Photoniques

N°125

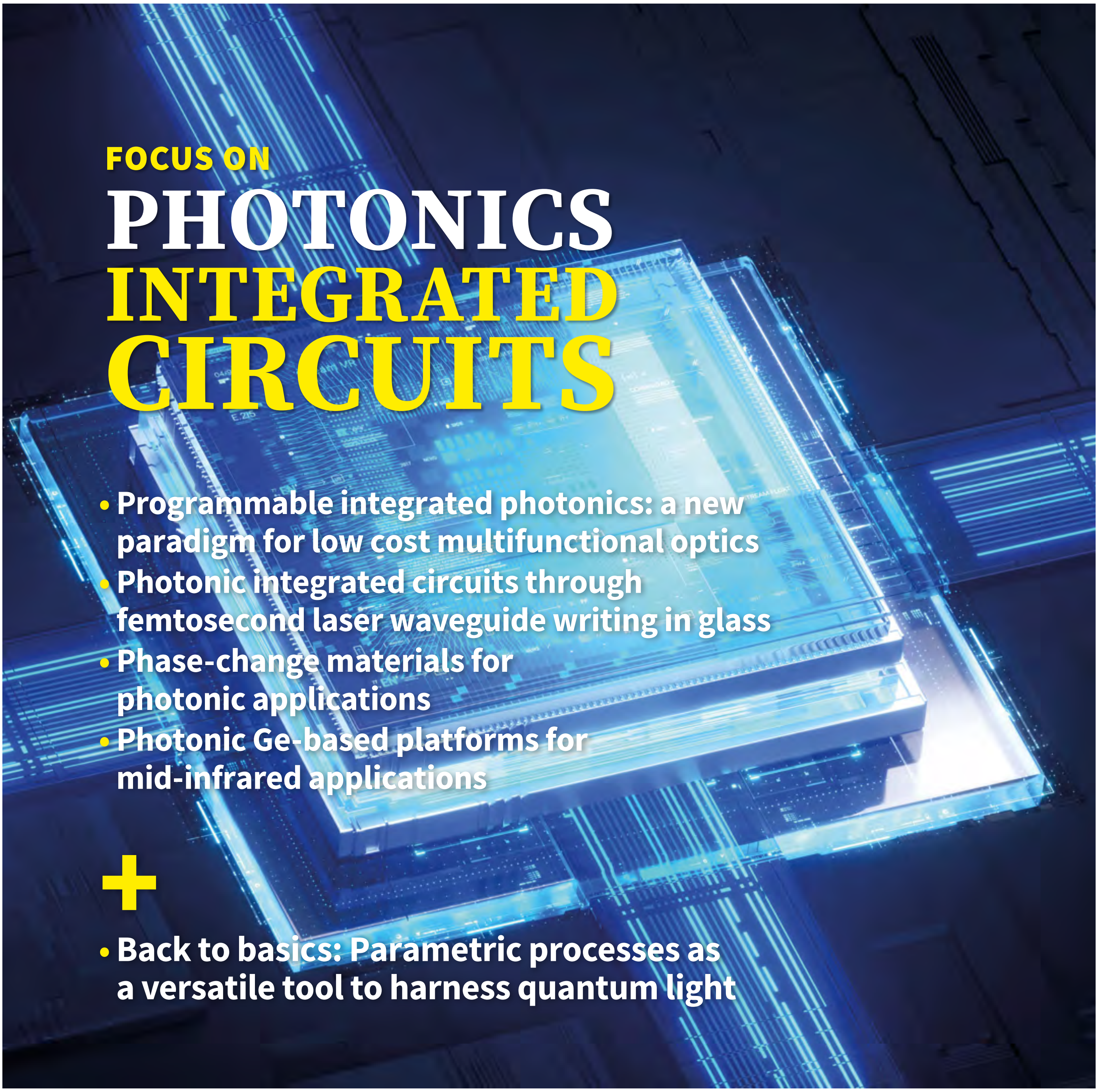
LIGHT AND APPLICATIONS | EOS & SFO JOINT ISSUE

INTERVIEWS
Anne L'Huillier
Patrick Paul

ZOOM
Photonics
in Italy

LABWORK
Hong-Ou-Mandel
experiment

BUYER'S GUIDE
Single Photon
Avalanches Diodes



FOCUS ON

PHOTONICS INTEGRATED CIRCUITS

- Programmable integrated photonics: a new paradigm for low cost multifunctional optics
- Photonic integrated circuits through femtosecond laser waveguide writing in glass
- Phase-change materials for photonic applications
- Photonic Ge-based platforms for mid-infrared applications

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- Back to basics: Parametric processes as a versatile tool to harness quantum light

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Editorial

NICOLAS BONOD
Editor-in-Chief

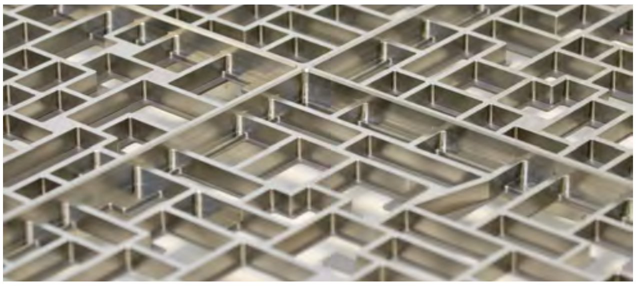
Shaping the Future with a European Strategic Vision in Photonics

Over the last two decades, integrated photonics have burgeoned into a robust ecosystem, with both academia and industry witnessing remarkable progress. The advent of Photonic Integrated Circuits (PIC), with their promise for large-scale integration of heterogeneous components on a chip, heralds a new era in photonics. As integration scales up, the range of applications expands, addressing critical fields such as all-optical information processing and computing, health monitoring and environmental sensing, lidars, while optical communications will continue to propel PIC technology forward. It is imperative for Europe to spearhead this transformation and to secure a leadership position in this strategically vital field.

Photoniques continues its exploration of photonics programs and landscapes across European countries, with Italy taking the spotlight in this issue. Presenting the entire ecosystem – encompassing education, academia, industry, programs, organisms – in a single article is no small feat. I extend my heartfelt thanks to the three authors of this article for sharing their complementary views and perspectives. The upcoming 2024 EOSAM meeting in Napoli next September will provide an excellent opportunity to release this issue, and I look forward to seeing you there.

Photoniques offers original articles, now fully available in free access, presented in a format that enables a comprehensive understanding of crucial concepts, products, and innovations in photonics. I encourage you to read the three articles of this issue in strong connection with quantum technologies. Firstly, the "Buyer's guide" is dedicated to Single-Photon Avalanche Diodes (SPADs) that have revolutionized single-photon detection by combining high performance with affordability. Secondly, the "Back to basics" provides an insightful overview of parametric processes for harnessing quantum light and in particular SPDC and SFWM. Lastly, the "Labwork" focuses on the seminal experiment on single-photon interference reported in 1987 by Hong, Ou, and Mandel, a set-up in which SPDC and single photon detectors play a key role.

The excellence of Europe in optics and photonics was recognized by the 2023 Nobel Prize in Physics awarded to European researchers – Anne L'Huillier, Ferenc Krauss, and Pierre Agostini. Do not miss the in-depth interview with Anne L'Huillier featured in this issue. Europe has a long experience in optics and photonics, and possesses many assets to reinforce its leadership position. This should motivate further our ambition to position Europe at the forefront of photonics research and technology.



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Advertisers

FRANÇOIS SALIN
President of the French Optical Society

The International Day of Light, ... all the Year!

The International Day of Light, May 16th, is approaching, and the SFO is actively engaged in extensive initiatives to make light shine everywhere.
Our iconic LightBox is on the way! A brief reminder of the LightBox philosophy: it is an educational and popularization kit for light sciences, with a cost-effective, frugal science approach. Adaptable to all audiences, it may evolve incorporating outcomes from local projects. LightBox kits are currently distributed in 11 countries thanks to a network of 30 colleagues serving as "points of contact" who help local actors to develop original projects. Already 65 successful implementations were reported, and more than 250 others are ongoing. Kudos to our partner and initiator, the AtoutSciences Association!
We express deep admiration and gratitude to colleagues who generously contribute their time to promote the merits of light. In recognition of outstanding achievements in disseminating knowledge within French-speaking territories, the SFO has created the "Lumières Arnulf – Françon" International Prize. The inaugural award ceremony will take place at OPTIQUE Normandie 2024 congress, with the presence of the international jury.
Indeed, OPTIQUE Normandie 2024 is on the horizon, in the picturesque city of Rouen. We eagerly anticipate reconnecting with familiar faces and extending a warm welcome to new ones. SFO Clubs and Commissions are actively in crafting an impressive scientific program. Industrial exhibition stands are almost booked, and several interesting additions include six hands-on workshops hosted by industry players. We are also delighted to announce an enhanced role for the SFO Youth Club, featuring a Science and Society round table. We anticipate a strong turnout and assure you that you won't be disappointed – our great Chairs, Ammar Hideur from CORIA and Patrice Camy from CIMAP, are putting "les petits plats dans les grands" to ensure a memorable experience.

Ariel Levenson,
Directeur de recherche CNRS, Past-President of SFO
François Salin,
President and CEO Ilasis Laser, President of SFO

PATRICIA SEGONDS
President of the European Optical Society

Join EOSAM 2024 organized with SIOF at Napoli !

Each year, EOS organizes with one of the National Optical Society (NOS), an Annual Meeting in a different place across Europe. In 2024, the Società Italiana di Ottica e Fotonica (SIOF) and EOS will make EOSAM a unique event again, 9th -13th September, in the beautiful city of Napoli.
Raffaele Velotta, University of Naples Federico II and Luca De Stefano, President of SIOF (General Chairs), Emiliano Descrovi and myself (Program Chairs), and Elina Koistinen (EOS Executive Director), come together every week to ensure to meet the expectations of the participants with the highest quality and novel research results and to provide nice networking events.
Exceptional plenary lectures will be given at EOSAM2024 by Hatice Altug, Anna C. Peacock, Claudio Conti, Miles Padgett, Fredrik Laurell and Kishan Dholakia. Tutorials will be taught by Sebastian Riese, Oliver Fähnle, Jacopo Bertolotti, Ignacio Moreno Soriano, Franscesca Intonti, Alberto Puliafito, Katerina Kusova, Giovanni Pellegrini, Luca Sortino, Stefiana Campopiano and Dawson Bonneville.
The attendees will present their last results in 10 Topical meetings (TOMs): silicon photonics & integrated optics (1), frontiers in optical metrology (2), optical system design, tolerancing & manufacturing (3), biophotonics & biosensors (4), nanophotonics (5), optical materials (6), ultrafast phenomena (7), nonlinear & quantum optics (8) optoelectronics, nanotechnologies & microsystems (9), applications of optics & photonics (10). There will be also focused sessions on holography and structured light, optical fibers technology, passive radiative cooling, photonics for cultural heritage and machine-learning for optics and photonic computing for AI. Extended papers can be submitted to the topical issue EOSAM2024 of the Rapid Publication Journal JEOS-RP.
Last but not least, EOSAM also welcomes you to EU projects sessions run with Photonics21, Early-Stage Research sessions organized by students, IMOTS sessions and the Industrial podium. EOS organization will report their work at the Annual General Assembly.

Do not miss EOSAM2024 in Napoli !
Patricia SEGONDS, Professor UGA, President of EOS

OPTIQUE Normandie 2024 will be a great success!
More than 620 attendees
01 - 05 July 2024 – Rouen – France

The optics and photonics community responded massively to calls for participation during this first stage. Focus on the young Club, the members of the industrial collective and of course scientific and technical communication.

Congratulations to the session chairs of OPTIQUE Normandie 2024 for successfully motivating large community for this new edition of the largest francophone congress of optics and photonics. We have received 476 abstracts which illustrate the dynamism of French research.

Round-Table discussion on 'Science and Society' organized by the SFO Young Researchers Club

PhD students and post-doctoral researchers are more than welcome in OPTIQUE Normandie 2024

Join us for an exhilarating discussion that promises to ignite your curiosity and broaden your perspective on the intricate interplay between science, society, and communication.

The SFO Young Researchers Club represented by Pierre BALAGE (CELIA, Bordeaux) & Paul JIMENEZ (INL, Lyon) is at the forefront of organizing a dynamic round table discussion on 'Science and Society', exploring hot questions such as the perception and impact of science in society, the challenges hindering the dissemination of ideas, the role of social media, … and featuring prominent figures in the field:

- **Etienne KLEIN**
(Research Director at CEA - LARSIM)
- **Anne-Marie LAGRANGE**
(Observatoire de Paris - CNRS)
- **Rafaële BRILLAUD**
(Educational Manager, ES Journalism, Lille)

We thank the participation of our collective members in the OPTIQUE Normandie industrial exhibition. It will be a pleasure to meet you again.

Join us on the official congress website
https://www.sfoptique.org/

LIGHTBOX,
THE PHOTONICS EDUCATIONAL KIT

From simple wonder about the properties of light to training, the LightBox kit continues its journey by being deployed on different continents. The LightBox is a partnership between the SFO educational Commission and the AtoutSciences Association and is labeled Année de la physique 2023-2024 and International Day of Light.

Join us on the official LightBox website
https://www.sfoptique.org/

EOSAM 2024 moves to stunning Napoli

If you didn't submit yet, not to worry, submissions are still accepted for oral or poster presentations for the following topical meetings and sessions: Focused Sessions, EU Project Session, TOM1- Silicon Photonics and integrated optics, TOM2- Frontiers in Optical Metrology, TOM3- Optical System Design, Tolerancing and Manufacturing, TOM4- BioPhotonics and biosensors, TOM5- Nanophotonics, TOM6- Optical Materials, TOM7- Ultrafast Phenomena, TOM8- Nonlinear and Quantum Optics, TOM9- Opto-electronics, Nanotechnologies & Microsystems, TOM10- Applications of Optics and Photonics.

Visit https://www.europeanoptics.org/events/eos/eosam2024.html

Visit the website to join and engage with leading minds and experience the forefront of optical sciences!

See you in Napoli!

VI INTERNATIONAL CONFERENCE ON APPLICATIONS OF OPTICS AND PHOTONICS, IN PORTUGAL

AOP2024 is organized by the Portuguese Society for Optics & Photonics (SPOF), at the University of Aveiro, Portugal, 16-19 July 2024.
https://aop2024.org/

UNITED KINGDOM : PHOTON 2024

This is the twelfth multi-disciplinary conference in a biennial series that started in 2002. It is jointly organized by the Institute of Physics (IOP). It will be held in Swansea, Wales, from 3 to 6 September 2024.
https://www.photon.org.uk/

For more information, visit the European Optical Society, EOS,website **https://www.europeanoptics.org/** or contact our Executive Director, Elina Koistinen: **elina@europeanoptics.org**.
Become a member of one of our National Optical Societies (NOS), and you will also become a member of EOS. Discover the benefits that EOS offers and learn how to strengthen your relationships with your peers!

Germany: 125th Annual Meeting

organized by DGaO at Aachen, May 21-24 2024. It will focus on different key topics from applied optics.
https://dgao.de/jahrestagung/

Optics & Photonics in Finland

OPD is an annual central event in Finland. OPD-2024 will be held at Scandic Marina Congress Center, 28 – 30 May 2024, Helsinki, Finland.
https://www.photonics.fi/opd2024/

Italy: National School of Optical Biosensors & Biophotonics

BiO&B is the fifth edition taking place in the charming city of Lecce, Italy, on 3-7 June 2024. It is organized by SIOF to promote the education and collaboration of young researchers.
https://www.scuola-biob.it/

Italian Conference on Optics and Photonics

ICOP will be held in Florence on 17 - 19 June 2024. It aims to bring together researchers from Italy and worldwide, networking & exchanging their last developments in a stimulating and multidisciplinary forum.
https://www.icop2024.it/

France OPTIQUE Normandie

The Société Française d'Optique, SFO, organizes the flagship congress OPTIQUE that is the largest French-speaking international congress, on 1-5 July 2024, in Rouen.
https://www.sfoptique.org/

100%

of Institut d'Optique's continuing education trainees were satisfied with their training in 2023. In 2023, Institut d'Optique's continuing education program counted also : more than **600 hours of training**, **66 experts** from industry and academia providing theoretical and experimental trainings,more than **70 experimental** set-ups.

CONTINUING EDUCATION AGENDA :

- **SC10 - Acquisition, perception and image processing**
  May 21 to May 23, 2024
- **CO6 - Design of optical systems based on off-the-shelf components with Zemax®**
  May 27 to May 28 and June 4 to June 5, 2024
- **CO_2VIS - Optical design with Zemax®- OpticStudio – Advanced**
  May 28 to May 30, 2024
- **EF5 - Colorimetry**
  May 30 to May 31, 2024
- **CO3 - Optical Design with CodeV®**
  June 3 to June 7, 2024
- **SC3 - Understand laser sources**
  June 3 to June 7, 2024
- **SC5 - Optical fibers and applications**
  from June 10 to June 14, 2024
- **SC1 - Optomechanics**
  June 11 to June 14, 2024

CONTACT

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A fine harvest for Institut d'Optique's student entrepreneurs

Students in the Institut d'Optique's Filière Innovation Entrepreneur (FIE)* program have a lot to be proud of. This spring, the young innovative projects leaders have been taking part in pitch competitions, and the prizes were pouring in!

© photo credits : Institut d'Optique

CorneaSight team and their coach after winning

In Bordeaux, the CorneaSight project won the Innovation category of the Kedge pitch competition. Cornea Sight is developing a tool for analyzing the transparency of the cornea.
And the Flowlume project won the Advanced Project category at Pepitch Day Paris Saclay. Flowlume is developing a blood vessel imaging system to improve diabetic foot ulcer diagnosis.
The juries recognized the high quality of the FIE projects. Congratulations to the winners, and we wish you every success in developing your projects.

* FIE is a 2-year education program where engineering students from Institut d'Optique have the opportunity to develop an entrepreneurial project.

TWO FIE ALUMNI IN THE FORBES "30 UNDER 30" RANKING

© Photo credits: Libu

Tinou Seguin and Manon Lousteau, co-founders of Libu

Manon Loustau and Tinou Seguin, alumni from the FIE program and cofounders of Libu (Talence), have been named in the Forbes "30 under 30" Europe 2024 list - in the "industry and manufacturing" category. These “under 30” lists highlight innovative and influential young entrepreneurs in various fields of industry. In the meantime, Libu announces a €1 million fundraising.
Manon and Tinou created Libu in 2019. Libu develops LED lighting solutions that evolve during the day, as the sun does, to give people's biological clocks the right light at the right time. The patented technology is based on a biomimetic system that reproduces the changes in intensity, spectrum and colour temperature of the 24-hour circadian cycle.
The body re-synchronizes with its internal biological rhythm. The benefits, demonstrated in a recent scientific study, are numerous: a reduction of 25% in stress, and an improvement in mood and sleep quality.
This fundraising will enable the company to accelerate its development along 3 priority axes:

- Expanding its product range, to extend the uses of the Libu solution to the industrial sector,
- An increase in industrial output,
- Strengthening its team.

A great dynamic for this young company. Stay tuned!

European Conference
on Quantum Technologies for Defence

The European Commission, Polish Technological Platform on Photonics, OpTecBB, ALPHA-RLH and Ukrainian Cluster Alliance organised the European Conference "Quantum Technologies for Defence: Current and future capabilities" on 13-14 March 2024 in Warsaw, Poland. The event took place in the framework of the European Network of Defence-related Regions.

The conference brought together 150 experts from 17 European countries, representing 125 companies, research, academic and government institutions as well as armed forces, to exchange on the state of the art of Quantum science and technologies in the European defence sector.
The event included presentations on defence applications of quantum sensing, communication and computation (Quantum Warfare), EU and national activities in the field, as well as workshops, pitches and matchmaking.
The speakers talked about their fundamental research or their real world use cases and the urgent need for operational Quantum innovative systems to be tested within the Ukrainian war context.

THE NEWSKIN WATER DAYS: 2 DAYS
EXPLORING WATER-RELATED TECHNOLOGIES

From 20 to 21 March, the NewSkin Water Days took place in Orléans or online and focused on new technologies for addressing water-related challenges.

The event was organised as part of the NewSkin OITB European project. NewSkin is an Open Innovation Test Bed that provides access to physical facilities and services for the development, validation, and marketing of nanoproducts with new functionalities.

Over two days, European experts from research organisations and companies presented various water challenges including water recycling, reuse, and desalination, as well as the solutions provided by NewSkin OITB and other European projects. More than 50 attendees gathered to learn about cutting-edge surface and membrane technologies, such as laser surface functionalisation and nano-coatings for anti-corrosion and anti-fouling applications.
ALPHA-RLH, a partner of NewSkin OITB, also participated in the event. It was also an opportunity for the cluster to attend the 8th NewSkin consortium meeting and the 1st prefigurative General Assembly of NewSkin AISBL, the association that will take over the project to continue providing the services.

PLI Conferences 2024

The event "PLI Conferences", organized by the Club Laser & Procédés, ALPhANOV, ALPHA-RLH, Amplitude and Lasea France, will be held from June 18 to 19, 2024 in Bordeaux (France). "PLI Conferences" is the unmissable event dedicated to industrial laser processes and their advances. An overview of the latest innovations in the field is presented through a rich program of expert conferences. 10 internationally renowned speakers are invited, coming from Japan, China, Germany, Spain, Scotland, and Czech Republic. The 2024 edition will highlight 7 key themes: laser micromachining, laser welding, laser additive manufacturing, large-scale manufacturing, process control & monitoring, machine learning & AI and laser safety. The program also includes an exhibition space, a networking evening, a panel meeting on air mobility and company visits.

More information:
https://www.clp-laser.fr/en/event/pli-conferences-2024

UPCOMING INTERNATIONAL EVENTS

- **PLI Conferences**
  June 18-19 in Bordeaux (France)
- **1st Photonics Talent International Summer School**
  July 8-12 in Bordeaux (France)
- **INPHO Venture Summit**
  October 24-25 in Bordeaux (France)

News in Brief

- **Our M1 students attended a workshop aiming to raise awareness of climate change** (https://fresqueduclimat.org/)
- **New agreement between the UTT and the University of Mumbai, India** *cf.* https://www.freepressjournal.in/education/in-a-first-mumbai-university-ties-up-with-french-university-for-dual-degree.
- **In February, a NANO-PHOT PhD student, Kevin Kim** (full Bright Scholarship holder), moved to the USA for 4 months to join the A.J. Drexel Nanomaterials Institute, Philadelphia.
- **A new class "nanomaterials and nanofabrication"** opened in February
- **New France-USA material science program,** entitled MAT-MOV, has just been launched by the University of Texas San Antonio. UTT and NANO-PHOT are involved.

NEW NANO-PHOT STUDENTS ARE CURRENTLY BEING RECRUITED. TO DATE, THE GRADUATE SCHOOL HAS 45 STUDENTS: 7 M1, 14 M2 AND 24 PHD STUDENTS. OUR GOAL IS TO EXCEED 100 STUDENTS BY 2028.

AGENDA

- **Coming summer school at UTT « Quantum hardware for quantum technologies » as part of the European project DigiQ: digitally enhanced quantum technology master.**
- **Conference META24 in July** **https://metaconferences.org/META24/index.php/META/index**

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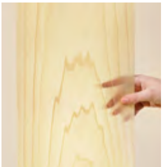
nanophot@utt.fr

Sustainability matters

The NANO-PHOT Graduate School offers an unparalleled program of excellence, with an international dimension and in direct contact with scientific and socioeconomic stakes related to the use of light, on nano and micro metric scales. Sustainability is a major concern. Three significant examples:

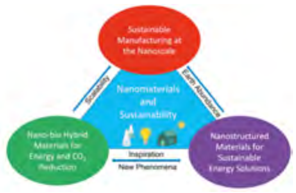
Optical Characterization of Translucent Wood



Ashima VASHISTHA, a NANO-PHOT PhD student at the L2n lab of UTT, is working in the domain photonics in collaboration with a biotechnological startup: Woodoo.

Her research project delves into the potential of translucent wood in optics and photonics, offering a sustainable solution to traditional industrial materials. By focusing on characterizing the optical properties of translucent wood, she explores how the structure of wood, influenced by growth conditions, affects fabrication processes and ultimately, optical properties. This study aims to establish a feedback equation linking wood anatomy, fabrication parameters, and optical properties, facilitating the production of translucent wood with precise characteristics. The project targets applications in the automotive industry and tactile display screens.

Nanomaterials & Sustainability



NANO-PHOT co-organized with Gary Wiederrecht from Argonne National Laboratory (USA) a workshop "Nanomaterials & Sustainability" held on May 4, 2023, as part of the annual Advanced Photon Source/Center for Nanoscale Materials Users Meeting. The workshop had more than 180 registrants and consisted of 12 invited talks covering a diverse range of subjects that included the impact of nanomaterials on sustainable energy solutions, nanostructured biomaterials, and sustainable manufacturing with nanomaterials. The workshop resulted in a multi-author publication in ACS Energy Letters https://doi.org/10.1021/acsenergylett.3c01303

Nanoplasmonics for organic photovoltaics

Within a French-Chinese consortium, NANO-PHOT takes part in the development of novel organic photovoltaics (OPV) through the use of metal plasmonic nanoparticles as scatterers that disperse light to increase the optical path of rays in the active layer. Recently, this approach improved the performance of semitransparent OPVs in the near infrared. For the first time, a power conversion efficiency of 16% and an average visible transmittance of 33% were achieved, offering promising prospects for application in building-integrated photovoltaic systems and greenhouses.

More details at: https://doi.org/10.1002/adma.202311305

International Nanophotonics workshop

On February 19-22, NANO-PHOT organized the 3rd Nanophotonics workshop at UTT, in collaboration with Sasha Govorov (Ohio University). 25 leading researchers came to Troyes from Italy, Germany, USA, Canada, China and France to present their work. The NANO-PHOT students had the opportunity to take part in discussions, present their work to distinguished researchers, and enrich their international connections.

More than 350 Executive representatives gather for the EPIC Annual General Meeting in Nice

EPIC recently celebrated its Annual General Meeting in Juan Les Pins, Nice, France. The event brought together over 350 CEOs and executive representatives from the global photonics community to discuss strategic topics such as Innovation, Entrepreneurship, New Markets, challenges and trends in photonics technologies. During the event, Axel Kupisiewicz, founder and CEO of LASEA, received the EPIC CEO Award 2024, while Viacheslav (Slava) Artyushenko, CEO of art photonics, was honored with the EPIC Lifetime Achievement Award. The occasion also marked the introduction of Dr. Björn Dymke, Managing Director of TRUMPF Laser, as a new member of the Board of Directors of EPIC.

The two-day convention featured conferences, an exhibition area, and networking activities including the traditional EPIC Run, Gala Dinner and Networking Reception, and a FUN Night, where entrepreneurs shared stories about the challenges they encountered on their paths. For the first time, part of the summit's agenda was open to non-EPIC members with the aim of fostering collaboration with key stakeholders in photonics from around the globe. Attendees had the opportunity to hear inspiring speeches, such as one by Benoît d'Humières from Tematys, who presented Market Trends in Photonics, and presentations by Claire Valentin from Exosens and Chantal Germain from HEF Group, who shared insights into Challenges in the Photonics Market and Investment, respectively. Additionally, Orange Labs discussed Fiber to Home and photonic integration in the fiber gateway. Scan the QR code to view all the pictures and an extended recap of the event.

EPIC Meeting on Specialty Optical Fibers hosted by Photonics Bretagne

12-13 June 2024 in Lannion, France

Specialty Optical Fibers are a key component in a lot of critical applications nowadays, such us sensing, lasing, telecommunications, spectroscopy... Throughout the meeting, we will explore the new solutions and designs of optical fibers, ranging from non-standard materials to photonic crystal structures, the novel manufacturing methods and their potential applications.
We will also understand the new technologies used for fiber preparation, characterization and the last developments in connectors. Confirmed speakers include representatives from companies such as Orange Labs, Infinera, Fluence Technology, Le Verre Fluore, Coherent, Nyfors, GLOphotonics, OFS, Lumoscribe and Arden Photonics. Attendees will also have the opportunity to visit companies in the area, such as Exail, LUMIBIRD and KERDRY.

AGENDA

- **EPIC Technology Meeting on Photonics for XR: through emerging technologies and challenges at Microsoft**
  27-28 May 2024
  Espoo, Finland
- **EPIC Online Technology Meeting on Photonics for Vision and Eye Research**
  3 June 2024 - Online Event
- **EPIC Technology Meeting on Photonic Integration and Packaging at Fraunhofer IZM**
  4-5 June 2024 -
  Berlin, Germany
- **EPIC HR Workgroup meeting**
  7 June 2024 - Online Event
- **EPIC Marketing Meeting on Social Media II – Special focus on B2B companies**
  12 June 2024 - Online Event
- **EPIC Technology Meeting on Specialty Optical Fibers: New Designs and Novel Applications at Photonics Bretagne**
  12-13 June 2024
  Lannion, France
- **EPIC Sustainability Workgroup Meeting**
  14 June 2024 - Online Event
- **EPIC Online Technology Meeting on Photonics for Sea Exploration and Oceanography**
  1 July 2024 - Online Event
- **EPIC Members Delegation to Taiwan**
  2-6 September 2024
  Taipei, Taiwan
- **EPIC Online Technology Meeting on Photonics Hybrid Photonics Integrated Circuits**
  16 September 2024
  Online Event

Sponsor our events!
Contact us by mail
(see below)

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NEW MEMBERS

Welcome to our new members: AERODIODE, CNRS-CNPS, KERANOVA, Lycée Jacques de Vaucanson (Tours) and STMicroelectronics.

AeroDIODE

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KERANOVA

ACADÉMIE D'ORLÉANS-TOURS
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A professional diploma
in 2024 for future photonics operators

The photonics industry in France is booming: over 1,200 companies throughout the country are recruiting nearly 2,000 operators and technicians every year.

A vocational baccalaureate in photonics is the missing level to recruit more photonics operators. Until now, companies recruited graduates with a bachelor degee to fill their needs. This specific training at baccalaureate level will also enhance the sector's visibility and attractiveness to secondary school students.

The vocational baccalaureate "Optics Photonics: Technologies of Light" will be launched at the start of the 2024 academic year in 7 vocational high schools, with the support of companies and regional training bodies. A further 6 are scheduled to open in 2025.

The new vocational baccalaureate will train future technicians and operators in charge of the manufacturing, assembly-adjustment, implementation and maintenance of photonic components and systems. It demonstrates the many career opportunities offered by companies in this field.

AGENDA

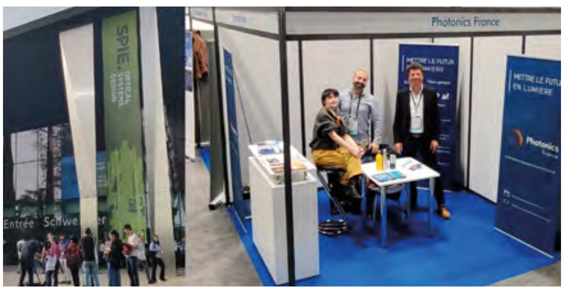
- **Photonics France general meeting**
  (for members only)
  May 13, 2024 - Paris
- **Business Meeting for Agriculture**
  May 31, 2024 – Rennes
- **French Photonics Days**
  October 16-17 - Besançon
- **Photonics with CNRS**
  November 2024 - Paris

Sponsor our events! Contact us by mail (see below)

TO CONTACT PHOTONICS FRANCE

contact@photonics-france.org
www.photonics-france.org

SPIE PHOTONICS EUROPE: MEETING OUR MEMBERS



SPIE Photonics Europe took place in Strasbourg from April 7 to 11, 2024. Nearly 2,500 attendees came from all over Europe and beyond. Photonics partnered with SPIE for the promotion and organization of the show, which featured photonics conferences and an industrial exhibition.

Photonics France visited its 25 members who were exhibiting at this major photonics event, held in France but attended by a European audience.
We thank all our members for their participation : ALPhANOV, Amplitude Laser, ARDOP Industrie, CRISTAL LASER, EVOSENS, Exail, Femto Easy, HEF Groupe, Imagine Optic, IREPA LASER, Le Verre Fluoré, LEUKOS, LUMIBIRD, NKT Photonics, Opton Laser International, Oxxius, PHASICS, Photonics Bretagne, Photonics Open Projects, Pro-Lite Technology, PYLA, SAVIMEX, SOMOS, SYMETRIE, Thorlabs.

Photonics Industry at Photonics Europe

The 2024 edition of SPIE Photonics Europe in Strasbourg was a resounding success.
Photonics Bretagne and 18 of its members exhibited: IDIL Fibres Optiques, Oxxius, Lumibird, Exail, Evosens, Le Verre Fluoré, Leukos, OBS Fiber, TOPTICA Photonics, HTDS, OptoSigma Europe, Kerdry/HEF Photonics, Imagine Optic, ALPhANOV, SOMOS, Amplitude Laser, Photonics Open Projects and KWAN-TEK. In addition, the latter two could exhibit free of charge in the Innovation Village. KWAN-TEK even won the prize of the best innovation by a company! Indeed, the fair was a great opportunity to catch up with our members, including visiting members such as Microcertec, Percipio Robotics, ENSSAT, Tematys and Wavetel, and with the rest of our network. The large number of visitors welcomed at our booth enabled us to highlight our capability to custom design specialty optical fibres and components, including our recently developed metallic coatings. Our biophotonics engineering activity was also showcased and presented in a poster entitled "Spatial-Frequency-Domain Hyperspectral Microscopy".

Quantum at the Heart of a Techno-Conference

"Journey to the Centre of Quantum - Sensors, Communications, Computing": Such was the theme of the techno-conference organised on April 4th in Lannion by the Images & Réseaux and Photonics Bretagne clusters and in partnership with Orange Innovation. Sold out 2 weeks in advance, the event brought together 140 participants, including researchers and big names from the sector (Thalès, Exail, Direction Générale de l'Armement), as well as internationally renowned experts, such as Pascale Senellart, CNRS silver medallist and member of the new Presidential Science Council. The programme centred around the landscape of new digital technological perspectives applied to quantum sensors, quantum communications and quantum computing. It included presentations, round tables as well as networking opportunities to initiate the emergence of future collaborations. The day ended with an exceptional visit to Orange Innovation's photonics and quantum laboratories. This conference gauged the scope of possible applications for quantum technologies in strategic sectors, such as health, agriculture, cybersecurity, defence and climate, as defined by the French government in its "France 2030" plan.

MEMBERS' NEWS

Jalis Meca is taking over the activities of SEFG Innovation, including the continued development of their flagship product, the BLACKSWAN SURFING lamp. Developed in partnership with Leano design and Evosens, this technology offers surfers a unique night-time experience. The parts will now be produced in STMP's workshops and distributed under the Jalis Meca identity.

Orange and three Breton engineering schools - IMT Atlantique, ENIB and ENSSAT- created Lab'Optic, a joint laboratory dedicated to optical telecommunications. Thanks to the resources of Orange, Institut Foton and Lab-STICC laboratories, Lab'Optic researchers will carry out various collaborative research projects and will focus on three main areas of research:

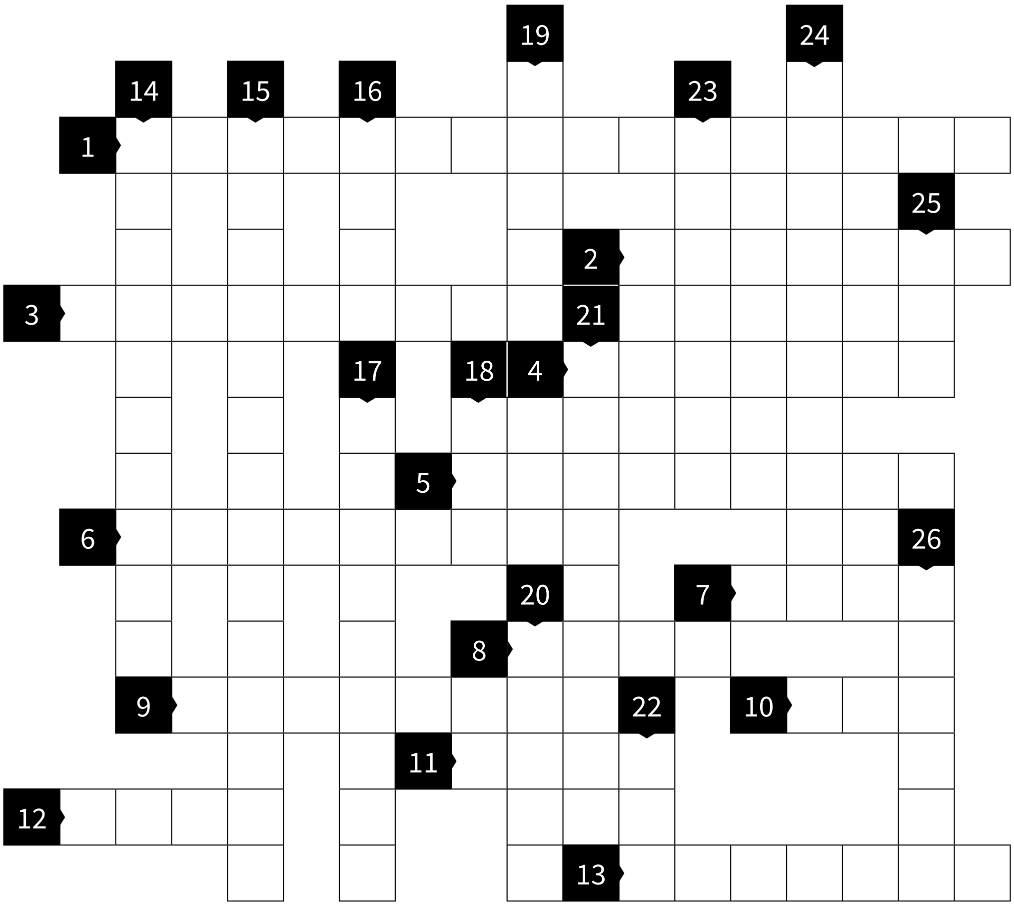
- **Increasing** the transmission capacity of optical transport networks for Internet, without modifying existing infrastructures and favouring energy-efficient solutions.
- **Improving** the efficiency of optical networks reaching business and residential customers by increasing throughput beyond 50 Gbit/s, reducing latency, enhancing security and optimising energy efficiency.
- **Developing** new digital signal processing techniques and algorithms for very high-speed optical transmissions, aimed at increasing throughput and at rationalising the optical interface power consumption, by incorporating advances in artificial intelligence.

AGENDA

- **Business Meeting: Photonics for Agriculture**
  May 31, Rennes (France)
- **EPIC Technology Meeting on Specialty Optical Fibres**
  June 12-13, Lannion (France)
- **General Assembly of Photonics Bretagne**
  July 5, Lannion (France)

CROSSWORDS
ON PHOTONICS INTEGRATED CIRCUITS

By Philippe ADAM



SOLUTION ON
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1 Transfers an optical pattern onto a photoresist
2 Giant industrial optical fiber network
3 Miniaturized and integrated laboratory
4 LIDAR-on-a-chip helps for autonomous operation in automative
5 Basic element to guide light on a PIC
6 Dry or wet sculpture process
7 Application Specific Integrated Circuit
8 Inventor of the phone. Famous laboratories bear his name
9 Micro-Opto-Electro-Mechanical-Systems
10 Multiplexing techniques in the wavelength domain
11 A substrate for integrated quantum optics
12 Wifi with light
13 A Lithium companion for the next gen of PICs
14 Components which make a waveguide either TM or TE transmitter
15 Describes an optical and electronic mix on a microchip
16 Useful components for optical interconnects
17 Critical process to improve the optical power injected into a PIC
18 Arrayed Waveguide Grating
19 Geometry of a raised waveguide with cladding on 3 sides
20 Australian physicist, the B in DBR stands for his name
21 A single chip with diverse functionnalities
22 Material with low losses: its use in PIC is not… a sin !
23 Periodic optical component ; integrated in AWG can MUX/DEMUX different wavelengths
24 Those for data storage are among PICs highly demanding requirements
25 Optical Parametric Generation
26 COMmunication INTelligence

Interview with Anne L'Huillier

Professor in atomic physics and light-matter interactions, Nobel Prize in Physics 2023 "for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter".

https://doi.org/10.1051/photon/202412513

How did you discover physics and mathematics?
During my studies, I had always been interested in scientific topics, and particularly mathematics and physics. After high school, I decided to study in a preparatory school for 2 years and selected the Mathematics-Physics line. After these 2 years, I entered the Ecole Normale Supérieure of Fontenay-Aux-Roses, in the south of Paris. During two years, I pursued a dual master degree in physics and mathematics. The third year was dedicated to preparing for a teaching exam in mathematics (agrégation). Then I focused on quantum physics with fantastic lecturers who greatly influenced me. Let me stress that I was not put off by mathematics. I simply wanted to push my knowledge as much as possible in mathematics, with the idea that it would serve my work in physics.

How did you select the topic of atomic physics for your master internship?
What appealed to me with this topic is that you can develop a thorough and fundamental description of light-matter interactions. I did a master internship at the Commissariat à l'Energie Atomique (CEA), in Saclay. At the end, I was offered a PhD position, which I gladly accepted. I joined the multiphoton group led by Gérard Mainfray in 1981 and defended my thesis in 1986. This field of research was at this time very small, and only a few teams in the world were working on this subject because it required intense lasers, which were expensive in the 1980s.

Your career shows that you have never put barriers between disciplines or between theoretical and experimental approaches.
That's true. My studies were 100% theoretical, while my thesis work was very experimental. It was during my thesis that I learned to align a laser beam, manipulate optical beams and master vacuum techniques. But part of my thesis was also theoretical on the interaction between multi-electron atoms and laser light. I think it comes from a desire to maintain some flexibility in my activities and to keep doors open for as long as possible.

What was the major result of your thesis work?
I showed that by absorbing several photons, one atom can be ionized not only once, but several times. In the case of double ionization, we were trying to determine if the 2 electrons were emitted simultaneously or sequentially. I showed that both processes were possible. The essential result of my thesis was published in 1983.

How did you continue your work after your PhD thesis?
After my thesis defense in January 1986, I went to Sweden for a few months to work on the theory of multiphoton ionization of many-electron atoms before being hired in October 1986 by the CEA. We wanted to better understand the interaction between atoms and an intense laser by measuring the emitted light. We developed a new experimental set-up and we could observe the generation of very high-order harmonics (up to order 33) during the summer of 1987. These harmonics had a spectacular behaviour with a plateau distribution from harmonic 7 up to a cutoff.

How was the research group at CEA organized?

There were three teams in the group led by Gérard Mainfray. There was a team composed of Pierre Agostini and Guillaume Petite who were specialists in photoelectron detection. A second team with Didier Normand, Christian Cornaggia and Jacques Morellec worked on resonances using a dye laser and later on molecules. I worked in a third team with Louis-André Lompré and Michel Ferray on measuring ions, and later photons. It was a small unit, and there were many discussions between the teams. My first contacts with Pierre Agostini date back to 1981.

How do you explain the originality of the research carried out in this team?

We had lasers that only a few groups had. We were working on a topic considered very fundamental and which was not seen as a hot topic at the time. Compared to the development of cold atoms, which was an exciting and very promising topic, our studies about atoms in strong laser fields seemed anecdotal and very peripheral. While I was passionate about my research topic, I had no idea that this work would lead me to attoseconds. It was impossible to have this vision at that time.

Did you anticipate the generation of high harmonics?

We knew that it was possible to obtain a few harmonics of orders 3, 5, 7, 9. We were aware of the results achieved by a research group in Chicago that reported the generation of the 11^{th} or 13^{th} harmonic, but with a femtosecond excimer laser at 193 nm that was delivering much higher power than our laser. Let me stress that we were not trying to generate these high harmonics, but rather to study fluorescence. Our result was quite unexpected and fascinating.

Did you figure out the importance of these results?

We published three articles, but afterwards, my colleagues moved on to developing further the laser towards even higher intensity, by implementing the newly discovered chirped pulse amplification technique, while I continued to work on high-order harmonic generation. I developed collaborations with Kenneth J. Schafer and Kenneth C. Kulander between 1989 and 1991 to describe theoretically the generation of high-order harmonics. In 1989 my first PhD student, Philippe Balcou, started his thesis and we carried out experimental studies.

How did you manage the soar of different laser technologies in the 1990s?

During my PhD thesis at CEA, I worked on 2 types of lasers. A neodymium-doped glass laser and a small Nd:YAG laser. The main laser was the neodymium-doped glass laser, with the 40 ps YAG laser being a small auxiliary laser. It was extraordinary to observe the generation of high-order harmonics with this small laser. We were working at the highest intensity achievable with this laser, and I think we were a bit lucky. After the implementation of the chirped pulse amplification technique at the beginning of the 90s, it became interesting to work with the neodymium-doped glass laser because the pulse duration was much shorter, 1 ps. While this laser allowed us to publish a very important article in 1993 with Philippe Balcou, in which we showed harmonics of order 100 and higher, the experiments took very long time since the laser repetition rate was only 0.1 Hz. When I was offered to carry out experiments in Sweden with a femtosecond Ti Sapphire laser at 10 Hz

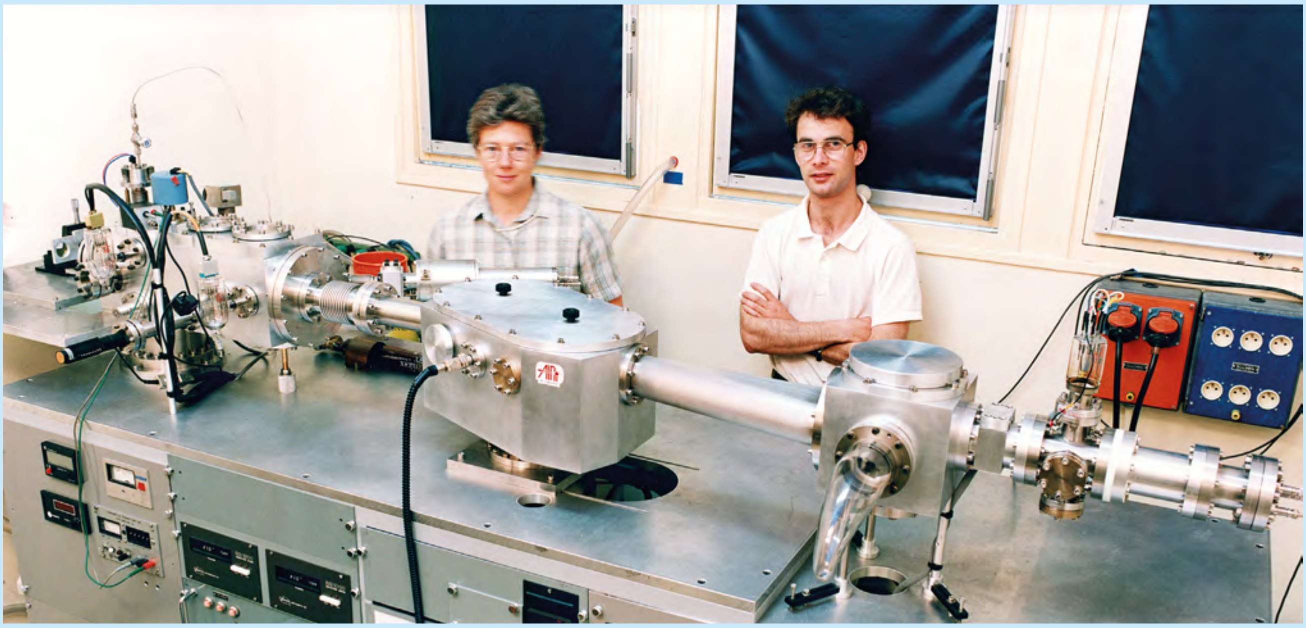

Photo of the experimental setup developed at Saclay in 1991 with Anne L'Huillier and Philippe Balcou, her first PhD student.

> ***The fact that Marie Curie existed was a major factor for me. While it took 60 years to have a second female Nobel Prize laureate with Maria Goeppert-Mayer, and 55 more years to the next one, three women have been awarded the Nobel Prize in Physics in the past five years. I think there will be more and more female Nobel Prizes, and this should give hope to young female scientists.***

repetition rate, getting results immediately became much easier. I also traveled to Livermore a few months later to work with a Li:SAF laser.

How did you start working in Sweden?
After my stay in Livermore, I went back to France for working at CEA before leaving again in 1994 for Sweden to join my husband. It was a risky decision because I didn't have a permanent position. CEA was extremely understanding and continued to employ me though I was often in Sweden. This period was certainly complicated on a personal level but very dynamic professionally.

What were the main challenges to generate and to detect attosecond pulses?
The idea of attosecond pulses wasn't so clear, and I was one of the scientists somewhat skeptical about the possibility of generating attosecond pulses. Numerically, we could predict the generation of attosecond pulses only in some particular cases. Another difficulty was to find a method to measure the duration of these pulses. In my group, we had tried for years to measure attosecond pulses using autocorrelation techniques unsuccessfully. Fortunately, in 2001, Pierre Agostini and Ferenc Krausz developed independently cross-correlation techniques and successfully measured the duration of attosecond pulses. Pierre Agostini and his group characterized a train of attosecond pulses with the help of the so-called RABBIT technique, while Ferenc Krausz and his colleagues managed to generate and measure isolated attosecond pulses using few-cycle laser pulses and the streaking technique. When I heard about Agostini's experiment, I proposed to my colleagues to modify our optical setup to perform a similar experiment. We could measure our first attosecond pulses in 2003 (the article was published in 2005).

What have been your main research topics since?
Since 2011, we have worked a lot on the study of the temporal dynamics of the electron emission due to photoionization. Our RABBIT technique approach allows us to understand this electron dynamics in the time domain. My group has grown, and several senior researchers are now working partly with me. While most of our activities belongs to fundamental research, I am also very interested in an industrial application consisting in the metrology of the next generation of integrated circuits using high-order harmonics.

How do you feel about becoming the fifth woman to receive the Nobel Prize in Physics and the second French woman after Marie Curie?
Since the announcement of this Nobel Prize, I have been very busy. Becoming a Nobel prize laureate implies taking on a new task and responsibility, consisting in communicating science, especially to the young generation. I am aware of the additional role I have to play as the fifth woman to be awarded the Nobel Prize in Physics. I believe it is very important to have role models; The fact that Marie Curie existed was a major factor for me. While it took 60 years to have a second female Nobel Prize laureate with Maria Goeppert-Mayer, and 55 more years to the next one, three women have been awarded the Nobel Prize in Physics in the past five years. I think there will be more and more female Nobel Prizes, and this should give hope to young female scientists. ●

Interview with Patrick Paul, CEO of LASER COMPONENTS GmbH

https://doi.org/10.1051/photon/202412516

When & how was your company founded?

The company was founded in 1982 by my father, Günther Paul. The context was to form a distribution and sales company in Germany, and the idea was to buy components from US companies and resell in a growing German market. My father used to be a director of sales in a German company that was sold to a large American corporation. The reason why this German company was sold was due to their manufacturing of CO_2 lasers for material processing and marking applications. The American buyers were more interested in the system and not so much in the components part of the business that my father was handling as a sales director. He was given the opportunity from his former boss to purchase this part of the business before the larger acquisition of the CO_2 laser systems business took place.

What were the initial activities when the company started?

My father started his activities in 1982. He was working in a little room in our house with four product lines from American suppliers. Step by step, he added a secretary, accounting, one or two salespeople, and started to introduce his products to the growing German laser industry. Then the company grew, and we rented another apartment close to our family home. That was followed by moving a few times within the small town of Olching in the west of Munich. The headquarters of LASER COMPONENTS is still located in the same area. Four years later in 1986, my father was given the first chance to make his own in-house product. He was representing an American company that manufactured laser optics and had a good partnership with this supplier. They specialized in dielectric and thin film coatings for laser optics. The owner of this supplier had the idea to move his own production close to his European customers. They started the joint venture in 1986, in which LASER COMPONENTS only held a minority ownership stake. They gave us the necessary know-how and machinery. It was my father's responsibility to run the operation and to hire people. However, the switch from a distributor to a manufacturer with no prior production experience proved challenging, taking my father at least one to two years to even get started. Initially, the quality of products was subpar, and recruiting experts to join a small startup was difficult. After two years, the Americans lost interest and my father was given the opportunity to acquire the whole venture company and merge it with LASER COMPONENTS. Shortly after assuming full ownership, he successfully met the quality standards and began manufacturing laser optics in line with market demand. During this time, my father found joy in crafting high-quality products that he could call his own. Making something special was what made us strong, and this is still at the core of our business today. Creating something unique is the core of LASER COMPONENTS business. Our objective is to produce custom components, and it is still our mission today. We can make these decisions as a manufacturer of custom components while also adding customization value as a distributor for our partners. The growth of our in-house laser optics outpaced that of all the other products in our trading portfolio.

How would you describe the composition of your product portfolio?

LASER COMPONENTS produces components tailored to meet the needs of laser/instrumentation manufacturers. We pride ourselves on avoiding direct competition with our manufacturing customers by exclusively offering components that our partners integrate into their complete systems. If we would manufacture a YAG laser for example, this would pose as a conflict of interest and all the other YAG manufacturers would stop buying our laser components. Instead, we focus on adding unparalleled value and customization on the components that we sell to empower our customers with precise solutions to their engineering challenges. Over the years, we saw the chance to expand our in-house component manufacturing, and by taking those chances we increased our product portfolio. This led into a growing need for a sales distribution network worldwide. This initiative started with opening a sales office in the UK. Following that, starting in 1996 we took a minority stake in a French distributor, that ultimately evolved into assuming a majority ownership in 2008 and rebranded the distributor to LASER COMPONENTS France. Today, our sales offices extend across the US and in Stockholm for the Scandinavian countries, and to ensure worldwide coverage we collaborate with trusted distributors so that we can reach customers globally with our diverse portfolio.

When did you personally start working in the company?

I started my activities in 2002. At this time, the ratio between internal and external products was 10% in-house products and 90% trading products. Throughout the 2000s, we strategically invested more into our in-house products. Presently, the group's operations have shifted to 70% of our portfolio consisting of in-house products and the remaining 30% consisting of trading products. The reason for this shift is our commitment to delivering superior value to our customers. If we take on the responsibility of the product lifecycle, we can make the best decisions in the interest of our customers.

Was it always evident for you to become involved in the family business?

When you grow up in an entrepreneurial environment with a family that operates a company, it offers a unique perspective of both the successes and sacrifices in building a company. I can remember a family vacation where my father drove us to Italy. He stayed with us for one or two days and then he had to return to the office because the company was too small and fragile to be left alone. When having dinner there was only one topic, it was always about the company. As a teenager, I started to think about forging my own path. The natural inclination is to not want to live like your parents did. However, I have always been involved in the company. Every time my father asked me to help him, I always did. I must admit that I always enjoyed it.

How did you begin your formal role within the company?

In 1999, a key manager left the company, leaving my father without a replacement. I was attending university at the time when my father asked me to pause my studies for six months and help him in the company. I was still young, lacking experience, but I agreed, promising to return to my studies afterward. During this time, I gained valuable insight into the business. For the first time, I understood the organizational structure, the business processes, how well defined they are, and what a smooth operation he was running. What struck me the most was the strong support from all employees, who treated the company as a family business. They were very eager for me to finish my studies and officially join with the company. At this time, we had 40 employees, and a lot of them felt that without a successor, soon or later, my father would sell the company. This prompted me to reconsider, the thought of new ownership did not sit right with me, after developing strong relationships with key members of the company, their encouragement ultimately helped me decide to join the company.

What were your initial responsibilities within the company?

Initially, I spent six months abroad as we established our US operations. My father sent me there to help build up this branch of the organization. Upon my return to Germany, I started as his assistant for the first two to three years, gradually assuming more responsibilities. We had a plan for the next decade that had me gradually rotating through every department. As I gradually took on more responsibility, my father stepped back, leaving the decision-making to me. He continued to oversee areas that I was not yet involved with. I started with administration, followed by marketing, accounting, sales, and technical departments. After seven or eight years, my father's involvement had diminished significantly, and I was left to manage the day-to-day operations.

Looking back, this was an ideal way for us to collaborate: I was eager to learn, while my father was willing to delegate. This arrangement allowed us to accomplish far more together than either of us could alone. It was the best time of my career; we had 200% capacity in management.

When did you assume full responsibility for the company?

During the years 2004 and 2005 we invested heavily to boost our in-house products. At that time, we had a problem with our largest external supplier. As a distributor, you can make two mistakes: the first is to not effectively promote and sell a product, the second is to sell the product so well that the supplier is motivated to establish their own operation. Our largest supplier chose the second mistake and contacted our customers directly. My father made the decision to reinvest significantly into the company. This led to starting two major operations, one in Canada for manufacturing laser diodes and another in Arizona for manufacturing photodiodes. Today, these two groups develop and manufacture the most important products in our portfolio. We created around 70 jobs in these two countries.

Can you describe the organizational structure of the company?

Previously, LASER COMPONENTS GmbH, based in Germany, held majority ownership of all the other LASER COMPONENTS companies, whether it is a sale company like Nordic, France, UK, US or a manufacturing site like in Canada and the US. LASER COMPONENTS GmbH functioned in two capacities: as a holding company and as the headquarters overseeing sales, marketing, and operations that consisted of three production sites in Germany. This was our structure for many years until about two or three years ago when we reorganized the company. The operational segment in Germany was separated and established as a new GmbH, leaving behind the original holding company shell, which was rebranded as Photona GmbH. With the growth in recent years, there was the necessity to hire managers from diverse industries to get a fresh perspective and new ideas. For the first time, we hired individuals from larger organizations to help us. These managers are now working at Photona GmbH. LASER COMPONENTS France is now a sister company to LASER COMPONENTS Germany and is a subsidiary company to Photona GmbH.

What are the primary markets your company serves?

We have a diverse portfolio, and we are always proud of our independence from reliance on a single customer, supplier, or market. Our largest market segment is industrial, with around 40% of our revenue originating from users of laser technology for welding and marking. Additionally, we cater to defense and aerospace, machine vision, and the analytical market, particularly where our IR detectors play a key role. Industrial sensing and the scientific market are also significant, with the automotive sector becoming increasingly important for us. In these markets we also serve a wide array of applications, sometimes finding overlap where a single application is seen in multiple industries. For instance, rangefinding applications are utilized in defense, aerospace, industrial, and automotive sectors alike.

What advantages do you believe come from being a family-owned company?

As a private family-owned company, we prioritize decisions with long-term implications. Everything we do is part of a long-term strategy. We do not think in quarters, we think in generations. Taking more risks could have accelerated our growth, but to do that, there would have been a need to rely on external capital. We only afford what we can pay. We do not have bank loans for example. The only exception is for building infrastructure. Even then we maintain ownership of our production facilities and headquarters. We plan for them, we build them, we pay for them. It is a more conservative approach that brings stability. This philosophy guided our decision to consolidate the companies under Photona GmbH, enabling us to reinvest our profits locally. When an office generates profit, we want this office to reinvest this profit provided it fits with our growth strategy. For a sales organization for example, this means that we go to more shows, we hire more salespeople, or we do more advertising. Any surplus funds are channeled back to the parent company, Photona GmbH. Accumulating over time, these funds enable the acquisition of small and mid-size companies within our industry. We recognize the potential of these businesses and their technology, but they face succession challenges common for those in my father's generation. Some of these small companies are very profitable but they are too small to be attractive to the investment industry and fly under the radar. By leveraging our resources, Photona GmbH can support the growth of these companies and ensure continued expansion in the coming years. ●

Photonics in Italy

Italy can boast a very diversified and lively panorama of educational, research and industrial activities pivoted about Optics and Photonics. Significant advancements in laser technology, optical communication, and optical materials are driving innovation in healthcare, manufacturing, agrifood and generally in promoting digital transition. The National Recovery and Resilience Plan is expected to greatly enhance the country competitiveness on a global scale.

A pictorial view of the VLBI experiment between Matera and Medicina using the Italian Meteorological Institute (INRIM) clock on the Italian Quantum Backbone https://doi.org/10.1364/OPTICA.393356
Credits: Valentina Di Sarno (CNR) and Mario Siciliani de Cumis (ASI)

https://doi.org/10.1051/photon/202412519

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Historical notes

Starting from the early works of Francesco Maria Grimaldi on the diffraction of light in the XVII century, optics has played a significant role in the development of scientific culture in Italy. In the post-World War I period, and more prominently, after World War II, Italy has witnessed a strong boost in both fundamental and applied research in optics. In 1927, the Regio Istituto Nazionale di Ottica was founded, based in Arcetri, Tuscany. Beside carrying out research activities, the new institute played a key role in spreading and disseminating knowledge on optical technologies across the Italian industrial environment at the beginning of the century. In the same period, the Consiglio Nazionale delle Ricerche (CNR), the largest public research institution in Italy, was founded in Roma. After several decades, the Istituto Nazionale di Ottica (INO), with headquarters in Sesto Fiorentino, merged into CNR in 2005, along with the Istituto per i Processi Fisico-Chimici of Pisa and the Centro su Bose-Einstein Condensation of Trento. Nowadays, CNR-INO is active on several sites, including Brescia, Lecco, Napoli, Pisa, Trento and Trieste.

In early 60s, Orazio Svelto started his pioneering works on the development of solid-state and ultra-short pulse laser sources at the Politecnico di Milano. Following the growing interest in the emerging field of laser technologies, the Center for Quantum Electronics and Electronic Instrumentation of CNR was then established and later integrated within the current Institute for Photonics and Nanotechnologies (IFN) together with the Institute of Solid State Electronics of Rome, a CNR Center for material science in Trento, a Centre for ultrafast spectroscopy in Milano and two Innovation Laboratories (in Padova and Bari) belonging to the Istituto Nazionale di Fisica della Materia (INFM). Meanwhile, a growing scientific interest in optics and photonics has led to consolidating research lines in the Physics and Engineering departments in various universities spread across the country, the most prominent being La Sapienza in Roma, the University of Napoli Federico II, the University of Pavia, Padova, Brescia, the University of Trento, University and Politecnico of Bari, as well as the Universities of Pisa and Firenze. At the latter, in early 90s, the European Laboratory for Nonlinear Spectroscopy (LENS) was established, targeting activities mainly focused on biophotonics, materials for optics, and, more recently, quantum technologies.

Thanks to such a solid background, Italy has emerged as a worldwide recognized country performing excellent research in the science of light, also providing a fertile ground for innovation and technological development in the fields of optics and photonics.

Photonics research and education in Italy today

Nowadays, research in photonics is very diversified in Italy, covering all traditional topics whilst continuously expanding toward new investigation and application areas. Through a network of world-renowned research institutes, cutting-edge universities, and international collaborations, thousands of Italian scientists are currently contributing to advance knowledge in crucial sectors such as quantum photonics, optical communications, biophotonics, nanophotonics, ultrafast photonics and laser technologies (including laser material processing and manufacturing). Such a vibrant activity relies on the indispensable technological support from large clean-room facilities such as PoliFab in Milano, Fondazione Bruno Kessler (FBK) in Trento, Inphotec in Pisa and NanoMicroFab (CNR facility) in Roma, and the expertise developed in semiconductor physics, material science and nanotechnology on the one side, developed in institutes such as the CNR Istituto Officina dei Materiali (IOM) and the Istituto di Struttura della Materia (ISM). With robust support from the national and regional governments, the European Union and several other funding agencies, photonics research in Italy continues to thrive, fuelled by scientific curiosity, a marked creativity, and commitment to addressing global challenges through advanced optical solutions.

Environments facilitating the cooperation among institutions such as CNR, universities, public-private organizations under a common roof are big fund attractors and play a prominent role on the national and international scene. As a remarkable case, the Milano area is witnessing an intense growth of sparkling research and entrepreneurial activities pivoted around Politecnico di Milano, CNR-IFN, Italian Institute of Technology (IIT) and University of Pavia, mainly focused on optoelectronics (with a prominent role played by STMicroelectronics), laser technologies (e.g. the CUSBO centre, part of the LaserLab Europe network), integrated photonics, nanophotonics, sensors and quantum optics. A bit more than a hundred kilometres west from Milano, the Politecnico di Torino, together with the Links foundation represents an excellence pole for optical communications. Still in Torino, the National Institute for Metrological Research (INRiM) is active in the fiber-based distribution of optical time-frequency references to various end-user such as LENS. INRiM has built the Italian Quantum Backbone, a 1800 km long fiber-based infrastructure covering the entire national territory, from Matera to the French border.

In North-east Italy, a significant research activity in optics and photonics is carried out at the Universities of Padova and Trento, the latter being particularly interesting because of the successful collaboration with FBK on optical materials, photonic devices and sensor technology. In Trieste, the Area Scientific Park hosts the ELETTRA synchrotron, the FERMI source (Free Electron laser Radiation for Multidisciplinary Investigations) and CNR-IOM.

Tuscany has a long tradition in optics too: the Scientific Pole in Sesto Fiorentino, close to Firenze, hosts vast infrastructures for institutes such as LENS, the CNR Istituto di Fisica Applicata (CNR-IFAC), the above mentioned CNR-INO and the Physics department of the University of Firenze. In Pisa cutting-edge research on integrated light sources, semiconductor heterostructures, THz emission, optomechanical systems is performed at the NEST Laboratory (joint infrastructure involving Scuola Normale Superiore, Scuola Superiore Sant'Anna, CNR-Nanoscienze, IIT) and the University of Pisa. Non-linear optics, optoelectronics, quantum optics and complex media photonics are some of the topics investigated by research institutions in the Rome area, including La Sapienza, Roma Tre, Istituto Sistemi Complessi (CNR-ISC) and CNR-Nanotec. In 2006, the Lazio region funded The Centre for Hybrid and Organic Solar Energy (CHOSE), with the strong involvement of the University of Roma Tor Vergata. Within the CNR "Area di Ricerca Tor Vergata" photonics is within the activity portfolio of institutes such as CNR-IFN, ISM and IMM.

Optical biosensing, structured light and digital holography are among the most relevant core expertise specifically developed, at the Institute of Applied Sciences and Intelligent Systems (CNR-ISASI) and the University Federico II, in the Napoli area. Fundamental research of polaritonics, at the edge between semiconductor physics and photonics, is carried out at CNR-Nanotec in Lecce. The University of Catania is an excellence centre for Silicon photonics and optoelectronics, also thanks to the synergic collaboration with STMicroelectronics (whose facilities have been recently empowered).

Last but not least, we mention research centres and institutes carrying out research and development in Optics and Photonics at different levels, from materials (Istituto per lo studio dei Materiali Nanostrutturati CNR-ISMN), to space applications (Agenzia Spaziale Italiana ASI; the Istituto Nazionale di Astrofisica INAF).

At Italian universities, Optics and Photonics are widely addressed in many teaching programmes, mainly within Physics and Engineering tracks. Generally, a fundamental scientific background is provided at the Bachelor level (Laurea Triennale), while the educational offer becomes more specialized at the Master level (Laurea Magistrale). Worth to mention a bachelor-level degree called Laurea in Ottica ed Optometria, available at several institutes such as the University of Torino, Milano Bicocca, Roma Tre, Firenze, Padova, Napoli Federico II, Perugia, Palermo and the University of Salento. At a higher level, education in Optics and Photonics is offered either as specialized tracks of the Master of Science (sometimes called "curricula") within Physics, Engineering Physics, Electronic Engineering, Telecommunication Engineering majors, or self-standing post-laurea masters, such as the Optics and Quantum Information master at the Sapienza, University of Rome. Master lectures are often given in English, with international student cohorts resulting from agreements in the framework of university networks and mobility programs such as the Erasmus Mundus.

As third-level or post-secondary education is concerned, in addition to traditional 3-year PhD tracks within research groups at universities or research centres, industrial PhD options have been recently introduced, after the boost from PNNR (Piano Nazionale di Ripresa e Resilienza), launched in 2021.

In order to further reduce the gap between universities and industries, several careers counselling initiatives are often organized at a local (often, regional) level. Worth to mention the participation of the Politecnico di Milano to the EU-funded consortium CARLA (2020-2023) and its updated version CARLA 360 (2024-2027), wherein outstanding research/educational institutes, innovation hubs and scientific societies facilitate the creation of new opportunities for the development of early-stage careers in Photonics at the European level.

National initiatives and networks

In recent years, several relevant actions have been undertaken by the central government to support university missions (i.e. research, education, knowledge dissemination and transfer), to facilitate collaborations with research institutes (e.g. CNR) and promote the creation of new entrepreneurial initiatives.

The Fondo Italiano per la Scienza (FIS) supports basic research in the framework of excellent research program replicating an application scheme from the European Research Council. FIS has made available 50 MEUR in 2021, that have increased to 150 MEUR yearly, starting from 2022. Other funding opportunities include the Fondo per gli Investimenti nella Ricerca Scientifica e Tecnologica (FIRST) and the periodic calls for proposals under the PRIN program (Progetti di Rilevante Interesse Nazionale). For example, in PE areas, about 865 MEUR have been provided across two calls in 2022.

The program named Dipartimenti di Eccellenza represents an innovative intervention with a strong financial support started in 2017, aiming at identifying and funding, on a five-year basis, the top 180 departments in public universities. These are departments distinguished by the quality of research produced and the quality of the development project, assessed according to quantitative parameters. In the period 2018-2022, 1.36 billion euros have been distributed. Among the beneficiary departments exhibiting a significant activity in optics and photonics, we recall the Physics departments at the University of Padova, Pavia, Pisa, Roma La Sapienza, Milano Bicocca and the department of Industrial, Electronic and Mechanical Engineering at the University of Roma Tre, collecting estimated funds amounting to about 7.9 MEUR overall.

Starting from mid-2021, the Italian Government has launched the implementation of one of the most massive funding and investment programs in the last decades, the so-called PNRR, supervised and coordinated by the Ministry of Economy and Finance. PNRR constitutes the Italian implementation of the Next Generation EU program, targeting the attenuation of the socio-economical impact of COVID-19 pandemic. Among the extremely varied and diversified investment portfolio, photonics plays a prominent role in the several initiatives.

The Photonic Platform for Quantum Technologies within the new National Quantum Science and Technology Institute (budget 116 MEuro) promotes fundamental research on the interaction between non-classical light and matter, in order to design single-photon sources, and new schemes for quantum-light manipulation and detection. Applications include the whole spectrum of QST applications from quantum communication to the simulation of quantum chemical and physical systems.

Photonic and Quantum technology constitute the core of I-PHOQS, a network of important national research infrastructures providing a unique integrated, interdisciplinary, and multifaceted approach to address complex scientific and technological issues. I-PHOQS offers full access to national and international users from the academic and industrial world, designed to promote interdisciplinary research in most areas of science.

Lastly, within the RESTART program (budget 118 MEuro), the largest national partnership for research and innovation in telecommunications, the spoke called "Pervasive and Photonic Network Technologies and Infrastructures" focuses on radically new technologies and paradigms for ultra-fast optical transport in the metro-core network, programmable, green, and ultra-fast interconnections between sites supported by optical transport and the design and fabrication of novel components and photonic integrated circuits for the optical networks domain.

Innovation and Industry

Optical technology and photonics are among the most widely used technologies in our daily lives, with countless applications. Photonic technologies trigger innovation in traditional production processes in various sectors: healthcare, manufacturing, agri-food, mobility and energy, security, space and defense, and digital infrastructure. In 2022 Italy has reached a record number for published patent applications to the European Patent Office (EPO), with a 5% increase with respect to the previous year (UnionCamere and Dintec data report). Since 2016, the number of filed patent applications is constantly growing, reaching a net increase of about 33%, a number that confirms a remarkable creative activity at the national scale. Furthermore, 20% of the 2020 Italian patents relate to enabling technologies, advanced manufacturing in particular. A significant growth of the photonics domain is also reported, with 74 patents filed in 2020.

EPR	A61	G01	C07	C12	H01	G06	B01	C08	A01	H04	B60	H02	G02	C01	A23
Consiglio Nazionale delle Ricerche - CNR	101	472	462	383	132	275	71	192	195	80	43	11	6	83	59
Politecnico di MILANO	96	272	371	78	40	110	165	99	76	24	130	124	49	51	29
Agenzia Nazionale per le Nuove Tecnologie, l'energia e lo Sviluppo Sostenibile - ENEA	100	19	96	24	14	44	11	33	5	13	2	9	9	4	32
Politecnico di TORINO	95	175	186	0	9	66	108	46	15	23	57	80	74	9	6
Fondazione Istituto Italiano di Tecnologia	120	313	99	54	50	54	41	17	37	12	4	0	16	38	27
UniversitÃ degli Studi di BOLOGNA	76	238	107	76	120	26	45	48	67	88	24	11	14	3	9
UniversitÃ degli Studi di PADOVA	27	338	96	83	120	66	67	16	12	31	43	4	55	8	8
UniversitÃ degli Studi di ROMA "La Sapienza"	60	293	129	89	159	49	38	25	12	16	32	12	20	18	26
UniversitÃ degli Studi di MILANO	82	289	63	180	95	14	23	32	39	40	3	0	0	0	3
UniversitÃ degli Studi di PISA	61	128	84	61	25	21	30	9	24	12	4	4	4	8	0
UniversitÃ degli Studi di GENOVA	23	113	63	66	32	5	12	17	18	6	9	6	17	2	2
UniversitÃ degli Studi di FIRENZE	48	133	91	51	31	24	20	2	0	13	17	15	3	18	0
Scuola Sup. di Studi Univ. e Perfezionamento S.Anna di PISA	93	247	51	5	12	3	27	3	2	5	18	17	11	4	0
UniversitÃ degli Studi di TORINO	28	218	58	24	80	0	17	8	11	10	8	0	0	0	0
UniversitÃ degli Studi di MILANO - BICOCCA	16	115	50	86	33	54	29	21	41	12	5	28	4	8	4

In the table above, the number of patents filed in various Intellectual Property Classification (IPC) areas is shown for the 15 largest Italian research institutions (source, Patiris-MISE). The IPC code G02 refers to "Optics" and certainly represents an underestimation for the whole Photonics domain.

According to the Market Data and Industry Report 2020 (source Photonics21, Tematys), photonics embraces about 200 companies in Italy with 150000 employees overall. As a mere illustrative and non-exhaustive list, we mention Think Quantum, OST-Optical Sensing Technologies, CareGlance, EYE4NIR, NIREOS, Cambridge Raman Imaging, Dynamic Optics, PioNIRS, Optosensing, PhotonPath, Julight, L-pro Antares Vision Group, OptoSmart, IPG Photonics Italia, Bright Solutions, Officina Stellare, Nirox, LithiumLasers, MicroPhotonDevices, Optoprin, Prima Industrie, Adige S.p.A. (BLM Group), Kirana, SM-Optics, Quanta System, ElEn, iGuzzini, TASI (Thales AleniaSpazio Italia), Ericsson, SAES Getters, Convergent Photonics, Laser Point, OPI Photonics, Cordon Electronics Italia, Univet.

Industrial production is estimated as 5.2 billion euros, constituting a 5% share on the European total production. Major sectors of Photonics production are: (1) Defence & Security, with Leonardo playing a major role, also in aerospace; (2) Laser machines and systems for imaging and optical measurement in industrial environment, such as barcode scanners and related equipment provided by Datalogic, the third-largest manufacturer in this segment; (3) Environment, energy and lighting, with many lighting companies producing LED-based lamps and modules; (4) Mobility, in particular automotive lighting, wherein Hella and Marelli Automotive Lighting have prominent role; (5) Healthcare, for example, spectacle lenses and contact lenses provided by Hoya and Essilor, plus many SMEs focused on imaging systems.

Beside big industrial actors promoting partnerships with universities and research centres (worth recalling the agreement of EssilorLuxottica and Politecnico di Milano for the first joint Smart Eyewear Lab, providing initial investments of over 50 MEUR), there are dozens of incubators and start-ups accelerators spread across the whole country. In this complex scenario, a new initiative called Fotonica District has been recently launched as an industry association with the mission of promoting the excellence of Italian Photonics. In particular, it aims at gathering all national innovative photonics SMEs, giving them support in terms of services and fund raising opportunities. Additional support for innovation is provided by the European Union, through successful initiatives such as PhotonHub and having Confindustria Toscana, CNR, Scuola Superiore Sant'Anna, CNIT, El.En (Italy's leading laser technology company), and Leonardo as Italian partners.

Currently, a significant boost to industrial innovation is provided by the above mentioned PNRR plan, through the creation of so-called Innovation ecosystems. A total investment of 1.3 billion euros is made available to facilitate networks of universities, public research institutions, local public bodies and other highly qualified public and private entities to operate in technological areas consistent with the regional vocations. As an example, the Innovation Infrastructure QMPI - Innovation Infrastructure on Quantum, advanced Materials and Photonics coordinated by Scuola Superiore Sant'Anna will be realized at the Sant'Anna Campus in San Giuliano Terme over about 3800 square meters equipped with a large clean room, laboratories and offices. Being rather pervasive in many different PNRR projects dealing with innovation and business creation, the Photonics sector is expected to grow sensibly in the next few years.

Coordination activities and scientific dissemination

In the complex scenario depicted above, coordination activities are of paramount importance to keep tight contact with funding agencies and to disseminate results toward the scientific community and the general public.

AEIT-CORIFI (COordinamento Ricerca Innovazione Fotonica Italia) was founded in 2014 as the national mirror of the European Technology Platform Photonics21. It gathers individual members, both from academia and public research institutions and from industries and collaborates with professional societies in the field of Optics, Photonics and Laser Manufacturing. In synergy with Photonics21, it contributes to the promotion of research and innovation in Photonics at the European and National level, participating at the preparation of European vision papers and strategic research agenda, interacting with national and regional/local institutions, and organising topical events to bring together photonics scientists and industrial players with end-users, policymakers, and general public.

The IEEE Photonics Italy Chapter was founded in 1997, then as LEOS Italian Chapter. It currently has 130 members and an Executive Committee of 17 members from universities, research centers and industries in Northern, Central and Southern Italy.

Every year it carries out dozens of activities aimed at promoting photonics, such as seminars, workshops and conferences, professional development activities, awards for young people, and dissemination activities.

The Italian Society for Optics and Photonics (SIOF, Società Italiana di Ottica e Fotonica) was founded in 1991 with the goal of promoting the research activities in the field of optics and photonics and coordinate them all over the national territory by favouring the spread of knowledge and the organization of scientific events, schools, conferences, and workshops, with a special emphasis on the formation of young scientists. SIOF is governed by a council of 12 members elected, and active members are currently over 300 distributed all over Italy with members also from abroad. SIOF is in charge of one of the most important conferences in Italy, the Italian Conference on Optics and Photonics (ICOP), organized every other year with the support of IEEE Photonics Society and other organizations.

In addition, there are several organizations and associations of students and researchers connecting optics and photonics scholars and facilitating the creation of networks of scientists. Societies such as Optica, SPIE, EPS and EOS support activities through local chapters in Napoli, Roma, Trento, Padova, Milano, Messina, Pisa, and Torino.

Future directions

As witnessed by the complex scenario depicted above, Photonics is probably one of the most powerful engines for innovation of this century. In order to fully deploy its potential and create a beneficial impact on the national economy and society, in the perspective of a sustainable growth, Italy needs to build one (or more) symphonic ecosystem(s) where education, research, innovation and knowledge transfer are seamlessly interconnected. The unprecedented investments enabled under the PNRR are an exceptional opportunity to achieve this ambitious goal and fill the competitivity gap with major industrial players on the global scene.

Being one of the six Enabling Technologies, Photonics has a basically ubiquitous role in achieving the missions Italy has set for its future development, which are on: Health; Digital and Aerospace Industry; Energy, Climate and Mobility; Natural Resources; Agriculture and Environment. At the time being, the implementation of the above-mentioned extended partnerships, national centres and innovation ecosystems is smoothly running according to the scheduled roadmap (source BOZZA IV RELAZIONE ATTUAZIONE PNRR – 21_02_2024). Whilst it is probably too early to provide precise projections on the expected socio-economical impact in 2026, when the PNRR is planned to end, but we can certainly forecast a very intense period of hard work for many Photonics experts and researchers in Italy.

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Two-photon interference and the Hong-Ou-Mandel effect

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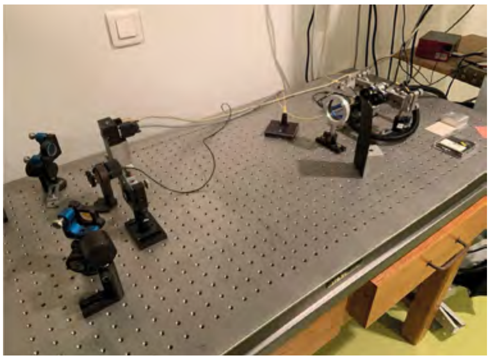

The Hong-Ou-Mandel (HOM) experiment is a landmark in quantum optics. A labwork version of this famous two-photon interference effect was developed at Institut d'Optique for students in engineering and MSc tracks. The setup enables the observation of the iconic HOM "dip" and the measurement of photon indistinguishability.

The HOM labwork setup @ Institut d'Optique.

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The Hong-Ou-Mandel experiment (HOM), performed in 1987 [1], is the first experiment reporting the observation of a two-photon quantum interference, occurring when two indistinguishable photons are sent simultaneously on the two input ports of a beamsplitter (BS). The photon distribution at the exit is properly astounding: indeed, the two indistinguishable photons leave the setup by the same output port and are never split by the BS ! This gregarious behavior is called photon bunching, and strongly contradicts the "classical" behavior: independent particles with a 50% chance of being either transmitted or reflected are expected to pick different output ports 50% of the time.

The HOM effect is exploited to provide a quantitative measurement of particles indistinguishability, an important requirement to create complex multi-particle superposition states, a common resource in quantum information. The HOM effect extends well beyond the exclusive case of photons: indeed, experiments have been notably performed to investigate the same effect with other quantum particles [2,3].

This experiment is now routinely proposed and performed as a Labwork session in the LEnsE (Laboratoire d'Enseignement Expérimental) of Institut d'Optique as both an illustration of the quantum weirdness and standard experimental protocol in the field of quantum technologies.

Classical description of a lossless beamsplitter

The HOM experiment relies on the concept of a beamsplitter (BS): a device that splits incoming light into a reflected and a transmitted wave. In classical electrodynamics, input and output fields are related via complex reflection and transmission coefficients r and t. We can write using matrix formalism:

$$\begin{pmatrix} E_c \\ E_d \end{pmatrix} = U \begin{pmatrix} E_a \\ E_b \end{pmatrix} \text{ (Eq. 1)}$$

$$\text{with } U = \begin{pmatrix} t & r \\ r & t \end{pmatrix}, \text{ the BS matrix}$$

The energy conservation condition writes $|E_c|^2 + |E_d|^2 = |E_a|^2 + |E_b|^2$. By multiplying Eq. 1 by its conjugate, we immediately get $U^\dagger U = I$. It is said that U is unitary, and this condition leads to constraints on the coefficients:

$$|r|^2 + |t|^2 = 1$$

$$rt^* + r^*t = 2Re(rt^*) = 0 \text{ or } r = \pm\, it$$

The first condition can be directly related to energy conservation. The second condition shows that the absence of losses impose a phase relation between the reflection and transmission coefficients. The HOM effect being an interference effect, this second condition plays a crucial role in the experiment.

Lossless beamsplitter in quantum optics

While the energy of a classical wave is a continuous quantity that splits into two output fields, the behavior of a photon, is different. It can be either reflected (with probability $|r|^2$) or transmitted (resp. $|t|^2$), but its energy is never divided into smaller parts.
This result is predicted by the quantum optics formalism: we replace classical fields by operators.
We introduce $\hat{a}$ and $\hat{a}^\dagger$ the annihilation et creation operators associated to the electric field $\hat{E}_a$ of input port a of the BS. We also introduce the number operator $\hat{n}_a = \hat{a}^\dagger \hat{a}$, so that the field hamiltonian writes $\hat{H}_a = \hbar\omega(\hat{n}_a + 1/2)$ Its eigenvectors are the Fock states : for example, $|n\rangle$represents a field state with n photons.
Similarly one introduces $\hat{b}, \hat{b}^\dagger$ and $\hat{n}_b$ for input port b and so on for output ports c and d of the BS.
The transformation induced by the BS can be expressed using relations between input port and output port operators. They are all encompassed by the same matrix U used in the previous part:

$$\begin{pmatrix}\hat{c}\\ \hat{d}\end{pmatrix} = U\begin{pmatrix}\hat{a}\\ \hat{b}\end{pmatrix}$$

The unitarity of U leads to a new formulation of energy conservation

$$\hat{c}^\dagger\hat{c} + \hat{d}^\dagger\hat{d} = \hat{a}^\dagger\hat{a} + \hat{b}^\dagger\hat{b} \text{ or } \hat{n}_c + \hat{n}_d = \hat{n}_a + \hat{n}_b$$

This time interpreted as a conservation of the number of photons. More generally, one can show that operators are related via [4]:

$$\hat{a}^\dagger = t\hat{c}^\dagger + r\hat{d}^\dagger$$
$$\hat{b}^\dagger = r\hat{c}^\dagger + t\hat{d}^\dagger$$

One photon on a beamsplitter

Let's start with a simple situation: a single photon is sent on input port a. This state can be expressed using $\hat{a}^\dagger$:

$$|1_a, 0_b\rangle = \hat{a}^\dagger|0,0\rangle$$

The previous relation enables us to rewrite the same state in the output space of the system:

$$|1_a, 0_b\rangle = \hat{a}^\dagger|0,0\rangle = (t\hat{c}^\dagger + r\hat{d}^\dagger)|0,0\rangle = t|1_c, 0_d\rangle + r|0_c, 1_d\rangle$$

We get a quantum superposition state. It explicitly shows that the photon can be either measured on output port c with probability $|t|^2$ OR on output port d with probability $|r|^2$. For a stream of single photons reaching the BS, two detectors placed at each of the BS output never click simultaneously. This measurement is an observation of photon anti-bunching, and an illustration of the particle-like behavior of photons [5].

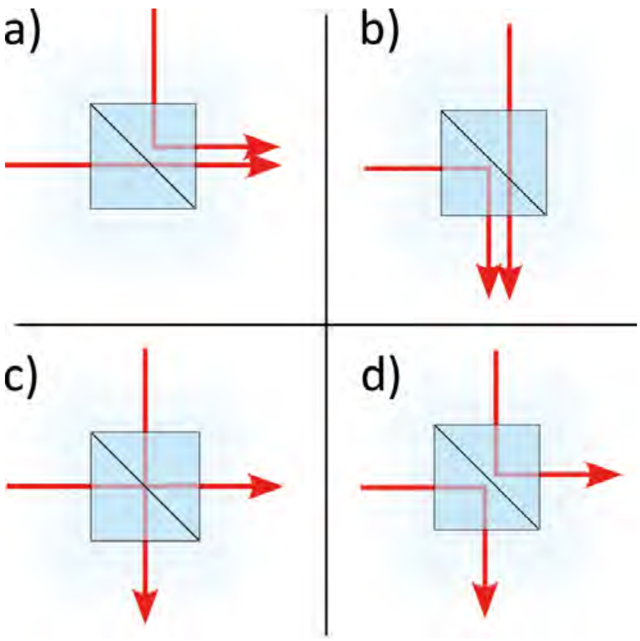


Figure 1. Four classical scenarios for a pair of photons impinging on a beamsplitter.

Two photons on a beamsplitter

In an HOM setup, two indistinguishable photons are sent at the two input ports of a lossless BS. Expanding the way of thought of the previous paragraph, we state that each photon is either reflected or transmitted, leading to four different scenarios (see Fig 1):

a) Photon *a* is transmitted and photon *b* is reflected ; both photons exit port *c*

b) Photon *a* is reflected and photon *b* is transmitted ; both photons exit port *d*

c) Both photons are transmitted ; photon *a* exits port *c* and photon *b* exits port *d*

d) Both photons are reflected ; photon *a* exits port *d* and photon *b* follows exits port *c*

We use creation operators and the vacuum states to write the quantum state corresponding to this situation :

$$|\Psi_{HOM}\rangle = \hat{a}^\dagger\hat{b}^\dagger|0,0\rangle$$
$$|1_a, 1_b\rangle = \hat{a}^\dagger\hat{b}^\dagger|0_a, 0_b\rangle$$

In the output space:

$$(t\hat{c}^\dagger + r\hat{d}^\dagger)\,(r\hat{c}^\dagger + t\hat{d}^\dagger)|0,0\rangle =$$
$$(tr\hat{c}^\dagger\hat{c}^\dagger + rt\hat{d}^\dagger\hat{d}^\dagger + t^2\hat{c}^\dagger\hat{d}^\dagger + r^2\hat{d}^\dagger\hat{c}^\dagger)|0,0\rangle = tr|2_c, 0_d\rangle + rt|0_c, 2_d\rangle +$$
$$t^2|1_c, 1_d\rangle + r^2|1_c, 1_d\rangle$$

and we can identify 4 terms for the 4 different scenarios discussed above.

The calculation is not over yet ! We have candidly "ommitted" to factorize the last two terms: indeed, $t^2|1_c, 1_d\rangle + r^2|1_c, 1_d\rangle$ can be written $(t^2 + r^2)|1_c, 1_d\rangle$.

This trivial operation hides a subtlety : this operation is acceptable provided that the output quantum state obtained when both photons are reflected is exactly the same as the quantum state obtained when both photons are transmitted. In other words, we considered that these two scenarios are *indistinguishable*.

Indistinguishability means here that there is absolutely no way, experimentally *or even in principle*, to perform any type of measurement that would allow us to tell, for a given photon pair, which one of the two scenarios (double transmission or double reflection) occurred in practice. This indistinguishability criteria requires:

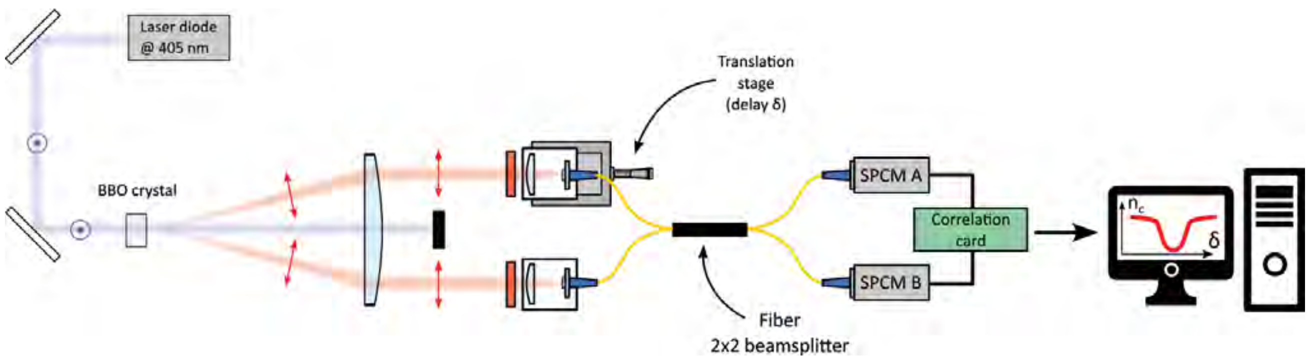
a) That the intrinsic properties of the photons are the same (polarization, energy/frequency)

b) That the photons cannot be distinguished spatially (in other words, a photon from input *b* experiencing transmission and a photon on input *a* experiencing reflection end up populating the same spatial mode of output *c*).

c) That the photons cannot be distinguished temporally (both photons must reach the BS simultanously, so that there is no timing information available to identify one photon or the other.)

These criteria being considered as fulfilled, the final step is now to measure the probability of observing each one of the 4 different scenarios listed. Let us start with the probability of

Figure 2. Two-photon interference setup as implemented in the LEnsE at Institut d'Optique.



measuring state $|2_c, 0_d\rangle$:

$$P(2_c, 0_d) = |\langle 2_c, 0_d|\Psi_{HOM}\rangle|^2 = |t|^2\,|r|^2$$

By symmetry, we have $P(2_c, 0_d) = P(0_c, 0_d)$. Finally, we derive the probability of observing the photons exiting distinct output ports:

$$P(1_c, 1_d) = |\langle 1_c, 1_d|\Psi_{HOM}\rangle|^2 = |t^2 + r^2|^2$$

This expression can look rather familiar in the context of an interference experiment: the probability can be interpreted as the interference between two complex probability amplitudes r^2 and t^2.
We now compute exactly the results for a balanced lossless BS. The coefficients can be chosen as $r = 1/\sqrt{2}$ and $t = i/\sqrt{2}$ and we get $P(2_c, 0_d) = P(0_c, 2_d) = 1/2$ and $P(1_c, 1_d) = 0$! **In other words, the amplitudes associated to $|1_c, 1_d\rangle$ interfere destructively *for a balanced lossless BS*** and the photons *never* exit the system using two different output ports. They are always travelling together, in output *c* 50% of the time or in output *d* 50% of the time. The total output quantum state now writes:

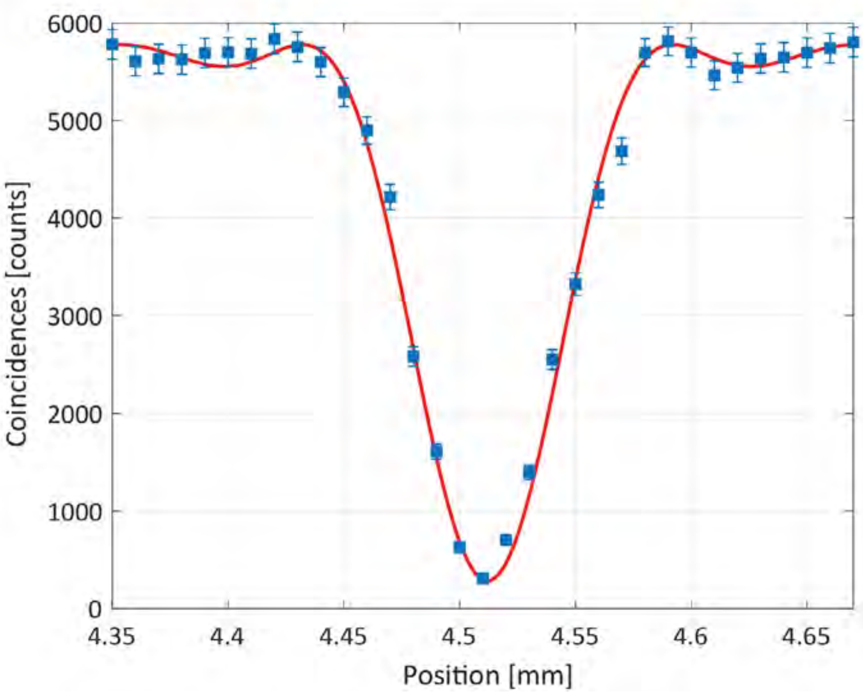
$$|\Psi_{HOM}\rangle = \frac{|2_c, 0_d\rangle + |0_c, 2_d\rangle}{\sqrt{2}}$$

(and the trained eye identifies an entangled state!)
As for every interference effect, the relative phase (here between coefficients *r* and *t*) is essential ; it stems here from the energy conservation. The quantum weirdness of the HOM effect has some connection with entanglement, in the sense that it deals with multiple-particle states, that have striking non-classical behaviors.

Experiment: coincidence measurement

The experimental protocole of the HOM effect relies on the observation of state $|1_c, 1_d\rangle$ **via coincidence measurements**.

Figure 3. Measured HOM dip (number of coincident counts in 10s as a function of the position of the translation stage).



One uses a pair of single photon detectors, placed symmetrically at each of the BS outputs: if the two photons involved in one run of an experiment exit by two different output ports, both single photon detectors will register detection events quasi-simultaneously. Following this idea, the correlation (hence the product) of the detector signals is linked to the probability of measuring $|1_c, 1_d\rangle$.

Two main regimes can be identified:

a) When both photons reach the BS with significant relative optical delays, the situation is all classical and no interference occurs: $P(1_c, 1_d)$ is non-zero and coincidence counts are registered at an average rate related to the pair generation rate.

b) For vanishing optical delays, the HOM interference effect progressively builds up. Eventually, all detection events correspond to photon pairs exiting via the same output: the coincidence rate decreases as we get $P(1_c, 1_d) = 0$.

A HOM experiment can therefore consist in a plot of the coincidence rate measured between two detectors as a function of the delay between the two incoming photons.

Hardware implementation

The practical implementation involves the generation of indistinguishable photon pairs using a type I single photon parametric down-conversion (SPDC) effect in a BBO non-linear crystal. This process and its symmetrical version (second harmonic generation SHG) are routinely used with wavelengths at 405 nm and 810 nm, that display several advantages: cheap GaN laser diode emitting in the 100 mW range are easily found, and the 810 nm wavelength matches the high sensitivity range of silicon detectors.

BBO crystals for SHG and SPDC are usually cut so that their optical axis is oriented at 29.2° with respect to the input face. When pumped at 405 nm at normal incidence and in ordinary polarization, one gets two non-collinear beams at 810 nm exiting the output face along a cone with an apex angle of 3°.

The SPDC process is broadband and emits photons in various directions. The rest of the setup must therefore be designed to select photons from a same pair and ensure intrinsic photon indistinguishability. Spatial mode indistinguishability can be conveniently achieved using single mode fibers and a fiber BS instead of a free-space setup.

Therefore, we place a 500 mm-focal length doublet to collimate the output mode of the crystal and we use mounted collimators to couple the photons in a 2×2 single-mode, polarization-maintaining fused fiber splitter. We get rid of the stray light by using band-pass filters of 10 nm spectral width around 810 nm.

One of the collimators is mounted on a translation stage with a 15mm range and a 10µm resolution in the direction of the incident beam to set a variable delay between the two photons. The two outputs of the fiber splitter are directly connected to two single-photon counting modules (SPCM-AQ4C from Perkin Elmer) with a dark count rate of 300Hz. The signal is sent to an FPGA board (Altera DE2), programmed to detect simultaneous events on two channels receiving 25 ns TTL pulses from the detector channels. We visualize the raw detector count and coincidence rates with a Labview interface. An experiment run consists of recording the coincidence rate as a function of the translation stage position, convertible into a path delay.

Results

The width of the HOM dip reveals the length of the two wavepackets and the shape of the dip is related to the temporal wavepacket, that means to the spectra. Assuming that the photons had a gaussian spectrum, the data is fitted with the product of a gaussian with a sinc function. We inferred a visibility of 95.4% and a full width at half maximum (FWHM) of 56 ± 8µm, in good agreement with the ~ 60µm expected for Fourier-transform-limited photons with a 10nm bandwidth. The dip depth shows that the photons of each pair are nearly indistinguishable and demonstrates that this simple setup can achieve a good degree of control over their parameters.

Conclusion

The LEnsE implementation of the HOM experiment is a robust setup operating since 2015 [6] in the optical engineering track and M2 tracks of IOGS and Université Paris-Saclay. The objective of IOGS is to further expand the scope of these quantum labworks to establish a full and versatile quantum photonics experimental platform adressing different physical platforms and enabling training on standard characterization procedures: this will include antibunching measurements for the characterization of a solid-state single photon source, quantum key distribution, NV center magnetometry and a progressive refinement of our historical Bell [7] and HOM setups.

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ECLAIRs, A CODED MASK APERTURE TELESCOPE ONBOARD THE SVOM SPACE MISSION

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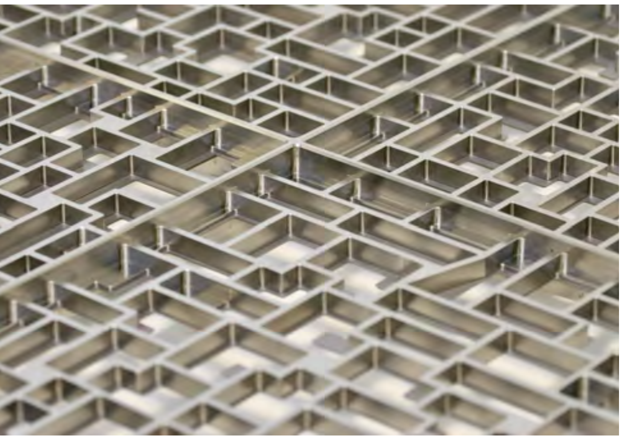

We introduce the coded mask imaging technique with a focus on the ECLAIRs instrument onboard the SVOM space mission. Detecting unknown astrophysical transient sources in the hard X-ray band requires monitoring a large part of the sky. Coded mask instruments are well suited to perform these observations. ECLAIRs, thanks to its low energy threshold, will open a new window on the transient universe but it comes with its own challenges, in particular in the design of its coded mask.

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On June 24, 2024, the SVOM (Space-based astronomical Variable Objects Monitor) space mission will be launched, concluding a collaborative effort between China and France aimed at studying high-energy astrophysical transient phenomena [1]. These phenomena, characterised by their short duration (ranging from seconds to weeks or years) compared to cosmic timescales and their significant energy releases, are typically associated with compact objects like black holes and neutron stars. They reflect profound physical changes within the astrophysical sources, sometimes resulting in the partial or complete destruction of the progenitor object. Observing transient phenomena, often done at various wavelengths, helps deepen our understanding of astrophysical mechanisms such as the accretion of matter in the vicinity of compact objects, particle acceleration to relativistic velocities, and the behavior of ultra-dense matter.

The SVOM payload comprises four instruments: a Visible Telescope (VT), a soft X-ray (0.2-10 keV) telescope (MXT), a Gamma-Ray Monitor (GRM) with scintillation counters operating between 15 keV and 5 MeV, and a hard X-ray/soft gamma-ray (4-150 keV) wide-field telescope, ECLAIRs (see Fig.1). SVOM's primary goal will be the detection of gamma-ray bursts (GRBs) linked to the final stages of the life of certain massive stars (insert 1). Investigating GRBs requires compliance with specific observational constraints. Initial detection of the gamma-ray flare is imperative, given its brief duration. Detecting and localising these GRBs will be the main task of the ECLAIRs telescope, over a wide field-of-view (FoV) covering 89×89 square degrees.

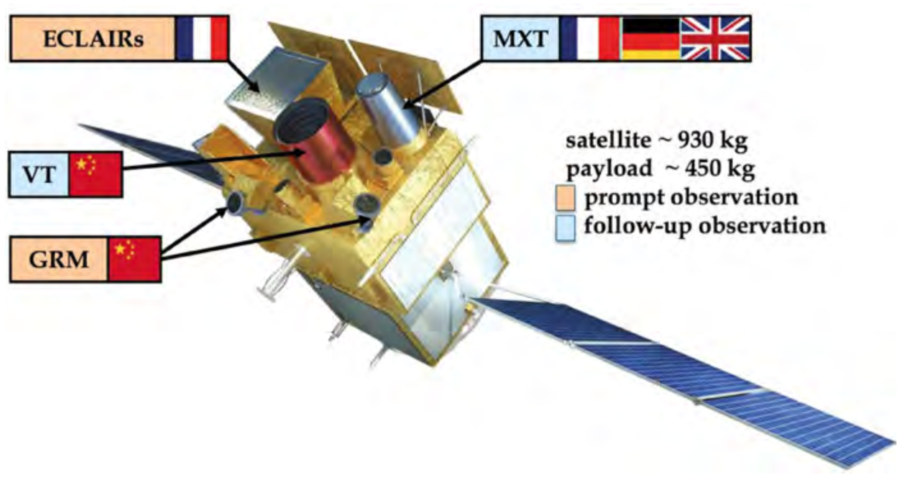


Figure 1. The SVOM satellite, with its four scientific instruments (flags indicate the countries involved in their construction). Taken with permission from CNES.

CODED MASK APERTURE TELESCOPES

Telescopes in the hard X-ray/soft gamma-ray (between ~10 keV and 10 MeV) like ECLAIRs are special since mirrors, which are ubiquitous at other wavelengths, are difficult to use in this energy range. First, as the grazing incident angle, used in X-ray mirrors, is inversely proportional to photon energy, the focal length, which is of the order of 10 m at 20 keV, would be of the order of hundreds of meters at 1 MeV. On the other hand, in the hard X-ray/soft gamma-ray domain, the radiation wavelengths become comparable to or shorter than the typical interatomic distances which then lead to absorption of the photons mainly through the photoelectric process.

Thus, at such energies, coded mask instruments (CMI) are generally used. They are multiplexing optical devices that allow reconstructing the flux and position of astrophysical sources in the FoV through the spatial modulation of the incident light depending on the source direction on the sky. CMIs follow the principle of the well-known sténopé or *camera obscura*: a hole in a mask is used to form an image on a screen. In such a system, the image of a point source is a single spot of the projected size of the hole. However, while the sensitivity increases with the aperture, the angular resolution is inversely proportional to the hole size. Hence, a practical alternative is to design a mask with several small transparent elements of the same size which modulate the signal arriving on a position sensitive detector located behind it (Fig. 3). The small size of the holes guarantees good resolution, while their large number ensures good sensitivity [4].

Assuming a detector with infinite spatial resolution and an infinitely thin mask composed of totally opaque closed elements and totally transparent open ones, the angular resolution of a coded-mask telescope is directly related to the size m of the mask elements and the mask-detector distance H by: $\theta = \arctan(m/H)$. The sensitive area instead depends on the number of transparent elements of the mask that are visible to the detector. Therefore, by either decreasing the size of the holes or increasing the distance between the mask and the detector while simultaneously increasing the number of holes, one can improve the angular resolution without sacrificing sensitivity. In addition, sensitivity is not uniform across the entire FoV, but is directly related to the fraction of the detector illuminated by a mask pattern (even if incomplete) for a given source. To characterise the FoV of a coded-mask telescope, two cases can thus be distinguished: the fully coded FoV for which the mask shadow fully covers the detector, and the partially coded FoV for which only a fraction of the detector is modulated by the mask (see Fig. 3).

With such a coded mask instrument, the detector image (also known as a shadowgram) is then a linear superposition of the shadows of the mask projected by the different sources in the FoV. The sky image is then reconstructed by applying a deconvolution procedure to the detector image based on the knowledge of the mask pattern (insert 2).

Coded masks were designed in the 1970's-1980's and have been successfully used since then in the field of high-energy astronomy. Initially deployed on balloon-borne instruments, they were later integrated into several space missions. Such a coded mask will also equip the ECLAIRs telescope onboard the forthcoming SVOM space mission. Its design is described in the following section.

THE ECLAIRs INSTRUMENT AND ITS UNIQUE CODED MASK

The ECLAIRs instrument is composed of four subparts: a coded mask, a 1024-cm^2 detection plane and its front end electronics, a passive lead shield and a processing unit. The detection plane consists of 6400 pixels made of CdTe measuring $4{\times}4{\times}1$ mm^3 each. The processing unit allows for the control of the telescope and runs a scientific software in charge of detecting new astrophysical transient events in real time. Upon detecting a new cosmic source, the information is relayed to the platform to initiate a slew, aligning the VT and MXT instruments with the direction of the ECLAIRs trigger in order to catch the GRB afterglow emission. Simultaneously, the platform transmits its data to the ground via a dedicated VHF network distributed around the Earth, which then forwards it to the Mission Center.

The operating principle of the ECLAIRs telescope is a matter of balance: it must detect bursts with maximum sensitivity, necessitating a large sensitive area, while also determining their locations with good accuracy across a wide FoV. These constraints heavily influenced the design of the ECLAIRs coded mask, as elaborated below.
The mechanical design of the mask is driven by the mechanical resistance to the important level of vibrations that the mask has to support at launch. To complicate further the design, the mask has to be self supporting; unlike conventional masks that utilise a supporting structure for the mask elements, such an approach would inadvertently impede photon absorption within the energy range of 4 keV to 15 keV. On the other hand, to indeed absorb photons between 4 keV to 150 keV, the opaque elements of the mask are made from a •••

GAMMA-RAY BURSTS

GRBs are among the most energetic cosmic explosions emitting luminosities 10^{44} J/s. They consist of two main phases: the non-thermal prompt emission, observed between 10 keV and 10 MeV and lasting between ~100 ms and ~1000 s, and the afterglow, most often detected from X-rays to radio and fading over a few months. Two classes of GRBs are identified: short GRBs with durations typically <2 s and long GRBs with durations up to hundreds of seconds. While long GRBs are associated with the death of massive stars, the detection of a gravitational-wave signal associated with a short GRB in 2017 [2], confirms that the latters are associated with the coalescence of two neutron stars. A well-accepted model for GRBs suggests that they are produced within an ultra-relativistic jet created after cataclysmic events like the formation of a black hole or a highly magnetised neutron star (see *e.g.* [3] and references therein). This scenario, described in Fig. 2, involves internal dissipation mechanisms within the jet which produces the gamma-ray prompt emission. In the final stage, the propagation of the relativistic jet in the interstellar medium creates a shock wave, leading to the deceleration of the jet. A fraction of the ejecta energy is converted into the amplification of magnetic fields and acceleration of electrons which re-emit part of this energy through synchrotron radiation, creating the long-lived afterglow. While these models provide a fundamental understanding of basic GRB properties, various complex features such as electromagnetic flares pose significant challenges for comprehensive explanation. This suggests that there are still substantial aspects of GRBs that require further understanding. Moreover, high-redshift GRBs are ideal probes of the epoch of the very first stars and galaxies, a few hundred million years after the Big Bang.

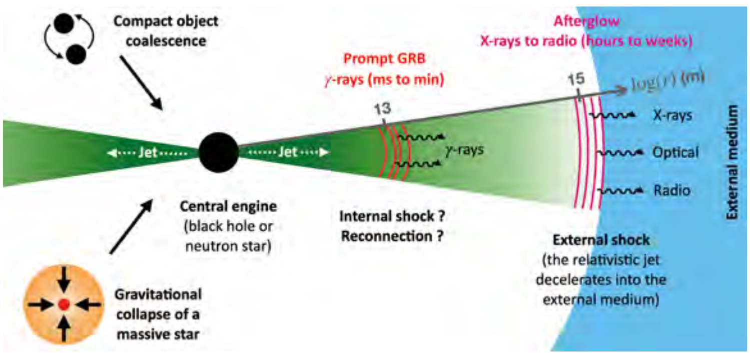


Figure 2. Model of the Gamma Ray Burst emission processes.

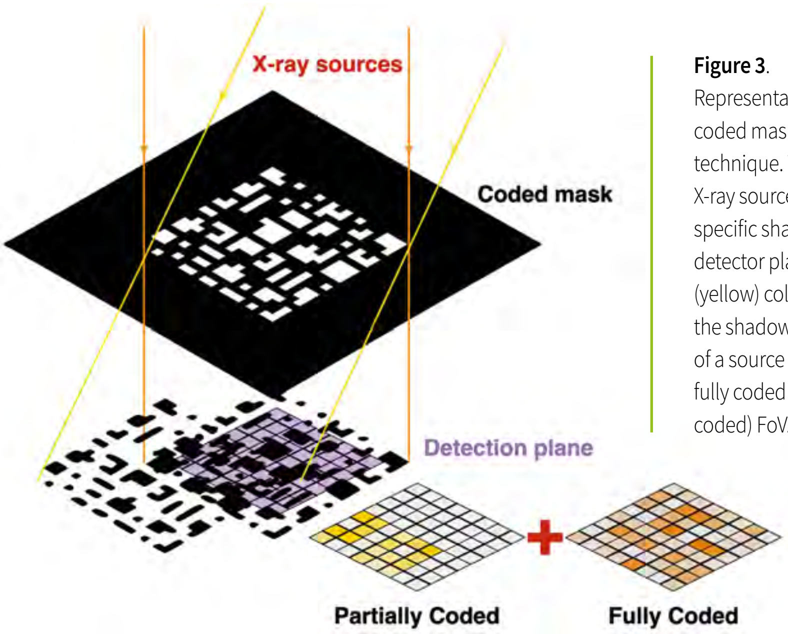


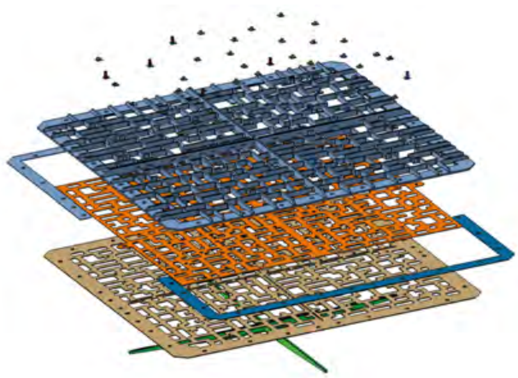
Figure 3. Representation of the coded mask imaging technique. Two X-ray sources cast a specific shadow on the detector plane. Orange (yellow) color illustrates the shadowgram of a source in the fully coded (partially coded) FoV.

compatible with the self-supporting constraint (*i.e.* the final pattern can be obtained by simply digging holes in a foil). To improve the resistance, holes were connected to other holes only by their edges and not by their corners. Due to these constraints, even if their design involves a random generative process, such patterns are called pseudo-random patterns. 600,000 23×23-element patterns were generated and their response simulated. To build the four quadrants, we selected the four patterns with the best sensitivity respecting the localisation constraints. Detailed mechanical simulations have then shown that a few elements were reducing locally the mechanical resistance and have been simply moved manually to allow the final design to meet the requirements.

tantalum foil of 0.6-mm thickness (Fig. 4). The mechanical resistance is achieved thanks to two titanium masks sandwiching the tantalum and firmly secured together with pins. Each of the titanium masks exhibits a large cross of 1.6-cm height in the centre, contributing significantly to the overall mechanical resistance of the final mask. Crucially, the design ensures that the titanium masks, including their crosses, do not interfere with the photons within the FoV of ECLAIRs as they traverse through the mask apertures.
The scientific pattern of the mask is divided into four independent quadrants of 23×23 (opaque or transparent) elements. The choice of the size of the holes (~11 mm-side squares) is determined by the requirement that the localisation error provided by ECLAIRs for triggered GRBs must be smaller than the FoV of the VT instrument onboard SVOM, which is equal to 26×26 arcmin^2. This ensures that the triggered GRB is in the VT's FoV after repointing the satellite in the source direction. The mask aperture (ratio of the surface of the transparent elements to its total surface) is 40% which has been shown by simulations to be a trade off to have a good mechanical resistance and a good sensitivity to GRBs.
Due to its large FoV and a large fraction being partially coded, the choice of a random pattern was imposed (see insert 2). A dedicated algorithm has been developed to generate and control the growth of the mask elements to ensure that the pattern is

CONCLUSIONS AND PERSPECTIVES

After its launch, SVOM will enter a commissioning phase, marked by instrument start-up, testing and calibration. These preliminary stages are crucial for guaranteeing data reliability and paving the way for future scientific exploitation. The first results from ECLAIRs could be available by the end of 2024, offering an unprecedented perspective on the cataclysmic Universe. While hard X-ray energies have traditionally served to monitor the transient sky due to the capacity to build large FoV coded mask instruments, observing in this energy



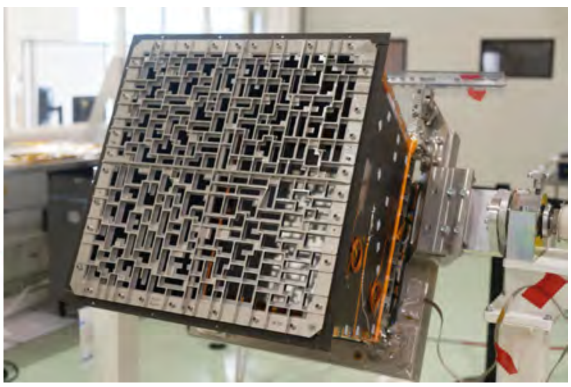


Figure 4. Left: Schema of the different parts of the mask. The tantalum mask is represented in orange and all other components are made of titanium. Credit: SVOM/APC. Right: Image of the ECLAIRs flight model during the integration process at CNES. Taken with permission from CNES.

band has a cost since it excludes the highly redshifted sources whose photon energy falls below the energy threshold of the instruments. In contrast, in the soft X-ray range (0.2 to 10 keV), a new generation of instruments, whose optical design mimics the lobster's eye, has been recently developed. These new X-ray optics consist of micro-channel plates arranged in a spherical configuration, effectively focusing light onto detectors while providing a significantly wider FoV compared to traditional optical configurations [5]. Such innovation presents exciting opportunities for monitoring the transient high-energy sky. Notably, instruments like the MXT onboard SVOM and the recently launched Einstein Probe satellite are pioneering this new optical approach, marking a significant advancement in astrophysical transient observing capabilities.

DECONVOLUTION OF THE DETECTOR IMAGE

The recorded detector image consists of a background together with the superposition of the shadowgrams produced by each source in the FoV. A reconstructed image of the sky is built by correlation between the detector image D and a decoding matrix G obtained from the coded mask pattern. If M is a matrix representing the mask with transparent (opaque) elements described by values equal to one (zero), then D is the correlation of the sky image S with M, to which is added the background noise B such as: $D = S \star M + B$. Hence, the sky image S' can be reconstructed by applying the decoding matrix G: $S' = D \star G = S \star M \star G + B \star G$. The reconstruction quality therefore depends on the choice of M and G. It is essential that, in absence of noise, there is a one-to-one correspondence between S and S′, *i.e.* that $M \star G = \delta$. On the other hand, it is desirable that the effect of noise appears uniformly in the deconvoluted image. Mask patterns M, satisfying these two conditions, are called optimal patterns. In such a case, if the background B is flat, then $B \star G$ is constant and can be easily removed. Uniformly Redundant Arrays (URAs) and their generalisations (*e.g.* Modified Uniformly Redundant Array ones - MURA patterns) were shown to be optimal for imaging which means that the point source response function of the telescope has a side-lobe-free central peak. Such an ideal response can be obtained due to the cyclic nature of the mask pattern and this only happens for sources in the fully coded FoV [4]. On the contrary, sources outside the coded FoV will produce secondary lobes a.k.a. coding noise in the reconstructed images. In this context, even if they do not produce ideal response for imaging, random mask patterns are often chosen since they do not limit the FoV of the instrument contrary to optimal cyclic patterns.

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PROGRAMMABLE INTEGRATED PHOTONICS: A NEW PARADIGM FOR LOW COST MULTIFUNCTIONAL OPTICS

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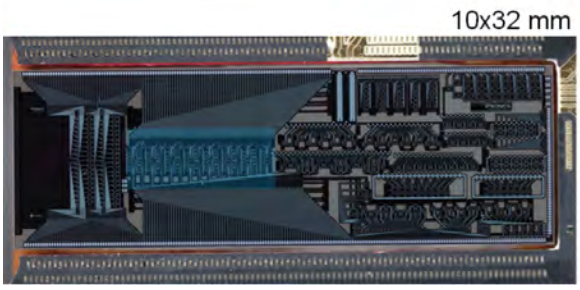

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This article presents the rationale, basic principles of operation, technology stack, and areas of application of a new technology approach called programmable integrated photonic. In essence, it is based on the same high-level concepts that inspired several decades ago the birth of programmable integrated electronic devices such as the microprocessor, the field programmable gate array, and the digital signal processor. We provide a final discussion on its current limiting challenges.

Integrated photonics is a technology with a clear objective, the research, development, fabrication, and testing of devices, circuits, and subsystems capable of generating, processing, controlling, and detecting guided-wave lightwave signals carrying useful information. It is an enabling technology that can support a myriad of applications that include telecommunications (optical networks, IoT, and 5G), switching and interconnections (cloud and edge data centers), computing (artificial intelligence and neuromorphic), sensing (lidar, bio, civil infrastructures), robotics and aerospace to cite a few.

From the *technology point of view*, integrated photonics shares common features with microelectronics as both are semiconductor technologies and, for certain materials, both can leverage from CMOS fabrication processes. There are also important differences. First of all, while Silicon reigns in microelectronics this is not the case in photonics. Silicon is an indirect gap material and thus not suitable for implementing active devices such as laser sources and amplifiers. These and others such as detectors and high-performance modulators are currently being implemented in other material platforms such as III-V InP or Lithium Niobate. While it is true that silicon on insulator (SOI) and silicon nitride (SiN) are predominant in the area of passive devices and circuits, no material platform can integrate monolithically all the required components. To overcome this limitation both hybrid and heterogeneous integration approaches are being pursued. In the first case, different chips implementing active and passive components are physically interfaced through input/output waveguide ports, while in the second active components are either flip-chip bonded or transfer printed on top of a passive silicon chip. From the *operational point of view* microelectronics is mainly digital, work with electrons, which can be stopped and stored and it is highly nonlinear thanks to the switching operation enabled by transistors. Photonics is on the contrary linear and analog, and works with photons, which neither can be stopped or easily stored, can provide huge bandwidths

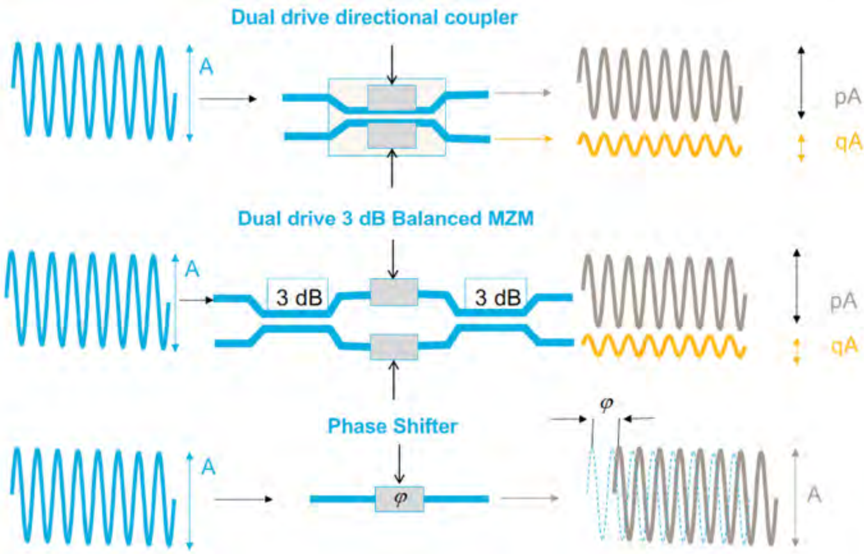


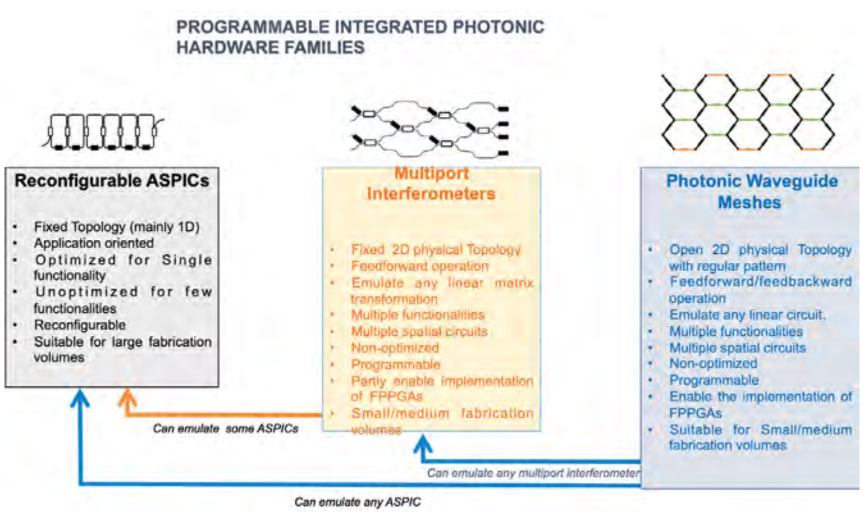
Figure 1. Basic building blocks in programmable photonics.

and low power consumption when moving data. It is clear therefore that both technologies are complementary, and the question is how and whether it makes sense to leverage this complementarity.

It turns out that the surge of applications requiring ever-increasing processing speed, bandwidth, and reduced power consumption is exerting considerable pressure on microelectronics, which is jeopardized by the saturation of its main scaling laws (Moore, Dennard, and Amdahal). This context opens a window of opportunity for integrated photonics especially for photonic integrated circuits (PICs). However, integrated photonics is a much less mature technology and still requires long development and fabrication cycles for application-specific circuits (ASPICs) with considerable impact as well on costs.

A way to overcome this limitation is to resort to programmability [1], [2], an approach that leverages on the fabrication of a single hardware that can be dynamically reconfigured *via* software to implement and emulate different circuits and subsystems enabling multiple applications with the same product. This approach leads to •••

Figure 2. The three families of Programmable Photonics Hardware.

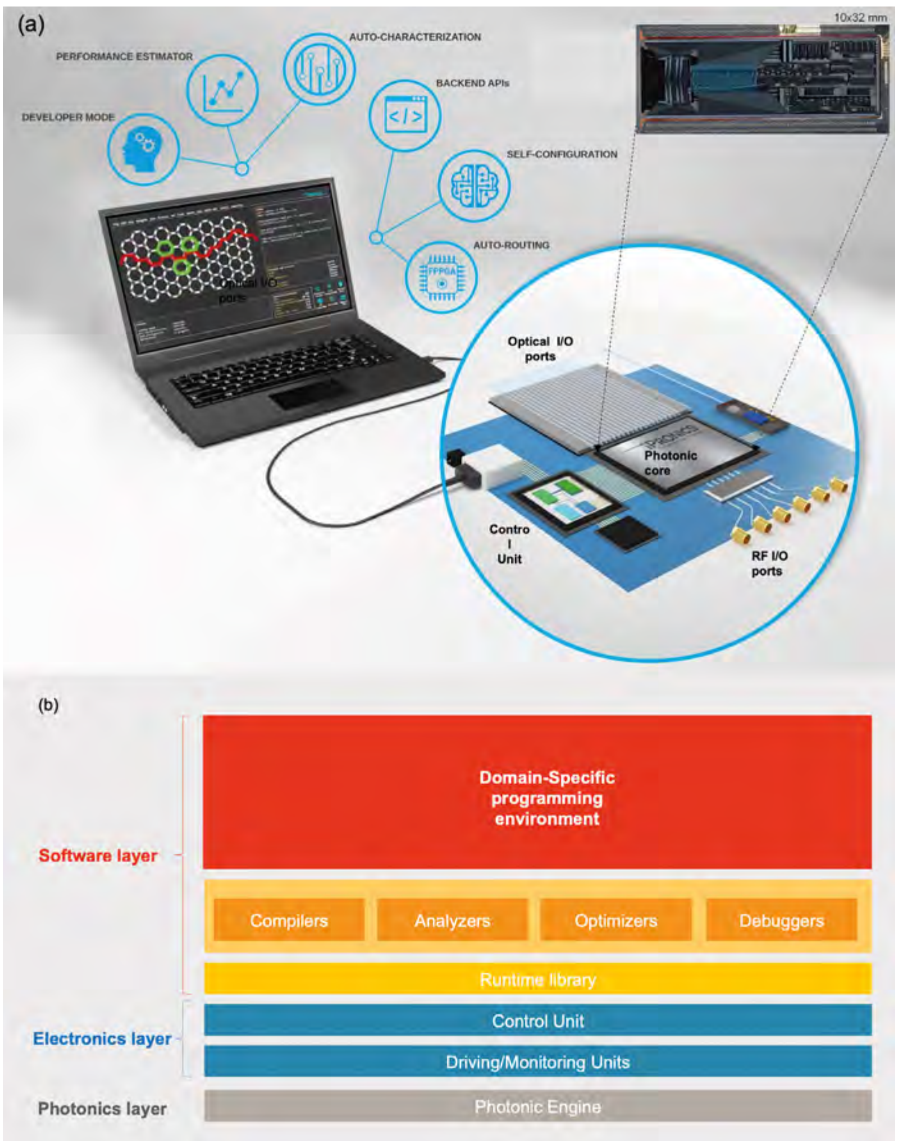


substantial cost savings by leveraging economies of scale and reduces non-recurrent (NRE) engineering costs. Programmability has been instrumental for the success of electronics (where microprocessors, digital signal processors, field programmable gate arrays, GPUs and CPUs account for more than a 50% of the world market) and we believe that it will have a similar impact in integrated photonics. In this short article we provide an introduction to the principles, applications and future prospects of programmable integrated photonics.

PRINCIPLES OF PROGRAMMABLE INTEGRATED PHOTONICS

Programmable photonics is a broadband analog technology that enables the programming of signal processing tasks based on the ability of photonic circuits to manage multiple optical interference [1-3]. In essence, this entails the independent setting of amplitude and phase characteristics of the multiple interfering signals. For the first task, it employs either tunable couplers or Mach-Zehnder interferometers, while for the second a phase shifter is needed (see Figure 1).

Figure 3. The technology stack of a general-purpose integrated photonics processor.



These are the basic building blocks, which can be programmed by the action of external electronic signals (which will be described in the next section). The combination and interconnection of these basic building blocks allows the implementation of programmable photonic circuits featuring various degrees of complexity and functionality, which can be grouped into three hardware families shown in Figure 2 and which we now briefly explain.

The most basic configuration for Programmable PICs, the reconfigurable ASPIC [2] is shown in the left part of Figure 2. It retains most of the main features of fixed designs but brings some degree of reconfigurability whereby the operation and bias points governing the circuit response can be programmed but the overall functionality of the chip is not changed. A second family, shown in the center block of Figure 2 is formed by multipoint interferometers [3]. These are based on two-dimensional (2D) fixed topologies built from tunable interferometers and can be programmed to emulate any linear feedforward arbitrary unitary matrix transformation. Finally, photonic waveguide meshes [4], based on balanced tunable interferometers assembled to form 2D topologies following regular geometric patterns are capable of emulating any reconfigurable ASPIC and multiport interferometer while in addition can implement any feedforward and feed backward transformation. The upper right part of Figure 2 shows, as an example, a hexagonal waveguide mesh but other 2D patterns (triangular, square) are possible.

THE TECHNOLOGY STACK

Implementing and operating a programmable integrated photonic processor involves the design and coordination of several layers that implement different tasks. This layered structure is known as the technology stack [5-6] and is shown in Figure 3.

Figure 3(a) shows a particular implementation where the different physical

Figure 4. Some examples of application fields for programmable integrated photonics.

elements, input and output ports, and control elements are displayed for reference. The technology stack architecture is displayed in Figure 3(b). It basically consists of three different layers. The photonic layer includes the optical programmable waveguide mesh chip with several surrounding high-performance blocks (an example is shown as an inset in Figure 3(a)) and the photonic input and output ports. The electronic layer includes all the elements required to monitor, control, and drive the photonic elements using electronic signals. It can also include radiofrequency ports and devices if required by the particular application. Finally, the software layer [7] is composed of two different sublayers. The top one is the programming environment for the specific application which allows the external user to easily program the system and circuit configurations to be implemented and/or emulated by the processor without needing to have a specific knowledge of the hardware configuration. The lower sublayer takes care of implementing and coordinating all the necessary operations to analyze, optimize, and implement self-healing actions if a failure is produced in the optical hardware or if, for example, a set of restrictions related to different performance metrics such as delays, energy consumption, number of hops are imposed on the available resources. Its action is transparent to the high-level user. It is the correct orchestration of the available resources that is pursued by the swift interaction of all the layers in the architectural pile and where in the last term resides much of the added value of a programmable photonic circuit.

APPLICATIONS OF PROGRAMMABLE INTEGRATED PHOTONICS

Programmable photonics is a transversal enabling technology approach and as such, can find applications in a myriad of areas. Figure 4 shows some of these areas, which we briefly describe in the following lines.

a) *Telecommunications and data centers* (Interconnection, routing, and switching). In this area of application, programmable photonic processor products can help to develop new generations of flexible and programmable intelligent optical transceivers, high-capacity routers, switches, and multiplexer/demultiplexers. A special area of interest is intra-data center interconnections, where ● ● ●

there is a need for the so-called elephant traffic of broadband, flexible and low power consumption circuit switching solutions.

b) *Flexible microwave photonic interfacing systems for 5/6G wireless communications.* In this strategic area, providing programmable interfaces in terms of functionality and operating band between the fiber optic segment and the radiofrequency segment is instrumental both in base stations and in central office centers. In addition, programmable photonic engines will be able to enable multiband, multi-channel, and multi-input multiple-output transmission and broadcast.

c) *High-performance computing.* Programmable photonics processors are well suited to support a new generation of hardware accelerators essential for parallel computing and interconnection of multi-core processors and disaggregated clusters with remote locations.

d) *Sensors.* Programmable photonic systems will provide the flexibility needed to simultaneously process communication and measurement or remote sensing channels, providing a compact solution in the Internet of Things (IoT), Smart Cities, LIDAR, and autonomous driving application environments.

e) *Artificial intelligence, neurophotonics, and novel approaches for computing.* Incorporating programmable analog photonics adds the possibility of integrating interconnections and very-high-speed matrix-vector multiplication (MVM) operations key in the implementation of hardware systems for deep learning and neural networks. Furthermore, programmable photonics offers unique hardware for the implementation of novel computing paradigms based on linear optic transformations.

f) *Application Specific Photonic Chip Manufacturing.* In this field, programmable photonics helps to accelerate the ASPIC circuit design cycle by allowing the emulation of designs on a hardware platform in a few days, thus avoiding the delay posed by manufacturing rounds with negative results.

g) *Quantum information systems.* Programmable photonics provides the possibility to emulate linear optical transformers needed to implement quantum logic gates, boson samplers, quantum transport emulators, and numerical operations such as Fourier and Hadamard transformations. On-chip integration of these transformers with specialized single-photon optical sources and detectors will lead to compact and decoherence-free processing systems.

We expect this list to be substantially enlarged as the field of programmable photonics matures.

CONCLUSION

We have briefly reviewed the emerging area of programmable integrated photonics providing, first of all a rationale for its development (i.e., the whys). We have them jumped into describing the basic principles behind the operation of programmable integrated photonic processors, including their basic building blocks and the generations developed so far (*i.e.* the How). A distinctive feature of these systems as compared to application-specific photonic circuits is that they need a complete layered stack architecture composed of software and hardware layers to operate. We have described the main components of this so-called technology stack. Finally, we have briefly addressed some of the current application fields for programmable integrated photonics, emphasizing that this list will for sure be enlarged in the forthcoming years. Recent work has been reported on the use of this technology to emulate artificial materials and topological photonics, and work is undergoing in exploiting its features for instance in the implementation of reservoir computing.

We would like to conclude by outlining some of the main challenges that this technology faces towards achieving its goal of global implantation. Scalability, that is the possibility of incorporating a higher component count in the available chip footprint is perhaps the most important limitation. Work is underway to reduce propagation and coupling losses and also to achieve building blocks with reduced insertion losses. The target here is to achieve overall losses in the range of or below 4 dB. In terms of the number of building blocks, the challenge is to jump from the current figure of <1000 to figures around 5000. Power consumption is also another limitation that can hamper scalability. Currently, the activation of photonic building blocks is done using thermo-optic mechanisms that consume a few milliwatts per unit. Lower or negligible power consumption can be achieved using non-volatile tuning mechanisms which are currently being investigated.

If these challenges are solved there is a real good chance that programmable photonics will become as instrumental in the future as microprocessors, FPGAs and digital signal processors (DSPs) have been for electronics.

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PHOTONIC INTEGRATED CIRCUITS THROUGH FEMTOSECOND LASER WAVEGUIDE WRITING IN GLASS

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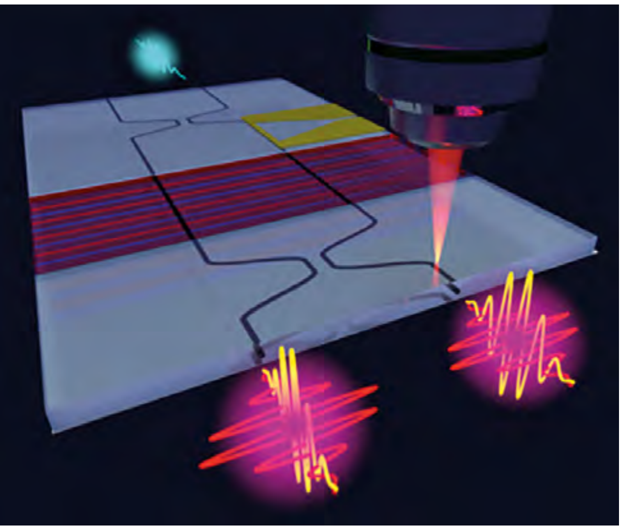

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Integrated photonics is increasingly pivotal across various fields due to its inherent stability, scalability, and compactness. In the landscape of integrated photonic platforms, femtosecond laser writing is a novel microfabrication technique that is swiftly emerging as a strong contender to established photolithography-based methods. This paper presents a primer on the femtosecond laser writing process and explores its capabilities for creating versatile and reprogrammable processors. Furthermore, we examine the application of this technology to the realization of integrated devices designed to leverage the distinctive features of this technology for critical areas such as quantum information processing and astrophotonics.

INTEGRATED PHOTONICS

Photonics serves as a cornerstone technology, pervasive in modern life, particularly in data communication for its high bandwidth, low energy consumption, and perfect electromagnetic compatibility. It plays an important role also in sensing for remote and extreme condition monitoring. In addition, photonics is also becoming an enabling tool in three-dimensional vision and imaging, as well as in classical and quantum computing. However, conventional discrete optical components are impractical for creating compact and complex devices (Figure 1a). For this task, integrated photonics is the technology of choice, with the fabrication of all necessary components on a monolithic substrate, allowing light to travel through optical waveguides and information to be processed by means of interferometric devices (Figure 1b).

The production of integrated photonic circuits is a mature and expansive field, often utilizing CMOS-compatible processes to benefit from the existing micro and nanoelectronics facilities, enabling cost-effective mass production in materials like silicon or silicon nitride. However, the reliance on these established processes has slowed the broader adoption of integrated photonics. • • •

Large foundries are not incentivized to develop processes for small product batches, hindering the penetration of integrated photonics into new or niche fields. Moreover, standard photolithography-based fabrication is efficient for mass replication but costly and slow for new development, limiting the technology's application in areas where it could offer significant benefits.

The need for a microfabrication technology that allows for the rapid and economical prototyping of integrated photonic circuits in small to medium volumes is clear. Such a technology exists in the form of direct waveguide writing with ultrashort laser pulses, also known as femtosecond laser writing (FLW). Discovered in 1996 [1], this approach has matured over more than two decades into a dependable industrial tool, now adopted by a growing number of companies. The subsequent sections will provide an overview of this technology, highlighting its several advantages over traditional methods, with a special focus on programmable integrated devices and applications such as quantum information processing [2] and astrophotonics [3].

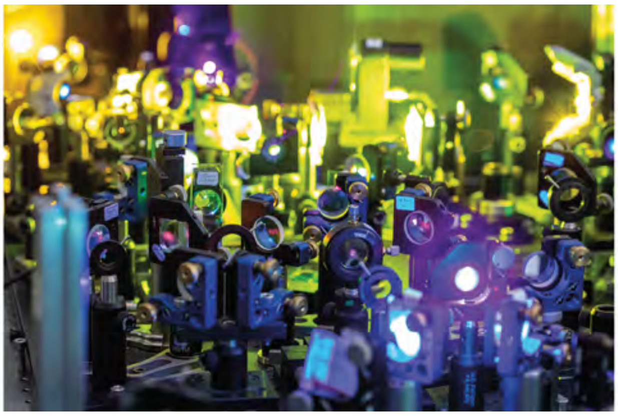
FEMTOSECOND LASER WRITING IN GLASS

Transparent materials are those that allow light to pass through without absorbing it. Simply put, in a transparent material the energy of the single incoming photons is not enough to overcome the energy gap between the valence and conduction bands and, as a result, photons are allowed to pass right through the material without being absorbed. However, when we focus intense, ultrashort laser pulses inside the same material, the concentration of photons in the focal volume at a given instant of time is high enough to induce multiphoton ionization and other nonlinear processes that cause a localized absorption of a fraction of the impinging photons. On the contrary, outside the focal volume the light spreads out and the probability of triggering such phenomena drops rapidly. As a result, this technique allows for precise and confined modification of the material properties at the microscopic scale. An example of this modification is the local increase of the refractive index in glasses such as borosilicate and fused silica, allowing for waveguide writing by simply translating the substrate with respect to the laser beam. Figure 2a depicts a graphical representation of the FLW process.

FLW is a serial fabrication technique and might not be ideal for mass production compared to photolithography. However, its speed and simplicity make it an attractive option for at least medium-scale production in rapidly evolving areas such as the quantum technology one. The change in the refractive index that can be achieved is modest, so devices are not as miniaturized as they could be with other platforms like silicon or silicon nitride. Yet, FLW stands out by allowing for three-dimensional circuit layouts (Figure 2b-c), compatibility with various materials beyond glass (facilitating the hybrid integration of composite devices) and low-loss connections to standard optical fibers. FLW is only one of the several micromachining processes made possible by the nonlinear interaction of ultrashort laser pulses with transparent materials. Another example is femtosecond laser ablation, which allows for the precise removal of material aimed at creating three-dimensional microstructures as the microtrenches depicted in Figure 2a. Combining FLW and laser ablation, one can enhance the performance of integrated photonic devices, as in the case of programmable photonic integrated circuits [5], which integrate waveguides, electrically programmable interferometers and hollow structures realized to achieve very low levels of

Figure 1. Comparison between bulk and integrated photonics. a) Experimental setup based on discrete optical components such as lenses and mirrors. Courtesy of Mr. Maurizio Contran (Politecnico di Milano) and Dr. Cristian Manzoni (IFN-CNR). b) Integrated photonic circuit encompassing a mesh of 28 programmable interferometers over a set of 8 optical modes. Courtesy of Ephos Inc.

a



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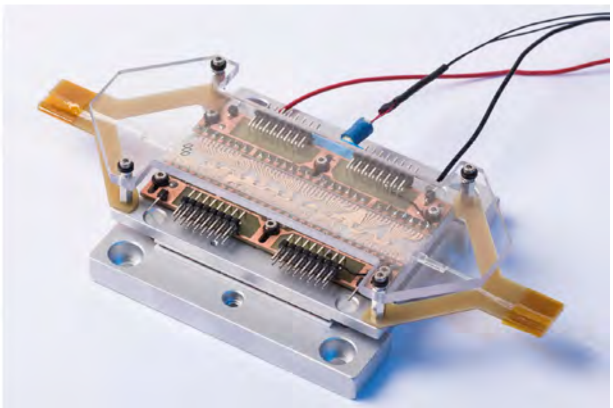


power dissipation during their operation. Like field-programmable gate arrays (FPGAs) in electronics, these devices are programmable for different uses and are key components in more complex photonic systems for a plethora of applications.

UNIVERSAL PHOTONIC PROCESSORS

Integrated photonic circuits become programmable by exploiting various physical phenomena, with thermo-optic phase shifters being the preferred technique for FLW circuits [8]. These devices integrate an electrical circuit atop the photonic structure, where resistive microheaters are placed on the waveguides to be tuned. Heating the waveguides through the microheaters changes the material's refractive index, causing the desired phase shift in the light path. For FLW devices, design must consider shallow waveguides (less than 30 µm deep) for effective thermal interaction and, as already mentioned, thermal insulation to focus heat and minimize power dissipation, with microtrenches and three-dimensional microbridges realized by femtosecond laser ablation being the most common choices in these devices.

A notable class of programmable photonic integrated circuits is represented by the universal photonic processors. These devices are designed to implement an arbitrary optical operation, usually represented as a unitary transfer matrix between the input and output photonic modes, reprogrammable by the user even at runtime. The simplest universal processor encompasses only 2 modes and can be implemented in an integrated fashion by resorting to a Mach-Zehnder interferometer (MZI), made programmable by two thermo-optic phase shifters, one external and one inside the MZI (Figure 3a, top-left inset) . This 2-mode universal processor can act as the basic building block for a rectangular interferometric network, such as the one reported in the rendering of Figure 3a, for multimode operation. FLW universal processors have now reached 6 modes [6], offering a rapid and cost-effective alternative to standard fabrication processes. Figure 3a (bottom-right inset) shows a microscope picture of an MZI column of the processor showing the trenches (dark lines) and the microheaters (thin gold lines in between). Moreover, these devices offer low insertion losses (< 3 dB) over the whole visible range up to the telecom band. and a very high fidelity (> 99.7% on average) between the implemented and the desired optical transformations. Finally, these circuits have the unique property of implementing the same transformation for any polarization state • • •

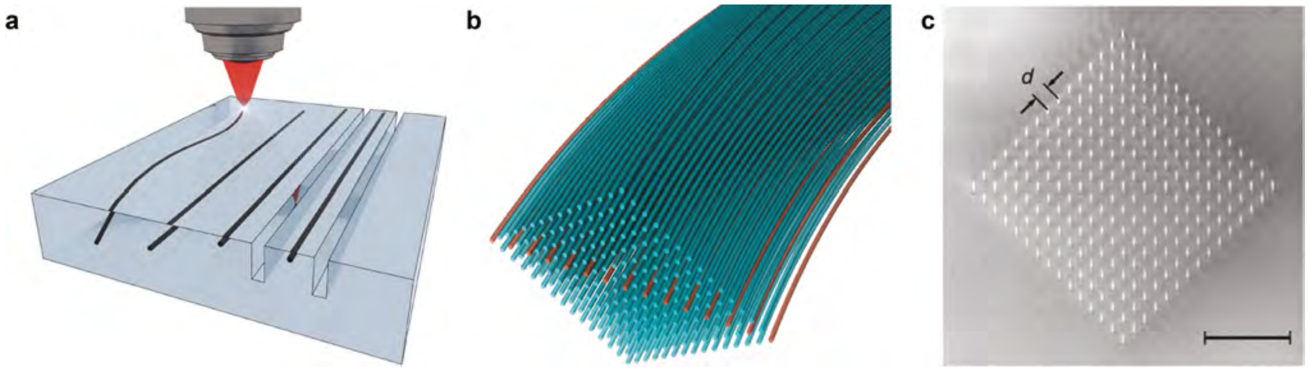


Figure 2. The capabilities of FLW for the realization of integrated photonic devices. a) The illustration shows two key fabrication processes enabled by using femtosecond lasers: the ability to inscribe waveguides in three dimensions and the ablation of material for realizing microstructures such as microtrenches. Reproduced under terms of the CC-BY license from [2]. b) A graphical representation of a three-dimensional waveguide matrix inscribed by using the FLW technology. Adapted from [4]. c) A microscope view of the cross-section of the same waveguide matrix, where the scale bar is 100 µm and the waveguides pitch is d = 19 µm. Reproduced from [4].

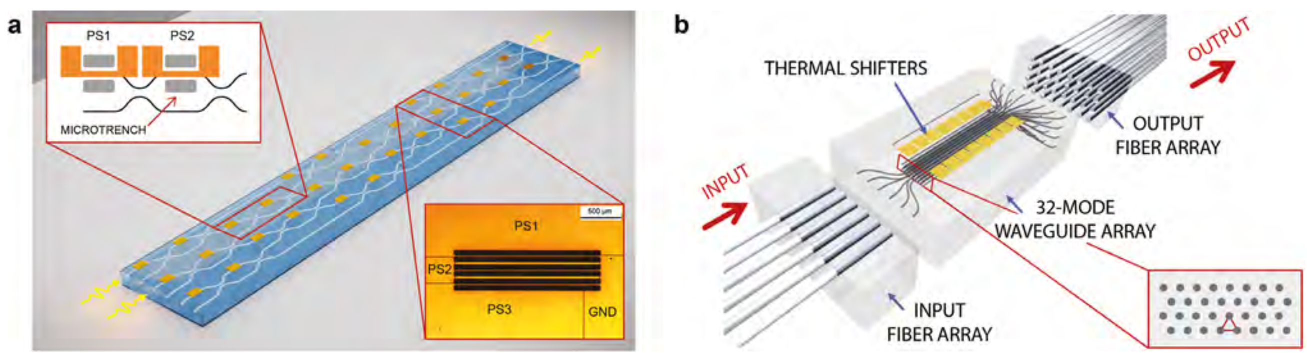
of the input light. This is very useful for processing signals that do not have a fixed polarization.

In terms of scalability, a major goal is to increase the number of optical modes without extending circuit length and thus without increasing losses. Since number of modes and length increase together in MZI-based processors, efforts include compactifying MZI cells and exploiting completely new photonic processor layouts, aiming at improving the scaling law between circuit length and number of modes. Regarding this second approach, Hoch *et al.* [7] recently proposed a novel FLW fabrication strategy based on a three-dimensional continuously-coupled waveguide matrix, including reconfiguration through thermo-optic phase shifters (Figure 3b). This approach promises to break the tradeoff between number of modes and length by moving from a linear scaling law to a square root dependence. A 32-mode processor with 16 heaters was developed and characterized to demonstrate the potential of this design. However, the development of a control algorithm for universal unitary transformations remains a key challenge, with machine learning emerging as a promising solution for these advanced devices.

APPLICATIONS

FLW photonic integrated circuits have a wide range of uses. They are key components in compact systems that merge integrated photonics with

Figure 3. Universal photonic processors and their realization using the FLW technology. a) A 6-mode universal photonic processor based on a planar mesh of MZI cells. Top-left inset shows the schematic layout of an individual MZI of the device with two thermo-optic phase shifters (PS1 and PS2) isolated by microtrenches. Bottom-right inset is a microscope picture of an MZI column of three thermo-optic phase shifters, where it is possible to see the microtrench structures (larger black rectangles), the metal film (orange) and the ablations in the film. PS1, PS2 and PS3 are three contact pads used to independently control the thermo-optic phase shifters, while GND is their common ground. Adapted under terms of the CC-BY license from [6]. e) A 32-mode programmable photonic processor built upon a three-dimensional continuously-coupled FLW waveguide matrix with thermo-optic phase shifters placed atop the device. Fiber arrays are used for light injection and collection in the circuit. Within the highlighted red rectangle, the waveguides are organized into a triangular lattice. Adapted under terms of the CC-BY license from [7].



microfluidics [8], important for analyzing biological samples, and they also play a critical role in realizing low-loss optical interconnects within telecommunications systems [9], linking dense waveguide circuits with fibers that have multiple cores or modes. This discussion will focus on two emerging areas where FLW's distinctive qualities have gained a role of paramount importance: quantum technologies and astrophotonics.

Quantum technologies aim at revolutionizing how we process and communicate data. Amongst the various quantum applications, building a scalable quantum computing system is considered the ultimate goal. This is driven by the potential to solve complex problems, like simulating specific chemical reactions for pharmaceutical development, that current computers cannot handle. Although we have seen significant progress, realizing this breakthrough still seems a distant dream, likely more than a decade away. Therefore, the field has shifted focus to more immediate milestones: proving that quantum devices can outperform classical computers in certain tasks. One such task involves sampling from the distribution probability of numerous identical bosons passing through a multimode linear interferometer, a challenge known as boson sampling. This task, in the specific case of an interferometer lacking any pattern or symmetry, is thought to be beyond the capabilities of classical computers. Photonic particles (Figure 4a) have emerged as the leading option for boson sampling demonstrations due to their relative ease of use in contrast to other quantum computing approaches. In this experiment, FLW has been pivotal, allowing the first practical demonstrations of boson sampling [10]. Today, different studies have demonstrated a quantum advantage, some of them employing photonic boson sampling methods [11, 12]. Although integrated photonic processors are a natural choice for the implementation of an N-mode interferometer, an integrated version of a boson sampling experiment that can achieve the quantum advantage regime has not been realized yet. This is because a large-scale experiment's success requires not just several modes, but also minimal photon losses to maintain a reasonable measurement time. However, as previously noted, expanding the modes while maintaining low losses in an integrated processor is challenging. A significant advancement was made with the FLW three-dimensional photonic processor described in [7], which could achieve 32 modes with only 3.5 dB of photon loss and broad reconfigurability thanks to the 16 thermo-optic phase shifters. With this processor, boson sampling experiments with 3 and 4 photons were successfully validated, proving the potential of FLW devices for large-scale quantum information processing systems.

FLW is also playing a significant role in the field of astrophotonics. This emerging application aims at enhancing the observation of celestial bodies by integrating photonic circuits with telescopes. The use of single mode waveguides for light collection provides spatial filtering which, along with controlled waveguide-to-waveguide interactions, yields interference effects with larger visibility and better scalability than traditional bulk interferometers, thus improving angular resolution for imaging astronomical objects. FLW's glass technology offers several advantages in this regard: it provides single mode waveguides optimized across visible and near-infrared spectra, exhibits low birefringence making devices polarization-transparent, and supports three-dimensional fabrication for stable pupil remapping and efficient beam combining. An example of this is represented by the aperture masking interferometry (Figure 4b), where light on a telescope's pupil plane is sampled and its interference pattern analyzed to reconstruct images. This technique, which offers improved resolution and atmospheric aberration resistance, uses integrated optical waveguides for signal sampling and remapping. The proposed device, *i.e.* a discrete beam combiner (DBC), has been successfully realized and tested thanks to the FLW technology at the William Herschel Telescope [13], demonstrating polarization •••

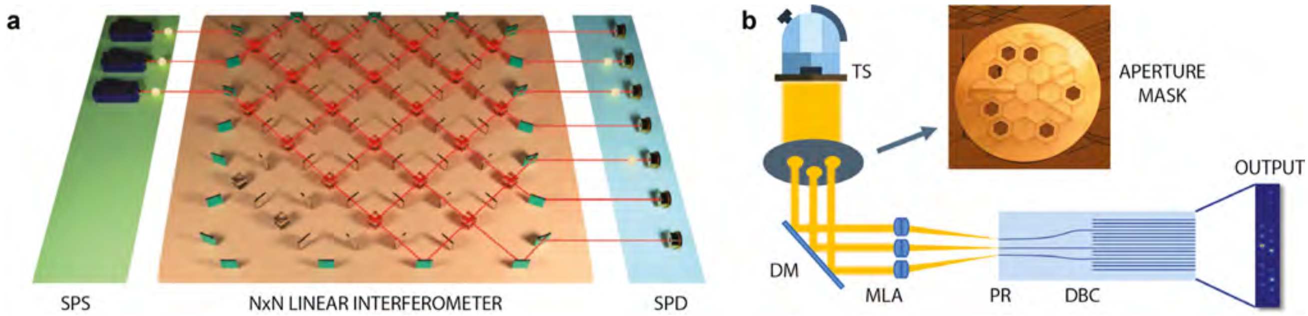


Figure 4. Applications of FLW photonic integrated circuits. a) Artwork of a photonic boson sampling experiment, which includes single-photon sources (SPSs), an N-mode photonic interferometer, and single-photon detectors (SPDs). Reproduced under terms of the CC-BY license from [10]. b) Graphic representation of the aperture masking interferometry system used at the William Herschel Telescope in 2019 for astral observations. This system comprises a telescope (TS), a deformable mirror (DM), a microlens array (MLA), a pupil remapper (PR), and a discrete beam combiner (DBC). To simplify the representation, only three input beams are shown and the circuit's fan-out area is not depicted. Full description of the experiment is reported in [13].

insensitivity and effective light analysis without the need for polarization filtering. Furthermore, DBCs are applied to the coherent combination of light coming from multiple telescopes to enhance angular resolution, simulating a larger synthetic aperture. This technique typically relies on complex interferometers that are difficult to scale. However, a laboratory-tested DBC manufactured by FLW has already shown the potential to combine signals from six telescopes simultaneously in the J band [14], indicating a likely path toward high-resolution astronomical observations.

CONCLUSION AND PERSPECTIVE

Over the past four decades, advancements in photonic technologies, such as lasers and optical fibers, have spurred a revolution across various sectors, including medicine, material processing in industry, and telecommunications. The next step is to integrate all the photonic components into a cohesive platform, which could vastly enhance the capabilities of many innovative applications. Presently, the integrated photonic technology equivalent to the CMOS one in electronics has not been clearly identified yet. Different platforms are emerging to fulfill specific functions within the field, leading also to a growing interest in hybrid integrated platforms. These platforms are particularly appealing for applications that demand the ultimate optimization of the entire photonic system — from the photon source, through the optical circuit, to the detector.

Our projection is that FLW will be critical in this landscape due to its efficient interfacing between photonic components with minimal photon loss and its versatility and adaptability to the rapidly evolving requirements of the applications. FLW photonic integrated circuits are now a commercial reality, bolstering fields like quantum information processing and astrophotonics. This article has highlighted FLW devices that have already been successfully utilized in these areas. Nonetheless, we anticipate that FLW devices have a much broader application potential and, consequently, we foresee that, in the coming years, FLW technology will establish itself as a leading platform in the integrated photonic field.

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PHASE-CHANGE MATERIALS FOR PHOTONIC APPLICATIONS

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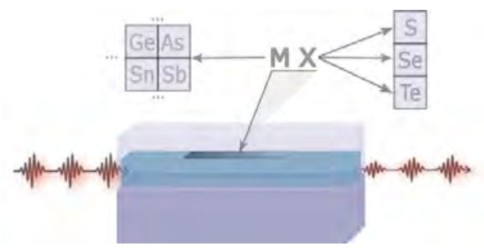

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Phase-change materials (PCMs) have been growing in interest over the last decade for photonic applications. In this article, we will firstly review their properties and their key benefits with respect to concurring technologies for reconfigurable photonic devices and systems. Then, we will highlight some key open challenges PCMs are currently facing for their ubiquitous adoption. Finally, we will provide some potential routes for addressing these challenges with a focus on current activities in the Grenoble (France) region.

The need for reconfigurability in integrated optics has been a key driving force since the very first demonstrations in this field. In particular, reconfigurable photonic devices such as Mach-Zehnder (MZ) and ring resonator (RR) modulators are fundamental building blocks in the vast majority of integrated optics applications. Reconfigurability provides several benefits such as compensation for fabrication tolerances, arbitrary splitting/combining ratios in interferometers, or modulation of light beams in waveguides.

Depending on the application requirements, there are a series of constrains for reconfigurability *e.g.*, power consumption, compactness, losses, non-volatile character, or CMOS-compatibility. Standard mechanisms are based on the thermo-optic effect through microheaters in proximity of waveguides, through electro-optic effects of different nature such as free-carriers absorption/dispersion, Pockels effect, or quantum-confined Stark effect (QCSE). While these effects are strongly used in modulators, they lack a non-volatile character and their strength in terms of refractive index contrast Δn is generally low *e.g.*, using p-n junction modulators (free-carriers dispersion effect) Δn is on the order of $10^{-3} – 10^{-4}$ while by using microheaters (thermo-optic effect) is on the order of $10^{-2} – 10^{-3}$ for standard driving conditions. These contrasts are relatively weak for implementing *e.g.*, a π shift and thus long devices (hundreds of µm to mm lengths) are often required to compensate for this weakness. Besides, these effects are volatile i.e., the stimulus needs to be constantly applied during the entire device operation. While for some applications, this can be tolerated because of continuous switching *e.g.*, in datacom applications for data encoding, for other applications where the reconfigurability time interval is much longer than the characteristic switching time, this can be deleterious from an energy-efficiency perspective. Examples of this latter category are packets switching in routers where large idle times are present or inference operation in photonic neural networks where the trained weights *e.g.*, implemented through phase shifters, shall not be modified any longer until the next training phase.

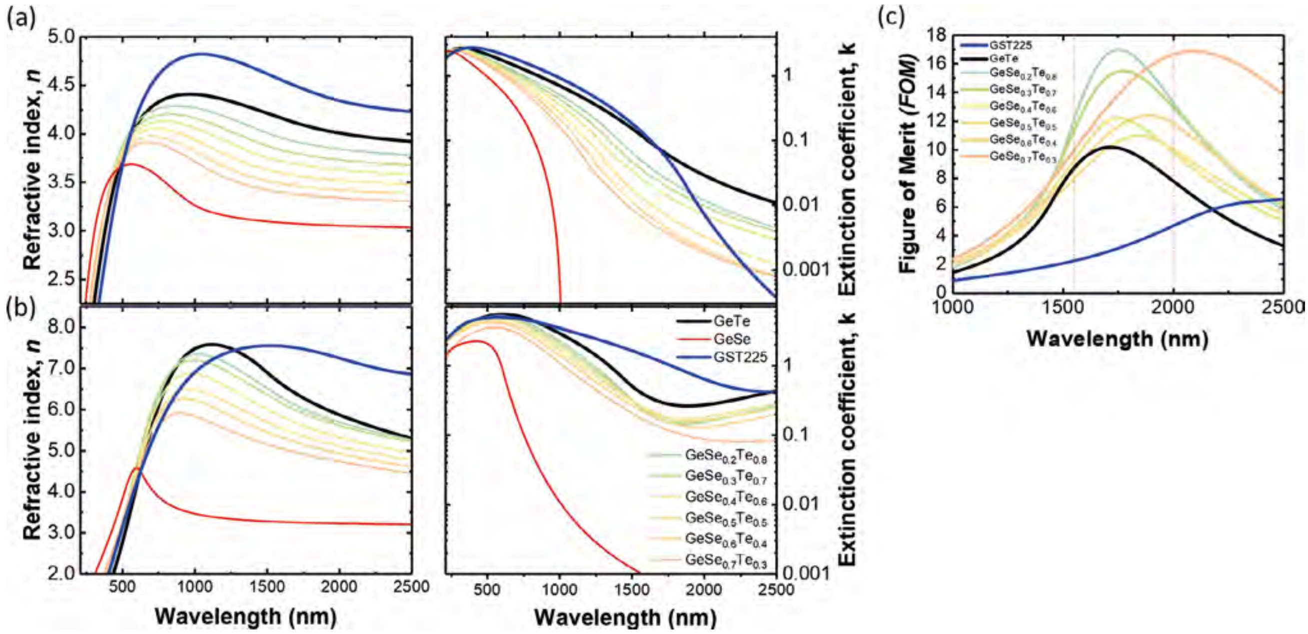


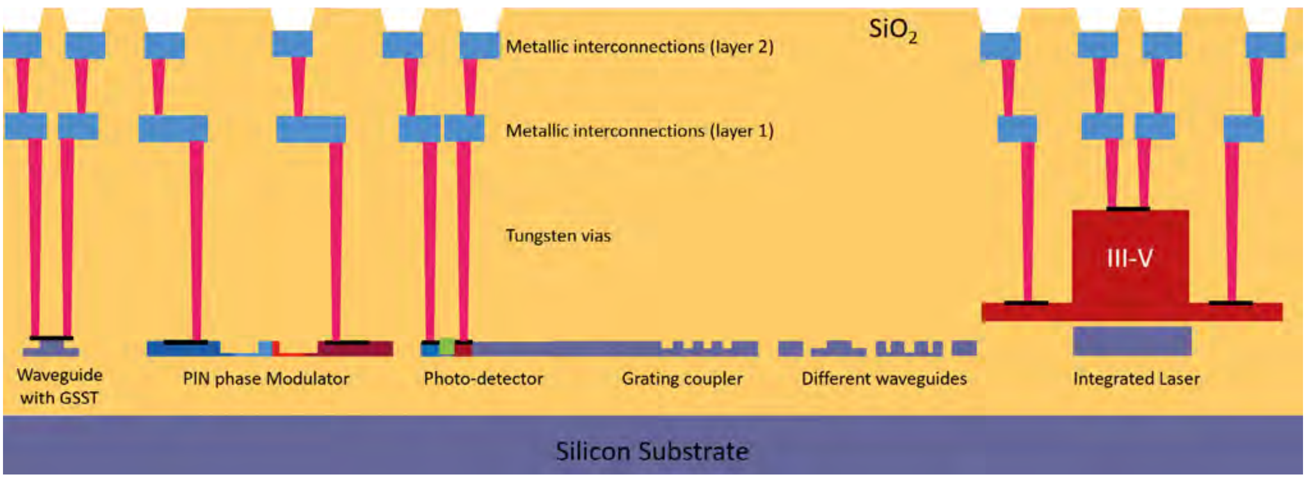
Figure 1. Linear refractive index (n) and extinction coefficient (k) as a function of wavelength for (a) the amorphous and (b) the crystalline phase of $GeSe_{1-x}Te_x$ (continuous) and GST225 (dashed) thin films obtained by spectroscopic ellipsometry data modelling. (c) Figure of merit (FOM = Δn/Δk) as a function of wavelength for the $GeSe_{1-x}Te_x$ and GST-225 thin films. All the $GeSe_{1-x}Te_x$ thin films have a FOM higher than the GST225 reference material. To be noticed, GeSe film is not plotted in a) because the as-defined FOM value tends to infinite. In fact, for this material Δk tends to zero [3].

However, chalcogenide-based phase-change materials (PCMs) have been emerging as a class of materials capable of addressing both these issues.

OPTICAL AND MATERIAL PROPERTIES

Chalcogenide materials have long been widely studied for their unusual electronic, structural, and optical properties. These exceptional properties are behind a huge number of applications in the fields of optics, electronics, and more recently photonics. The most known optical applications range from infrared (IR) optics and nonlinear photonics to non-volatile memory devices for photonic computing [1]. Among the large family of chalcogenides, phase-change materials (PCMs) are now recognized as the most attractive candidate for producing reconfigurable photonic

Figure 2. Platform under development in the NEUROPULS project at CEA-LETI. Reproduced with permission from [7].



devices based on electro-optical switchable materials and metamaterials and on their ease of integration in CMOS-compatible platforms [2].

Conventional PCM alloys lying on the GeTe-Sb_2Te_3 pseudo-binary line of the Ge-Sb-Te ternary phase diagram, such as GeTe or $Ge_2Sb_2Te_5$ (GST225), have been widely studied for years for optical data storage, such as CD-RW, DVD-RAM and Blu-ray disks. These alloys exhibit relatively low crystallization temperature ($T_x \approx$ 150-230°C), and a huge and uncommon refractive index contrast in the visible range between their amorphous and crystalline phases. The transition between both phases can be easily, quasi-infinitely and reversibly obtained by means of laser pulse applications of various duration and power (*e.g.*, $\Delta n = n_{cr} - n_{am} = 2.97$ at 1550 nm for GST). However, at telecom wavelengths (1.55µm), these Ge-Sb-Te alloys are absorbing with extinction coefficient k values that increase by an order of magnitude (*e.g.*, from $\Delta k = k_{cr} - k_{am} \approx 1.5 - 0.1$ for GST225) upon crystallization (see Figure 1) [3]. This is particularly detrimental for most integrated optics applications. Therefore, at telecom wavelengths, new PCMs with large Δn, but small Δk upon phase-change are desired for low-loss reconfigurable photonic platforms.

In order to compare PCMs, a very simple figure of merit (*FOM*) can be used and is defined as $FOM = \Delta n/\Delta k$. It should be noted that this simple *FOM* could be considerably improved by taking into account insertion loss and contrast ratio in real optical devices. Standard GST225 and GeTe thin films exhibit a FOM = 2.2 and 6.2, while one of the recently introduced PCM compounds $Ge_2Sb_2Se_4Te_1$ exhibits $FOM \approx 4.2$ at 1.55 µm. In this context, to further improve these *FOM*s, innovative PCM alloys have recently been introduced, based on compounds located along the GeSe-GeTe pseudo-binary bond line of the Ge-Se-Te ternary phase diagram. These $GeSe_xTe_{1-x}$ alloys offer a compromise between the high transparency of covalently bonded GeSe alloys and the phase-change properties of "metavalently" bonded GeTe, with properties that can be finely tuned between the two alloys simply by modifying the Te/Se ratio in the $GeSe_xTe_{1-x}$ composition (see Figure 1). With the exception of GeSe, for which the FOM tends towards infinity due to near-zero absorption in both phases, the FOM of all $GeSe_{1-x}Te_x$ films shows very high FOM values compared to other materials in literature making it an ideal candidate for low-loss phase shifters. Controlling the Se/Te content makes it possible to tailor the alloy's properties to the desired applications. It should be noted that PCMs Sb2S3 and Sb2Se3 with similar ultra-low-loss characteristics have also recently been introduced [4].

PCM-BASED OPTICAL DEVICES AND RELATED APPLICATIONS

One of the key challenges to achieve ubiquitous adoption of thin-film PCMs for photonics consists of their integration in already existing CMOS-compatible Silicon photonics platforms. Major efforts in the Grenoble region are focusing on integrating thin-film patches (below 100 nm) above Silicon waveguides next to III-V materials for additional functionalities. Their integration acts generally as a perturbation allowing to modify the effective refractive index of the unperturbed optical waveguide mode.

In particular, Figure 2 shows the cross-section of the platform that we are developing within the framework of the Horizon Europe project NEUROPULS which aims to develop secure low-power neuromorphic photonic accelerators for edge-computing. Devices under development in this platform are ultra-low-loss non-volatile phase shifters and MZ interferometers (MZI) based on GeSe which presents very low losses around 1550 nm wavelength as discussed in the previous section. MZIs with very low optical loss and non-volatile phase setting are a key component to enable matrix vector multiplication (MVM) cores for neuromorphic applications.

Here, the phase values encoded in the PCM-based MZIs may act •••

as weights in analogy to classical artificial neural networks (ANNs). One of the goals of the NEUROPULS project is to develop a low-power architecture where no energy is used for weights (phase) setting in the inference phase. Besides, we are currently considering novel energy-efficient spiking neuromorphic architectures where the accumulation-like behaviour of PCM-based devices i.e., the act of gradually changing their crystalline versus amorphous ratio in a distributed patch, can be used to integrate different signals both statically, but also dynamically *i.e.*, without reaching thermal equilibrium between two consecutive stimuli. Other works have taken advantage of this accumulation property to build spiking neuronal circuits where a PCM patch was used to sum optical spikes after weighting based on PCMs and then, depending on the sum value, would allow an optical spike at the output as shown in Figure 3 [5]. Such system could allow pattern recognition in the optical domain using an unsupervised training approach based on spiking time dependent plasticity (STDP).

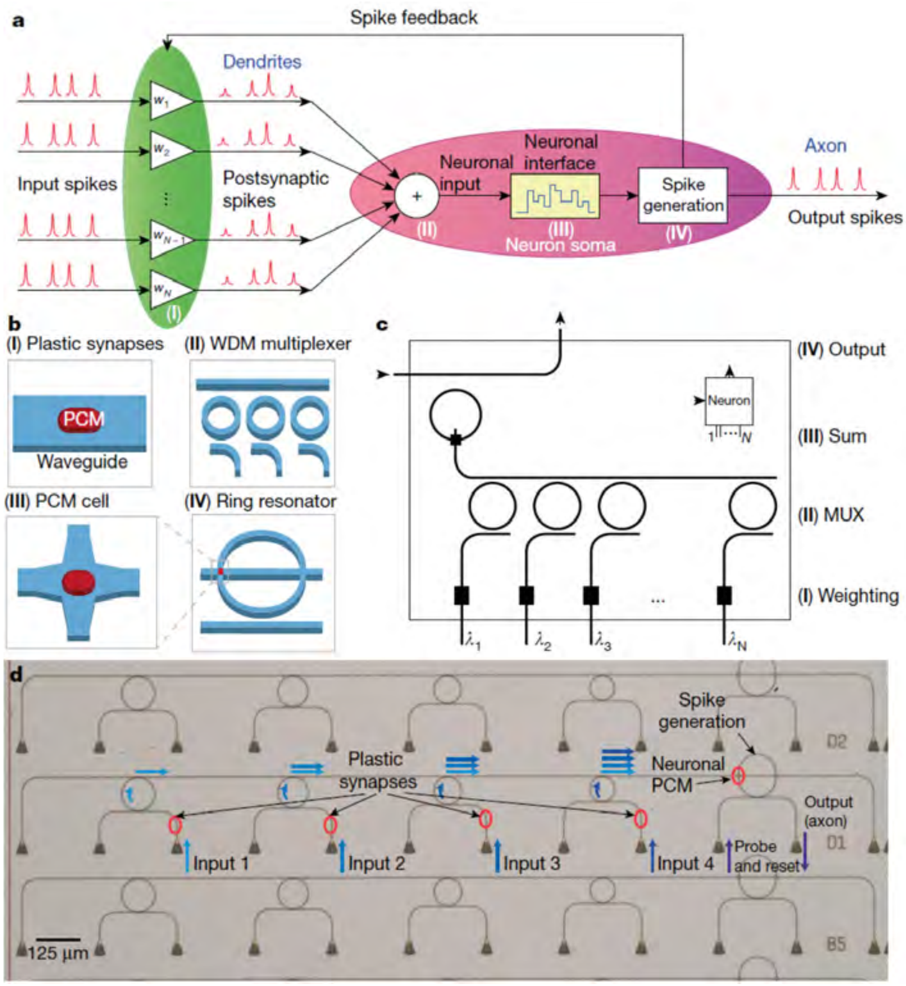


Figure 3. All-optical spiking neuronal circuits. a, b, Schematic of the network realized in this study, consisting of several pre-synaptic input neurons and one post-synaptic output neuron connected via PCM synapses. The input spikes are weighted using PCM cells and summed up using a WDM multiplexer (MUX). If the integrated power of the postsynaptic spikes surpasses a certain threshold, the PCM cell on the ring resonator switches and an output pulse (neuronal spike) is generated. c, Photonic circuit diagram of an integrated optical neuron with symbol block shown in the inset (top right). Several of these blocks can be connected to larger networks using the wavelength inputs and outputs. d, Optical micrograph of three fabricated neurons (B5, D1 and D2), showing four input ports. The four small ring resonators on the left are used to couple light of different wavelengths from the inputs to a single waveguide, which then leads to the PCM cell at the crossing point with the large ring. The triangular structures on the bottom are grating couplers used to couple light onto and off the chip. Reproduced with permissions from [5].

Another application where thin-film PCMs have found a lot of interest is for photonic memories. In this case, the state of the PCM patch is associated with a certain value of the optical attenuation at the output of the device. By carefully adjusting the input optical power in the writing phase, it is possible to achieve a multi-level operation during the read-out phase where a lower optical power is needed to probe the memory value. This type of memory can operate above GHz speeds due to the rapid phase change which can be well below hundreds of ps or shorter. In a pioneering work, PCM photonic memories with up to 8 levels (3-bit) with 13.4 pJ of switching energy were demonstrated using tens of ns pulse duration [6]. Our current focus concerns the modelling of this type of memories by taking into consideration the full computing infrastructure i.e., in terms of photonics, but also communication interfaces and processor operation. Such an analysis can provide an accurate description of the trade-offs that shall be considered for these memories with respect to more standard electronic ones and novel insights in terms of optimal designs.

CURRENT CHALLENGES

Although thin-film PCMs have been successfully applied to several applications, there are still some challenges that are limiting their ubiquitous adoption in photonics.

One of the limiting factors concerns their current absence from the offer *e.g.*, in multi-project-wafer (MPW) runs, of photonic platforms openly available to the scientific community. This is mainly due to their current level of maturity for integration in CMOS-compatible platforms, but also their only recent adoption in several applications.

A device-level challenge with multiple consequences in terms of applications concerns limited resolution in terms of data encoding *i.e.*, the number of bits that can be encoded in standalone PCM patches is still very limited and, while for certain applications this might not be a major concern, for others that involve photonic memories or neuromorphic computing, this can be a strong constraint for their adoption over more mature technologies, especially when looking at the bit resolution/area metric.

Lastly, from a system-level perspective, a major challenge consists of addressing these devices when write/read operations are carried out in the optical regime. The scaling of optical interconnects for device-dense applications *e.g.*, for photonic memories, is not simple due to the size of the photonic components that are involved. In the future, a 3D integration of multiple guiding layers could be foreseen for this technology to enable higher component densities with different wavelengths of operation to optimize writing and reading operations.

CONCLUSIONS

To conclude, we discussed about how PCMs can be integrated in Silicon photonic platforms and what are their key properties for photonic applications. In particular, Se-based PCM thin films are promising for reconfigurable photonics applications with ultra-low on-chip losses. For telecom wavelength applications, these alloys have a figure of merit that exceeds that of GST225, currently the standard PCM for non-volatile reconfigurable photonics, by 550%. Then, we proposed a platform for their integration and addressed relevant devices and applications that can benefit from PCMs unique properties. Finally, we underlined some of the main challenges that currently prevent their widespread adoption in the field.

ACKNOWLEDGMENTS

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VERSATILE AND MULTI-FUNCTIONAL: AN OPTICAL SPECTRUM ANALYZER (OSA) FOR EVERY APPLICATION

Yokogawa Test&Measurement
***tmi.yokogawa.com**

Yokogawa OSAs have gained a reputation as the favourite tool of engineers working in optical communications applications such as wavelength division multiplexing (WDM).

In fact, the OSA has many uses in fields other than communications. It offers photonics researchers and engineers the ability to characterize and obtain information about optical power and wavelength over a wide wavelength range in domains such as:

- Sensing for safety, security and pollution control
- Healthcare
- Quantum computing

A SHOWCASE FOR THE OSA'S HIGH PERFORMANCE: QUANTUM COMPUTING

Quantum computing is one of the sectors showing the fastest growth in the use of photonics systems and components. This will drive increasing demand for optical measurement instruments that can accurately characterise the lasers at the centre of a quantum computer's photonics system.

In quantum computing, the most commonly deployed laser applications are ion trapping and laser cooling. These applications demand lasers that deliver extremely high performance and low noise when operating in single longitudinal mode (at a single frequency).

One type of laser suited to this function is the fibre laser. While other instruments in the test laboratory might be used to characterise the line width and phase noise of a fibre laser, an OSA can contribute to characterisation of the source spontaneous emission suppression ratio and the rejection ratio of the pump laser.

These measurements are frequently made in research and development, but an OSA can also be usefully deployed in the production of a fibre laser, where it enables precise parameter adjustment.

Another type of laser used in quantum computing is the wavelength conversion laser. There is a thriving market of such products suitable for quantum computing, and an OSA can also play a role in their characterisation.

For both the quantum computing optical functions, ion trapping and laser cooling, the laser is required to emit at a precisely specified wavelength that is determined by the characteristics of the ions. Quantum computer scientists can use an OSA to characterise the seed laser's performance, and the suppression ratio of the seed laser.

MAKING AN INFORMED CHOICE: UNDERSTANDING DIFFERENT OSA STRUCTURES

Because there are important differences in the internal design and in the operating principle of different OSAs, an understanding of the features of an OSA is key.

Whether in quantum computing or any other of the other applications where optical spectral measurements are required, an OSA is a valuable tool because of its high precision. In fact, the

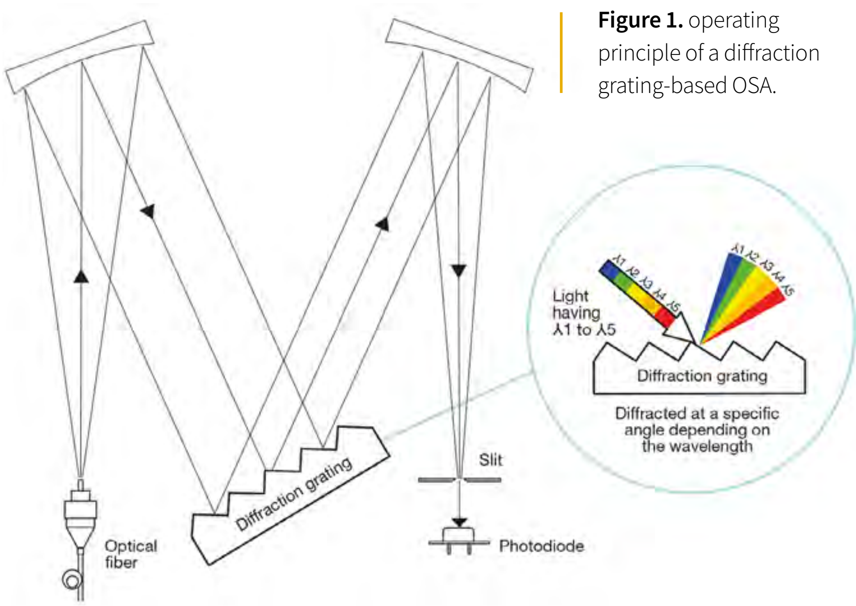


Figure 1. operating principle of a diffraction grating-based OSA.

performance of an OSA is determined by the combination of four main performance parameters:

- Sensitivity
- Spectral resolution
- Measurement speed
- Close-in dynamic range

Every OSA on the market operates on one of two principles:

- Reflectometers adopt the Fourier Transform (FT) interferometer principle, in which the measured beam is split, reflected and recombined.
- Grating-based OSAs have a diffraction grating (see Figure 1). The OSA disperses the input light using the diffraction principle of a diffraction grating in a monochromator.

In a grating-based OSA, the grating diffracts the light at a specific angle depending on the wavelength. By rotating the diffraction grating and controlling the angle of incidence, a specific wavelength can be guided to a photodiode. Here, the optical power of that wavelength can be measured. By sequentially selecting wavelengths across the range of interest to the application, a complete spectrum can be measured, and the spectral waveform displayed on the instrument's display screen.

THE DIFFERENT PERFORMANCE CHARACTERISTICS OF FT INTERFEROMETER-BASED OSAS (REFLECTOMETERS) AND GRATING-BASED OSAS

The main advantage of the reflectometer is its very high spectral resolution, in the low picometres. It also offers high measurement throughput, as it can measure all wavelengths simultaneously, and a high signal-to-noise ratio.

The high resolution can induce some researchers to choose an FT interferometer for characterising lasers. Grating-based OSAs also offer very good resolution, even if not as high as the reflectometer's. But a grating-based OSA offers the additional advantages of:

- Wider dynamic range
- Flexibility to configure multiple measurement parameters

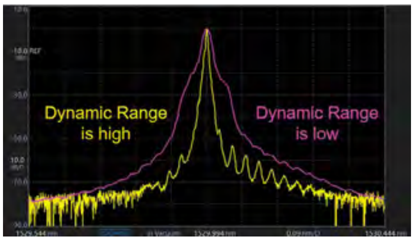


Figure 2. Comparison of OSA measurements with high and low dynamic range.

A GRATING-BASED OSA IN ACTION

The wide dynamic range is a key feature of the grating-based type of OSA. Dynamic range refers to the ability of a spectrum analyser to measure large and small signals in the same sweep. The difference that wide dynamic range makes can be seen in Figure 2: the yellow trace shows much more of the waveform's detail than the purple trace because the dynamic range is much higher.

When you compare the AQ6370E with a typical dynamic range of 78dB, with that of an interferometer-based OSA that is typically only 35dB, the AQ6370E will be able to show the sidemodes.

The wide dynamic range and accuracy of the AQ6370E are due in part to a design of the OSA's monochromator, which reduces the interference attributable to stray light.

FLEXIBLE SETTINGS TO ADJUST MEASUREMENT PERFORMANCE TO APPLICATION REQUIREMENTS

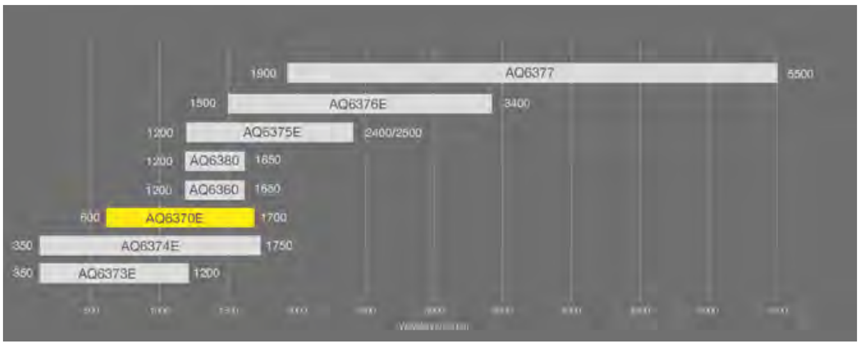
Yokogawa OSA's such as the AQ6370E can provide the user with superior measurements. One example is the freedom to adjust the balance of speed, sensitivity and resolution in instrument's configuration.

AN OSA FOR ANY APPLICATION FROM YOKOGAWA

Yokogawa offers a comprehensive range of eight OSAs, covering a wavelength range from ultraviolet light at 350nm up to far infrared at 5.5µm (see Figure 3).

The AQ6370 series and the high-accuracy AQ6380 are used for precision measurement in the fields of communications, healthcare, quantum computing and environmental sensing. But whatever the application or measurement requirement, there is a Yokogawa grating-based OSA that offers a configurable combination of high accuracy, high resolution, high sensitivity and wide dynamic range.

Figure 3. Yokogawa's OSA portfolio covers a broad wavelength spectrum up to 5.5µm.



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PHOTONIC GE-BASED PLATFORMS FOR MID-INFRARED APPLICATIONS

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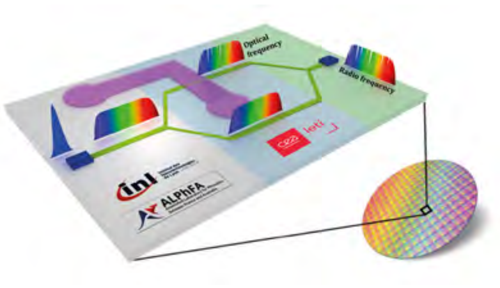

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Silicon photonics, initially developed for data communications in the near infrared (NIR), has been extended over the last ten years to the mid-infrared (MIR) region. Efforts have been made to fully integrate MIR functions at chip level on Ge and Si planar substrates, to achieve greater reliability and higher performance at lower cost. The fields of application are vast, ranging from IR imaging of biological tissues to environmental monitoring, control of industrial processes, security and many more.

Spectroscopic systems operating in the Mid-infrared (*e.g.* the MIR- wavelength region between 3 and 15 µm) can track specific chemical and biological fingerprints for molecule identification and quantification. They are based on light absorption induced by the excitation of rotational and vibrational energy levels of target molecules. As the light is absorbed by the target molecule, and analysed spectrally (e.g via the spectral analyser), multiple absorption lines appear in the absorption spectrum, their linewidths and peaks depending on the surrounding environment (gas/liquid phases, temperature, pressure etc.). The wavelengths and amplitudes of the absorption in the spectrum provide information about the detected species and their amounts. Figure 1 shows examples of molecules of interest accessible in the mid-infrared covering the field of environmental monitoring, defence and security, industrial process monitoring and medical diagnostics.

Our long-term vision is to create integrated photonic absorption sensors wherein the evanescent part of the propagating optical mode is absorbed by a medium/target molecule located outside in the vicinity of the waveguide. One approach relies on the use of tunable light sources (or an array of light sources) with narrow linewidths, with wavelengths that are absorbed by the substances/analytes to be detected. The transmission is then measured with a detector. Another approach involves using a broadband and bright optical source called supercontinuum (SC) generated in Ge or SiGe waveguides and placing a spectrometer before the photodetector to measure transmission as a function of wavelength. We present here examples of Ge-based integrated photonic circuits used for environmental detection and the working principles of supercontinuum light sources and integrated spectrometers.

GE-BASED INTEGRATED PHOTONIC CIRCUITS

Over the past 10 years, optoelectronic components based on germanium (Ge) have been developed to expand the potential of silicon (Si) photonic circuits. Photodetectors, modulators, and Ge-on-Si lasers have been demonstrated in the mid-infrared region. Ge's main advantage lies in its large transparency window, ranging from 1.8 to 14 µm in wavelength and its CMOS compatibility. Ge and SiGe alloys have quickly been regarded as preferred materials for the development of integrated photonic components. Thick Ge and SiGe layers (up to 40% of Ge) are conventionally grown on 200 mm and 300 mm Si(001) wafers by chemical vapor deposition in industrial epitaxy cluster tools. Further details on Ge and SiGe growth can be found in reference [1]. SiGe or Ge on insulator (like SiN) wafers can be fabricated from the previous epitaxies. In such a case, two wafers need to be bonded: the first ones with Ge or SiGe epitaxial layers capped with SiNx layers and thin SiO_2 layers, the second ones being oxidized Si wafers. After SiO_2 to SiO_2 bonding, the starting substrates on which Ge or SiGe thick layers were grown, are removed by grinding followed by chemical mechanical polishing steps. Polishing improves the Ge crystalline quality by removing the heavily dislocated interface between Si and Ge. Waveguides are then patterned by conventional photolithography and deep reactive ion etching (RIE) down to the Si substrate (Figure 2a and Figure 2b) or the SiN layer (Figure 2c).

A set of passive functions, such as wavelength multiplexers, couplers, paperclips, spirals, Mach Zehnder interferometers and ring resonators can be fabricated using conventional lithographic steps on epitaxial wafers. A review on silicon-based mid-IR integrated photonics can be found in reference [1,2]. Such miniaturized integrated devices offer higher accuracy, reliability, portability, and cost effectiveness compared to existing systems, enabling their use in new application fields like oil and gas process monitoring, gas leak detection, agri-food manufacturing monitoring, and point-of-care and portable laboratory bioanalyses. On-chip absorption sensing of parrafin oil has, for example, been achieved with Ge/SiN spiral waveguides (Figure 2c and Figure 2d). The propagation losses were evaluated for several wavelengths (5.9 µm, 6.7 µm) • • •

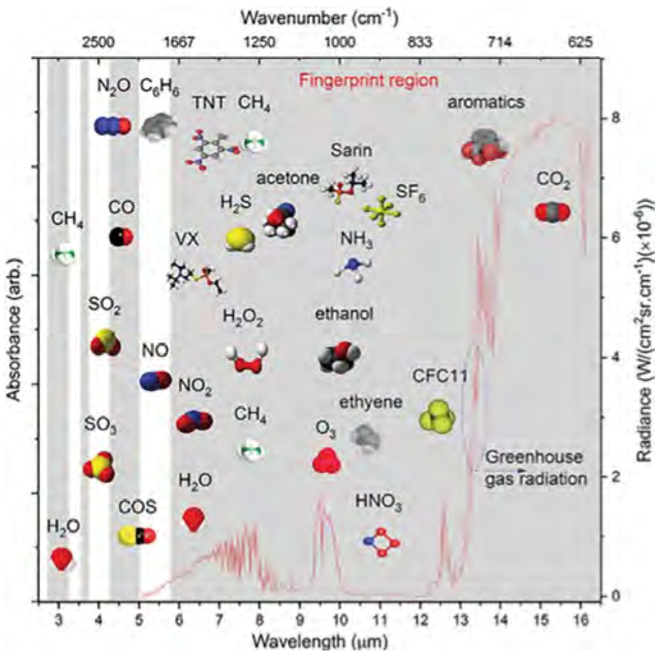
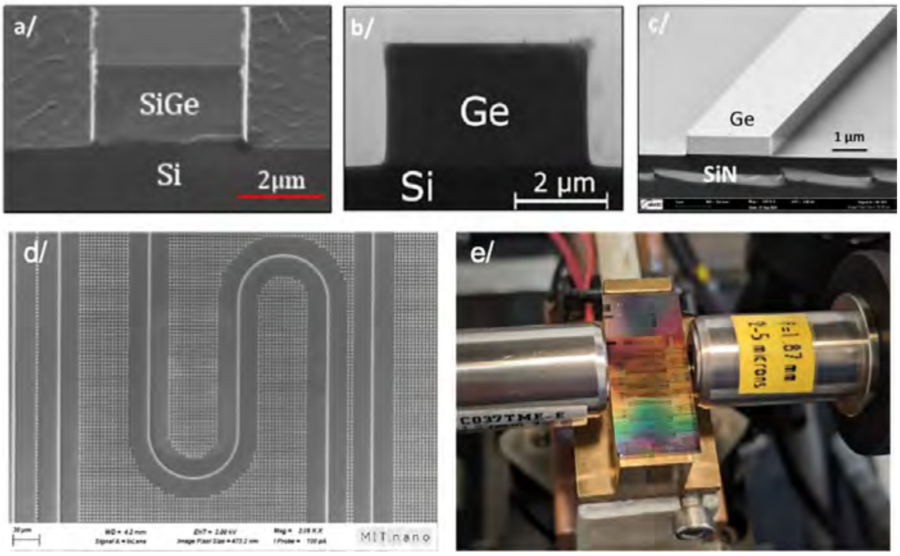


Figure 1. Examples of molecules of interest accessible in the mid-infrared covering the field of environmental monitoring, defence and security, industrial process monitoring and medical diagnostic. Reproduced from Laser Photonics Rev. **11**, No. 2, 1700005 (2017).



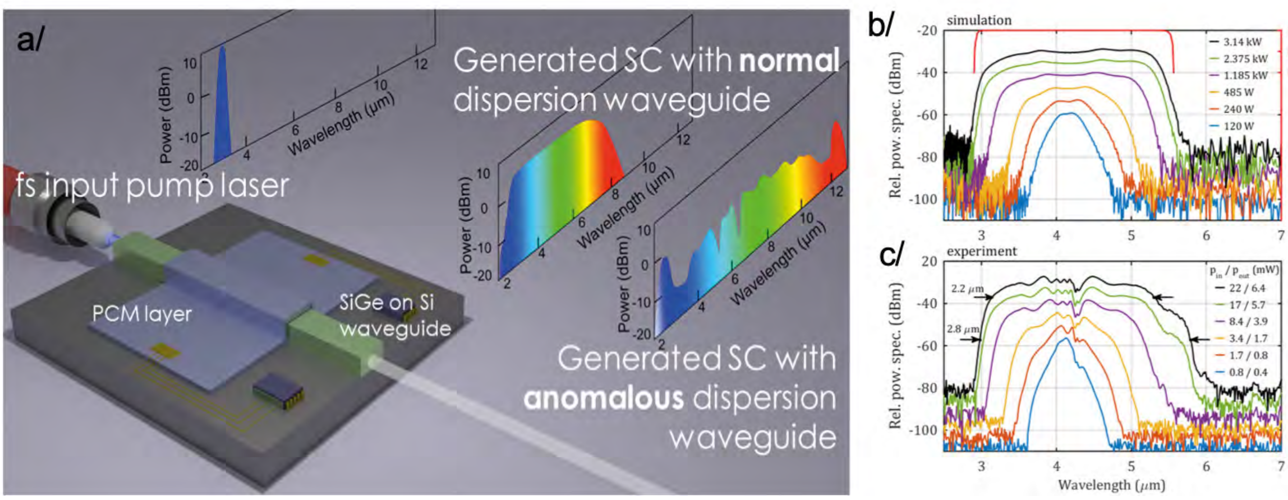
in so-called butt-coupling configurations (Figure 2e). An increase in propagation losses of 0.9 dB/cm in the presence of chemically inert paraffin oil was obtained at 6.7 µm corresponding to the maximum peak absorption of the paraffin liquid. Apart from the absorption peak at 6.7 µm, an increase less than 0.15 dB/cm in propagation losses at 5.9 µm was measured in the presence of the oil (the mode deconfinement due to the presence of the liquid explains, among other things, this increase of losses at 5.9 µm). Such approach could also be applied in the medical field to identify chemicals and quantify the concentration of liquids thanks to their characteristic infrared absorption features. For example, more patients could benefit from absorption spectroscopy analysis to detect biomarkers of metabolic variations or inflammatory phenomena. These biomarkers provide valuable information for the early detection of cancer, avoiding false positives, improving prognosis and lowering treatment costs.

Figure 2. Electron microscopy image of
a/ a cleaved SiGe 40% on Si waveguide,
b/ a Ge on Si waveguide and
c/ a Ge onSiN waveguide,
d/ SEM top view of a Ge spiral waveguide on SiN,
e/ Injection set-up of laser light at 5.9 µm and 6.7 µm into the spirals of a silicon photonics circuit.

GE-BASED LIGHT SOURCES

A key ingredient for MIR integrated spectroscopic systems is the light source. A lot of progress has been made with important research efforts on direct band gap lasers (as III-V or group-IV lasers), interband cascade lasers, quantum cascade lasers (QCLs), optical parametric oscillators (OPO) or fiber-based-lasers, to name a few. QCLs, probably the current MIR sources of choice, are already commercially available but often require low temperature operation and are costly. They otherwise have a restricted tunable spectral

Figure 3. (a) Illustration of supercontinuum generation in a SiGe waveguide with either normal or anomalous dispersion dynamically controlled by top cladding phase change material (credit Alberto Della Torre), (b) Simulated and (c) measured (b) SC spectra for All Normal Dispersion waveguide for various coupled average powers. The top red curve in (b) shows the SC spectra's calculated coherence at the highest (3.14 kW) peak power. The black arrows in (c) indicate the 10 dB and 30 dB limits of the spectrum. The measured coupled input and on-chip output average powers are given in the inset (c) and the estimated coupled peak powers in the inset (c). Reproduced from [4].



range, so that a single QCL cannot cover the entire molecular fingerprint. Instead of multiplexing the output of a series of fixed wavelength QCLs, a single bright and broadband source that can access all the wavelengths in parallel like a supercontinuum (SC) [3], seems an attractive alternative. Supercontinuum generation is usually achieved by broadening, via cascaded nonlinear effects (Figure 3), the spectrum of a mode-locked pump laser, constituted of hundreds of thousands closely spaced frequency lines (frequency comb). This comb structure results in a supercontinuum that can cover a spectral band of more than one octave in the molecular fingerprint region. It is therefore well suited for high-resolution multi-species parallel molecular spectroscopy with high throughput.

Generally speaking, SC generation can be achieved in either anomalous dispersion (*i.e.* positive group velocity dispersion) or normal dispersion *(i.e.* negative group velocity dispersion) regime (Figure 3). The former is characterized by a broad spectrum, which is, however, not spectrally flat, and has low coherence. Our group demonstrated such SC back in 2018, with the first SiGe waveguide-based SC reaching the onset of Si absorption (8.5 um) that was broadband (1.4 octave span) and bright (20 mW on-chip average power with potentially 70% conversion efficiency). The latter allows to generate flat and low noise SC spectra but generally to the detriment of the bandwidth. We demonstrated these so-called ANDi SC for the first time in the MIR in SiGe waveguides in the early 2020 [4]. Recently, we leveraged the potential of integrated optics for a precise dispersion control to go a step further. We designed a multi stage waveguide (anomalous dispersion section followed by a varying width section resulting in a varying dispersion from anomalous to normal) to simultaneously increase the bandwidth of the generated SC and improve its spectral flatness. We exploited such SC for a proof-of-principle demonstration of multi-species gas (water vapour and carbon dioxide) spectroscopy in our laboratory environment [5]. We are currently exploring heterogeneous integration schemes with phase change material to dynamically control the waveguide dispersion state and therefore the supercontinuum spectral and temporal properties (Figure 3).

As previously stated, the high manufacturing cost of quantum cascade lasers remains a significant hurdle in their widespread adoption for chemical sensing applications. However, the integration of Mid-Infrared sources onto silicon substrates utilizing CMOS technology presents a promising way for mass production at a low cost. Additionally, leveraging a silicon-based fabrication platform enables the simultaneous integration of QCL Mid-Infrared sources with SiGe-based waveguides, facilitating the development of fully integrated optical sensors on a planar substrate. Distributed-feedback QCL sources, operating at 7.4 µm and bonded onto 200 mm Si wafers, were recently fabricated in the CEA 200 mm CMOS pilot line (Figure 4a). This advancement is a significant step toward the realization of Mid-Infrared spectrometers at the silicon chip level [6].

GE-BASED INTEGRATED SPECTROMETERS AND DETECTION

Various integrated spectrometers based on SiGe or Ge waveguides have been evaluated to analyse the absorbed light that was beforehand emitted by a supercontinuum. SiGe 40 % arrayed waveguide gratings (AWG) on Si and Ge AWG on Si have been demonstrated in the 3 to 8 µm and the 8 to 12 µm ranges, respectively. They were operational for both TE and TM light polarizations. The working principle of a demultiplexing AWG is presented in Figure 4b: (1) waveguide containing several wavelengths from a supercontinuum or from an array of lasers, (2) planar waveguide, (3) an array of waveguides, (4, 5) a recombination guiding area, (6) several output waveguides containing different wavelengths. Figure 4c shows transmission losses and spectral characteristics of a multiplexing device with a Ge core embedded in thick $Si_{80}Ge_{20}$ layers. A channel spacing of 2.96 ± 0.16 cm^{-1} was reached with a crosstalk of 7.4 dB in this particular AWG [3].

Photodetection within this wavelength

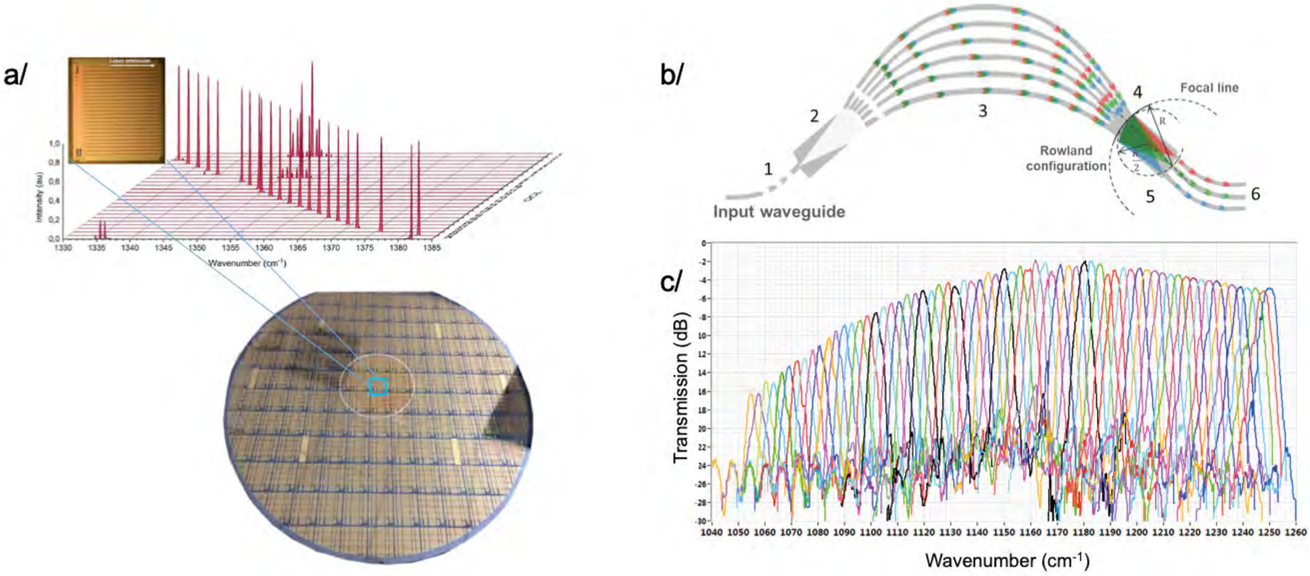


Figure 4. (a) Typical spectral power densities of a QCL array emitting at 7.4 µm bonded on 200 mm silicon wafer, reproduced from [6], (b) Principle of operation of an AWG, (c) Spectra measured for 67 outputs of the AWG, reproduced from [3].

range requires semiconductors having small, direct band gaps, typically less than 0.4 eV to be placed after the spectral analyser. Widely used mid-infrared (mid-IR) photodetector materials encompass mercury cadmium telluride (HgCdTe), III–V compounds like InAs and InSb and group-IV compounds such as GeSn alloys. Additionally, commercially available detectors use lead salts or lead chalcogenides such as PbSe, and PbS or PbTe [7]. Interband cascade detectors with III-V materials or quantum cascade detectors are among the device architectures currently under investigation. Finally, photoacoustic detectors are as well good candidates for MIR detection as they can be integrated onto planar substrates [2].

CONCLUSION

Ge-based photonics is a solution widely explored today for the development of photonic systems in the mid-infrared. Common technological platforms for integrated and cost-effective mid-IR photonic components are essential for novel applications such as chemical sensing in liquid and gas phase and could have an important impact in the field of sensors for the general public. Currently, the research primarily focuses on demonstrating various aspects with elementary components. Ultimately, the integration of these different elements will be key to fabricate complex systems. The upcoming challenges will focus on the integration of MIR light sources and photodetectors on photonic platforms.

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PARAMETRIC PROCESSES AS A VERSATILE TOOL TO HARNESS QUANTUM LIGHT

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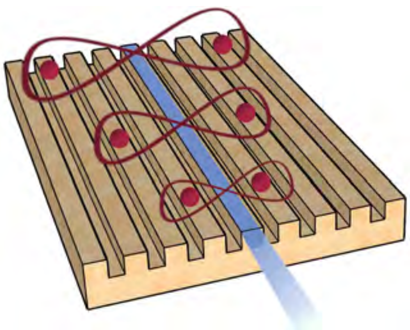

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The parametric generation of quantum states of light holds a central position across various fields of quantum technologies. Starting from the seminal experiments in the 1970's, we retrace the history of this powerful approach for creating and tailoring entangled photon pairs or squeezed states of light from the interaction of strong laser fields with optically nonlinear media. From its inception to its latest applications, this technique not only continues to play a pivotal role in the burgeoning fields of quantum computation, communication, and metrology, but shares also fundamental links with general concepts of quantum field theories in curved space-times.

In our childhood, all of us had great fun in experiencing that a periodic motion of our legs and feet can induce a wildly wide oscillation of the swing on which we are sitting. In this article we explore how similar parametric processes can be a powerful tool to generate quantum light and also underlie fundamental phenomena in many fields of physics, from quantum optics to gravitation.

When a dielectric material is illuminated by strong light fields, a number of novel optical phenomena can be observed thanks to the nonlinear optical response of the medium, such as harmonic generation, frequency conversion, or parametric amplification. While many such processes are well captured by Maxwell equations with suitable nonlinear polarization terms, other nonlinear phenomena require a quantum description of light-matter interaction including the vacuum fluctuations of the quantized electromagnetic field. This is the case of spontaneous parametric down-conversion (SPDC) and spontaneous four-wave mixing (SFWM) phenomena. In SPDC, a photon from an intense pump laser gets converted into a pair of photons, called signal and idler (Fig. 1a), while in SFWM two pump photons collide and get converted into a photon pair (Fig. 1b). These nonlinear processes are fully general and only require a nonlinear optical response of the medium, so that they are observed both in dilute atomic vapors and in dense solid-state materials.

FOUNDING EXPERIMENTS

The first experimental demonstration of SPDC was reported in 1970 by Burnham & Weinberg using a barium borate (BBO) crystal [1], whose birefringence was exploited to achieve the phase-matching (wavevector conservation) of the nonlinear process. Following this seminal demonstration, several striking peculiarities of the photons generated by SPDC were successively evidenced. In 1986, Hong & Mandel demonstrated that thanks to the simultaneity of emission of the two down-converted photons, one photon of the pair can be used to herald the emission of its twin. This allows realizing so-called heralded sources of single-photons which, despite their probabilistic nature, still play a central role today in quantum technologies thanks to their simplicity and ability to operate at room temperature.

The intrinsically quantum nature of the emitted photon pairs was soon after highlighted by Hong, Ou & Mandel who made the two photons forming an SDPC pair to interfere on a 50/50 beamsplitter. In symmetric configurations the two photons are indistinguishable, so their bosonic nature implies that processes where they would emerge from different ports undergo destructive interference, leaving only scenarios where the two photons exit together from the same port. This intriguing two-photon interference effect is experimentally evidenced by measuring the coincidence counts between detectors placed at the two outputs of the beamsplitter and manifests itself as a dip when varying the time delay between the two incident photons. The visibility of this dip around zero delay is a direct measure of the indistinguishability of the interfering SPDC photons and can reach very high levels (>99%) in state-of-the-art experiments.

The next milestone was the demonstration of entanglement between photons created by SPDC. Using a BBO crystal, for a careful pump configuration the signal and idler photons turn out to be emitted along two cones, which support photons with orthogonal polarizations and intersect at two points in a given detection plane (Fig. 1c). Placing oneself at one of these intersection points, it is therefore impossible to predict the polarization of the emerging photon, which can randomly change from horizontal to vertical from measurement to measurement; however, the polarization of the photon emerging at one intersection must be orthogonal to the one of the other photon, which corresponds to having a polarization-entangled state of the two photons. A slight improvement of this general principle was exploited by Kwiat et al. to demonstrate in 1995 a strong violation of Bell inequalities by over 200 standard deviations in less than 3 min [2].

At the turn of the 20th century, SPDC continued to make crucial contributions to the demonstration of foundational concepts of quantum information. These include the first demonstration of quantum teleportation (1997), entanglement-based quantum key distribution (2000), as well the first realization of an optical controlled-not gate (2003) soon after the landmark proposal of linear optical quantum computing by Knill, Laflamme and Milburn.

In parallel, another branch of quantum information has been actively explored since the mid-80's, pushing ●●●

parametric generation beyond the single photon-pair regime by increasing the pump power or/and the nonlinear interaction length. In this situation, the probability of generating double, triple, etc. photon pairs becomes sizable and the generated quantum state of the field is a squeezed state involving the superposition of many photon-number states. This marks the transition into the continuous-variable regime, where quantum information is encoded within the quadratures of quantum electromagnetic fields rather than in individual photons. The first forays into this realm were realized by placing a nonlinear crystal in a cavity so as to resonantly reinforce the parametric processes. For instance, a degenerate parametric down conversion (PDC) process operated below the oscillation threshold leads to the generation of single-mode squeezed vacuum states, while nondegenerate PDC operated above the oscillation threshold leads to two-mode squeezed coherent states, also called twin beams as they feature strong mutual intensity correlations in the form of a strong squeezing of their amplitude difference [3].

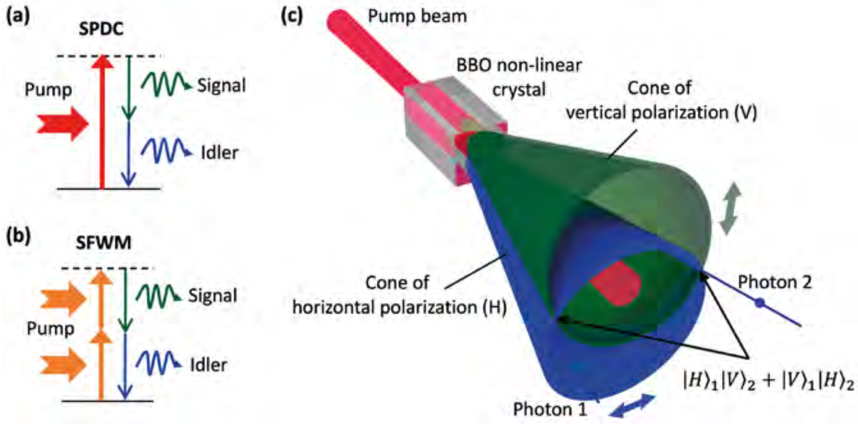

Figure 1. (a) Energy diagram for Spontaneous Parametric Down-Conversion (SPDC) and (b) for Spontaneous Four-Wave Mixing (SFWM). (c) Sketch of an SPDC experiment in a Barium Borate (BBO) crystal, leading to the generation of polarization-entangled photon pairs (modified from open-access Wikimedia Commons CC BY-SA 4.0).

APPLICATIONS TO QUANTUM TECHNOLOGIES

In the early 2000s, progresses in microfabrication techniques made parametric generation possible also in integrated optical structures. This provided a strong reduction in the device footprint, but also a large increase of the process efficiency: the strong modal confinement of the three fields in microscopic waveguides allows indeed for a diffractionless propagation as well as a reinforced nonlinear overlap of the fields. The on-chip parametric generation of quantum states of light was demonstrated by SPDC in periodically poled lithium niobate (PPLN) and in AlGaAs waveguides, as well as by SFWM in optical fibers, silicon-based and glass microresonators. While these early demonstrations operated in the photon pair regime, recent years have seen a significant progress towards the on-chip generation of squeezed states (Fig. 2b).

Concurrently, another layer of complexity was introduced into the quantum optics landscape by the emergence of quantum photonic circuits, which allowed in 2008 the first on-chip demonstration of two-photon quantum interference and controlled-NOT gate operations using a combination of passive waveguides and beamsplitter elements. This area of research has then experienced rapid evolution, transitioning from centimeter-scale static circuits, manipulating a small number of photons with only few optical components, to millimeter-scale reprogrammable circuits, capable of processing multiphoton states with hundreds of components.

Initially, these two research trajectories progressed independently, with a separate development of parametric sources and of passive optical circuits. Recently though, the convergence of these streams has led to remarkable integrated photonic devices combining the on-chip generation and manipulation of quantum states of light (Fig. 2a), in particular on the Silicon, PPLN and AlGaAs platforms. The high fabrication reproducibility of integrated parametric sources is here exploited to realize of a large number of identical sources on the same chip (*e.g.* 16 SFWM sources in Ref. [4], with a mutual indistinguishability > 90%). Photons emitted by these integrated sources can then interfere in the following elements of the optical circuit to produce high-dimensional entangled states, paving the way to scalable applications in linear optical quantum computing, boson sampling or quantum simulation. An alternative strategy for these tasks is based on continuously-coupled systems such as the nonlinear waveguide arrays illustrated in Fig. 2c. Here, photons are generated and interfere along the entire propagation length rather than solely at discrete optical elements. This allows to unveil novel phenomena stemming from an intertwined instead of sequential combination of the generation and manipulation steps of photonic quantum states [5].

In addition to the spatial degrees of freedom, further possibilities are offered by the spectral ones. For instance, by pumping SPDC with a multi-frequency laser, complex networks of multi-mode squeezing can be generated: an optical comb pump source containing a lattice of equispaced frequencies simultaneously generates squeezing in all pairs of frequencies that sum up to a comb tooth [6]. In the same way as entanglement in waveguide arrays can be manipulated via the coupling of neighboring waveguides, techniques inspired by synthetic dimensions provide manipulation tools in the spectral domain. Combining together all degrees of freedom, and possibly exploiting also topological protection effects [7], complex high-dimensional entanglement lattices can be generated with high interest for quantum information applications.

While in the late 1990s, parametric sources supplanted atomic cascades as flexible and user-friendly sources of quantum states of light, in the recent years they are encountering an increasing competition from high-quality two-level emitters such as semiconductor quantum dots, which can emit single photons in a deterministic manner without trade-off between brightness and photon purity. In spite of this, parametric sources still play a pivotal role nowadays thanks to various practical assets, including their room temperature operation, high fabrication reproducibility, and quality and versatility of the emitted quantum states, including the generation of squeezed states. These assets underlie a number of recent breakthrough advances in quantum technologies, from fundamental tests of quantum mechanics (where parametric sources were used to close loopholes in Bell tests), to quantum computation and simulation (leading *e.g.* to the demonstration of a quantum advantage in the Boson sampling problem), to metrology (where the use of squeezed states as an input improves the sensitivity of the LIGO interferometer for gravitational wave detection) [8].

FURTHER PERSPECTIVES

From a wider perspective, it is interesting to note that spontaneous parametric processes are at the heart of a number of exciting phenomena that are attracting a strong interest in many other areas of physics. A simplest such example is the dynamical Casimir effect, that can be straightforwardly understood as the spontaneous parametric emission of photon pairs when a neutral body (*e.g.* a dielectric or a mirror) is accelerated in space: here, the role of the optical pump beam is played by the mechanical motion and, most remarkably, the electromagnetic emission takes place even though no net currents are present in the set-up.

At a higher level of complexity, parametric processes play a crucial role also in cosmology and gravitation: the parametric generation of particles during and right after the fast •••

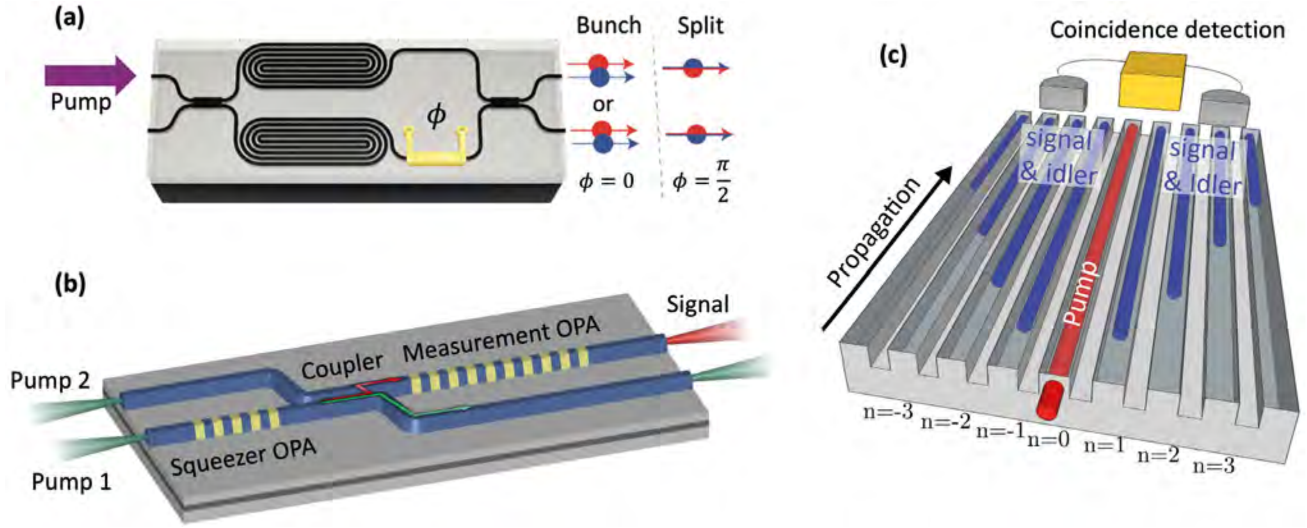

Figure 2. (a) Silicon photonic circuit embedding two SFWM sources, beamsplitters and a phase shifter: depending on the phase shift ϕ, one can switch from a regime where bunched photons are generated in the same output arm to a regime where the photon pairs are split into the two arms (adapted with permission from Silverstone *et al.*, Nature Photonics **8**, 104 (2014)). (b) Lithium niobate circuit allowing the generation and all-optical measurement of squeezed states within a single chip: the pump beam 1 injected into a squeezer optical parametric amplifier (OPA) generates a squeezed vacuum state, which is coupled into an adjacent waveguide and amplified by a second OPA (seeded by the pump beam 2) for measurement (adapted with permission from Nehra *et al.*, Science **377**, 1333 (2022)). (c) Nonlinear waveguide array for the controlled generation of spatially entangled states of light: the pump beam (sketched in red) continuously generates photon pairs that undergo quantum walks (blue), resulting in spatial entanglement over the whole lattice [5].

inflationary expansion of the early Universe has contributed to the generation of visible matter. And also the Hawking radiation from black holes can be physically understood as the result of the parametric emission of photon pairs traveling on either side of a black hole horizon: here, the role of the pump is played by the curved black hole space-time and entanglement ends up being shared between the black hole and the emitted radiation. In spite of the harsh experimental difficulty of investigating these phenomena in their original contexts, first experimental evidences are coming from the so-called analog models of gravity, namely table-top condensed matter systems whose dynamics is ruled by quantum field theories on effective curved space-times. Here, evidences of Hawking radiation and dynamical Casimir emission are available, as well as hints of their quantum entanglement properties [9,10].

This exciting on-going research highlights the generality of the parametric emission concept and further confirms the importance of its full understanding in view of quantum technology applications as well as for fundamental science to get a deeper insight into the mysteries of our Universe.

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SINGLE PHOTON AVALANCHES DIODES

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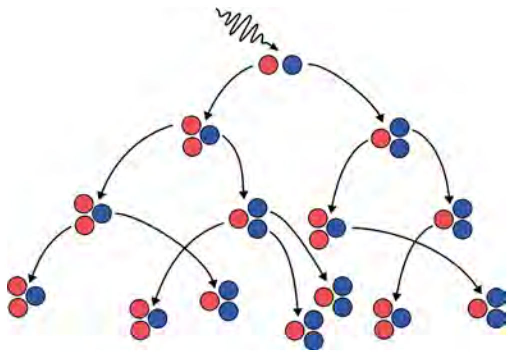

Twenty years ago the detection of single photons was little more than a scientific curiosity reserved to a few specialists. Today it is a flourishing field with an ecosystem that extends from university laboratories to large semiconductor manufacturers. This change of paradigm has been stimulated by the emergence of critical applications that rely on single photon detection, and by technical progresses in the detector field. The single photon avalanche diode has unquestionably played a major role in this process.

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Light sensors like pin photodiodes, CCDs, or CMOS image sensors generate a signal with an amplitude proportional to the amount of light hitting the detector. While this signal can eventually be converted in a digital form for easiness of elaboration, they are natively analog detectors. Single photon detectors are radically different, as they generate a standard pulse for each photon hitting the detector. The information about the light intensity is not encoded in the pulse-amplitude but can be obtained by counting the number of pulses in a short amount of time.

In the first part of this article, we will provide a few examples to illustrate why photon counting has become so important in many fields, ranging from fundamental science to consumer electronics. Then we will focus on a specific type of detector, the single-photon avalanche diode or SPAD, that has become very popular thanks to its combinations of remarkable performance, affordability, and easiness of use. We will review its working principle, its performance metrics, the materials, and we will briefly compare it with other single-photon detectors.

WHY COUNTING SINGLE PHOTONS?

The capability of detecting single photons has opened the way to a multitude of exciting new applications that would not have been possible with analog detectors. While the measurement of **faint optical signals** may appear the most obvious domain of application, there are other and even more important fields in which these detectors are essential. The emerging fields of optical **quantum information processing** and quantum sensing rely on the quantum properties of a photon to enhance data communication, processing, and sensing. For example, quantum key distribution (QKD) exploits the impossibility of cloning the quantum state of a photon to detect the presence of an eavesdropper; ghost imaging takes advantage of the correlation between entangled photons to image a scene by measuring photons which have never interacted with the scene itself. All these applications require to take decisions depending for example on which path a photon has taken, in which timeslot it has arrived, or whatever two photons have arrived at the same time or not. The capability of signaling the arrival of a single photon is therefore crucial.

Single photon detectors not only excel in this task, but most of them can also do it with an excellent temporal precision, down to a few tens of picoseconds. This property is widely exploited for the reconstruction of **ultrafast optical** •••

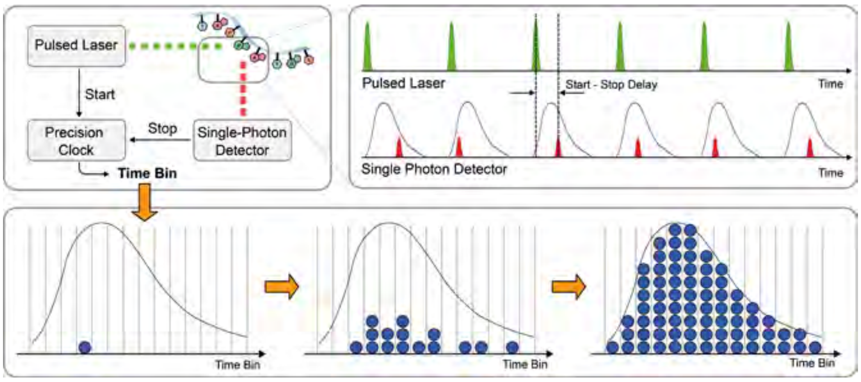


Figure 1: Fluorescence lifetime measured by time-correlated single-photon counting (TCSPC). The sample is excited by a pulsed laser and the delay between the excitation pulse and the emitted photon is measured by a precision clock. By repeating multiple times, it is possible to build a histogram of the delays that reproduces the shape of the optical signal.

signals. A typical example is the measurement of the fluorescence emitted by a sample when excited by a short (ps or fs) laser pulse (Figure 1). If the intensity is low enough (either intrinsically or because it has been purposely attenuated) the quantization of the light will result in (at most) one photon reaching the detector at a random time, with a probability distribution that follows the shape of the optical signal. Therefore, by repeating the experiment multiple times, it will be possible to build a histogram of the arrival times that reproduces the shape of the signal with tens-of-ps details. This technique is known as time-correlated single photon counting (TCSPC). Attaining the same level of detail with conventional techniques is incredibly challenging as it would require an entire acquisition chain (detector, amplifiers, analog-to-digital converters, etc.) operating at tens of gigahertz.

The temporal precision of single-photon detectors is exploited in a multitude of applications, like LiDAR. In this case the 3D features of a scene are reconstructed by measuring the time it takes for a laser pulse to travel from the source to the scene and back to the detector.

SINGLE PHOTON AVALANCHE DIODES

PRINCIPLE OF OPERATION

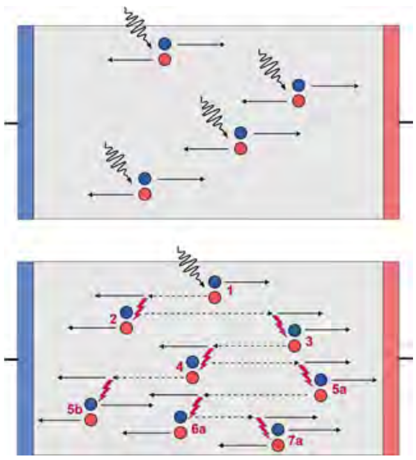
Photodiodes are light sensors that rely on a semiconductor material to convert a photon flux in an electric current. When absorbed in the semiconductor, a photon generates two carriers of opposite charge, an electron and a hole. In a common photodiode, the carriers are accelerated in opposite direction by an electric field and are collected at the electrodes, resulting in a current proportional to the number of incident photons (Figure 2, top). When moving along the detector, the carriers are accelerated by the electric field and, once in a while, they release the acquired energy by colliding with the semiconductor reticle. Usually, this process has no significant effect on the photodiode behavior; but, if the electric field is increased, the energy acquired by the carriers can become high enough to induce ionization, *i.e.* to break the bonds in the reticle and create another electron-hole pair (Figure 2, bottom). This process increases the number of circulating carriers and tends to self-sustain. In fact, as the two carriers move in opposite directions, one will be travelling toward the edge of the device while the other will head toward its center where it can generate additional pairs. The new carriers are in turn accelerated, generate further pairs, and so on.

If the average number of pairs created in each iteration is lower than one, the process comes to an end after some iterations; the electric current recorded at the electrodes is again proportional to the number of incident photons, although a factor M larger than in a conventional photodiode. In this case the detector is referred to as an APD or avalanche photodiode. On the contrary, if the electric field is so high as to create more than one pair per iteration, the multiplication process diverges and the current at the electrodes increases exponentially (until some saturation phenomena occurs). This allows to easily detect the absorption of a single photon and the detector is called single-photon avalanche diode or SPAD. Once this self-sustained avalanche multiplication has been triggered in a SPAD, the absorption of an additional photon does not significantly change the current flowing in it, so the detector is effectively blind. To be able to detect additional photons, the SPAD must be coupled with a quenching circuit that turns the avalanche off and resets the initial operating conditions.

PERFORMANCE METRICS

When selecting a SPAD, there are many performance metrics to look at. Many of these metrics are in trade-off with each other (see Figure 3 for some examples), and the relative importance of each of

Figure 2: In analog photodiodes (top) each photon generates a pair of carriers, which are collected at the electrodes. In SPADs (bottom) a single photon starts an avalanche process resulting in a self-sustained current.



them strictly depends on the applications. So, in single photon detection there is (still) not a one-size-fit-all solution.

Size of the Active Area. The active area, *i.e.* the part of the SPAD which is photo-sensitive, may extend laterally from a few microns to a few hundreds of microns. Diameters ranging from 20 – 100 µm are usually preferred to collect the light from a microscope. Larger diameters may be needed when the light scattered by the sample cannot easily be focused on the SPAD, as it happens for example in two-photon microscopy and diffuse optical tomography. By contrast, smaller diameters are preferred when the light comes from a single-mode fiber or when SPADs are arranged in large arrays to build an image sensor.

Photo Detection Efficiency (PDE). A photon impinging on a SPAD may go undetected either because it is not absorbed in the semiconductor material or because the photogenerated carriers fail to trigger an avalanche. This can be quantified by looking at the photon detection efficiency (PDE), which represents the probability that a photon impinging on the detector active area successfully triggers an avalanche. The PDE is especially important when the number of available photons is limited. An example is the single molecule analysis, where a freely diffusing molecule spends only a limited amount of time in the focus of a confocal microscope. Even more critical are those applications in which coincidences must be measured. In fact, the coincidence of n photon-events is properly recorded only if all the n SPADs involved succeed in detecting the corresponding photon. The probability of success scales therefore with $(PDE)^n$.

Dark Count Rate (DCR). In a semiconductor, an electron-hole pair can occasionally be generated by phenomena different from a photon absorption. For example, impurity atoms favor the thermal breaking of the bonds that keep an electron tied to the reticle, leading to the formation of a pair. Such pairs are as effective in triggering an avalanche as those that have been photogenerated. That means that a SPAD can fire even in dark, and the average number of events recorded in absence of light is called dark count rate (DCR). While the DCR can be assessed and subtracted from the measurement, its statistical fluctuations remain and may hide the useful signal. The lower •••

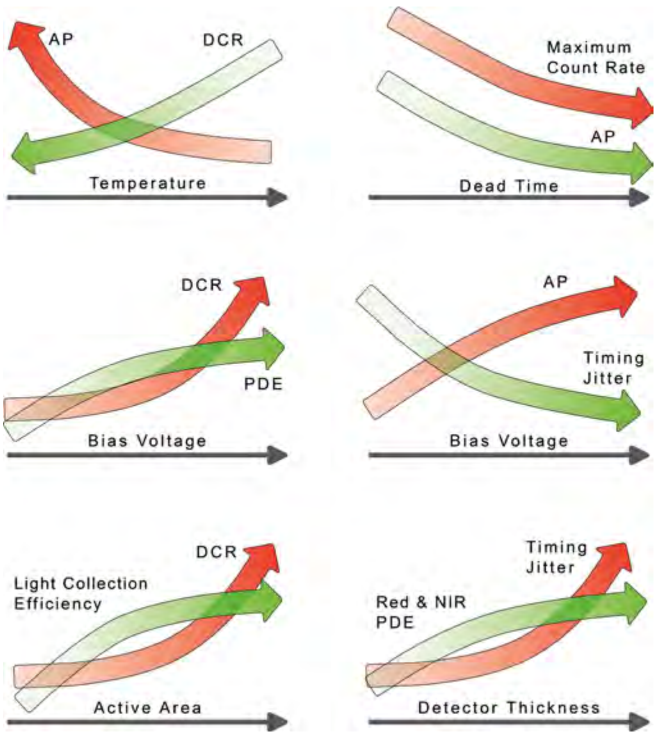


Figure 3: By changing the operating conditions or the design parameters, it is possible to improve some performance metrics at the expenses of others.

is the DCR, the lower are also its fluctuations. A low DCR value is especially important whenever faint light signals must be acquired.

Afterpulsing Probability (AP). During an avalanche, a large number of carriers flows through the device. If one of them is trapped in a defect and is released at a later time, it may trigger an additional avalanche known as afterpulse. Afterpulsing is especially deleterious where a SPAD is used to measure temporal correlations. An example is fluorescence correlation spectroscopy (FCS), where the autocorrelation in the light emitted by a small number of molecules is used to assess molecule properties like the diffusion coefficients.

Dead Time. The detector is inevitably blind for the time it takes to quench the avalanche and reset the initial operating conditions. In addition to this, the detector is intentionally kept off for a time sufficient to release most of the carriers trapped in the previous avalanche without re-triggering a new one. The overall time for which the SPAD remains blind is called dead time. The dead time limits the minimum time-distance at which two photons can be detected. Short dead times are thus needed to operate the detector with high photon fluxes or to measure short interval correlations.

Timing Jitter. Ideally, the delay between a photon absorption and the generation of the corresponding output pulse should be perfectly constant. However, the randomness of the impact ionization process introduces fluctuations in the way the avalanche-current grows after a photon absorption, resulting in slightly different delays each time the detector is triggered. The statistical distribution of the photon detection delays is called temporal response. The broadening of this curve is usually called timing jitter and it is quantified by providing the full width at half maximum (FWHM). It must be remarked that, although very convenient, the FWHM does not provide a complete description of the phenomenon and the whole temporal response must be inspected to identify the presence of slow components with an amplitude that falls below the half maximum. Timing

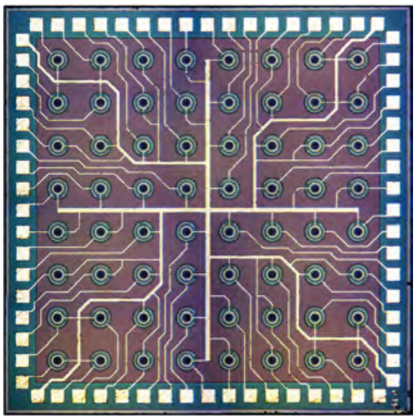


Figure 4: An example of an array of 8 × 8 SPADs.

Manufacturer	Model	Active Area Diameter (µm)	DCR (cps)	Peak PDE		Jitter FWHM (ps)	AP (%)	Dead Time (ns)	At a glance
				Value	Wavelength				
Excelitas Technologies	SPCM-AQRH	180	25 - 1500 (1)	50 - 65% (2)	650 nm	350 (3)	0.5 - 1 (4)	22 - 42 (1)	High PDE
	SPCM-AQRH-TR		100 - 1500 (1)	75% (3)	650 nm	225 - 250 (4)	1 - 3 (4)		
	SPCM-NIR		100 - 1500 (1)	64 - 70% (2)	780 nm	350 (3)	1 - 3 (4)		
Laser Components	COUNT®	100	10 - 250 (1)	55 - 75% (2), (8)	670 nm	1000 (3)	0.2 - 1 (4)	42 - 48 (9)	High PDE
	COUNT® BLUE		10 - 250 (1)	60 - 70% (2), (8)	532 nm	1000 (3)	0.2 (3)		
	COUNT® NIR		50 - 500 (1)	55 - 70% (2), (8)	670 nm	1000 (3)	0.2 - 1 (4)		
	COUNT T		100 - 250 (1)	55 - 75% (2), (8)	670 nm	350 (3)	1 (3)		
MPD Micro Photon Devices	PDM Series	20	5 - 25 (1)	44 - 48% (2)	550 nm	35 - 50 (4)	0.1 - 3 (9)	77	Low Jitter
		50	25 - 250 (1)						
		100	25 - 500 (1)						
ID Quantique	ID100	20	7 - 1000 (1)	30 - 35% (2)	500 nm	40 - 60 (4)	< 0.5	45 - 50 (4)	Low Jitter
		50	60 - 1000 (1)						
	ID120	500	300 - 4000 (1)	80 %	800 nm	200 - 1000 (9)	N/A	1000	High PDE, Large area
Hamamatsu	C11202 series	50	7 - 25 (4)	60 - 70% (2)	450 nm	N/A	0.1 (5)	N/A	High PDE
		100	30 - 100 (4)						
	C16531 series	50	20 - 60 (4)	55 - 65% (2)	630 nm	N/A	0.1 (5)	N/A	
		100	150 - 450 (4)						
AUREA Technology	SPD_A_VIS Red	N/A (6)	25 - 500 (1)	> 65%	700 nm	< 350	N/A	20 - 40 (7)	Built-in gated electronics
	SPD_A_VIS Blue			70%	550 nm	< 350			
	SPD_A_VIS Timing			45%	550 nm	< 50			
Thorlabs	SPDMA (10)	500	300 - 1500 (4)	66% (3)	650 nm	N/A	N/A	< 35	High PDE, Large area
	SPCMxxA	20	25 - 60 (4)	35% (3)	500 nm	N/A	3	35 (3)	Integrated counter
		50	150 - 200 (4)					45 (3)	
	SPDMH series	100	100 - 250 (1)	70% (8)	670 nm	1000	0.2 (3)	45 (3)	High PDE

(1) Depending on the selected model
(2) Min. - Typ. values
(3) Typ. value
(4) Typ. - Max. values
(5) AP events integrated only between 100 and 500 ns
(6) Fiber receptacle for SMF or MMF
(7) Min. programmable value
(8) At the center of the active area. PDE reduces considerably moving away from the center
(9) Min. - Max. values
(10) Adjustable bias voltage. All parameters measured at max bias voltage

Table 1: Single-pixel detection modules based on silicon SPADs.

jitter and temporal response are important parameters when the photon arrival time must be measured with high accuracy. Examples are fluorescence lifetime imaging (FLIM) and Förster resonant energy transfer (FRET) measurements, where subtle variations in the fluorescence lifetime are used to assess changes in a molecule conformation or in its environment.

When SPADs are arranged in an array (Figure 4), there are additional metrics that may become relevant.

Fill Factor (FF). The active area of a SPAD is typically surrounded by structures which are essential for the proper operation of the detector, but that are not capable of detecting photons. Also, electronic circuits needed to operate the detector and acquire the data are frequently integrated next to each SPAD. Consequently, only a fraction of the pixel is photosensitive. The ratio of the photosensitive area to the entire pixel area is called fill factor (FF). The FF is particularly important in those applications where the SPAD array is flood illuminated, like flash-LiDAR, because it results in a fraction 1-FF of photons being lost. A low FF can be partially mitigated by using micro-lenses, either integrated on the detector chip or added externally. It must be noted that, in the SPAD-array community, it has become quite common to indicate the efficiency of a single SPAD as photon detection probability (PDP), and to use the term PDE to indicate the product of the PDP times the FF.

Optical crosstalk. A small number of photons may be emitted by a SPAD during an avalanche because of the large number of energetic carriers that flow through the device. Occasionally, one of these photons can be reabsorbed in a nearby detector and trigger an avalanche. Such a correlated event is called optical crosstalk. Optical crosstalk is especially detrimental when infrequent coincidences must be measured by using pixels within the same array. This is for example the case in quantum enhanced microscopy, where entangled photons are used to increase the spatial resolution of an optical microscope.

MATERIALS

Silicon is by far the most popular material to fabricate SPADs. Silicon SPADs can be operated at room temperature with low DCR or can be slightly cooled (*e.g.* -5°C) to decrease further the noise. They can detect photons from about 400 to 1000 nm, with a typical peak-PDE around 50% in the green. To extend the sensitivity at longer wavelengths, other semiconductors must be used. Up-to-now the best results have been attained by absorbing the infrared photons in an InGaAs layer and by multiplying the carriers in InP. To mitigate the higher DCR, InGaAs/InP SPADs are typically operated at much lower temperature (*e.g.* -50°C). However, this worsens the afterpulsing problem that intrinsically plagues these devices. Absorption in germanium, combined with multiplication in silicon, is being explored as an alternative to reduce the afterpulsing problem and improve the integrability. Despite significant progresses have been made in the last few years, improvements are still necessary to make SiGe SPADs a viable alternative.

COMPARISON WITH OTHER DETECTORS

SPADs are not the only single-photon detectors available. The detection of single photons has been possible since the 1930's, thanks to Photomultipliers Tubes (PMTs). In PMTs, an electron is emitted when a photon is absorbed in the photocathode. The photoelectron is accelerated to generate other electrons by hitting a metal target. These are in turn accelerated to generate other electrons and so on, until a large electric pulse is obtained. To work properly, the entire structure must be enclosed in a vacuum tube. Compared to SPADs, PMTs are bulky, cannot form large arrays, and attain a significantly lower detection efficiency, especially at red and near infrared wavelengths. By contrast, PMTs can achieve low DCR even on centimeter-size active areas.

An alternative approach to detect a single photon is to flow a current in a superconductive wire. If the wire is only a few tens-of-nanometer-wide, the absorption of the photon can break the superconductivity, which results in a voltage pulse. ●●●

Superconducting nanowire single photon detectors (SNSPDs) attain exceptional performance in terms of PDE, that can extend from deep-UV to mid-IR, DCR, and timing jitter. However, SNSPDs must be operated at temperatures between 1 and 4 K. Whether the improved performance justify the significative increase in cost, complexity and size of the system depends on the specific applications. For example, fundamental science experiments have widely adopted SNSPDs while biological, industrial, and consumer applications favour SPADs.

CONCLUSION

In the last twenty years SPADs have moved from the lab to the market. While the majority of commercial products are single-pixel detectors manufactured in silicon (see Table 1) or, to a smaller extent, in InGaAs/InP (see Table 2), arrays of silicon SPADs have recently started to populate the market (see Table 3). For the coming years, a significant increase in the number and in the performance of the available products is foreseeable. LiDAR for autonomous driving is leading the development of large arrays of SPADs with photon-timing capabilities. Quantum information processing requires detectors with astonishing performance. Safety and security applications are pushing for an extension of the detection spectrum toward the infrared.

Manufacturer	Model	Optical Coupling	Opearting Mode	Performance at a selected PDE value*			Gate Generation	Gate Width	Gate Frequency	Deadtime
				PDE @ 1550 nm	DCR (cps)	Jitter FWHM (ps)				
MPD Micro Photon Devices	PDM-IR	Free Space (ϕ = 25 µm) or MMF 50 GI [1]	Free running & Gated mode	10 %	1.7k [2]	N/A	Internal and External	User Adjustable 1 ns - 1.5 ms	User Adjustable 100 Hz - 100 MHz	User Adjustable 1 µs - 3000 µs
				25 %	14.9k [2]	111 [2]				
		SMF-28		10 %	0.5k [2]	N/A				
				25 %	3.5k [2]	61 [2]				
ID Quantique	ID Qube NIR	Free Space or MMF 62.5 [1]	Free running or Gated mode [1]	10 %	< 0.8k - 1.2k [1]	N/A	External	> 3 ns (Gated) > 500 ns (Free run.)	< 100 MHz (Gated) < 1 MHz (Free run.)	User Adjustable 100 ns - 80 µs
				25 %	< 6k - 10k [1]	150 - 200 [3]				
	ID230	SMF or MMF 62.5 [1]	Free running	10 %	< 0.05k - 0.08k [1]	N/A	External	N/A	N/A	User Adjustable 2 µs - 100 µs
				25 %	N/A	150 - 200 [3]				
AUREA Technology	SPD_A_NIR	SMF or MMF [1]	Free running and Gated mode	10 %	< 1k - 5k [1]	N/A	Internal and External	User Adjustable 1ns - 100 ns	User Adjustable 0 Hz - 20 MHz	User Adjustable 100 ns - 1000 µs 1 µs - 1000 µs [1]
				25 %	N/A	180 - 200 [1]				

* Performance depends on the selected bias voltage. The performance in the table have been measured when the detector is biased to attain a PDE a 1550 nm either of 10% or 25%.

(1) Depending on the selected model
(2) Typ. values
(3) Typ. - Max. values

Table 2: Single-pixel detection modules based on InGaAs/InP SPADs. These modules are highly configurable, with specific performance that depends on operating conditions. Please see the manufacturer datasheet for further details.

Manufacturer	Model	Pixels	Pitch (µm)	Microlens Arrays (MLA)	FF	Peak PDE			DCR (cps)	Operating Modes	Frame Rate	Jitter FWHM (ps)
						PDP	PDE = PDP * FF	Wavelength				
MPD Micro Photon Devices	Argo Panoptes	7 x 7 or 8 x 8 [1]	75	Optional	12.6% native 76% with MLA	28 - 43% [2], [1]	23 - 34% [2], [1]	450 nm	< 500 [4]	Direct Output	Not Applicable	130 - 175 [3],[1] w/o MLA 67 - 92 [3],[1] with MLA
	Hermes	64 x 32	150	Optional	3.14% native 70% with MLA	33 - 42% [2]	20 - 29% [2]	450 nm	< 100 [4]	Frame-based Gated	96 kfps @ 8 bit 6 kfps @ 12 bit	Not Applicable
pi imaging	SPAD23	23 Hexagonal	19.92 / 23	Yes	> 80%	55%	44% [6]	520 nm	< 100 [5]	Frame-based Gated Time Stamping [8]	N/A	< 120
	SPADλ	320 x 1	29	Yes	> 80%	50%	40% [6]	520 nm	< 250 [5]	Frame-based Gated Time Stamping	< 555 kfps	130
	SPAD512^2	512 x 512	16.38	Yes	> 50%	50%	25% [6]	520 nm	< 25 [5]	Frame-based Gated	0.4 kfsp @ 8 bit continuous 5 kfps @ 4 bit semi-continuous 100 kfps @ 1 bit for 1 s	Not Applicable
Photon Force	PF32-1M PF32-500k	32 x 32	50	Optional	1.5% native 20% with MLA	27 %	5.4% [6]	500 nm	< 100 [4]	Frame-based Time Stamping	150 kfps @ 16 bit 225 or 300 kfps @ 8 bit [1]	200
Horiba	FLIMera	192 x 128	18.4 / 9.2	No	13 %	34% [7]	4.4% [8]	560 nm [7]	25 [7]	Time Stamping	30 fps	219 [7]
Canon	MS-500	1920 x 1080	6.39 [9]	Yes [9]	N/A	N/A	69.4% [9]	510 nm [9]	1.8 [5], [9]	Frame-based	25.5 - 59.94 fps @10 bit	Not Applicable

Operating Modes
Direct Output: single-photon pulses made available externally on a dedicated connection for each pixel.
Frame-based: counts are accumulated for a fixed integration time and then downloaded for the entire array in a frame.
Gated: counts are accumulated only in a small, selectable, time-window after a sync signal (e.g. from a pulsed laser); the procedure is repeated for n times before downloading the entire frame.
Time stamping: the time-of-arrival of each photon with respect to a sync signal is measured. Download strategy may depend on the architecture.

(1) Depending on the selected model
(2) Min. - Typ. values
(3) Typ. value
(4) Most of the detectors have a DCR below this value. See datasheet for more details
(5) Median
(6) Calculated from PDP and FF values
(7) Not specified by Horiba. Indicative data from Henderson et al, IEEE JSSC 2019, 10.1109/JSSC.2019.2905163
(8) A Direct Output module based on the same SPAD-array is commercialized by PicoQuant as PDA-23
(9) Not specified by Canon. Indicative data from Morimoto et al, IEDM 2021, 10.1109/IEDM19574.2021.9720605

Table 3: Detection modules based on silicon SPADs arrays. Please refer to the manufacturer datasheet for more details on performance and operating modes.

Software for Time-Correlated Single Photon Counting

Snappy new API (snAPI) is a Python wrapper which enables seamless communication and configuration with PicoQuant's Time-Correlated Single Photon Counting (TCSPC) and Time Tagging Electronics. It harnesses the advantages of C++ for optimal speed and performance and bridges the gap between the high-speed capabilities of PicoQuant's TCSPC devices and the ease of use and versatility of Python.
https://www.picoquant.com/products/category/software/snapi-fast-intuitive-and-versatile-python-wrapper?goto=white_rabbit#description

HIGH-POWER CW DIODE PUMPED LASER

The Cobolt JiveTM is a continuous-wave single-frequency diode pumped laser (DPL) operating at 561.2 nm in a TEM00 beam (M2< 1.1). Now with up to 1 W CW output power, the Cobolt JiveTM is well suited to applications in fluorescence microscopy, especially for super resolution microscopy such as DNA-PAINT, as well as interferometric based techniques such as particle flow analysis.
https://hubner-photonics.com/products/lasers/single-frequency-lasers/05-01-series/

Dielectric Ultrafast Laser Mirrors

TECHSPEC® Low GDD Dielectric Ultrafast Laser Mirrors feature a multilayer dielectric coating on fused silica substrates for reflectivity higher than 99.9% and low coefficient of thermal expansion. These mirrors have a group delay dispersion (GDD) of near zero at their design wavelength range, minimizing dispersion of the reflected beam. They are well adapted for the 1st and 2nd harmonics of Ti:sapphire and Yb:doped lasers for applications such as laser machining and welding.
https://www.edmundoptics.com/f/techspecr-low-gdd-dielectric-ultrafast-laser-mirrors/39997/?utm_source=website&utm_medium=homepage+banner+slot+1&utm_campaign=gdd

UV-SENSITIVE MINI-SPECTROMETER

Hamamatsu Photonics introduced a UV-sensitive model of mini-spectrometer micro series. This C16767MA model is highly sensitive to UV light in the 190 - 440 nm range. It is designed and developed by leveraging Hamamatsu's micro-electro-mechanical system (MEMS) technology and advanced opto-semiconductor manufacturing technology.
https://www.hamamatsu.com/jp/en/news/products-and-technologies/2023/20231101000000.html

Single-Photon Detector

The ID281 Pro (ID Quantique) is a compact rack-mounted Superconducting Nanowire Single-Photon Detector. It is designed to be integrated in quantum platforms for photonic quantum computing or quantum communication systems. The ID281 Pro cryogenic system can host up to 16 superconducting nanowire single-photon detectors which can be selected from the comprehensive range of detectors developed and manufactured by ID Quantique.
https://www.idquantique.com/id-quantique-launches-the-id281-pro/