^{out}$. That is, the propagation of a paraxial beam through a medium whose index of refraction depends on the polarization direction changes the polarization state of the beam. These media are called anisotropic, because the index of refraction depends on the polarization direction. *Waveplates* are optical elements made of anisotropic materials which are designed to tailor the polarization state of a paraxial beam in a certain way. There exist different kinds of waveplates, depending on the kind of polarization transformation that they carry out. Next, we will explore the properties of three different kinds of waveplates: half-wave plates, quarter-wave plates, and radial polarizers.

HALF-WAVE PLATES

Half-wave plates are birefringent materials, *i.e.* an anisotropic material with two different indexes of refraction, which are used as *polarization rotators*. Polarization rotators take a linearly polarized state and rotate it to yield another linear polarized state rotated by 2θ. A rotation by an angle 2θ implies that the fast axis of the waveplate and the polarization direction of the incoming beam form an angle of θ (see Fig. 1). Half-wave plates can also be used to transform a right circularly polarized beam into a left circularly polarized beam or vice versa.

QUARTER-WAVE PLATES

Quarter-wave plates are birefringent materials which are a particular case of polarization retarders. Assuming that the fast axis of the polarization retarder is along **x**, then the polarization retarder takes a polarization state $\mathbf{u^{in}}=u_x\mathbf{x}+u_y\mathbf{y}$ and transforms it into a state $\mathbf{u^{out}}=u_x\mathbf{x}+e^{i\Gamma}u_y\mathbf{y}$. Quarter-wave plates are polarization retarders with a phase lag $\Gamma=kd(n_x-n_y)=\pi/2$. This is equivalent to say that the retardance, which is defined as $d(n_x-n_y)$ is equal to $\lambda/4$. Hence, when the incoming beam is linearly polarized and its polarization state forms and angle of 45 degrees with respect to the fast axis of the waveplate, then the output is a circularly polarized beam (see Fig. 2). The inverse transformations are also possible, *i.e.* an incoming circularly polarized beam will be transformed into a linearly polarized beam (see Fig. 2).

LIQUID CRYSTAL POLARIZERS

Even if they are not typically called waveplates, one could consider liquid crystal polarizers to be waveplates too. As mentioned earlier, (linear) polarizers carry out projection transformations: not only they change the polarization state of a beam, but also they modify the value of E(x,y). In contrast, waveplates carry out unitary transformations which turn a polarization state into another. Liquid crystal polarizers do exactly this. The difference between them and the two previously mentioned waveplates is that liquid crystal polarizers are non-homogeneous. That is, the polarization change given by the liquid crystal polarizers potentially changes point to point, whereas the polarization change given by half and quarter-wave plates is the same for all the points of the material. This allows for the realization of more complex polarization states such as azimuthal or radial (see Fig. 3).

I WOULD LIKE TO BUY SOME WAVEPLATES. WHAT SPECS SHOULD I BE LOOKING AT?

As it always happens when thinking about a purchase, making a good decision is not a simple task. Due to the large amount of waveplates that can be found in the market, the task might even become overwhelming when we are constrained by a limited budget. Next, we show the most important parameters that we need to look at when purchasing waveplates, and we give some tips and perspectives to help our readers to make an informed choice.

Retardance. The retardance is the parameter that defines the behaviour of the waveplate. Half-wave plates have a theoretical retardance of λ/2 and quarter-wave plates of λ/4. Liquid crystals are a bit more complex as they are not uniform. Make sure that you choose the right retardance for your application.

Wavelength. As it was shown above, the phase that a beam picks up going through a medium is linearly proportional to $k=2\pi/\lambda$, where λ is the wavelength of the beam. Consequently, the retardance of waveplates is defined for a single specific wavelength. Hence, make sure that you choose a waveplate that has been designed to work at your operating wavelength.

Transmission. Waveplates absorb and reflect some of the incoming light. Even if waveplates tend to have transmissions over 90–95% for their design wavelength, their transmission at your operating wavelength might vary in a few %. If losing a few % of your power might be detrimental for your goal, do not forget to look at the transmission curves of waveplates.

Damage threshold. Waveplates, as any others optical elements, can be damaged by high power lasers. Most of waveplates will not be damaged if the power of the laser is below 100 mW. But make sure that you take the damage threshold into account if you are using a high power laser.

Clear aperture. Most of waveplates are sold in Ø1/2" or Ø1" mounts, yet their clear aperture can vary depending on the manufacturer. Make sure that you choose a clear aperture that is wide enough for your beam waist.

Temperature. Even if the variations are not as significant as those with respect to the wavelength, the retardance of waveplates depends on the temperature. Take this into account especially if you do not work at room temperature.

Spectral behaviour. The retardance and transmission of a waveplate are sensitive to wavelength variations. Depending on how sensitive they are to wavelength variations, manufacturers tend to group waveplates in three categories: achromatic, zero order and low order. Achromatic waveplates are the least wavelength-sensitive among the three. Typically, they are needed for experiments that require polarization control at multiple wavelengths. Zero order waveplates are more sensitive to the wavelength than the achromatic ones, but they can still be used with broadband lasers. Low order waveplates are well suited for monochromatic lasers. Here, it is important to note that most waveplate manufacturers do not usually make waveplates for any kind of wavelength (There are some exceptions, such as Solid Photon or Optique Fichou). That is, waveplate producers tend to make waveplates (with different specs) at certain common wavelengths such as 405, 488, 532, 633, 780 nm, *etc.* If your operating wavelength is different, you might struggle to find a waveplate made for that wavelength. Yet, if you just need to create a certain fixed polarization state, and do not need to dynamically control it while your experiment is running, then you can easily overcome this drawback. The phase lag of waveplates $\Gamma = kd(n_1-n_2)$ is designed so that they work at normal incidence. Therefore, if we tilt the waveplate, which effectively reduces the thickness d, we can effectively adjust Γ to the desired value. It is important to bear this in mind when purchasing a waveplate.

Delivery time. Some manufacturers do not have large stocks and make waveplates on demand. Take into account that

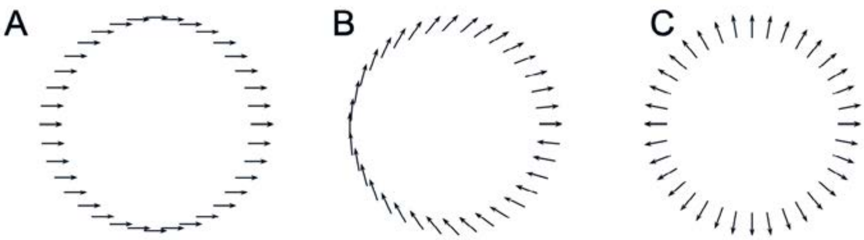

Figure 3.
A linearly polarized beam (A) interacts with a liquid crystal polarizer oriented as in B. The interaction yields a radial polarized beam (C). Adapted from [7].

MANUFACTURER	PRODUCTS	DELIVERY TIME	PRICE RANGE	CONTACT
Foctek Photonics, Inc.	λ/2 and λ/4. Low order, zero order and achromatic.	1-5 weeks	30-500€	Kevin Chi, kevin.chi@foctek.com sales@foctek-lens.com +86-591-38266618
EKSMA Optics, UAB	λ/2 and λ/4. Low order, zero order and achromatic.	1-8 weeks	100-500€	Povilas Ziedelis, p.ziedelis@eksmaoptics.com +370.5.2729900
Fuzhou Solid Photon Inc.	λ/2 and λ/4. Low order, zero order and achromatic.	1-6 weeks	150-500€	+86 591 87886596 sales@solid-photon.com
Lambda Research Optics, Inc.	λ/2 and λ/4. Low order and zero order.	1-8 weeks	200-400€	+1 714 327 0600 sales@lambda.cc
Optique Fichou	λ/2 and λ/4. Low order, zero order and achromatic.	1-8 weeks	100->10000€	Guillaume Dubois guillaume.dubois@optiquefichou.fr optiquefichou@optiquefichou.fr +33(0)146661518
Thorlabs, Inc.	λ/2 and λ/4. Low order, zero order and achromatic. Liquid Crystal Polarizers.	0-2 weeks	200-1000€	sales.fr@thorlabs.com +33 (0) 970 444 844
Newport Corporation	λ/2 and λ/4. Low order, zero order and achromatic.	0-3 weeks	200-1600€	+33 1 60 91 68 68 https://www.newport.com/contact-us
ARCoptix S.A	Liquid Crystal Polarizers	1-4 weeks	1500-3500€	info@arcoptix.com +41 32 731 04 66

the delivery time can reach 8 weeks some times.

Price. Due to the large diversity of features and produces, prices of waveplates vary tremendously. Their price can go from less than 100 € for low order waveplates to more than 1000 € for the achromatic ones. Liquid crystal polarizers are more expensive and their price can go up to more than 3000 €. As a rule of thumb, two parameters have a clear impact on the price: clear aperture and spectral behaviour. Wider clear apertures are usually more expensive. And wavelength sensitivity makes the price goes down, *i.e.* the cost of achromatic waveplates is higher than that of zero order, and the cost of zero order is higher than that of low order.

CONCLUSION

Waveplates are optical elements that are used to transform the polarization state of collimated optical beams in a controlled fashion. The polarization transformations are done without changing the intensity pattern of the beam. The market offers a huge variety of options both for the features and the quality (and price) of waveplates. As a result, choosing the right waveplate for a given application and budget is not an easy task. Some of the parameters that one needs to take into account are: retardance, wavelength and spectral variations, transmission, clear aperture and delivery time. In the previous pages, we have described these parameters and have given some advice so that our readers can make an informed choice if they ever need to purchase some waveplates.

ACKNOWLEDGEMENTS

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