Photoniques

THE MAGAZINE OF THE FRENCH OPTICAL SOCIETY

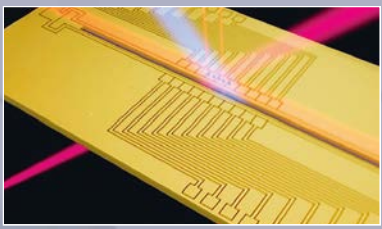
Special EOS Issue · March-April 2019

EUROPEAN WAY OF PHOTONICS

special EOS issue

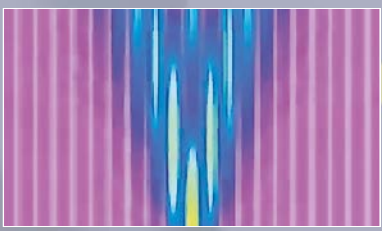
FOCUS

Photonic techniques and technologies



BACK TO BASICS

Counting time-correlated photon



PORTRAIT

Augustin Fresnel

BUYERS GUIDE

A femtosecond oscillator

France/EU : 19€ – Rest of the world: 25€

www.photoniques.com

Photoniques

The magazine of the French Optical Society

European way of life. That's why.

Here is the third European issue of the French magazine *Photoniques*. Starting from a modest national journal trying to cross the boarders and to forge new relations, it now turns to be a collection of original and enthusiasming texts about research and technology that are *Made In Europe*. Today, you are about 20,000 readers throughout 21 countries in Europe. You are in research, industrial or training bodies, involved in a common destiny and defending a similar way of life. Photonics is one of our several links, as it helps building a better future for our society, in the issues of energy, medicine, transport, ecology, communications, and much more.

As a matter of fact, this year more than ever before, this European issue of the magazine *Photoniques* can be seen as a building block of our global destiny. Please accept it as a gift from a close friend.

Riad HAIDAR
Editor-in-chief

Bonne lecture !

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IMPRIM'VERT

Dear SFO and EOS Members,

The European Optical Society (EOS) is proud to serve the Optics and Photonics community in Europe through its continuous promotion of networking between its individual and member societies, among which the SFO (Société Française d'Optique) is one of the most active. One example of the strong ties developed between EOS and SFO is precisely the yearly publication in English of Photoniques since 2017. This initiative has paid a two-fold service both to the French photonics to present their news to a broader audience and to the international optics community to be aware of the state of the art of the discipline in France. For 2 years now, this issue also welcomes technical articles from throughout Europe, and heralds news from European consortia like EPIC and the EOS. It would be desirable in the future to extend this example of cooperation to other European national societies, members of EOS and other international partners like the Japan Society of Applied Physics (JSAP); Optical Society of Japan (OSJ); the Chinese Optical Society (COS); the Optical Society of Korea (OSK) and the Taiwan Photonics Society (TPS).

In the era of internet and social networks, the new EOS website under the domain **europeanoptics.org** will serve as a gathering point for those members of the optics and photonics community who are interested on keeping the personal contacts made in EOS biannual meeting, like the last successful one celebrated in Delft in 2018 or the next one that will be held in Porto in September 2020. This congress will cover a broad spectrum of photonic techniques, through the joint celebration of different TOMs (Topical Optics Meeting) that will attract specialists from all over the world to discuss the last advances in optical fabrication, lasers, optical metrology, optical communications, nanophotonics, biophotonics, optical sensors, etc. The industrial exhibition that will take place in parallel with the congress will attract the leading photonics companies in Europe and the gala dinner in the spectacular Stock Exchange Palace in Porto will close on a high note this important event, where all the optics and photonics community in Europe is welcome to attend.

Humberto Michinel,
President of the European Optical Society

This is now our 3rd edition of Photoniques in English, and we truly hope there will be many more to come. Photoniques is a periodic journal and newsletter for the members of the Société Française d'Optique (SFO). SFO is a member of the International Commission for Optics (ICO), and it is also the representative of the French community in optics at the European Optical Society (EOS) since the creation of EOS in the early 90s.

SFO is a non-profit organization, gathering about 800 individual members, coming from both academia and industry, and 40 corporate members. We welcome student as well as professional members. We all know optics/photonics is a very broad and diverse field, covering a wide range of applications, and our organization really reflects this diversity. We are indeed organized through 20 "topical clubs", each of them being focused on a dedicated topic, again, as varied as nanotechnology, guided optics, quantum technology and so on... Each of this club aims at bringing advances in its field and being the vector of technological innovation for various industries. Among their activities, the organization of scientific workshops bringing together the academic and industrial stakeholders of optics and photonics. We also started a few years ago the club "Women & Physics, reaching parity in Optics". This very active club promotes personal and professional growth for women and promotes gender diversity in the field of Optics.

Every even year, SFO has its signature event, the congress "OPTIQUE", which is co-organized with and hosted by a French University, different each time. This congress gathers most or our "topical clubs", and aims at fostering collaboration across the different fields of optics. This congress includes multiple sessions in parallel as well as several plenary sessions with renowned speakers in various field of optics. We have a regular attendance of 500 to 600 participants. After the success of 2018 congress, hosted in Toulouse, we are now organizing 2020 edition in Dijon. We wish this edition the same success as the previous ones, with as many inspiring and enlightening talks.

I truly hope you will enjoy reading this special Photoniques issue.

Pascale Nouchi
President of SFO

OPTIQUE Dijon 2020: save the date!

From July 7 to 10, 2020, Dijon will be the showcase for the flagship congress of the French Optical Society SFO, which will highlight the richness and vigour of all optical sectors in France. OPTIQUE Dijon 2020 will provide a global vision of cutting-edge research from the fundamental to the applied, industrial developments and pedagogical innovations. An essential moment for fruitful exchanges in a friendly atmosphere.

OPTIQUE Dijon 2020 will include several plenary lectures by invited speakers, associated with several thematic conferences and poster sessions. In addition to scientific presentations, a session devoted to relations with industry and an educational session will also provide fertile ground for exchanges. An exhibition area for photonics industry, including start-ups, will be set up at the heart of the congress. Thus a wide range of optical technologies ranging from components to complete systems will be presented to meet the needs of fundamental research and industrial applications.

In symbiosis with the commission "Women and Physics, achieve parity in optics" the congress aims to propose solutions to increase the number of women working in optics, at all responsibility levels. OPTIQUE Dijon 2020 aims to ensure that half of invited conferences (plenary and thematic) are given by women. Some conferences will be open free of charge to undergraduate and master students. An essential feature of this optics congress is that any PhD student can participate at least once during her/his thesis, without the financial obstacle can be invoked. Our goal is therefore to keep costs as low as possible. In order to perpetuate this peculiarity the organization of OPTIQUE Dijon 2020 involves the use of the

Village of Pernand Vergelesses, with the vineyard of Corton Charlemagne on the hillside to the right, on the famous Butte de Corton. (Credit: Guy Millot)

infrastructures of the Dijon campus.

The local organising committee orchestrated by Guy Millot will do its utmost to welcome participants under the best conditions. It is made up of members of the partner structures, in particular the ICB laboratory in Dijon and the FEMTO-ST institute in Besançon. Attending the congress will allow you to meet all the main national players in science and industry. So see you at the Faculty of Sciences on the Dijon campus at the beginning of July 2020!
www.sfoptique.org

The 2019 JNOG invest Paris-Saclay in July 2019

For their 39th edition, the JNOG (Journées Nationales d'Optique Guidée) will take place from 2 to 4 July 2019 at the Centre de Nanosciences et de Nanotechnologies (C2N) on the Paris-Saclay campus.

The "First French Symposium on Monomode Transmissions" in 1980 brought together about fifteen participants at Issy les Moulineaux, with the objective of "ensuring a rapid exchange and dissemination of information on single mode optical fibres at the French level". This symposium was then renewed annually until 1984 when it became the "Journées Nationales d'Optique Guidée (JNOG)" to reflect the growing expansion of the themes addressed. since then, the JNOG has brought together the French-speaking guided optics community annually in a friendly atmosphere around optical telecommunications, integrated optics, fibre or integrated lasers, sensors and optical instrumentation. The JNOG strongly encourages the participation of doctoral students and young researchers, who can thus take their first steps as lecturers, as well as exchange with their peers and more experienced researchers.

After the days organized in Limoges (2017) and Toulouse (2018), the JNOG (Journées Nationales d'Optique Guidée) and CFOR (Club Fibres Optiques & Réseaux) clubs have joined their forces to propose a common event for the 39th JNOG programme.
https://jnog2019.sciencesconf.org/

AGENDA

Fiber Links and Frequency Combs
23-26 April 2019 – Les Houches (SFO Thematic School)
High precision physics using an optical fiber link and optical frequency comb.

Photorefractive Photonics and beyond (PR'19)
18-21 June 2019 – Gérardmer (SFO co-sponsored)
The conference PR'19, Photorefractive Photonics and beyond, is the 17th in a series of biennial Topical Meetings that started in Los Angeles (USA) in 1987.

JCOM 2019
7 June 2019 - ENIB-Plouzané (SFO Club conference)
The next annual conference day of the SFO Club "Optique et Micro-ondes" (Optics and microwave) (JCOM 2019) will take place in Brest, jointly organized by ENIB and Lab-STICC.

39th JNOG
2-4 July 2019 - C2N, campus Paris-Saclay (SFO Club conference)
The 2019 JNOG (Guided Optics Days in France) invest Paris-Saclay in July 2019.

SFO conference agenda :
www.sfoptique.org/agenda/

Photonics France
first birthday candle

One year ago today, on 24 April 2018, Photonics France, the French Federation of Photonics was created by the merger between AFOP and CNOP.

Since 1 January 2019, the CNSO association for the promotion and defense of optical security has merged into Photonics France.

With more than 125 members, the network and representation of French photonics is strengthened by bringing together photonics skateholders such as:

- french manufacturing, distribution and service companies,
- companies that use photonics in their processes,
- associations, unions and clubs, clusters such as ALPHA RLH, Photonics Bretagne, Minalogic, Optitec, Microtechniques Cluster, SFO and CLP,
- Research organizations,
- initial and continuing training organizations such as Universities or major schools such as the Graduate School Optics Institute.

Since its creation, Photonics France works with the public authorities to attain much recognition of our sector and defend its interests:

- On 4 June 2018, Photonics France has presented the French Photonics Roadmap to 300 people at the Ministry of Economy,
- through the support of nearly 600 French personalities who signed its petition in September 2018, it defends KET photonics with the French Ministries and with the European Commission.

It federates the photonics community by creating

- coordination between the French associations of the sector,
- a commission for training and employment,
- a France pavilion at major Photonics West and Laser World trade fairs in Munich.

It creates new services for its members by

- creating a new website with many services for its members,
- organizing Business Meetings with application markets identified in its Roadmap,
- providing general terms and conditions of sale,
- providing legal and regulatory services and purchases.

New members in 2018:
a nice display of French Photonic's know-how

Since the creation of Photonics France last April 2018, the Council has welcomed over 20 new members.

Welcome to : Assystem - Curve One - Fibertech - Gaggione - HEF - III-V Lab - Irepa Laser - Iumtek - Laser Conseil - L'Oréal - Minuitune - NKT Photonics - Optosigma - Piseo - Pole Optitec - Polyrise - Pro-Lite Technology - Qiova - Savimex – Silltec.

If your company is based in France (head office, subsidiary...) and you are interested in joining us, don't wait any longer and contact us!

A single France Pavilion for Laser World of Photonics

June 24 to 27, Munich

LASER World of PHOTONICS

On the occasion of Laser World of Photonics Munich 2019, to be held on June 24 to 27, Photonics France, ALPHA - Route des Lasers & Hyperfréquences, Photonics Bretagne, Minalogic, Optitec and Business France offer to share a single and common French pavilion!

In an area of 370 m² spread over 4 islands, many exhibitors will provide information about their technologies and know-how.

Come and meet us at Hall B3 and learn about companies: Alphanov - ALPHA-RLH - Cristal Laser - Curve One - Electronic Development Normandy - Evosens - Femto Easy - Fichou - Irisiome - ISP System - Ixblue - Kerdry - Minalogic - Nanotec International - Novae - Photonics Bretagne - Piseo - Pyla - Qiova - Savimex - Symetrie.

SPIE PHOTONICS EUROPE: SAVE THE DATE FOR THE FRENCH PAVILION!

March 29 to April 2, 2020, Strasbourg

SPIE. PHOTONICS EUROPE

Photonics France and its members have selected SPIE Photonics Europe to represent French photonics in 2020 with the ambition to make it THE French photonics show to be held every two years, alternating with Laser World of Photonics Munich.

After the successful France pavilion in 2018 with 34 participating organizations – associations and manufacturers – Photonics France with French clusters will again propose, for this new edition, advantageous rates, access to the single France pavilion and greater visibility.

For more information, please contact us!

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EOSAM 2018 was a great success

The EOS Biennial Meeting (EOSAM), a major international event for the European optics and photonics community, was held in the congress center of TUDelft in Delft, Netherlands, 8-12 October 2018. With a full week of interesting optics and photonics presentations in its 9 Topical Meetings (TOMs), a Grand Challenges of Photonics Session, EU project dissemination session, tutorials and workshops, industrial exhibition, as well as networking and social events, the EOSAM 2018 was a great success. An exhibition with 20 exhibitors was nicely bridging the gap between science and industry. With over 400 participants from over 30 countries, 5 days of scientific, industrial and social program, and around 350 presentations, EOSAM was a great success.

Organized already for the third time at EOSAM, tutorials dealing with the topics of the TOMs, interested not only students but also other attendees. EOS plans to continue organizing these popular tutorials also in future EOSAM events. Several student presentations

were held during the week. From these very high quality presentations the award committee had a difficult task to choose the best student oral and poster presentation. These awards, sponsored by Carl Zeiss, went to Anne de Beurs (Vrije Universiteit Amsterdam), and to Kévin Cognée (Institut d'Optique d'Aquitaine).

On Wednesday, the EOS Annual General Assembly and the ceremony for the new EOS Fellows was held after the scientific program. The new EOS Fellows are Luc Bergé, Trevor Benson, Riad Haidar, Juan Ariel Levenson, Pedro Andrés Bou, and Ralf Bergmann. Congratulations to all the Fellows! The new compositions of the EOS Board and the Executive committee can be found on EOS website: www.europeanoptics.org

To bring research closer to industry, EOSAM included an Industrial exhibition, and industrial posters that highlight the know-how of the companies, and a "Meet and Greet" networking event organized for students and companies (hosted by TNO).

EOSAM will be held next in Porto, Portugal in September 2020. We hope to see you there!

More information on the event will be published soon on the EOS website www.europeanoptics.org.

Elina Koistinen
EOS Executive Director

EOS fighting for the status of KET Photonics in Europe

The EOS has sent a letter to the Commissioner of the Digital Economy and Society in Europe, expressing concerns about the European Commission's funding decisions. Within the forthcoming European research framework program Horizon Europe, KET Photonics (started in 2009) is not listed among the nine priority technological intervention areas in Europe. This would mean that the funding for Photonics in H2020 would no longer be certain and Photonics Public-Private-Partnership would not be renewed. The EOS is not alone in these concerns, and many others have also reached out to make a change (including Nobel laureates).There are also other exciting things planned, among others, a "Meet and Greet" for companies and students.

More information on the event website: www.myeos.org/events/eosam2018

EOS has a new look – check out the website

The EOS renewed its look beginning of 2019. The website received a new domain, and the look was refreshed. Now you can find us and the European Optics platform here:
https://www.europeanoptics.org/

Joining EOS as an individual member is easy through the website system. Individual membership is 50 € for the year (only 10 € for students) and includes some amazing benefits and discounts on events (not only EOS organized but also EOS co-sponsored).

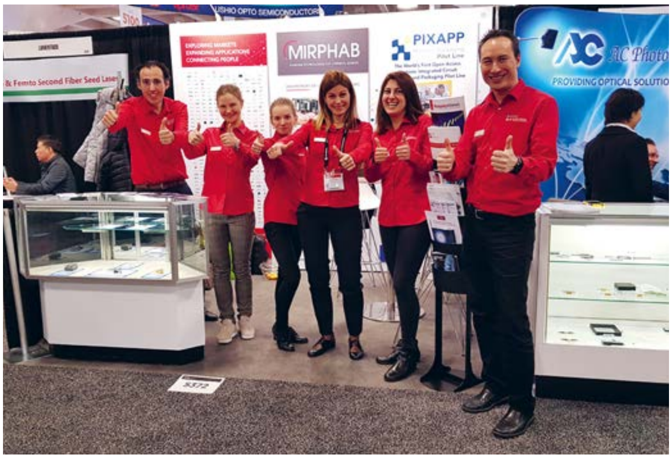
UPCOMING EOS EVENTS IN 2019 – SAVE THE DATES!

- EOS Optical Technologies Conferences in Munich, Germany, 24-26 June 2019, including
  - 6th Conference on Manufacturing, Tolerancing and Testing of Optical Systems
  - 5th Conference on Optofluidics
- Topical Meeting on Diffractive Optics in Jena, Germany, 16-20 September 2019
- Topical Meeting on Integrated Optics in Joensuu, Finland, 26-28 November 2019

More about the events:
https://www.europeanoptics.org/events/eos/

EPIC at Photonics West 2019

EPIC was actively present at Photonics West 2019 organising range of networking events and activities for EPIC members including, golf, running, reception and breakfast, a Tech Watch in conjunction with SWISS Photonics and a technology breakfast for the photonics manufacturing Pilot Lines (PIXAPP, MIRPHAB, InPulse, and PIX4life). We interviewed a photonics leader, Michael Lebby, and we also exhibited and visited the show floor.



EPIC VIP Networking Reception took place on the evening of 4 February in San Francisco Museum of Modern Art. This was a purely networking event to enable more than 270 CEOs/CTOs/Presidents/Managing Directors of photonic companies around the world to network in a relaxed atmosphere. Members enjoyed creating new connections and strengthening existing ones against the background of a live jazz band and great food.

EPIC Tech Watch in conjunction with SWISSphotonics took place on the afternoon of February 4th at the SWISSnex building om Pier 17 in San Francisco. There were 12 short, interesting presentations by Swiss EPIC member companies. The event attracted a top level audience from across Europe and USA with ample time for discussion and networking.

A technology breakfast was also held on 5th February for the photonics manufacturing Pilot Lines (PIXAPP, MIRPHAB, InPulse, and PIX4life), before the Photonics West show started.

The traditional **EPIC 5 Miles Executive Run** was organised for the early morning on 6 February at the San Francisco water front. It was a great success as we managed to bring together at 6:30 am around sixty C-level officers from photonic companies to network and build friendships by running and walking together. After the event, participants had the chance to share a recovery breakfast.

UPCOMING EPIC EVENTS

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

- 31 March - 3 April 2019: **EPIC Delegation to Israel**
- 11-12 April 2019: **EPIC Annual General Meeting, Glasgow, United Kingdom**
- 2-3 May 2019: **EPIC Executive Meeting on Industrial Lasers at Coherent, Göttingen, Germany**
- 23-24 May 2019: **EPIC Meeting on Automation Tools for Manufacturing at Amicra, Regensburg, Germany**
- 5-6 June 2019: **EPIC World Industrial Quantum Photonics Technology Summit at ICFO, Barcelona, Spain**

Find out about upcoming EPIC events on www.epic-assoc.com/epic-events

Optitec competitive cluster

French photonics delegation to Singapore in October 2018.

Optitec is a competitive cluster that has been dedicated to deep tech photonics and imaging for over 15 years. It hosts an ecosystem of 220 actors, from industry professionals to research institutions and training organisations. The cluster strives to promote and support disruptive innovations, sources of wealth creation and employment.

Based in Provence-Alpes-Côte-d'Azur and Occitania in the south of France, Optitec also maintains an office in Brussels. Its fundamental mission as a competitive cluster is to support the industry's innovation dynamics so that it is an engine for growth.

Renowned for the quality of services it provides to its network of companies, Optitec assists them in their development, R&D, funding, intellectual property and export strategies. A proven impetus in project leadership, the cluster assists the whole value chain in a bid to transform R&D in industrial and economic opportunities for businesses.

Optitec is the only cluster to propose a comprehensive photonics and imaging solution spanning across 5 strategic business areas within the following high-growth markets: defence and security, health and life science, smart cities and mobility, industries 4.0 and digital agriculture.

The Optitec Cluster asserts its European standing via:

- the presence of a full-time representative in Brussels to actively monitor and guide SMEs on Horizon 2020 programmes;
- managing European projects:
  - the EPRISE project 'Empowering Photonics through Regional Innovation Strategies in Europe' to promote and support the European photonics industry by focusing on three fields of application: medical, pharmaceutical, and agriculture and food;
  - the KETs4DualUse project, within the framework of the European programme COSME, which aims to implement a partnership with European clusters in order to facilitate access to international security and defence markets for European SMEs;
- launching the 'Optitec2Bruxelles' collective initiative designed to help innovative SMEs in the field of photonics and imaging orientate and position themselves at European level, with the aim of maximising their chances of involvement in European projects.

OPTITEC signs Memorandum of Understanding with Lux Photonics Consortium from Singapore

Optitec Cluster has signed a Memorandum of Understanding (MoU) with Lux Photonics Consortium from Singapore. Preliminary discussions about collaboration between the two organisations were initiated during the visit of French photonics delegation to Singapore in October 2018, followed by the official signature in February 2019. The document represents a first step towards a closer international collaboration between the members of Lux and OPTITEC.

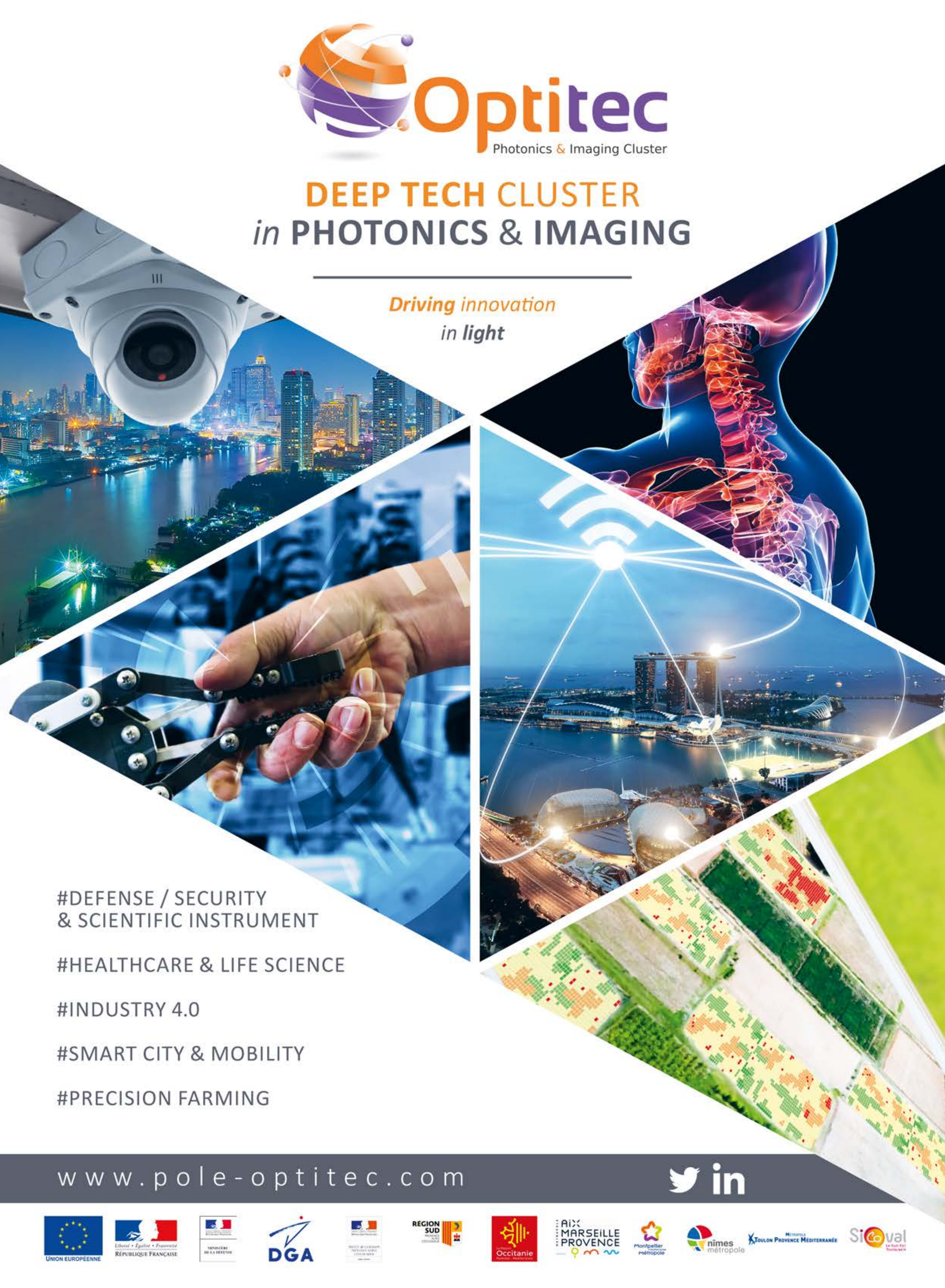
Learn more about OPTITEC:
http://www.pole-optitec.com/en
Learn more about Lux Photonics Consortium:
http://luxphotonicsconsortium-sg.org/

WE WILL ATTEND THE FOLLOWING EVENTS, PLEASE CONTACT US TO JOIN OUR BUSINESS TEAM!

- **25th April 2019** | Réalité virtuelle & augmentée : une vision techno et marché à 360°, Marseille - France

- **24 to 27 June 2019** | Laser World of Photonics, Munich - Germany
- **24 to 26 September 2019** | Measurement World, Paris - France
- **19 to 22 November 2019** | Milipol, Paris - France

contact@pole-optitec.com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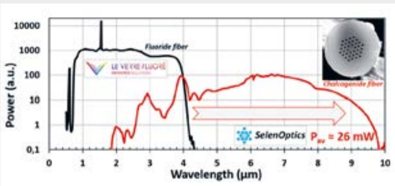
Photonics Bretagne at Photonics West exhibition in San-Francisco, February 2-7

Another successful year for Photonics Bretagne and its 17 members present at Photonics West! Co-exhibiting this year on the French pavilion with its new member ELDIM, Photonics Bretagne has presented the latest developments of its technology platform with new types of Photonic Crystal fibres but also represented its cluster members during the visit of Intel facility in Santa Clara and the different networking events organised during the week in SF (EPIC, Quebec, CEA-LETI, SPIE, PW welcome reception...). Photonics Bretagne also co-financed with Business France and other French clusters present in PW the traditional cocktail on the French Pavilion which was a great occasion to network and promote the French companies in a relaxed atmosphere.

Toward 10 µm supercontinuum source commercialization



After several months of development, Le Verre Fluoré and Selenoptics are proud to introduce their last results: supercontinuum source emitting up to 9.8 µm. The association of high quality fluorozirconate fibres and microstructured chalcogenide fibres made it possible to obtain a supercontinuum broadening up to 9.8 µm with a corresponding output average of 26 mW. Covering a large part of the fingerprinting region and of the atmospheric transparency windows (3-5 and 8-13 µm), this laser will be used as light source in applications such as multigas sensing, spectroscopy, medical diagnosis... Commercialization of 10 µm supercontinuum source is expected by the end of 2019.

Successful international Business Meeting "Photonics 4 Agri-Food" at CFIA exhibition

In the framework of the European projects NEXTPHO 21 and EPRISE, Photonics Bretagne and Photonics France co-organized a business meeting "Photonics 4 Agri-Food" on March 13 at the CFIA (largest "Tech for agri-food" exhibition in France) in Rennes (Brittany). After an introduction by Tematys to understand issues of the sector, Wageningen University, Roullier Group, d'Aucy Group, Nestec (the R&D center of Nestlé), and CTCPA presented their needs about food safety, raw material control, packaging, conditioning and preservation, and real-time process monitoring. Then, 5 photonics providers (Greentropism, Idil Fibres Optiques, Indatech, Photon Lines and New Vision Technologies) pitched about their innovative technologies. The 50 attendees exchanged further during the networking lunch and BtoB meetings in the afternoon.

Moreover, a visit of the showroom was organized to discover innovative demonstrators on the pavilion "Food Factory of the Future" on which exhibited Photonics Bretagne members: Polytec, Greentropism, Idil Fibres Optiques, Microbs, Institut Maupertuis, CEAtech, E-Mage In 3D, CRT Morlaix, Photon Lines, Bizerba Luceo.

A very successful event which created great opportunities to link agri-food industries and photonics companies!

iXblue and Photonics Bretagne optical fibres available through Photonic E-store

iXblue have just launched an e-store on its website which allows customers to buy specialty optical fibres and associated components online (https://photonics.ixblue.com/e-store). There is most of the products currently sold by Ixblue Photonics classified in 4 categories (Fibers for space & nuclear environments, Lasers & amplifiers fibres, PM/polarizing & spun fibres and Custom fibres & FBGs) but also Photonic Crystal Fibres (PCF) developed by Photonics Bretagne (Product line PERFOS). Both teams stay obviously available to assist customers if a custom solution is needed.

AGENDA

Blueday « sea & light », *May 16, Lorient, France*
A technological day about photonics for sea applications, with conferences and a show-room. Registration will be open soon.

Meeting at Laser World of Photonics, *June 24-27, Munich (Germany), Booth B3.423*
For the first time, Photonics Bretagne and Bretagne Commerce International teams up with Business France and other clusters to create a large French Pavilion including Brittany companies at the Laser World of Photonics exhibition in Munich. More than 25 members of Photonics Bretagne will be exhibiting in Munich with 8 members present on the pavilion: iXblue, Evosens, Idil Fibres Optiques, BKtel Photonics, Cailabs, Kerdry, SelenOptics, Le Verre Fluoré. Meet us booth B3.423 and stay tuned!

General Assembly of Photonics Bretagne and inauguration of its agrophotonics partnership with Arvalis, *July 5, Lannion, France*

ALPHA-RLH accredited for the next four years

The ALPHA-RLH cluster has been selected by the French government in the call for applications process for phase 4 (2019-2022) of its competitiveness cluster initiative.

Boosting its position in Europe is central to this new step, with the aim of developing innovative collaboration projects and seeking European partners and funding. For several years, ALPHA-RLH has been proactive in pursuing an ambitious strategy in Europe to meet its members' needs and position itself as a leading player in the fields of photonics and electronics-microwaves.

The cluster is seeking to extend its reach via European networks and strengthen its international presence through its activities in China and the USA, as well as by the launch of a project to establish representation in Japan. Building on its existing operations, the cluster is prepared to take up the challenge of phase 4, which offers promising opportunities in Europe and worldwide for all the stakeholders in its Nouvelle-Aquitaine ecosystem.

ALPHA-RLH and members target the American market

From 2 to 7 February 2019, the ALPHA-RLH Competitiveness Cluster was in San Francisco with its members at the international BIOS and Photonics West trade fairs dedicated to photonics, lasers and biomedical optics. Ten companies showcased the French expertise in photonics: AA OPTO-ELECTRONIC, ALPhANOV, Amplitude Laser Group, AUREA TECHNOLOGY, Femto Easy, GLOphotonics, Irisiome, Leukos, Novae and Spark Lasers.

In parallel to the Photonics West fair, pitch sessions were organized in partnership with the French Tech Hub in San Francisco and the European project PIMAP during the event "Photonics : trends and applications in the Industry 4.0", and gave the opportunity to Femto Easy and Muquans to promote their technology in front of industrials and investors.

ALPHA-RLH coordinates the European PIMAP project, which brings together clusters from three other countries: Finland, Portugal and Sweden. PIMAP aims to support the integration of photonics and electronic-microwave technology in markets involved in the industry of the future. It promotes the internationalization of companies towards the North American market. The project partners met with major American and Canadian photonics clusters during the Photonics West fair.

SAPHyR: photonics and microwave solutions for aeronautics

SAPHyR
SOLUTIONS PHOTONIQUES ET HYPERFRÉQUENCES POUR L'AÉRONAUTIQUE

SAPHyR (Aeronautical, Photonics and Microwave Systems in the Region) is an ambitious developmental project initiated and led by the ALPHA-RLH cluster and backed by the Nouvelle-Aquitaine region.

SAPHyR brings together players from the research and industrial worlds and develops synergy in order to create a sector based on photonics and microwave solutions for the aeronautics industry. The project was launched in 2017 and is set to reach an important milestone by presenting ten innovative technology prototypes at the International Paris Air Show, to be held in Paris Le Bourget from 17 to 23 June 2019.

ALPHA-RLH appoints a European-International Manager

Isabelle Tovena Pécault holds an engineering doctorate in material sciences and technology and has worked at the CEA (French Alternative Energies and Atomic Energy Commission) for 26 years. She is an international expert in the field of cleanrooms and contamination control. In 2016, she completed an executive education program in innovation and startup management at HEC. Isabelle joins the team as International and European Project Manager and will be contributing to extending the international scope of the ALPHA-RLH cluster's activity.

At the European level, she will lead the development of R&D projects, participate in the Europe Commission of the Association Française des Pôles de Compétitivité, and support inter-cluster cooperation (PIMAP European project). At the international level, she will be responsible for overseeing projects in China and the US, as well as the future project in Japan.

UPCOMING INTERNATIONAL EVENTS

- **International Microwave Symposium (IMS)**
  June 3-7, 2019 in Boston (USA)
- **International Paris Air Show**
  June 17-21, 2019
  Paris Le Bourget (France)
- **Laser World of Photonics**
  June 24-27, 2019 in Munich (Germany)
- **European Microwave Week (EuMW)**
  September 30 - October 4, 2019 in Paris (France)

Nanometa 2019

The 7th International Topical Meeting on Nanophotonics and Metamaterials was organized at Seefeld (Austria) from January 3rd to 6th and gathered 242 presentations over the 4 days including 5 plenary, 2 breakthrough, 58 invited including 5 upgrades, 36 oral contributions, 2 technology talks and 139 posters from 21 different countries.

NANOMETA 2019 aims to bring together the international Nanotechnology, Photonics and Materials research communities where most recent and challenging results and plans are discussed in the informal setting of Seefeld, which is a major ski resort in the heart of the Tyrol Mountains, Austria, at the centre of untouched nature.

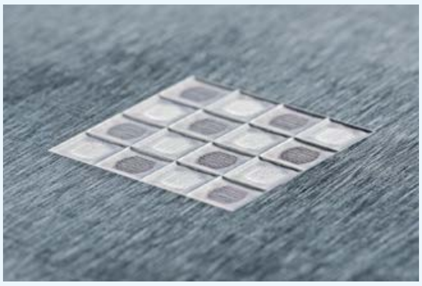
The conference covered a large area of hot topics of nanophotonics and plasmonics including: Quantum Nanophotonics, Chiral Sensing, Opto Nanomechanics, Active Plasmonics and Novel Phenomena, 2D & Topological Materials, Nano Optics and Electronics, Strong Coupling and Chemical Plasmonics, Atomic Nanophotonics, Ultrafast and Nonlinear as well as Metamaterials and Hot Carriers.

During this conference, the 4th Prize for Research into the Science of Light, on behalf of the European Physical Society through its Quantum Electronics & Optics Division (QEOD), was awarded to Professor Javier García de Abajo, ICFO-Institut de Ciencies Fotoniques, Castelldefels (Barcelona), Spain for *"pioneering contributions to the understanding of the behavior of light at the nanoscale, in particular in plasmons and in light interactions with free electrons"*.

A. Boudrioua

Making ultrafast lasers faster

Lasers with ultrashort pulses in the picosecond and femtosecond range are known for their ultra-precise ablation and cutting results. A consortium of six partners from industry and research is planning the next step in the development of the USP-laser process technology. They will develop a powerful 1 kW laser source and combine it with a special optical system that delivers a pattern of more than 60 switchable beamlets. One can see this as a late descendant of the dot-matrix printer.



Surface textures on tool steel fabricated by means of ultrafast laser radiation. © Fraunhofer ILT, Aachen, Germany.

The consortium consists of the research institute Fraunhofer ILT and the RWTH Aachen University from Germany as well as Amplitude Systèmes, LASEA France, AA Opto-Electronic from France and LASEA from Belgium as industrial research and development partners. The European Commission is supporting the project, named “MultiFlex”, within the framework of the program ICT-04-2018 for three years with an amount of € 4.7 million.

The partners intend to deliver a prototype with all the necessary control technology ready for the shop floor. It will start with a 1 kW laser machine that can deliver up to 1 mJ pulse energy either at the regular 1 MHz repetition rate or in a burst mode with less than 20 ns pulse separation. It has already been estimated that the prototype will improve the productivity by about 100 fold compared to current standard ultrafast laser processing systems.

ALPAO is in the ranking of the 500 French growth champions

On February 8, 2019, the business newspaper Les Echos announced the ranking of the 500 French growth champions. This survey lists the companies whose turnover grew the most between 2014 and 2017. ALPAO, who specializes in adaptive optics and wavefront control, is part of this ranking and positions itself on the podium of Isere companies thanks to an increase in its turnover of +107% over this period.
https://doi.org/10.1021/acs.nanolett.7b05351

SUSS MicroOptics bets on freeform optics

SUSS MicroOptics is setting up an excellence center for the manufacturing of wafer-level optics (WLO) in order to meet the increase in demand for precision optics applications. According to the company, high volume applications in consumer markets especially in automotive, mobile phones, lighting and high-end cameras have emerged.

The excellence center will be part of 800 m^2 of new cleanroom space currently build in Neuchâtel and certified for the main markets targeted by SUSS MicroOptics. The goal is to enable volume manufacturing from pilot production all the way to high-volume production in Europe and in particular in the city of Neuchâtel, Switzerland, famous for its watches manufacturing facilities.

Dr. Rolando Ferrini, Section Head MicroNano Optics & Photonics at CSEM has been appointed in charge of linking wafer-level R&D lines to volume manufacturing, explains: *“finding synergies between the huge technological developments in wafer-level micro-optics, which have happened in Europe in the last decade, mostly funded by European H2020 grants and regional funds, positions today Europe as a leader in bringing freeform micro-optics to higher volumes: it is now or never to create volume manufacturing capabilities in Europe in this strategic field, which is foreseen to have strong impact in several application domains.”*

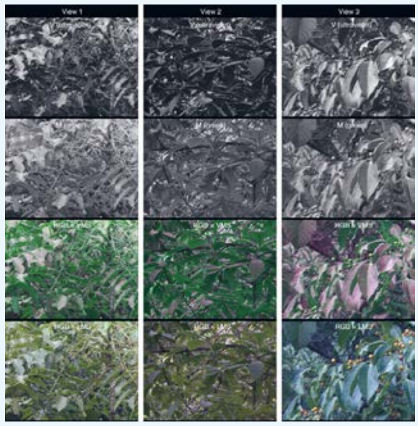
Unique camera to see the world the way birds do

Human colour vision is based on three primary colours: red, green and blue. The colour vision of birds is based on the same three colours – but also ultraviolet. Biologists at Lund University in Sweden have shown that the fourth primary colour of birds, ultraviolet, means that they see the world in a completely different way.

This was achieved with the help of a unique camera and advanced calculations. The camera was designed within the Lund Vision Group and equipped with rotating filter wheels and specially manufactured filters. The camera imitates with a high degree of accuracy the colour sensitivity of the four different types of cones in bird retinas.

Among other things, birds see contrasts in dense forest foliage, whereas people only see a wall of green. For birds, the upper sides of leaves appear much lighter in ultraviolet. From below, the leaves are very dark. In this way the three-dimensional structure of dense foliage is obvious to birds. This in turn makes it easy for them to move, find food and navigate.

C. Tedore, *Nature Communications*, https://doi.org/10.1038/s41467-018-08142-5



C. Tedore, Nature Communications, Creative Commons Attribution 4.0 International License, http://creativecommons.org/licenses/by/4.0/

The amazing progress of high-power ultrafast thin-disk lasers

An old thought experiment now appears in a new light. In 1935 Erwin Schrödinger formulated a thought experiment designed to capture the paradoxical nature of quantum physics. A group of researchers led by Gerhard Rempe, Director of the Department of Quantum Dynamics at the Max Planck Institute of Quantum Optics, has now realized an optical version of Schrödinger's thought experiment in the laboratory. In this instance, the superposition of two states of an optical pulse serves as the cat.

Ultrafast lasers continue to be at the forefront of many scientific breakthroughs and technological achievements and progress in the performance of these systems continues to open doors in many new and exciting interdisciplinary fields of research. In the last decades, the average power of ultrafast lasers has seen exponential increase, opening up exciting new perspectives. Among the different technologies that have shaped these advances, thin-disk lasers have generated particularly spectacular breakthroughs, nowadays exceeding the kilowatt average power with pulse energy levels of hundreds of millijoules. In their work, the authors review the latest state-of-the-art of the technology and highlight new application fields of these cutting-edge laser systems.

C.J. Saraceno et al., Congrès SFO Toulouse 2018 (to be published in JEOS:RP, 2019)
clara.saraceno@ruhr-uni-bochum.de

IR imaging: a promising tool for early cancer diagnostic

Sébastien Février, researcher at XLIM (CNRS/Université de Limoges), and his team demonstrated that a bench-top, optical fibre-based laser source can be used to perform infrared spectromicroscopy with a precision rivaling, and in some regards even surpassing, that of experiments at large-scale synchrotron facilities.

Synchrotrons are accelerator facilities that provide powerful infrared light used for analyzing the chemical content of biological tissues with micrometer scale resolution. This high precision chemical imaging technique enables an early diagnosis of pathologies such as cirrhosis and cancer. However, up to now, the very high cost of ownership and limited availability of synchrotron sources has hindered the deployment of chemical imaging technique in the hospital.

Replacing the synchrotron with a compact laser source could unleash the potential of this technique and ease its implementation in the hospital, thus accelerating access to diagnosis and treatment.

The demonstration involved a consortium including researchers from XLIM and the synchrotron Soleil in Saclay as well as engineers from the company Novae, a start-up founded in 2013 by researchers from the University of Limoges. Novae targets industrial and scientific markets such as laser-based bio-imaging and materials micro-processing. The infrared laser is now part of Novae's portfolio of products.

F. Borondics et al., Optica (2018), https://doi.org/10.1364/OPTICA.5.000378

Laser physics pioneers awarded Nobel Prize in Physics

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2018 *"for groundbreaking inventions in the field of laser physics"*, with one half to Arthur Ashkin (Bell Laboratories, Holmdel, USA) and the other half jointly to Gérard Mourou (École polytechnique, Palaiseau, France; University of Michigan, Ann Arbor, USA) and Donna Strickland (University of Waterloo, Canada).

Gérard Mourou - Donna Strickland © Nobel Media AB

Arthur Ashkin invented optical tweezers that grab particles, atoms, viruses and other living cells with their laser beam fingers. This new tool allowed Ashkin to get laser light to push small particles towards the centre of the beam and to hold them there. Optical tweezers had been invented. A major breakthrough came in 1987, when Ashkin used the tweezers to capture living bacteria without harming them. He immediately began studying biological systems and optical tweezers are now widely used to investigate the machinery of life.

Gérard Mourou and **Donna Strickland** paved the way towards the shortest and most intense laser pulses ever created by mankind. Their revolutionary article was published in 1985 and was the foundation of Strickland's doctoral thesis. Using an ingenious approach, they succeeded in creating ultrashort high-intensity laser pulses without destroying the amplifying material. First they stretched the laser pulses in time to reduce their peak power, then amplified them, and finally compressed them. If a pulse is compressed in time and becomes shorter, then more light is packed together in the same tiny space – the intensity of the pulse increases dramatically.

Strickland and Mourou's newly invented technique, called *chirped pulse amplification*, CPA, soon became standard for subsequent high-intensity lasers. Its uses include the millions of corrective eye surgeries that are conducted every year using the sharpest of laser beams.

MORE INFORMATION:
www.nobelprize.org

Flying optical cats for quantum communication

An old thought experiment now appears in a new light. In 1935 Erwin Schrödinger formulated a thought experiment designed to capture the paradoxical nature of quantum physics. A group of researchers led by Gerhard Rempe, Director of the Department of Quantum Dynamics at the Max Planck Institute of Quantum Optics, has now realized an optical version of Schrödinger's thought experiment in the laboratory. In this instance, pulses of laser light play the role of the cat. The insights gained from the project open up new prospects for enhanced control of optical states, that can in the future be used for quantum communications.

"According to Schrödinger's idea, it is possible for a microscopic particle, such as a single atom, to exist in two different states at once. This is called a superposition. Moreover, when such a particle interacts with a macroscopic object, they can become 'entangled', and the macroscopic object may end up in superposition state. Schrödinger proposed the example of a cat, which can be both dead and alive, depending on whether or not a radioactive atom has decayed – a notion which is in obvious conflict with our everyday experience," Professor Rempe explains.

In order to realize this philosophical gedanken experiment in the laboratory, physicists have turned to various model systems. The one implemented in this instance follows a scheme proposed by the theoreticians Wang and Duan in 2005. Here, the superposition of two states of an optical pulse serves as the cat. The experimental techniques required to implement this proposal – in particular an optical resonator – have been developed in Rempe's group over the past few years.

A test for the scope of quantum mechanics

The researchers involved in the project were initially skeptical as to whether it would be possible to generate and reliably detect such quantum mechanically entangled cat states with the available technology. The major difficulty lay in the need to minimize optical losses in their experiment. Once this was achieved, all measurements were found to confirm Schrödinger's prediction. The experiment allows the scientists to explore the scope of application of quantum mechanics and to develop new techniques for quantum communication.

The laboratory at the Max Planck Institute in Garching is equipped with all the tools necessary to perform state-of-the-art experiments in quantum optics. A vacuum chamber and high-precision lasers are used to isolate a single atom and manipulate its state. At the core of the set-up is an optical resonator, consisting of two mirrors separated by a slit only 0.5 mm wide, where an atom can be trapped. A laser pulse is fed into the resonator and reflected, and thereby interacts with the atom. As a result, the reflected light gets entangled with the atom. By performing a suitable measurement on the atom, the optical pulse can be prepared in a superposition state, just like that of Schrödinger's cat. One special feature of the experiment is that the entangled states can be generated deterministically. In other words, a cat state is produced in every trial.

"We have succeeded in generating flying optical cat states, and demonstrated that they behave in accordance with the predictions of quantum mechanics. These findings prove that our method for creating cat states works, and allowed us to explore the essential parameters," says PhD student Stephan Welte.

A whole zoo of states for future quantum communication

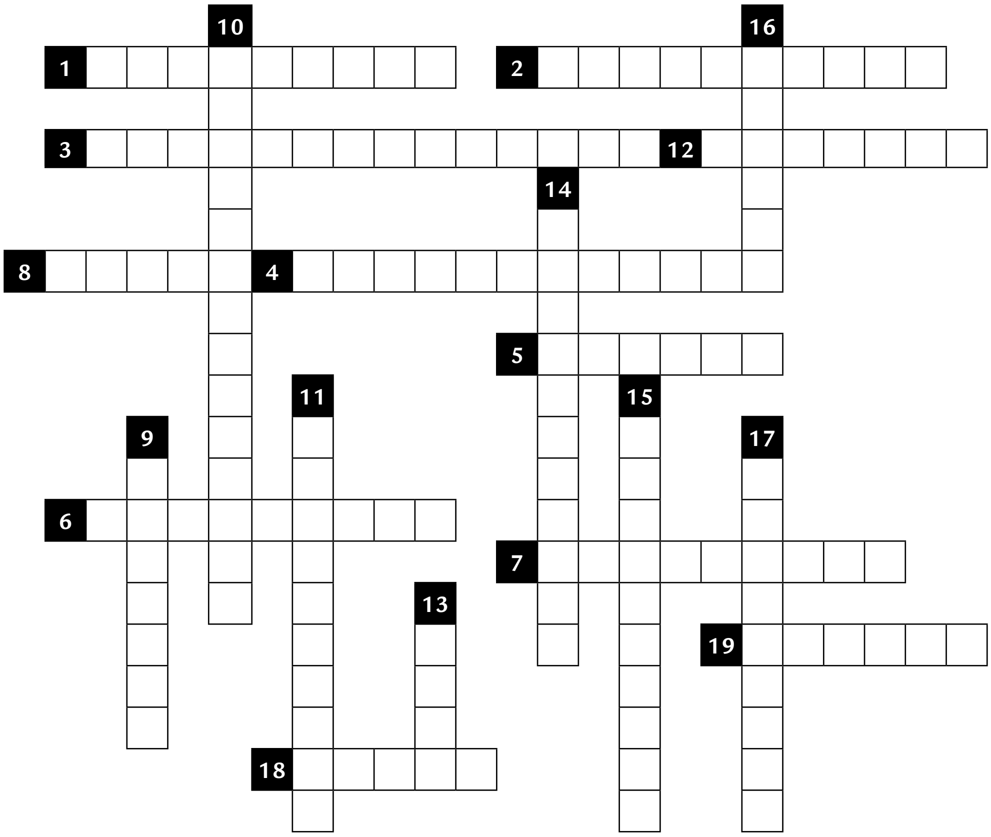
"In our experimental setup, we have succeeded not only in creating one specific cat state, but arbitrarily many such states with different superposition phases – a whole zoo, so to speak. This capability could in the future be utilized to encode quantum information," adds Bastian Hacker.

"Schrödinger's cat was originally enclosed in a box to avoid any interaction with the environment. Our optical cat states are not enclosed in a box. They propagate freely in space. Yet they remain isolated from the environment and retain their properties over long distances. In the future we could use this technology to construct quantum networks, in which flying optical cat states transmit information," says Gerhard Rempe. This underlines the significance of his group's latest achievement.

Bastian Hacker *et al.*, *Nature Photonics* (2019), https://doi.org/10.1038/s41566-018-0339-5

ADVERTISER INDEX

CROSSWORDS: OPTICAL COMPONENTS AND DEVICES



1 The king of focus
2 For angle measurements
3 Making beautiful fringes
4 Spread!
5 Beware: sharp optics!
6 One floor up
7 To bring stars closer
8 Travelling through the oceans
9 A well combed hair…
10 Fast modulation
11 Seeing larger
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Augustin Fresnel and the wave theory of light

Jean-Louis BASDEVANT
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jean-louis.basdevant@polytechnique.edu

Augustin Fresnel was born in 1788, in the Normandy village of Broglie where his father was employed as an architect by the duc de Broglie. The author of the wave theory of light was thus born on lands that would later belong to Louis de Broglie, the author of the wave theory of matter, whose birth came a century later. Fresnel's work was accomplished in less than a decade[1].

Augustin Jean Fresnel in 1825. Drawing and engraving by Ambroise Tardieu. *(Credit: Paris Observatory)*

To escape the tumult of the French Revolution, his family withdrew to their house in Mathieu, near Caen. Augustin was not interested in literature, but his teachers and schoolmates were fascinated by his practical ingenuity and mathematical prowess. After completing his high-school education in Caen, he was admitted to the École polytechnique in 1804, a year after his brother Louis, and 3 years before his younger brother Léonor.

Fresnel's talent was noticed by his professors, Monge, Poisson and Legendre. After graduating, he joined the Department of Civil Engineering and began a career as an engineer in 1809, working on a new road network.

An ever-inquiring mind

Fresnel was inexorably drawn to fundamental science, and in 1814 started to ponder the nature of light. Was it corpuscular – the view imposed by the towering figure of Newton – or wave-like?

His interest had been sparked by reading a newspaper article. On May 15th 1814, he wrote to his brother Léonor that "*I saw in* Le Moniteur *a few months ago that Biot presented a very interesting paper to the Academy of Sciences on the polarization of light. I have tried hard, but I cannot figure out what that is*". Determined to find answers to questions his professors had never explored, he asked his brother to send him some books. However, in a letter sent a year later on July 12th, his friend and protector Arago admitted that *"I do not know of any book that describes all the experiments on light. Mr Fresnel can only acquaint himself with that part of optics by reading the works of Grimaldi and Newton, and the memoirs of Brougham and Young."* A frustrated Fresnel replied on September 23rd 1815 that, *"as for the work of Young, I had a strong urge to read it, but I don't know English, so I can only understand it with the help of my younger brother. When he is not here, the book becomes unintelligible to me."* Fresnel did not suspect that he would end up writing the book he had wanted to read.

Fresnel's early works

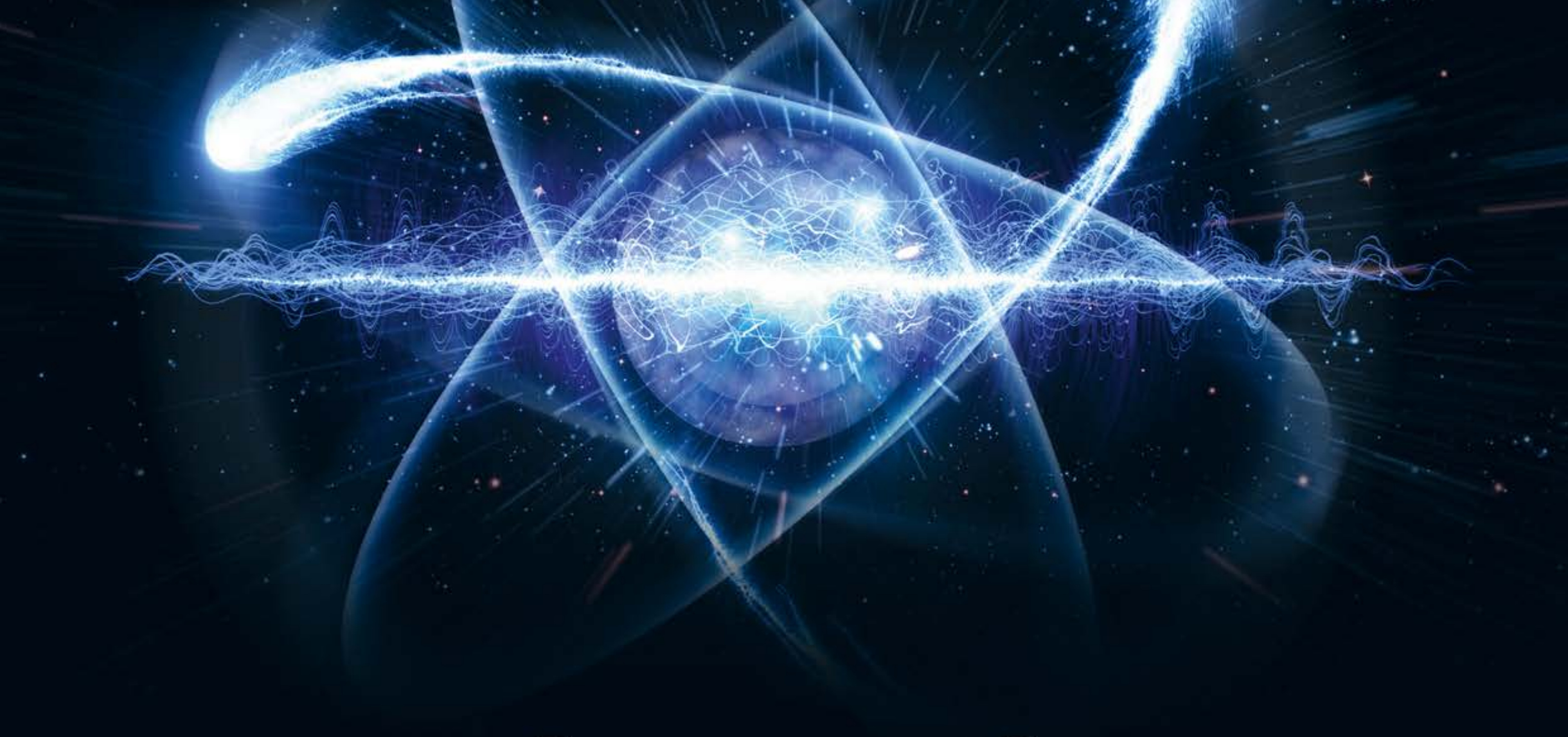
Thomas Young (1773-1829), who performed his famous interference experiment in 1802, was the first to criticize Newton's ideas, and to suggest revisiting Huygens' wave theory of light. However, as we have seen, Fresnel was not initially aware of Young's research, and indeed was largely ignorant of most of the relevant theories. It is not even clear he knew about Huygens' theory when he started his investigations.

Napoleon's return from exile on the island of Elba was to give Fresnel the opportunity he needed to work on his ideas! Like many of his companions, he publicly rose up against the Emperor, calling the Hundred Days *"an attack on civilization"*. Suspended by the Civil Engineering Department (he was reinstated in July 1815, after Waterloo) and placed under police surveillance, Fresnel duly returned to the family home in Mathieu and dedicated his enforced leisure to his thoughts about light.

Fresnel initially studied diffraction, using improvised equipment to explore the shadow of a narrow wire lit by a ray of sunshine. He noticed that with a magnifying glass, he could observe and measure the diffraction fringes with a high degree of precision. Interestingly, the error estimates Fresnel gave in his articles allowed Jed Z. Buchwald to determine Fresnel's exact visual acuity[2]!

[1] A full and remarkable account of Fresnel's discoveries, his central role, and the contributions of his colleagues is provided by J. Z. Buchwald in *The Rise of the Wave Theory of Light*, The University of Chicago Press, 1984; 498 pages.
[2] J.Z. Buchwald, Op. cit., page 124.

https://doi.org/10.1051/photon/2019S418



The history of ideas in optics

One of the major questions in optics arose from the observation of light rays. These only appear when light is partially screened out, and yet light seems to be a medium in which the whole world is bathed. The concept of light rays is fundamental, but how can they be explained?

Published in 1704, Newton's *Opticks: or, A Treatise of the Reflexions, Refractions, Inflexions and Colours of Light* was regarded as the authoritative work on the subject throughout the 18th century. In it, Newton set out his *corpuscular or emission theory*, whereby light consists of molecules emitted by luminous bodies. This idea explained rays of light, insofar as these corpuscles were said to travel in straight lines. Newton was familiar with interference phenomena, but discounted the wave theory of light, claiming that interference came from interactions between the molecules and matter.

However, there had previously been two important observations. Diffraction had been discovered by Francesco Maria Grimaldi, who drilled a small hole in a window shutter and observed that, instead of a small dot, a ray of sunshine produced a pool of light reminiscent of the surface of a stream. In his treatise *Physicomathesis de lumine*, posthumously published in 1665, he concluded that *"light is a substance that may travel in waves"*. The other observation, which dated back to the Vikings, concerned the birefringence of Iceland spar (some crystals split light into two rays!), analyzed by Erasmus Bartholin in 1669.

At around the same time, Christiaan Huygens (1629-1695) was putting forward some remarkable ideas, drawing analogies with mechanical vibrations in order to construct a wave theory of light, whereby each point of a wave front is the source of spherical wavelets whose envelope then determines the wave front at a later instant. He could explain the Snell-Descartes law of refraction, but not the existence of light rays. His triumph was the explanation of double refraction with a molecular model for an anisotropic medium. However, Huygens was completely overshadowed by Newton and only brought back into favor by Fresnel.

In order to refute Newton's assumption of an interaction between the wire and the molecules of light, Fresnel put a screen on one side of the wire and reported that *"I at once had the following thought: since intercepting the light from one side of the wire makes the internal fringes disappear, the concurrence of the rays that arrive from both sides is therefore necessary to produce them."* A few years later, Arago dubbed this concurrence *interference*, based on the principle established by Young. It was this interference that explained the dark fringes: *"The vibrations of two rays that cross each other at a very small angle can contradict each other when the crest of one corresponds to the trough of the other"*.

Fresnel pursued his experiments between 1814 and 1818, introducing the notion of wavelengths, exploiting the Huygens principle, and formulating the mathematical framework for calculating diffraction intensities, by introducing and calculating (to nine significant figures!), the integrals that bear his name. In 1816, he carried out his double mirror experiment.

His first memoir (1815) was nothing short of an all-out attack on Newton's theory, a challenge to a mighty duel across 140 years: *"I observed that shadows never clearly end as they should if light only propagated in its initial direction. Instead, the light spreads within the shadow, and it is difficult to define the point at which it disappears."*

Scientific fame

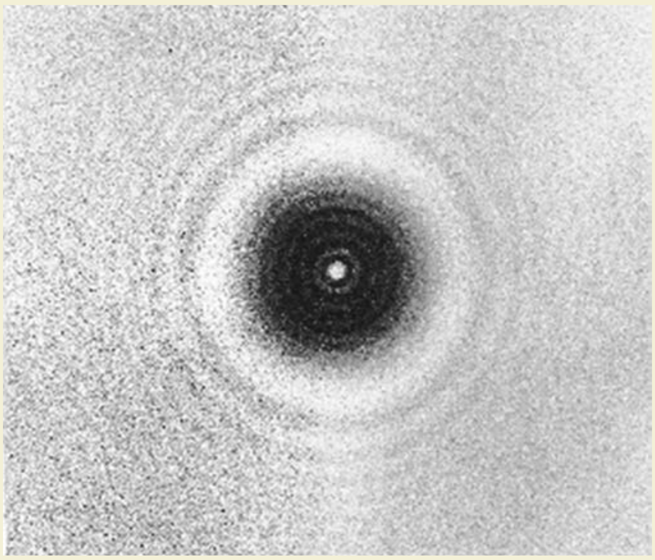
In 1816, after the blockade had ended, Fresnel was somewhat disappointed to learn from Arago, who had travelled to England with Gay Lussac, that Young had reached the same conclusions as him some years earlier. He was, however, a good loser, and eventually became a close friend of Young, telling him, *"What you left for me was as difficult as what you had done. You had picked the flowers, and I laboriously dug to reach the roots"*.

The first Academic award came in 1819. The Academy of Sciences had decided 2 years earlier to dedicate its biannual Grand Prix of Mathematical Sciences to the experimental and theoretical study of diffraction. Encouraged by Arago and Ampère, Fresnel entered a memoir and won the prize. The rapporteurs were Laplace, Biot and Poisson, who favored emission theory, and Arago and Gay Lussac who favored wave theory.

In his prize memoir, Fresnel revived the Huygens principle, emphasizing its depth and importance. This was to become known as the Huygens-Fresnel Principle (deposited in a sealed envelope at the Academy, opened 4 years later).

There was a moment of bewilderment when Poisson pointed out that, according to the theory of diffraction, as the waves would be in phase, a bright point should paradoxically be observed in the center of the shadow of a small disk! Fresnel subsequently confirmed this observation in an experiment (*Figure*).

Fresnel introduced the notions of wavelength and the propagation of vibrations through the ether, with both spatial and temporal periodicity. His ideas were originally based



Bright spot in the center of the shadow of a small disk or sphere. (Source: Institut d'Optique Graduate School, France)

https://doi.org/10.1051/photon/2019S418

on an analogy with pendular motion. He had noticed that the amplitude of vibrations propagated by a system can be separated into its components, just as the components of a force can. He therefore calculated the overall effect of a set of light waves, or vibrations, on one another.

Every element of the wave surface can be considered to emit elementary wavelets. In contrast to Huygens' results, however, Fresnel found that these wavelets interfere, thereby giving him an explanation for light rays, or beams. As the interference of these wavelets at some distance from the main direction of the beam of light is completely destructive, this beam, which is wave-like in nature, preserves its geometric characteristics during its propagation (the first complete proof was given in 1870, by Kirchhoff and Helmholtz).

Polarization and the optics of anisotropic media

In May, 1818, Fresnel was transferred to Paris, where he studied the polarization of light discovered by Malus, and chromatic polarization discovered by Arago. He established that light waves differ fundamentally from sound waves, in that they are transverse. This highly controversial finding, which even Arago questioned, allowed him to formalize the notion of polarization.

In 1819, he studied birefringent crystals, and turned his attention to double refraction and the associated properties of polarization. In a memoir and supplements published between November 1821 and March 1822, he worked out the theory of double refraction in uniaxial and biaxial crystals, the crowning achievement of his scientific work.

Fresnel the engineer

In 1818, Fresnel was seconded to the Lighthouse Commission. Commercial shipping had resumed and it was vital to improve maritime safety and provide clearly marked shipping lanes. Following an original idea by Buffon, Fresnel devised multi-part lenses for use in lighthouses. The resulting *Fresnel lenses* were made up of concentric annular prisms and had the same optical performances as large lenses with a strong curvature, which were impossible to build and transport.

This technology was worked out between 1819 and 1825, with the first full-scale test conducted after nightfall in Paris in September 1821, on the Arc de Triomphe. The light could be seen 25 km away, and its brightness and luminosity exceeded all expectations. Very soon, all lighthouses were equipped with Fresnel lenses.

The end

Fresnel was elected to the Academy of Sciences on May 12th 1823. His remarkable achievements were rewarded not only by his fellow scientists, but also by the Lighthouse Commission and the Department of Civil Engineering. However, his health rapidly declined, and it became obvious that he had tuberculosis.

He therefore stopped his scientific work and dedicated himself to his engineering tasks. One week before his death in 1827, Arago, his faithful friend, admirer and protector, came to present him with the Rumford Medal, which was awarded to him by the Royal Society *"for his development of the Undulatory Theory as applied to the Phenomena of Polarized Light, and for his various important discoveries in Physical Optics"*. The Royal Society had appointed him as an associate member in 1824.

In 1861, Gustave Rouland, Minister of Public Instruction and Worship, decided that Augustin Fresnel's *Complete Works* should be published, although this was to take longer than anticipated, owing to the deaths of the first three editors, Henri de Sénarmont, Emile Verdet and Léonor Fresnel. They are available in three volumes from Forgotten Books (Classic Reprint series). ■

AGENDA

OSA Digital Holography and 3-D Imaging topical meeting
19-23 May 2019 – Bordeaux (France)
www.osa.org

AOP2019
31 May-4 June 2019
Lisboa (Portugal)
www.aop2019.org

JCOM 2019
7 June 2019 – Brest (France)
www.sfoptique.org

Photorefractive Photonics and beyond (PR'19)
18-21 June 2019 – Gérardmer (France)
pr19.event.univ-lorraine.fr

ONLYLIGHT
19-20 June 2019 – Lyon (France)
http://onlylight-event.com/

CLEO/Europe-EQEC 2019
23-27 June 2019 – Munich (Germany)
www.cleoeurope.org

Laser World of Photonics
24-27 June 2019 – Munich (Germany)
https://world-of-photonics.com

JNOG 2019
2-4 July 2019 – Palaiseau (France)
www.sfoptique.org

SPIE Optics+Photonics
13-15 August 2019 – San Diego (USA)
http://spie.org

LIP2020
22-28 August 2019, Warsaw (Poland)
http://lip-conference.org/

PRE19
4-6 September 2019 – Nice (France)
pre19.sciencesconf.org

Diffractive Optics 2019
16-20 September 2019
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A NEW ERA FOR SOLAR ENERGY: hybrid perovskite rocks

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With the world population swelling and rapid technological innovations imposing global network and connections, the growing energy demand has reached unprecedented levels: *"The energy industry is facing decades of transformation,"* reported the World Energy Council at the end of 2018 [1]. Increasing use of renewable energy sources and photovoltaics is thus utmost for Europe to meet the goals imposed by the Paris Agreement. From a research point of view, this pushes an enormous effort into discovery of new materials, new physical phenomena and development of new technologies to sustain such paradigm shift to a low-carbon society.

Photovoltaics (PVs), where electricity is generated directly from sunlight, can represent an ideal solution to supply sustainable, environmentally-friendly and grid-free electricity. The past decade has witnessed an enormous boom in photovoltaics, where combined efforts in material science, physical-chemistry and technology lead to create a new generation of advanced functional materials for more efficient devices at reduced costs. As a result of substantial price reduction in recent years, solar power has now established itself as a cost effective and reliable source of energy. The production cost of solar cells has declined by 75% within less than a decade, leading to an increase in the total photovoltaic cumulative installed capacity by top ten countries from 2014 to 2019, as shown in the chart in *Figure 1* [1].

Presently, several new PV technologies are the focus of an intense research, aiming for alternatives with high efficiency, a lower cost and higher accessibility to the general population, key points for a paradigm change in sustainable energy. In this frame, stemming from research in low-cost semiconductors, hybrid perovskite (HP) semiconductors *i.e.* methylammonium lead iodide ($MAPbI_3$), have been leading a recent revolution in efficient and low-cost new generation PVs [1-3]. Long explored in the past

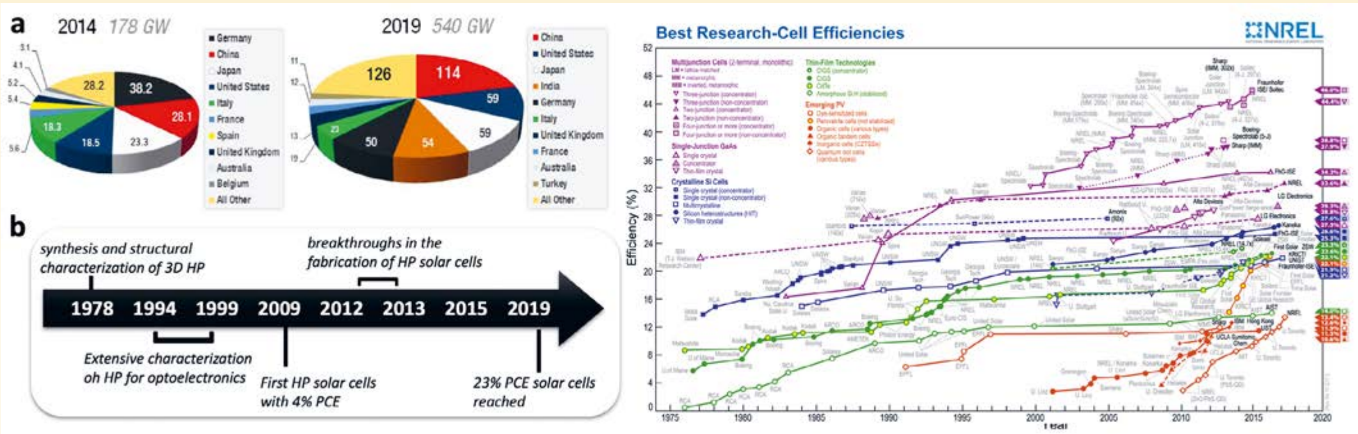

Figure 1. (a) Pie chart depicting the total PV cumulative installed capacity by top ten country in 2014 and 2019 ([1], reprinted with permission from Elsevier). (b) Timeline of research into the optoelectronic properties of HPs and important discoveries in the development of HP solar cells. Weber was the first to determine $MAPbI_3$ crystal structure in 1978. During the 1990s, Mitzi and co-workers at IBM York town laboratories synthesized and characterized HPs for use in electronic devices. The first report on a HOIP-based solar cell was published in 2009, followed by enormous advances during the period 2012–2014. Today, photovoltaic power conversion efficiencies of >23% as reported in (c).

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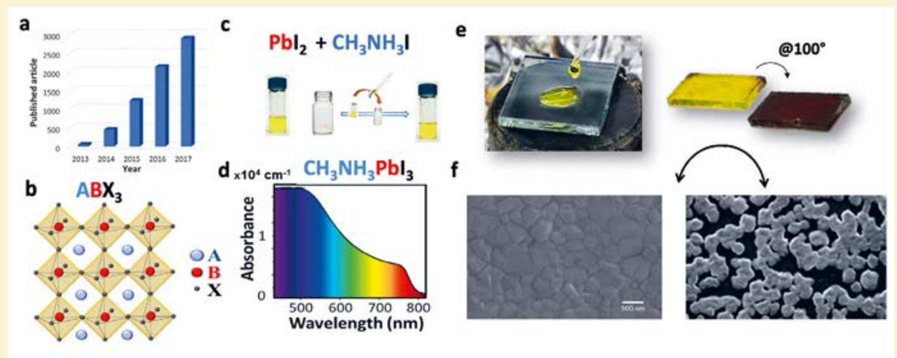

Figure 2. (a) Graph representing the evolution of number of publications related to HP in the last decade. (b) Structure of the 3D HP. (c,e,f) Representation of solution-based deposition process starting from precursors in solution. (f), in particular, represents two possible different morphology which can result from solution process: either a uniform optimized film or a non-uniform film with many cracks and pinholes. Two-years of intense investigation (between 2012 and 2014) lead to the solutions for getting reproducible and uniform perovskite thin films. (d) Absorption spectrum of the $MAPbI_3$ showing the panchromatic response [1-3].

as potential semiconductors, superconductors and for their optoelectronic and magnetic properties, HP demonstrated to be efficient light antennas and charge transporters – ideal properties for capturing solar power [3]. Solar cells with a HP as the PV-active material, prepared by low-temperature solution-based methods, achieved over 23% certified efficiency after just 10 years of research from a starting efficiency of ~4% (*Fig. 1c*) [3]. To put this in perspective, the best single-junction inorganic laboratory cell (GaAs) has reached ~29% efficiency after nearly 60 years of research, having started at 4% in 1956. We are now just entered in 2019 the "decade" of perovskite research, in which HP solar cells (HPSCs), have demonstrated impressive performances posing a remarkable challenge to thin film and multi-crystalline silicon PVs (see extract from NREL chart in *Fig. 1c*). However, for practical application, PV technologies need to be more than efficient – they also need to be stable and scalable, which are the real challenges for the next generation of perovskites solar cells. Stability, in terms of solar cell lifetime, is utmost to address. In addition, HPs present the serious drawback related to the presence of toxic materials, *i.e.* lead [3], with the associated health and environment concerns.

Hybrid halide perovskites materials and solar cells

3D halide perovskites: structure and chemical composition

HP are considered one of the most attractive research topic of our time, as clear from the rapid increase in the amount of publication per year reported (see *Fig. 2a*). The 3D HPs, such as $CH_3NH_3PbI_3$, consist of a 3D organic-inorganic crystalline network organized in an ABX_3 structure (see *Fig. 2b*). A is a small organic cation (e.g. MA = $CH_3NH_3^+$), B a metal cation (e.g. Pb^{2+}, Sn^{2+}), and X a halide anion (e.g. Br, I) [1-3]. The size of the A cations must be small enough to fit within the octahedral unit (*Fig. 2b*), keeping the integrity of the 3D perovskite structure. The so-called *Goldschmidt tolerance factor (t)* sets an empirical limit for it. For the case of $CH_3NH_3PbI_3$ it reads as: $t = (r_A+r_I)/(\sqrt{2}\,(r_{Pb}+r_I))$, with $r_{A,I}$ the ionic radii of the A cation and the halide, respectively. The optimal values for the cubic perovskite structure are $0.8 < t < 1$ [1-3]. Considering $t = 1$ as a limit, the maximum RA is 2.6 Å (with $R_{Pb} = 1.19$ and $R_I = 2.2$ Å). However, although this represents a *useful rule of thumb* for the screening of new organic cations, the inorganic lattice can

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accommodate even slightly larger organic cations, as for the case of formamidinium (FA = $CH(NH_2)_2$) or guanidinium (Gua = $C(NH_2)^+$) [1-3]. Compositional engineering has been as one of the keys to improve the structural stability, device stability, and device performance by introducing multiple cations or halides in the perovskite structure. The great advantage of this class of materials, as mention above, relies in the easy of deposition methods, adaptable for flexible and large area substrates. For instance, $MAPbI_3$ can be deposited from solutions. If, at one side, these methods are easy and inexpensive, on the other side, they require the establishment of a precise deposition steps protocol and parameters to obtain, even from solution, high quality crystalline films with large grains and reduced grain boundaries, as shown by the scanning electron microscope images in *Figure 2f*. Not optimal annealing leads for instance to incomplete coverage and not ideal morphology, as shown in *Figure 2f*.

Optoelectronic properties

HPs combine unique electrical and optical properties: high absorption coefficient (that reduces by 10^3 times the optimal device thickness with respect to Si), see *Figure 2d*. In addition, they are characterized by direct photo-generation of free carriers (ionized excitons at room temperature with low exciton binding energy) [3], efficient charge transport and long carrier diffusion lengths, efficient charge transport and wide band gap tunability, achieved by the manipulation of the A cation or the X halide, as shown in *Figure 3a*. Another striking attribute of these materials is their low non-radiative recombination rates compared to other thin-film polycrystalline semiconductors [3]. These materials show an incredible "defect tolerance", with low trap density. This property manifests in their high open-circuit voltage (V_{OC}) exceeding 1 V [3]. This places the HP technology in fourth place out of all solar technologies, behind GaAs, crystalline Si and CIGS. Remarkably, the fundamental losses of this new technology are already lower than CdTe, which is the technology of choice for the world's largest solar company.

Device architectures and efficiency

The unprecedented rate of increase in PV efficiency of HP cells has benefited greatly from earlier research in other classes of PVs. Specifically, the architectures used today draw from dye-sensitized, organic and thin-film polycrystalline compound semiconductor devices, almost without any need to adapt the original architectures to the new

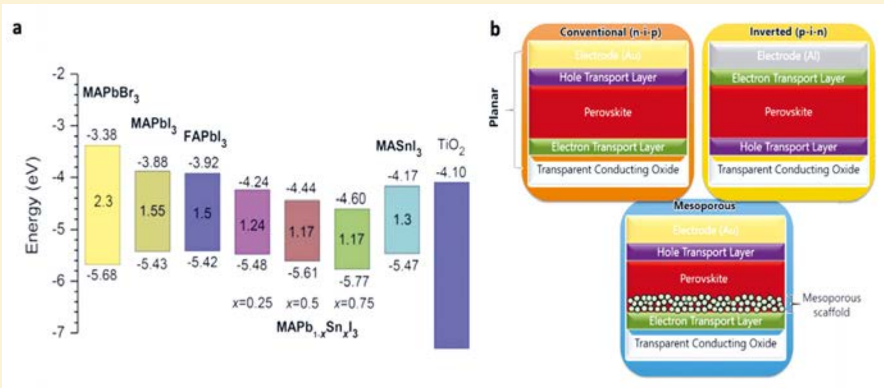

Figure 3. (a) Sketch of energy level for $MAPbBr_3$,$MAPbI_3$,$FAPbI_3$,$MAPb_{1-x}Sn_xI_3$,$MASnI_3$ and TiO_2 ([1], reprinted with permission from Elsevier). (b) Commonly studied perovskite cell structures in literature: regular (n-i-p) planar, inverted (p-i-n) and regular (n-i-p) mesoporous cell [1-3].

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material [1-3]. The solar cell consists of a multi-layered structure (*Fig. 3b*) where the perovskite is deposited in between an electron transport layer (ETL), and a hole transporting material (HTM). More in details, to sum up, three are the main device architectures, as shown in *Figure 3b*: mesoporous n–i–p, planar n–i–p and planar p–i–n. A typical mesoporous HPSC comprises an ETL scaffold with nanoscale pores. A perovskite absorber layer covers the scaffold, forming a compact capping layer and also penetrating into the scaffold, leading to an inter- mixed layer. The planar p–i–n architecture is generally referred to as an inverted structure because the carrier extraction layers are inverted with respect to the n–i–p structure. Devices with a p–i–n architecture are often constructed with a planar structure with a compact HTL. As shown from the statistical analysis in *Figure 4* and reported in [4], the mesoporous configuration has been the one mostly adopted and the one responsible for the record efficiency. However, in the last year, also the planar configuration made enormous steps forward. *Figure 4* depicts the performance of common cell structures through the years in terms of average efficiency as found in literature [4].

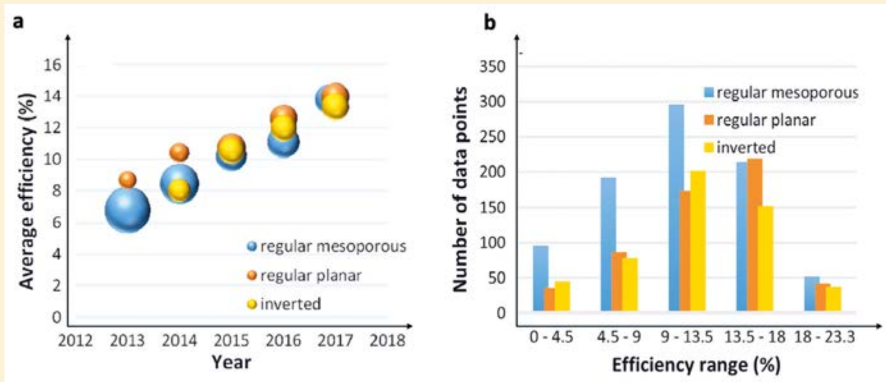

Figure 4. (a) Change of average efficiencies (ball size shows fraction of data in each year). (b) Distribution of data over the efficiency levels [4].

The actual challenge: stability & toxicity

State of the art on material and device stability

Despite the full potential of this technology and the big excitement that came along, a big barrier hampers their commercialization: the poor device stability under operative conditions (HPSCs degrade in ambient air) [3, 5]. For instance, MA-based hybrid perovskite which has been the pioneer and state-of-the art performances for this class of materials suffers from inherently high instability (i.e. $MAPbX_3$ decomposes to gaseous methylamine and hydrogen iodide) and susceptible to degradation by heat or moisture [5]. In presence of water they react breaking the 3D crystal structure and then undergoes irreversible decomposition back into the precursors such as PbI_2 [5]. $MAPbI_3$, for instance, starts to decompose at a humidity of 55%, inducing a remarkable bleach of the color that changes from dark brown to yellow due to conversion into PbI_2 (*Fig. 3b*). Phenomena such as light induced ion movement, "photo-instability", or structural deformations not only disturb the material stability, but also alter the device behavior, contributing to the anomalous hysteresis observed in the device current-voltage characteristics that has not yet been clearly understood [3-5]. Despite the urgency, only in the last couple of years research attention has been devoted to

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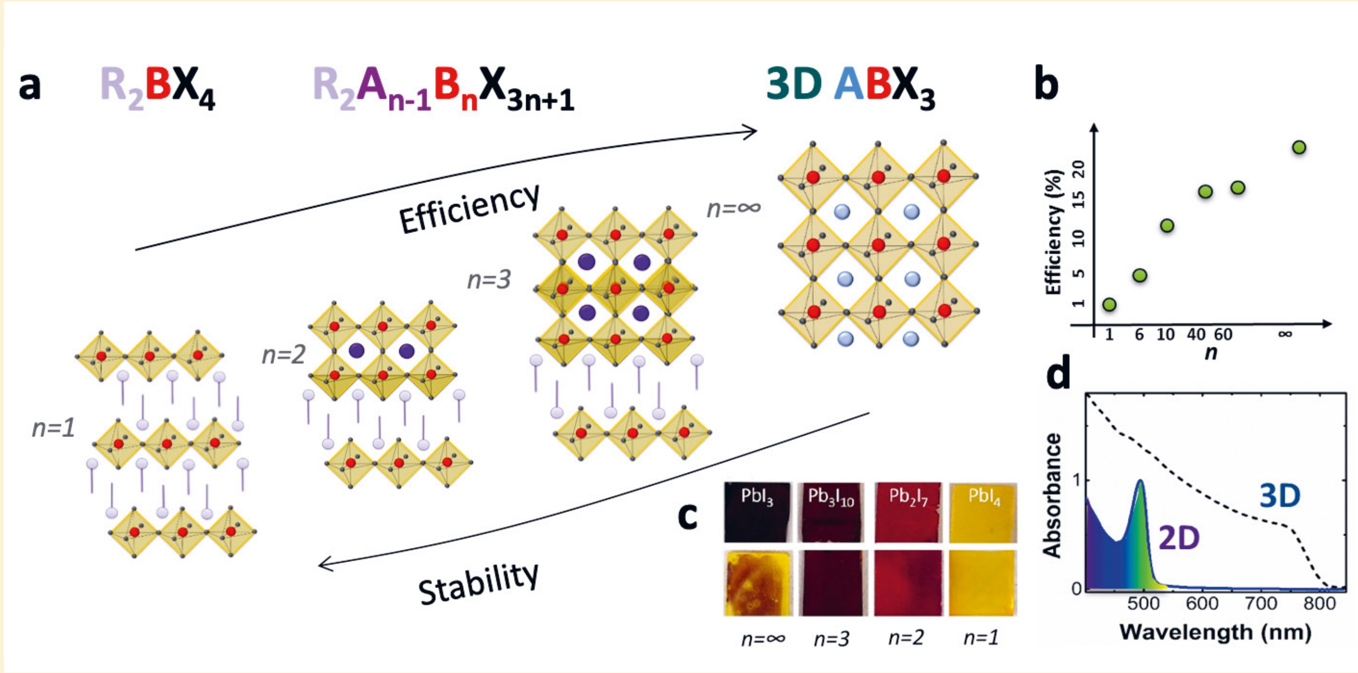

Figure 5. (a) Structure of perovskite from 2D to 3D. (b) PCE versus the number of layers of the quasi 2D perovskites converging into 3D for n = ∞. (c) Degradation of perovskite thin films comparing 3D to 2D. (d) Comparison of the absorption of a typical 3D versus 2D perovskite thin film.

this issue. On the other side, from the device perspective, each interface and contact layer of the device stack have a key role in determining the overall stability.

Layered perovskite: a solution towards stability

Recently, dimensionality tuning of the perovskite has attracted many attentions in this field. Compared to 3D perovskites, low-dimensional (2D) perovskites exhibit superior stability against the moisture because of the hydrophobic properties of the R cation[ref]. 2D perovskites arrange to *Ruddlesden-Popper* structure with a general formula of $R_2A_{n-1}B_nX_{3n+1}$, where R is a large organic cation (for example, aliphatic or aromatic alkylammonium) which functions as a spacer between the inorganic sheet and n determines the number of inorganic sheets that is being held together [5].

This structure, shown in *Figure 5a*, makes 2D perovskite very tunable by controlling the cations.

For instance, by controlling A/R ratio, the n value could be adjusted from $n = 1$ (2D), $n > 1$ (quasi 2D), and $n = \infty$ (3D) [5]. Since the 2D perovskites have different structure, they possess unique optoelectronic properties. 2D perovskites have narrower absorption because of their larger bandgap, which depend on the number of n [5]. In addition, 2D perovskites form stable exciton at room temperature (see *Fig. 5d*) with large exciton binding energy due to the dielectric mismatch between organic and inorganic layers [5]. As a result, these properties are not ideal for photovoltaic action, leading to poor performances in solar cells [5]. Relative to 3D perovskites, 2D perovskites show remarkably higher moisture resistance (see *Fig. 5c*). This greater stability is mainly due to the hydrophobic nature of the R cation, as well as the highly oriented structure and dense packing, which reduces the density of the grain boundaries and prevents direct contact of adventitious water with the perovskite [5]. The integration of 2D perovskites into HPSCs as a stabilizer component has been recently proposed as an approach to increase the lifetimes of HPSCs.

Stable and efficient 2D/3D solar cells, is it the future?

Combining low-dimensional perovskites with 3D perovskites in layered 2D/3D composites has been proposed as a strategy to overcome the HPSC stability issue. The aim of this approach is to combine the high efficiency of 3D perovskites with the superior stability of 2D perovskites, in a synergistic

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action. Several studies have demonstrated the benefits of combining 2D and 3D perovskites, and 2D/3D junctions have been used in both mesoporous solar cells and inverted architectures as shown in *Figure 6a*.

For instance, a two-step method was used for the deposition of a 3D/2D bilayer composed of $MAPbI_3$ and PEI_2PbI_4 [5]. As the 2D perovskite is at the top surface at the interface with the HTM (*Fig. 6a*), interfacial charge-carrier recombination is reduced and the PCE increases to >20%. These PSCs retained 85% of their initial PCE under 1 sun illumination for 800 h at 50 °C even in an ambient environment (*Fig. 6b*), providing the first example of a highly efficient and stable 3D/2D device. Importantly, this result demonstrated that it is possible to achieve enhanced stability without compromising the PCE, reaching efficiencies comparable to those of 3D PSCs. The 2D perovskite can be also developed at the bottom surface covering the TiO_2 surface while improving the electron transfer. This layered 2D/3D architecture has been implemented in standard mesoporous TiO_2/spiro-OMeTAD solar cells as either a 3D/2D or 2D/3D active layer in an inverted configuration and in monolithic solar cells in which the HTM and gold electrode are replaced by a carbon layer [5]. For this configuration (see *Fig. 6c*), the 2D/3D composite approach enabled a world-record stability of more than 1 year to be achieved. These devices showed no loss in performance over 10 000 h of testing (at 55 °C, 1 sun illumination for 24 h per day, sealed under ambient atmosphere).

Toxicity: towards lead free perovskites

Despite the enormous potentiality of this class of materials, 3D and 2D HP are both affected by a serious drawback due to the toxicity of lead, with the associated health and environment concerns, which can limit their commercial applications [1-5]. Despite the abundance of lead and its low percentage (about 0.1%) in final devices, its use represents a risk for the environment and an economic disadvantage for HPSC commercialization. Huge theoretical effort in screening "less toxic" materials is ongoing, however, so far, viable alternatives to Pb are only a very few due to the very stringent criteria they must have to match the performance of lead-halide perovskites. Examples include Tin (Sn) used in $MASn_xPb_{1-x}I_3$ now reaching PCE close to 10%, but easily prone to oxidation

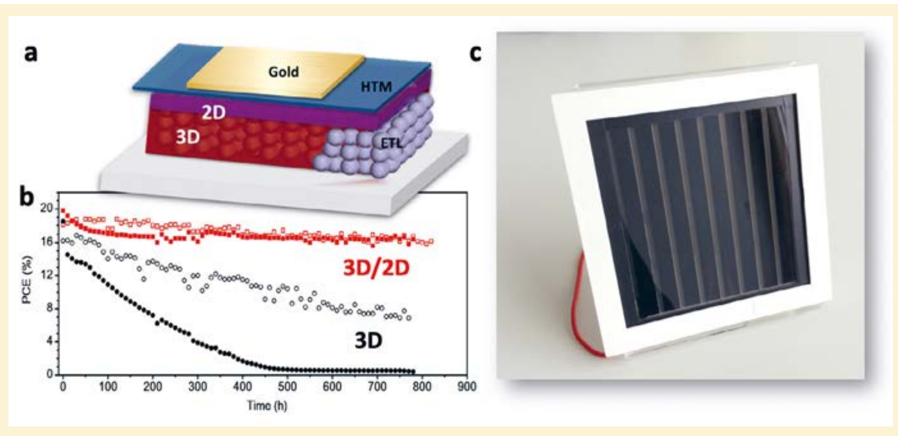

Figure 6. (a) Cartoon of the device structure based on mesoporous HPSC consisting, as an active layer, of a mixture of 3D and 2D hybrid perovskites. (b) Comparison of recent results on stability measuring the PCE under accelerating testing conditions between pure 3D perovskite and 3D/2D perovskite devices. The 2D/3D shows superior stability without sacrificing the device efficiency as reported in [5] (reprinted with permission from Springer Nature). (c) Picture of a carbon-based module 10×10 cm² developed by our group at EPFL Valais in collaboration with Solaronix.

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(Sn^{2+} into Sn^{4+}) or incorporated in A_2SnX_6 structures (e.g. Cs_2SnI_6), which exhibit better stability due to the presence of Sn in its stable oxidation state. Other alternatives are the "2D derivative" in the form of $A_3Bi_2X_9$ (using bismuth (Bi), X=halogen and A=MA or Cs) and the "double perovskites" such as $Cs_2BB^{3+}X_6$ (with B^{3+}=Bi or Sb; B=Cu, Ag, Au). Another viable option for reducing the hazards of Pb exposure is to develop effective encapsulation strategies. Pb does not pose a problem if it remains contained within the solar module; however, lead-based perovskites tend to release toxic PbI_2 by-product, possibly contaminating the environment.

Conclusions and future prospects

This article has presented a critical and inclusive summary of gradual advances, frontiers in the field of perovskite photovoltaics materials and devices, showing the main challenges and near future perspectives. Recent progress in engineering the perovskite dimensionality has been presented as an interesting new way towards efficient and stable devices. This is the next major issue which requires to be focused urgently to launch them in the market for outdoor photovoltaic applications. Interface engineering is also utmost to impart better carrier dynamics cross the solar cell junctions inclusive of charge production, transportation and extraction, and thus aids to optimize device performance. Furthermore, bandgap engineering of perovskite materials unveiled that highly efficient HPSCs can be realized by properly tuning their bandgaps which opens applications in optoelectronics even beyond photovoltaics. Exploration of novel materials synthesis and fabrication techniques will also open the way for easy and low temperature deposition protocols, minimizing the number of steps and making it feasible for large area production. Narrow bandgap perovskite materials and plasmonic photovoltaics are expected to eventually open the door for better light harvesting strategies that will span over wide electromagnetic spectra. Toxicity due to the presence of Pb atoms still hinder their commercialization. This issue calls for an urgent effort combining theoretical screening of new materials to guide synthetic chemists and engineers in the development of alternative compounds. In addition, future research directions regarding perovskite devices should also include the development of better and deeper fundamental understanding of the structural and photophysical properties of the materials as well as of the device functioning, crucial in order to realize optimum designs. The answer, crucial for a deeper understanding and for upscale and technology uptake is still not yet-identified. Unravelling the mechanisms behind material crystallization is certainly of high interest for further tuning the material optical and electronic properties, and broaden their impact far beyond PVs. ■

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FIBER OPTIC MONITORING OF ACTIVE FAULTS AT THE SEAFLOOR: the FOCUS project

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Laser reflectometry (BOTDR), commonly used for structural health monitoring (bridges, dams, *etc.*), will for the first time be applied to study movements of an active fault on the seafloor 25 km offshore Catania Sicily. The goal of the European funded FOCUS project (ERC Advanced Grant) is to connect a 6-km long strain cable to the EMSO seafloor observatory in 2100 m water depth. Laser observations will be calibrated by seafloor geodetic instruments and seismological stations. A long-term goal is the development of dual-use telecom cables with industry partners.

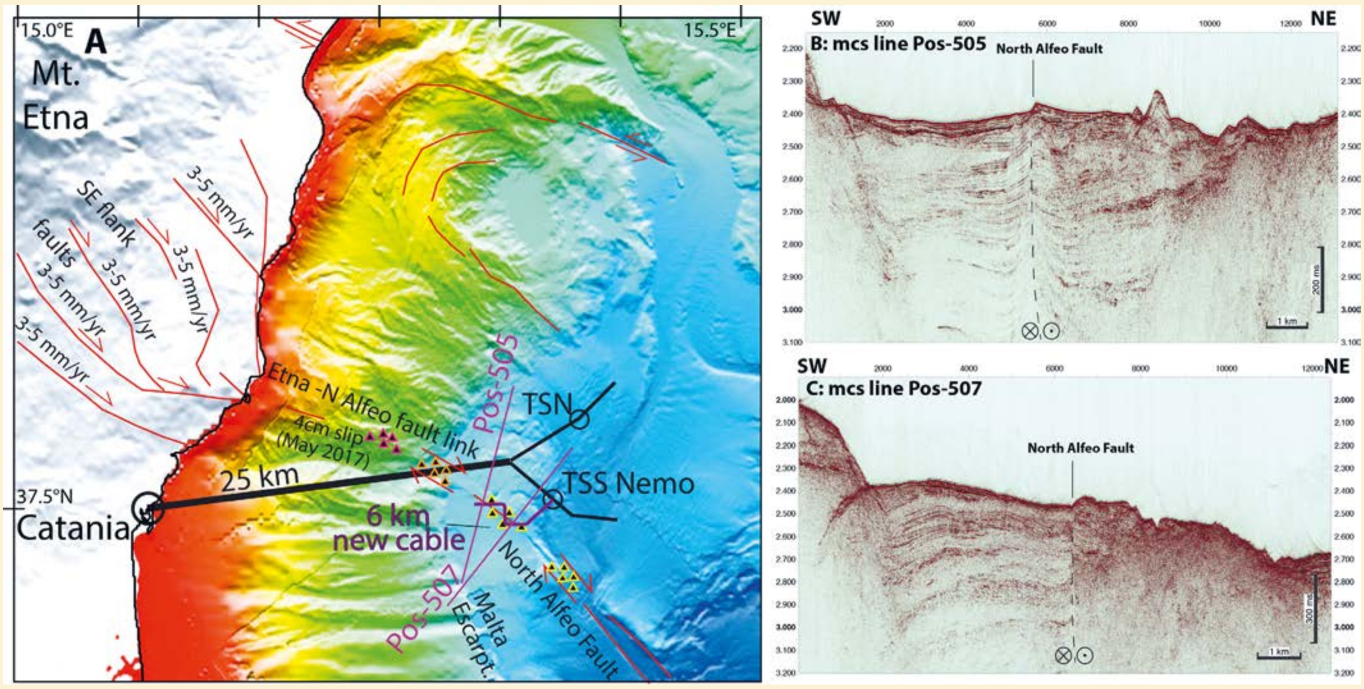

Figure 1. (A) Map of North Alfeo Fault (shown in red), the EMSO Catania cabled seafloor observatory (black lines) and the planned deployment of a 6-km long dedicated strain cable (shown in purple). (B, C) Multi-channel seismic reflection profiles crossing the North Alfeo fault and which show a sharp break in the continuity of reflectors (sedimentary strata) caused by the deformation along the nearly vertical strike-slip fault (for location see Fig. 1A).

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Two-thirds of the earth's surface is covered by water and thus largely inaccessible to modern networks of seismological instruments. The global network of submarine telecommunication cables, if properly adapted, offers tremendous possibilities as a large-scale seismological monitoring tool for the future. It was recently demonstrated that fiber optic telecommunication cables both on-land and at sea can detect earthquakes [1,2]. Application of laser reflectometry in fiber optic cables can potentially be used to detect movement across active submarine faults in near real time. This is the objective of the ERC (European Research Council) funded project FOCUS (Fiber Optic Cable Use for seafloor studies of earthquake hazard and deformation). BOTDR (Brillouin Optical Time Domain Reflectometry) is commonly used for structural health monitoring of large-scale engineering structures (e.g. bridges, dams, pipelines, etc.) and can measure very small strains (<< 1 mm/m) at very large distances (10–200 km). However, this technique has never been used to study faults and deformation on the seafloor.

During the 5-year FOCUS project we aim, using a variety of different instruments, to detect small (1–2 cm) displacements across the recently mapped North Alfeo Fault, about 20 km offshore Catania, an urban area of 1 million people. Here, the Catania EMSO (European Multidisciplinary water-column and Seafloor Observatory) station is located in 2100 m depth and connected to land by a 25 km long electro-optical cable (*Fig. 1*). The laser reflectometry observations will be calibrated by seafloor geodetic stations and earthquake activity will be monitored simultaneously by seafloor and onland seismometers. This cable, which crosses the Alfeo Fault, will be the focal point of the FOCUS project.

Instruments for monitoring fault activity on the seafloor

Fiber optic cables and monitoring technology

Laser reflectometry techniques permit the use of fiber optic cables to measure fluctuations in temperature and in strain. These techniques are widely used for structural health monitoring of large-scale infrastructure (bridges, hydro-electric dams, tunnels, cooling towers of nuclear power plants, wind turbines, pipelines, skyscrapers, train tracks, etc.) (*Fig. 2A*). There have also been some studies regarding specific geo-hazards on land, for instance monitoring slow creep of a landslide [3] or collapse of roadways over karst (sinkholes in limestone) [4]. One of the earliest pilot studies in a marine environment tried measuring seafloor displacement across an incipient submarine landslide offshore Santa Barbara California using a strain sensor cable, but proved *"unsuccessful in several attempts"* due to *"broken fiber cable"* during deployment [5]. Thus, to this day, there are no documented examples regarding the use of laser reflectometry for monitoring submarine faults.

BOTDR (Brillouin Optical Time Domain Reflectometry), is performed by firing a laser pulse from one end into an optical fiber (*Fig. 2B*). As laser light diffracts off microscopic imperfections in the fiber it produces several characteristic diffraction peaks (Raleigh, Brillouin, Raman). If the fiber optic cable is disturbed (through strain or temperature variations) then the Brillouin spectrum will vary at this exact location along the fiber (*Fig. 2C*) compared to a previous measure. Under optimal conditions, deformation on the order of 50 µm/m, (1/3rd the thickness of a human hair), can be easily measured at distances of several tens of km, and located to within 1 m [6]. These detection limits are 2 orders of magnitude better than typical land-based GPS techniques. Testing BOTDR in a deep-sea offshore environment is a great technological challenge. It requires vessels, highly specialized equipment and is very expensive. Application of this method could revolutionize the study of submarine faults, plate tectonics and earthquake hazard, while helping to improve early warning capability.

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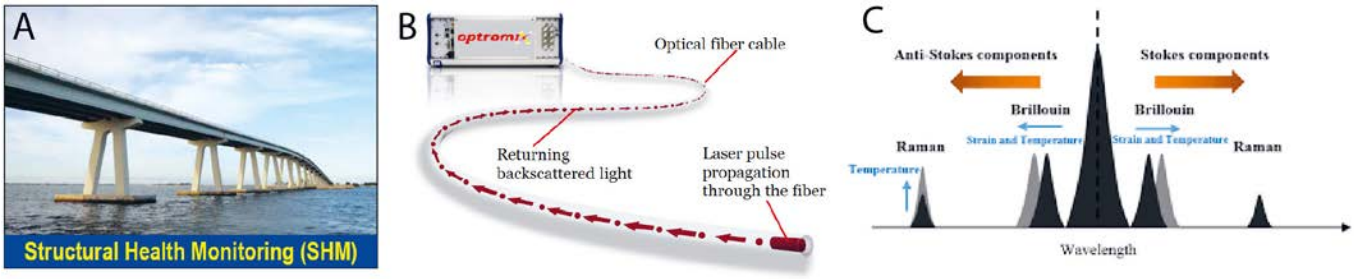

Figure 2. BOTDR (Brillouin Optical Time Domain Reflectometry) (A) Application to monitoring large scale infrastructure. (B) Principle how laser light is diffracted by minute imperfections in the optical fiber. (C) Three diffraction peaks, central peak is the Raleigh peak, the Brillouin peak is sensitive to temperature and strain variations.

A private company, IDIL fiber optics, is a partner of the ERC project FOCUS and has already conducted preliminary experiments on the EMSO cable infrastructure (in the framework of a Brittany Region funded BoostERC project – pre-FOCUS). IDIL will be in charge of the laser reflectometry measurements to be performed over several years on the EMSO Catania cable and the 6-km long extension (dedicated fiber optic strain cable). The Italian Physics Institute (INFN-LNS), operator of the EMSO cable infrastructure in Sicily (Catania and Capo Passero) collaborated for the preliminary experiments. They are also closely involved in the FOCUS project and will provide logistical and operational support during the planned marine expedition in summer 2020 and in particular the operations of cable deployment and cable connection.

Seafloor geodetic instruments

Seafloor geodetic stations communicate via acoustic signals at regular intervals with each other, while continuously measuring the sound velocity in water, and can therefore measure the length of all the interconnecting baselines continuously (*Fig. 3*). The stations also have pressure sensors and tiltmeters to ensure that any movement recorded is not simply settling or sliding of a single instrument. This methodology will be applied during the FOCUS project to calibrate the displacement along the target fault. GEOMAR and Laboratoire Géosciences Océan are among the pioneers in Europe in seafloor geodesy and have already worked together using this method in the Marmara Sea [7].

An array of five seafloor geodetic instruments was deployed by Geomar and the Univ. of Kiel along the offshore continuation of strike-slip and normal faults accomodating a gradual eastward gravitational collapse of the southeast flank of Mt. Etna (*Fig. 4A*) [8]. This network was deployed in water depths of 900–1200 m and recovered in August 2018. Analysis of baseline length changes during the 20-month observation period indicates a dextral strike-slip movement of 4 cm (*Fig. 4B*) along the fault trace [8], with nearly all the movement having occurred during a slow slip event in May 2017. The cumulative motion of the Etna flank faults (*Fig. 4A*) is estimated to be about 2-4 cm/yr [8,9]. The slip observed by the seafloor geodetic network is roughly of the same order and indicates an active submarine fault about 20 km to the east of Catania, an urban area of 1 million people, and crossed by the EMSO Catania cable (*Fig. 2A*). The seismic hazard posed by this major fault and its deep offshore continuation, with a total length of ~80 km [10] and unknown prior to 2010, has yet to be properly estimated. The FOCUS project can provide a major contribution to this seismic hazard assessment by measuring the spatial variation in coupling (i.e. the degree to which the two sides of the fault are locked/sliding) along the fault and by quantifying current slip rates.

Seismological stations

During the fiber optic and laser reflectometry observations, a regional passive seismological experiment is planned to record regional seismicity (*Fig. 5*). A temporary network of OBS (Ocean Bottom Seismometers) will be deployed on the seafloor to record regional earthquakes, which will also be simultaneously recorded by INGV seismic stations on land (*Fig. 5*) supplemented by deployment of temporary seismic stations on land. The regional seismicity as observed by only land based seismological stations (*Fig. 5*) is characterized by a concentration of events related to volcanic activity of Mt. Etna (as magma rises through the

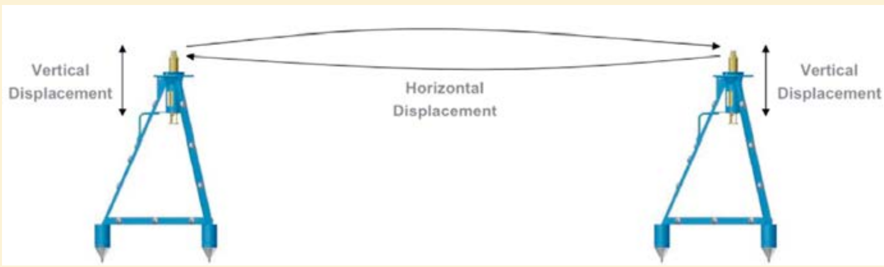

Figure 3. Seafloor geodetic stations, which communicate through acoustic transponders thus measuring the baseline length. Typical baseline lengths are 200–3000 m.

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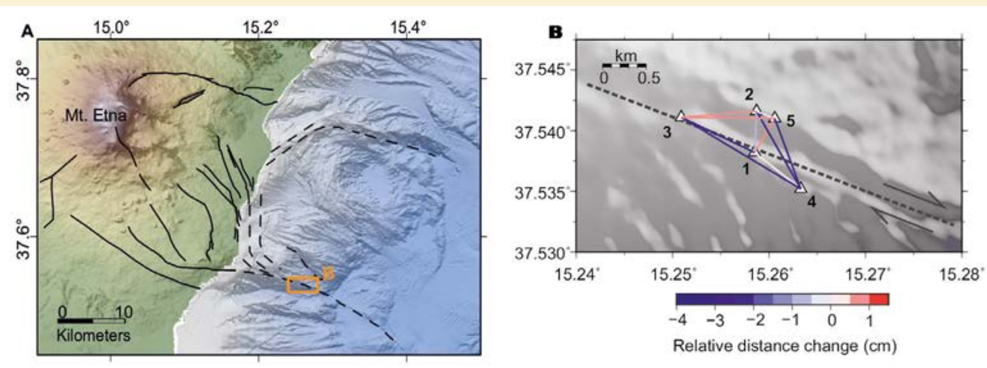

Figure 4. (A, left) Regional map showing position (red square) of seafloor geodetic network deployed offshore Catania / Mt. Etna (Apr. 2016 - Aug. 2018) by Geomar and Univ. Kiel [8]. (B, right) Change in base-line lengths over 20-months (Apr. 2016 - July 2017) with 4 cm of dextral strike-slip movement detected between the NE stations (2 and 5) and the SW stations (3, 1 and 4), and interpreted to have occurred during an 8 day slow slip event in May 2017 [8].

deep conduits and erupts at the surface). There is also a zone with broad diffuse seismicity observed offshore (east of Sicily and south of Calabria) in the Ionian Sea, without any apparent structural pattern (alignment along specific faults). This seismicity is possibly the result of two types of tectonic activity at different depths. In this region there is the gently northwest dipping subduction interface of the Calabria subduction zone, which lies in the depth range of 15–30 km. The other major tectonic structures are the strike-slip faults, well expressed in the morpho-bathymetry [9] and observed in seismic profiles as well (*Fig. 1B*, *C*). Given the low magnitudes (2.5–3.5) and absence of nearby seismological stations providing good azimuthal coverage, it is very difficult to locate these earthquakes properly, horizontally and particularly in depth.

Therefore, one of the major goals of the planned marine expedition in 2020 is to deploy a network of 35 ocean bottom seismometers, at a fairly dense spacing in proximity to the EMSO Catania cable and the North Alfeo fault, but also spanning a broader regional zone including the other major strike slip faults and the NW portion of the subducting Ionian slab. Italian partners INGV are ready to cooperate through

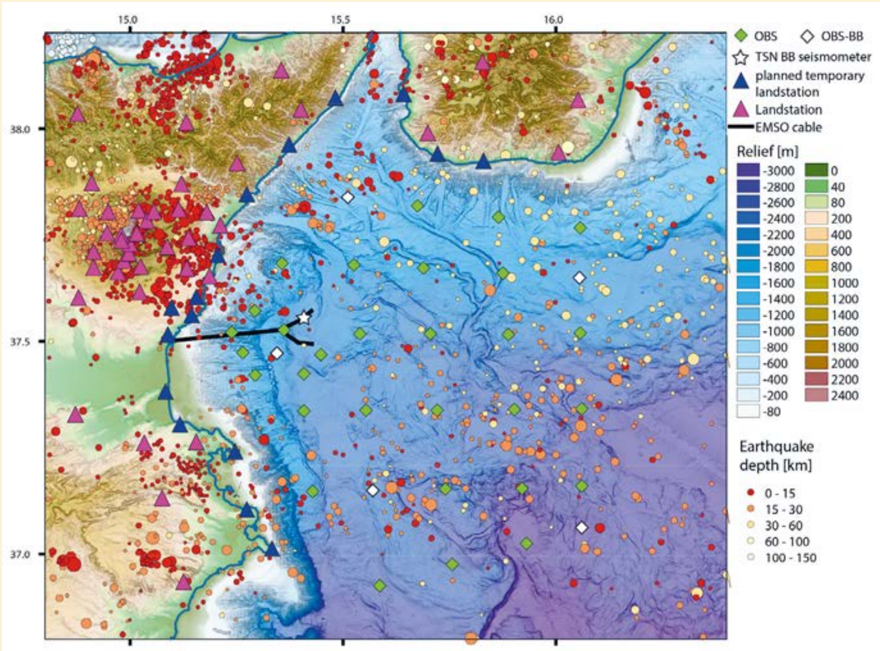

Figure 5. Map of the East Sicily – SW Calabria – Ionian Sea region, showing regional seismicity (colored circles), the existing network of land stations operated by INGV (magenta triangles), the planned temporary network of 30 short-period ocean bottom seismometers (green diamonds), and 5 broad-band OBS (white diamonds). Possible deployment of 16 temporary land-stations is also shown (blue triangles).

sharing of the earthquake recordings from their land-based seismological network (magenta black triangles, *Fig.* 5). There is a high concentration of seismic stations on the summit region of Mt Etna and around most of the slopes. However, the SE slope, and where recently mapped strike-slip faults show displacement rates of a few mm/yr (*Figs.* 1, 4*A*), is sparsely covered by seismic stations. INGV has agreed to add stations here, in the region directly north and northeast of Catania and on the SE flank of Mt. Etna.

Project status and outlook

Currently the project is in its earliest stage, having begun on 1 Oct. 2018. Nearly all the necessary equipment has been ordered / purchased. Upon delivery an initial phase of testing will take place, first in the lab, next in the 25 m deep Ifremer test pool, and then in shallow water in the nearby Bay of Brest (Rade de Brest). The critical factor for beginning the deployment of instruments on the seafloor offshore Sicily is the availability of ship time. A requested 4-week marine expedition FocusX1 could take place in summer 2020 if approved. Otherwise there may be options for cable deployment through collaboration with Orange (a major telecommunications cable operator). Once the cable, seafloor geodetic stations and ocean-bottom seismometers have been deployed, there will be a 3-4 year period of observation, with PhD students and young post-doctoral scientists who will contribute together with the permanent staff involved to collect and process the data collected and to calibrate the measurements obtained from the different methods. If all goes according to plan, slow or sudden displacements along the North Alfeo fault will be detected by the BOTDR technique as well as by the seafloor geodetic stations. ■

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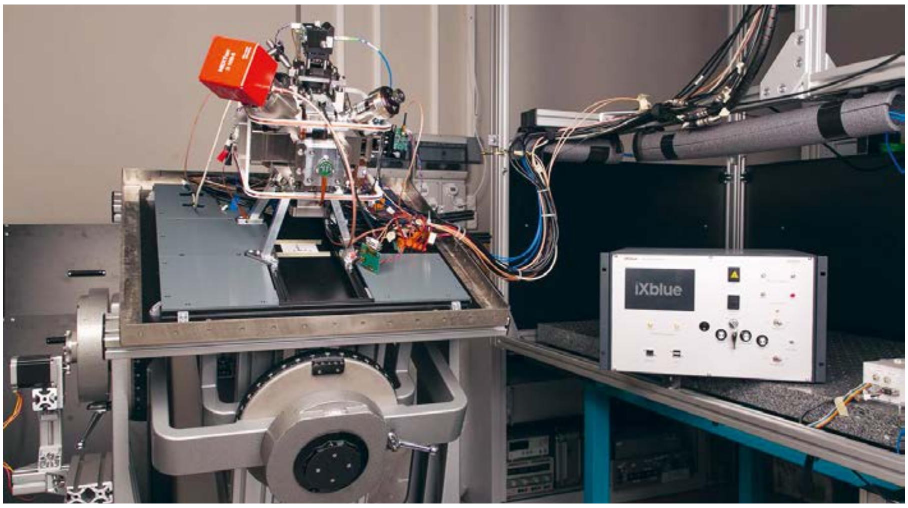
iXblue

ModBox CS-SSB: the agile iXblue laser source for cold atoms accelerometers



iXblue is a high-tech enterprise originally founded in 2000 to provide a new class of instruments based on fiber-optic gyroscope technology. They now offer a range of cutting-edge components and instruments that are unsurpassed in terms of sensitivity, precision and stability for applications in navigation, positioning and attitude control. iXblue's vertically-integrated organization incorporates the development and production of specialty optical fibers, lithium-niobate phase modulators, and quartz accelerometers. In its continuous pursuit of scientific innovation, iXblue has invested in the most advanced technologies for inertial navigation—most recently in the field of cold-atom physics, which has emerged as a potential breakthrough technology due to the inherent advantages of atomic spectroscopy and matter-wave interferometry. For this reason, iXblue has been collaborating for the past five years with LP2N (Laboratoire Photonique, Numérique, et Nanosciences) at the Institut d'Optique d'Aquitaine (IOA) in Bordeaux. LP2N is today one of the world's leading laboratories in the physics of laser-cooled atoms and atomic inertial sensors—a field which has made spectacular progress over the past two decades. The coherent control and manipulation of atomic wavepackets with light can be harnessed to construct extremely sensitive and low-bias inertial sensors—making them interesting candidates to replace classical sensors. However, the use of cold atoms in navigation and positioning applications still faces many scientific and technological challenges.

The joint Laboratory iXAtom was created within the IOA, with a team of researchers, engineers and PhD students. The aim of this collaboration is to make technological advances using laser-cooled atoms to develop the next generation of inertial sensors for industrial, military and Space applications. In the near future, iXAtom plans to develop a compact three-axis accelerometer based on new techniques in atom interferometry. The ultimate goal of this collaboration is to build an autonomous hybrid device which can compete with technologies based on global positioning systems without the drawback of external communication for recalibration.

Work is being carried out on three major axes: (i) the development of a navigation-compatible cold-atom sensor head, (ii) new theoretical approaches to the operation and enhanced performance of such an instrument, (iii) feasibility experiments carried out to verify the validity of relevant concepts. The laser system is an essential building block of these quantum sensors. Using recent developments in Telecom fiber-based technology, a new laser architecture was developed for laser-cooling and manipulating rubidium atoms. This ModBox laser source, patented in 2018, is based on an iXblue MXIQ-ER CS-SSB optical modulator operating at 1560 nm and second-harmonic generation to 780 nm. This key component suppresses the carrier frequency by 25 dB at 1560 nm and generates two optical sidebands that can be independently controlled in power, frequency and phase using off-the-shelf RF components. These principle sidebands are used to induce optical transitions in rubidium—allowing one to split, reflect and recombine atomic wavepackets to realize an inertial sensor. With this innovative architecture, the characteristics of the RF source in terms of agility, stability, and response time are directly transferred into the optical signal thanks to electro-optic modulation. The iXAtom team recently realized an atomic accelerometer with this new ModBox laser source, and demonstrated improved performance compared to other laser architectures based on standard phase modulators. Beyond these promising scientific results, the collaboration between iXblue and the LP2N is exemplary of successful transfer of knowledge and technology between a prestigious academic laboratory and high-tech industry.

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ESA'S GAIA MISSION: a billion stars with a billion pixels

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Astrometry is the astronomical discipline of measuring the positions, and changes therein, of celestial bodies. Accurate astrometry from the ground is limited by the blurring effects induced by the Earth's atmosphere. Since decades, Europe has been at the forefront of making astrometric measurements from space. The European Space Agency (ESA) launched the first satellite dedicated to astrometry, named Hipparcos, in 1989, culminating in the release of the Hipparcos Catalogue containing astrometric data for 117 955 stars in 1997. Since mid 2014, Hipparcos' successor, Gaia, has been collecting astrometric data, with a 100 times improved precision, for 10 000 times as many stars.

Although astrometry sounds boring, it is of fundamental importance to many branches of astronomy and astrophysics. The reason for this is that astrometry can determine direct, that is model-independent, estimates of stellar distances and velocities through the measurement of parallax – the periodic, apparent displacement of a star on the sky as a result of the changing position of the observer as the Earth revolves around the sun – and of proper motion – the continuous, true displacement of a star on the sky as a result of its velocity in space relative to the sun. Measuring the distances to (and motions of) stars has been a central theme for hundreds and even thousands of years, primarily driven by the human urge to understand the cosmos and the place of the earth (and the heavenly bodies). Despite huge efforts, and even with the invention of the telescope in 1608, the first reliable parallax measurement of a star other than the sun was only made in 1838. The reason for this late success is the fact that stars are located at extremely large distances such that parallaxes are typically tiny, of the order of (fractions of) milli-arcseconds (there are 60 arcseconds in an arcminute, 60 arcminutes in a degree, and 360 degrees in a circle). ESA's Gaia mission, however, has made an industry of measuring parallaxes and proper motions, by collecting vast amounts of astrometric data – and also photometric and spectroscopic data – for more than 1000 million stars with micro-arcsecond precision [1].

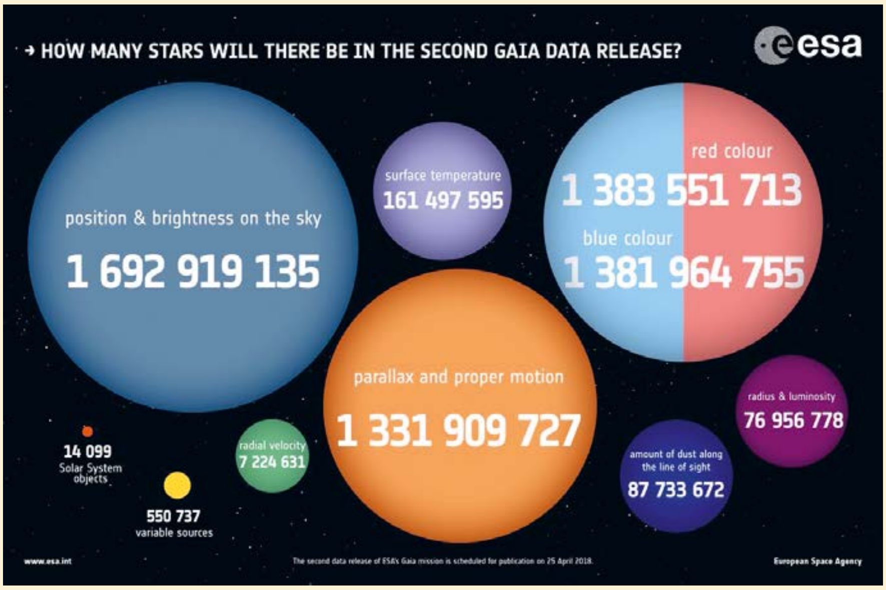

Figure 1. Schematic overview of the contents of Gaia DR2, released on 25 April 2018. Original: http://sci.esa.int/gaia/60147-waiting-for-gaia-s-second-data-release/

The Gaia mission

Launched in December 2013, Gaia has been scanning the sky since mid 2014 without interruption. The science data collected by Gaia is being converted to useable format, *i.e.*, to star catalogues, by the pan-European, mostly nationally-funded Gaia Data Processing and Analysis Consortium (DPAC). DPAC combines the astronomical and information technology knowledge of more than 400 individuals, spread over dozens of mostly academic institutes throughout Europe. Before

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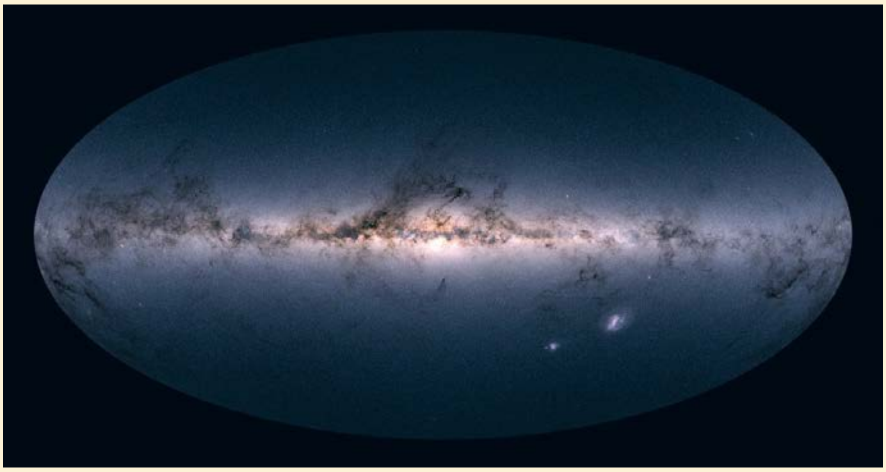

Figure 2. Gaia's all-sky map in colour, based on the Gaia DR2 catalogue. Original: https://www.esa.int/spaceinimages/Images/2018/04/Gaia_s_sky_in_colour2

being released, the Gaia data are being processed in six data processing centres (Madrid, Barcelona, Toulouse, Cambridge, Genève, and Turin).

So far, ESA and DPAC have made two intermediate data releases, Gaia DR1 in September 2016 and Gaia DR2 in April 2018 (*Figs. 1* and *2*; [2]). With unlimited excitement, astronomers have been sifting through the data to enable them to claim breakthrough discoveries such as the discovery of velocity structures in the disk of the Milky Way caused by the fairly recent infall of a satellite galaxy, the discovery of crystallisation of degenerate matter inside the cores of white dwarf stars, and the discovery of a cannibalistic event some 10 billion years ago in which our Milky Way, in its younger years, devoured an innocent, smaller galaxy – named Gaia-Enceladus – that happened to be passing by. Obviously, these discoveries reflect the unique contents and unique quality of the data. These, in turn, reflect the unique design of the Gaia telescopes and instruments.

Gaia satellite and payload

Gaia's implementation phase started in 2006, with EADS Astrium, nowadays Airbus Defence & Space, in Toulouse as prime contractor. The Gaia satellite consists of two parts: the service module and the payload module (*Fig. 3*). Two large telescopes with rectangular apertures are installed on a stable ceramic support structure called the torus. The lines of sight of the two telescopes are ultra-stable and form

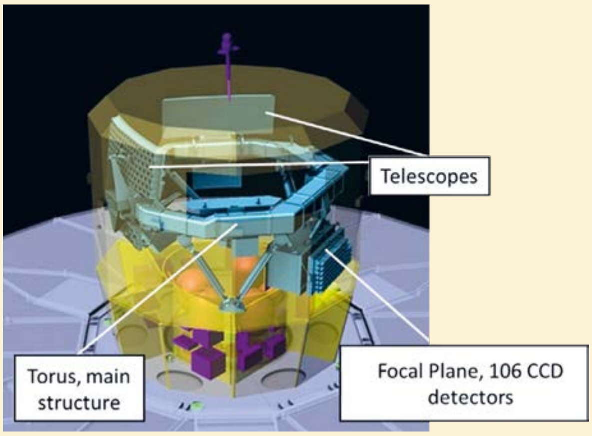

Figure 3. Gaia satellite and payload schematic. Image courtesy Airbus Defence & Space.

the so-called basic angle of 106.5°. The images of the two telescopes are projected on the largest focal plane operated in space [3]. Some 106 Charge Coupled Device (CCD) sensors are assembled in the focal-plane assembly, containing 938 million pixels. Sixty-two sensors are devoted to the main objective, collecting astrometric data, using the broadest possible band pass (330-1050 nm). The function of the remaining sensors is described below.

The satellite rotates once every six hours, with the rotation axis slowly precessing around the solar direction to achieve full sky coverage every few months. Due to the six-hour rotation, stars seen by the two telescopes are travelling slowly across the focal plane. A star crosses a single CCD sensor during 4.4 seconds. During this time, the charges released in the silicon by the photons impinging on the detector are shifted electronically, with atomic-clock precision, with exactly the same speed as the optical images move over the detector surface. At the output of each CCD row, all charges generated by a star travelling across the focal plane are collected, before being digitized and transmitted to ground for science analysis. Since stars from both telescopes are measured in the same focal plane, the angular distance of any pair of stars originating from different telescopes can be measured with extreme precision. Considering that the basic angle between the two telescopes is stable, the angular distance between the two stars can be measured with the required micro-arcsecond precision.

Gaia optics

The Gaia optics consist of two main, identical telescopes, two optical instruments (Radial Velocity Spectrometer – RVS; Blue and Red Photometers – RP/BP), and three optical sensors (Basic Angle Monitor – BAM; Wave Front Sensor – WFS; Star Mapper – SM). The two telescopes are off-axis Three-Mirror-Anastigmat (TMA) designs of the type concave-convex-concave with an intermediate image between the secondary and tertiary mirrors (*Fig. 4*). Three more flat folding mirrors, shared by both telescopes, bring the photons to the focal plane. The rectangular aperture size of the telescopes is 1.45×0.50 m^2; the focal length is 35 m. Such a telescope is challenging to build and align but TMAs have excellent image quality and an enormously large field of view. Each telescope has a field of view of 1.8°×0.7° and achieves diffraction-limited image performance in the visible wavelength range (330-1050 nm).

All mirrors, as well as the main Gaia payload structure, are made of silicon carbide (SiC). This ceramic material provides the extreme payload stability that is required for the science objectives of the mission. In order to minimise the mirror masses, the mirror blanks have been light-weighted by a pattern consisting of triangular cells (*Fig. 5*). Each primary mirror weighs about 40 kg.

Twelve of the 106 CCD sensors in the focal plane are dedicated to the Radial Velocity Spectrometer (RVS). This instrument mainly measures the radial velocity of an observed object, that is the velocity along the line of sight from the observer to the star, by Doppler shifts of absorption lines in the spectral range between 845 and 872 nm. Optically, the RVS consists of a band pass filter plate, a number of prisms, and a transmission grating. Two of the four prisms employ curved optical surfaces for optical correction. Such prisms are called "Féry prisms" and are challenging to manufacture. The spectrometer is installed close to Gaia's focal plane and is an integral-field unit: since stars are basically point sources, neither a spectrometer slit nor extra spatial masking is required.

The Gaia photometric instrument consists of two prisms (a Blue Photometer named BP and a Red Photometer named RP) that are part

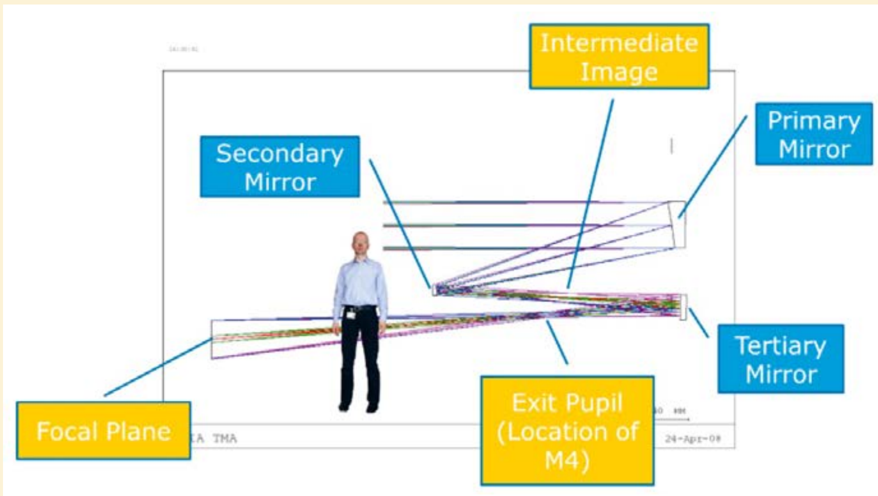

Figure 4. Gaia TMA telescope design with one of the authors depicted for scale. Image courtesy Airbus Defence & Space and M. Erdmann.

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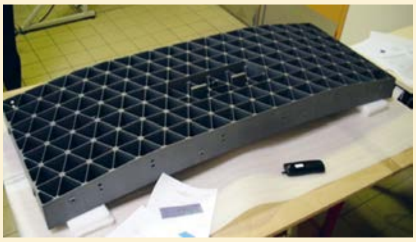
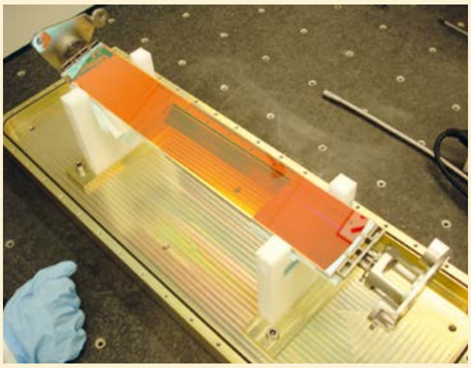


▲ **Figure 5.** Gaia primary-mirror blank. Image courtesy Airbus Defence & Space.



► **Figure 6.** Gaia red photometer prism. Image courtesy Airbus Defence & Space.

of the focal plane assembly (*Fig. 6*). Each prism has a selective band pass filter, implemented through a coating, that allows a limited spectral range in the blue (330-680 nm) or red (640-1050 nm) to pass through the prism and to reach the focal plane. The two prisms form low-dispersion spectrometers and the colours of stars, as well as more sophisticated astrophysical properties such as their surface temperature and gravity, can be derived from the two recorded low-resolution spectra. Fourteen of the 106 CCD detectors are dedicated to the photometric instrument.

The Basic Angle Monitor (BAM) is one of the key optical sensors of the Gaia payload [4]. The two lines of sight of the two telescopes of the Gaia payload are separated by 106.5°. This angle (the "basic angle") is the reference for all astrometric measurements. Its variation over the six-hour rotation period of the spacecraft must be known at sub-micro-arcsecond levels. The BAM therefore continuously measures variations in the basic angle by injecting two optical laser beams into each of the two telescopes. These beams have a diameter of about 1 cm and are separated by 600 mm in the rotation plane of the satellite. The optical configuration of the BAM represents a Young's interferometer. For each telescope, the two beams interfere, forming Young's fringes that are observed in the CCD sensor. Any variation in the basic angle results in a relative yet measurable shift of the fringe patterns produced by both telescopes and that are imaged in the same sensor in the focal plane. In the scientific data processing on ground, the astrometric star positions are corrected according to the BAM readings. Two of the CCD sensors are used as BAM sensor, one nominal and one redundant. In case of a laser source failure, a redundant source can be activated. The nominal and redundant sources are separated such that they end up at one of the two BAM sensors in the focal plane. The BAM detectors are the two extreme left detectors in *Figure 7*.

Two wave front sensors (WFS) are installed directly on the focal plane of Gaia. Each WFS is of Shack-Hartmann type. Each sensor consists of an optical mirror that images both telescope entrance pupils on a dedicated CCD sensor in the focal plane. Each telescope pupil image is segmented into 3×9 sub-pupils by the WFS optics. The two WFS measure the actual Gaia telescope wave front errors in orbit through observation of (bright) stars (*Fig. 8*). Each of the two telescopes contains a high-precision actuator that can move their secondary mirror in five degrees of freedom, with only a rotation around the optical axis not being supported. Since the telescope alignment was done on ground, under 1g conditions, it was significantly influenced by gravitational forces acting on the whole payload. Gravity forces were considered during alignment insofar possible, but a vanishing remain of unpredictable unknowns could not be taken into account. In order to achieve the required optical performance, it was necessary to measure the actual wave fronts of both telescopes in orbit and to improve them as needed by a slight movement of the secondary mirrors. This has been done once during the commissioning phase [5], after thermal equilibrium of the payload was reached, and several times during nominal operations, mainly to refocus the optics after thermal decontamination of the payload.

For the angular measurement precision of Gaia, it is paramount to have the images of both telescopes superimposed on the same focal plane. However, for the proper scientific evaluation of the images on ground, as well as for the on-board software that governs the read out of the CCD detectors, it is important to know which of the two telescopes a given star originates from. Two columns of 7 CCD sensors each are used for this purpose. Together with two masking

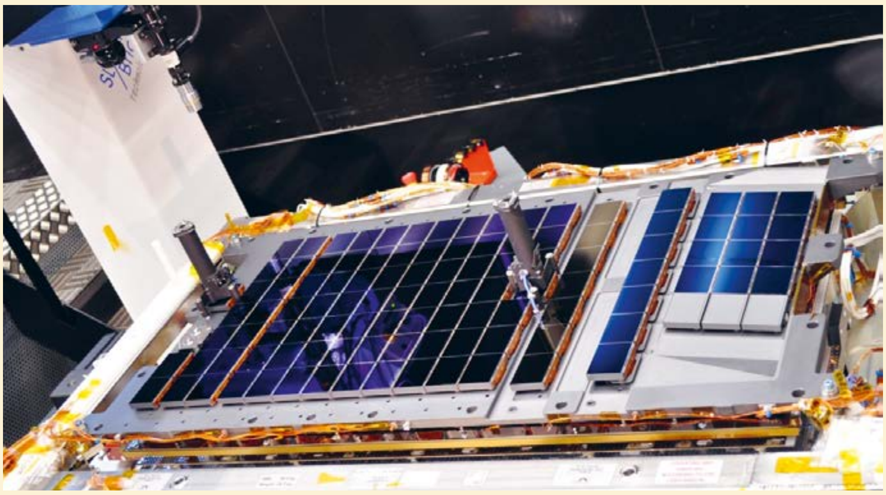


Figure 7. Gaia focal-plane assembly consisting of 106 CCD detectors. The two Wave Front Sensors are the booms sticking out vertically in the middle and at the left edge. The 3×4 block of CCDs on the right belongs to the RVS. Image courtesy Airbus Defence & Space.

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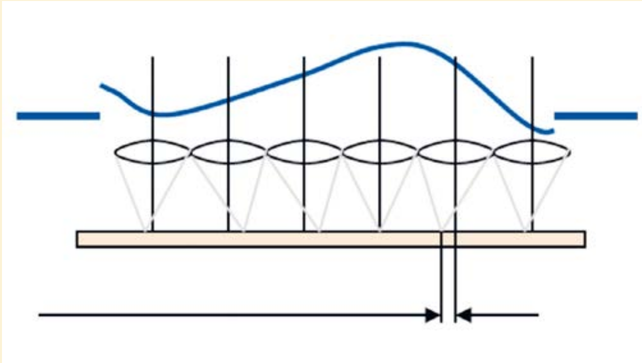

Figure 8. Principle of the Shack-Hartmann wave front sensor. The measurable distance between the two arrows is proportional to the local slope of the wave front error.

elements in the telescope optics, each effective for only one of the telescopes, they form the Star Mapper. The 14 Star Mapper sensors are shown on the left side, next to the two BAM CCDs, in *Figure 7*.

Conclusion

ESA's Gaia mission, with its custom optical design and high-quality instruments and metrology sensors, is revolutionising astronomy through the measurements of the distances and motions, as well as intensities and colours, of more than 1000 million stars. The two data releases made so far have led to hundreds of exciting discoveries, varying from stars zipping by the Sun in the recent past to a major collision that helped shaping our Milky Way galaxy some 10 billion years ago. At least two more data releases are being planned and a mission extension of 1.5 years on top of the nominal, five-year mission has been approved. Propellant on board would allow extending the mission to late 2024, which would allow improving the quality of the science data products to levels such that they will remain an astronomical treasure trove for decades to come. ■

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THE FRESNEL TRIPRISM AND the circular polarization of light

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In 1822 Augustin Fresnel discovered the circular polarization of light with an experiment in which a plane polarized beam was resolved into its left- and right- circularly polarized components after refraction at slightly different angles at the interface between two different species of quartz that formed a composite prism, called the Fresnel triprism. Fresnel's landmark experiment, once popular, remains today a very little known method for producing circularly polarized light.

In a rapid sequence of discoveries made in France, starting in 1811 with the observation of optical rotation in quartz by François Arago [1], and roughly spanning over 10 years, most of our modern understanding about the polarization of light was established. The leading figure was the brilliant mathematical physicist Agustin Fresnel, often stimulated by preliminary experimental discoveries of Arago. By 1820 Fresnel had already realized that light could be understood as a transverse wave and the Fresnel-Arago laws of interference and polarization had been just published [2]. At that time however, circular polarization was still not fully understood and the property of "polarization of light" was, by default, associated only with linear polarization. Nonetheless, circular polarization was already a main ingredient of the experimental research as, for example, in 1817 Fresnel had already reported that after two total internal reflections in a glass prism light seemed "depolarized" [3]. Indeed this was the earliest description of a Fresnel rhomb, but it would take Fresnel a few years more to realize that the light was actually circularly polarized instead of being depolarized. The concepts of linear polarization, circular polarization and elliptical polarization in the wave picture of light were established by Fresnel in the conclusion of his memoir from 1822 [4]. The main subject of this memoir was the circular double refraction of light propagating along the optic axis of a quartz crystal (*cristal de roche*) in an experiment that is little known today, but that was crucial for Fresnel to understand circular polarization and its relation to optical rotation. Unlike the well-known double refraction phenomenon in calcite, already well understood by Fresnel in terms of polarization, light does not split by polarization in two different paths when propagating along the optic axis of a quartz crystal. However, Fresnel thought that the phenomenon of optical rotation, first observed by Arago in 1811, could be explained by a special form of double refraction and made an experiment to demonstrate it.

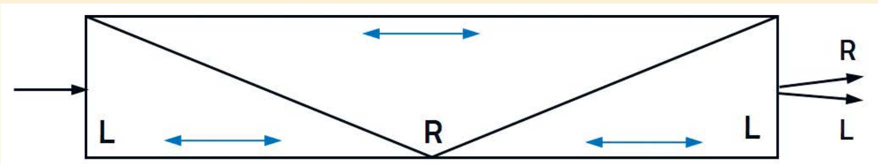

Figure 1. The Fresnel triprism. A prism made of quartz cemented in between two other half prisms made of quartz of opposite handedness splits the incident light into its right (R) and left (L) circularly polarized components. The double headed arrows indicate the directions of the optic axes of the crystals.

Fresnel took a very acute isosceles prism of right-handed quartz and cemented it in between two half prisms of left-handed quartz, forming a composite prism, named "Fresnel triprism" and schematically shown in *Figure 1*. In the experiment, light always propagated substantially parallel to the optic axes of the quartz prism components, so it could not be affected by standard double refraction but, at the exit facet, Fresnel still observed two beams emerging with a small angular separation. Fresnel used double refracting calcite to check that these emerging beams were not linearly polarized as in standard double refraction, yet he checked that when the beams were totally internally reflected in a glass prism, linear polarizations were recovered, each beam being orthogonal to the other. With this experiment Fresnel postulated the circular polarization of light and understood that the optical rotation of quartz and other materials was due to the different indices of refraction for left- and right-circular polarizations. To generate the angular divergence (i.e. the circular double refraction) interfaces between quartz prisms of different species were needed, since according to Snell-Descartes's law left- and right-handed waves refract with slightly different angles at such interfaces.

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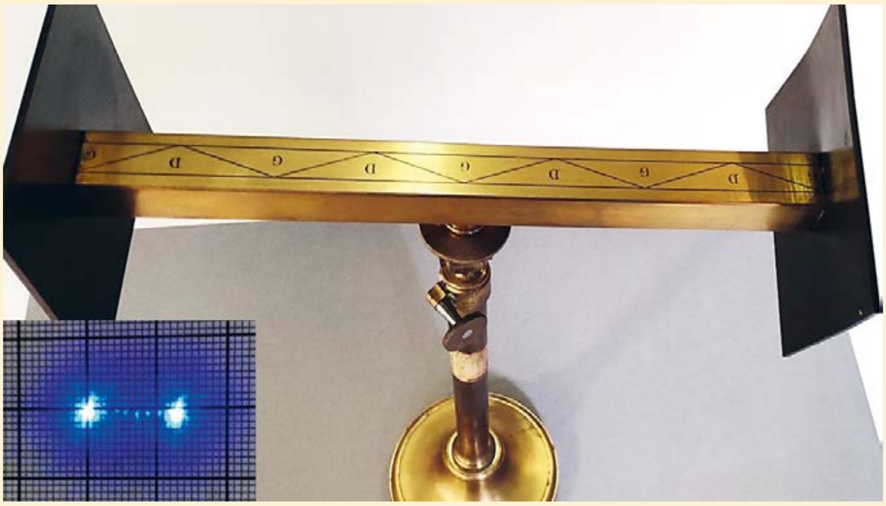

Figure 2. Photo of the historical Fresnel polyprism composed of nine prisms. The inset shows the beam splitting of a laser beam. More details in Ref. [5].

Fresnel triprisms became popular optical devices in the XIX and the first part of the XX century as they were often used in teaching demonstrations that plane polarized light can be resolved into right-and left-circularly polarized components. However, Fresnel triprisms remain nowadays very little known optical devices and they are not available as commercial optical components. In our quest to find a Fresnel triprism we were lucky to discover that in the recently inaugurated museum of the École polytechnique (Palaiseau, France), institution where both Arago and Fresnel were trained, there is one of such composite prisms (see *Fig. 2*) manufactured by Henri Soleil some time before 1872. This unit held a surprise: instead of a triprism, it contained nine different prisms of alternating handedness, so it is better referred to as a polyprism, a feature that to our knowledge is unique of this unit. Essentially, each interface doubles the angular separation between the emerging light beams, so with this device it is easy to achieve a large macroscopic separation between the right and left circularly polarized beams, something that we could test *in situ* in a series of experiments we performed with this historical polyprism during the summer of 2018 [5].

The Fresnel triprism, or more generally, polyprism can be regarded as the experimental culmination of what perhaps was the most fruitful decade in the history of polarization optics, started with Arago's observation of optical rotation also found in quartz. Beyond this historical significance, we think that this optical device, today almost forgotten, can be again of scientific relevance in the XXI century as methods to produce and detect circularly polarized light are becoming more and more important in today's research and technology. ■

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FROM BASIC RESEARCH to innovations in quantum technologies

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First the physics, then the technology. The two main revolutions that took place in physics in the 20th century were quantum physics and relativity. Quantum theory has never been disproved, and although scientists continue to wrangle over what its concepts actually mean and how they should be interpreted, it has been successfully applied in many areas, and new applications are constantly emerging.

We owe almost all the fundamental discoveries in quantum physics to work conducted in the previous century by Bohr, Heisenberg, Schrödinger, Dirac, Pauli, de Broglie and many others. These discoveries have enabled us to understand the laws that govern matter, light, and the interactions between the two. Above and beyond these basic concepts, quantum physics has given rise to unprecedented technological developments (transistors, microprocessors, lasers, etc.) that have revolutionized our daily lives. The extraordinary experimental advances that have been made over the past few decades mean that we are now able not only to observe quantum objects such as photons, atoms and ions, but also to control them both individually and collectively, using the concepts of quantum superposition and entanglement to prepare and manipulate them (see Box). The applications are so promising that several countries, not least the United States and China, have made them a national priority. For its part, the European Commission launched its Quantum Technologies Flagship in October 2018, funding some 20 projects selected in an initial call for projects. In this article, we look at the Flagship's four application areas, namely quantum communication, quantum computing, quantum simulation, and quantum metrology and sensing, where spectacular results are expected over the short, medium and long term.

Secure quantum communication between cities and continents

Standard modes of communication and information processing have revolutionized society over recent decades. All five inhabited continents are now connected by undersea fibre-optic cables, and countries are criss-crossed with terrestrial and satellite links, allowing information to be carried and routed at high speed with no data loss over virtually limitless distances. However, when it comes to ultra-secure communication, the story is somewhat different. In many areas of public and private life, the need for data security has become a fact of life cornerstone, and represents a key strategic issue for businesses, large industrial groups, banks, governments, as well as for individuals. Current protocols for ciphering and unciphering messages are having to use increasingly complex codes and longer public keys, in a bid to keep one step ahead, as the classical computers capable of breaking these keys become ever more powerful. A more effective strategy must therefore be found, and this is where quantum physics comes in, as it can guarantee long-term immunity to hacking and spying on secure data exchanges.

Like classical cipher methods, quantum analogues rely on the exchange of randomly generated binary bits. However, whereas classical bits must be either 0 or 1, these two states can be superposed in quantum bits, or *qubits* (see *Box*). Photons are the preferred carriers for sending qubits over long distances, as they allow information to be encoded into observables such as light polarization (see *Figures* in *Box*). These photons are emitted either as single ones or by pairs by so-called single-photon (colour centres in diamonds,

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quantum dots) or photon-pair (parametric nonlinear optics) sources. Some of the quantum protocols for establishing secret cryptographic keys therefore use individual qubits, while others use pairs of entangled qubits.

Quantum cryptography can serve to generate keys for use in classical cipher protocols. This technology is already quite advanced, and has been used by a number of small companies to develop systems that are now on the market. For example, the Swiss firm ID-Quantique has applied it several times in real-world situations, including collecting information about online voting in the canton of Geneva. Tokyo has had a quantum crytography network since 2011, while China launched a quantum fibre link between Beijing and Shanghai in 2017. These cities are some 1200 km apart, and for the time being, data can only be reliably carried over distances of a few hundred kilometres in the absence of secure repeaters. A whole new area of research has therefore emerged to design quantum repeaters that can store bipartite entangled states at two remote locations, then synchronize the reemission of the photons. Alongside this research, quantum communication is starting to make inroads in space, as a source carried on a Chinese satellite distributed entangled photons to ground stations a record 1200 km apart. A new era of intercontinental quantum communication is therefore opening up for researchers and *quantum engineers*.

In a bid to increase the rate and range of quantum communication and make it even more secure, scientists are taking a close interest in the latest technological innovations in photonics and microelectronics. This should lead to the development of genuine quantum cryptosystems, starting with prototypes and eventually arriving at tested and certified devices. Recent experimental advances in the manipulation of entanglement at telecommunication wavelengths mean that researchers can now envisage quantum communication protocols on a large scale, whether this is in terms of the number of users who are connected or the

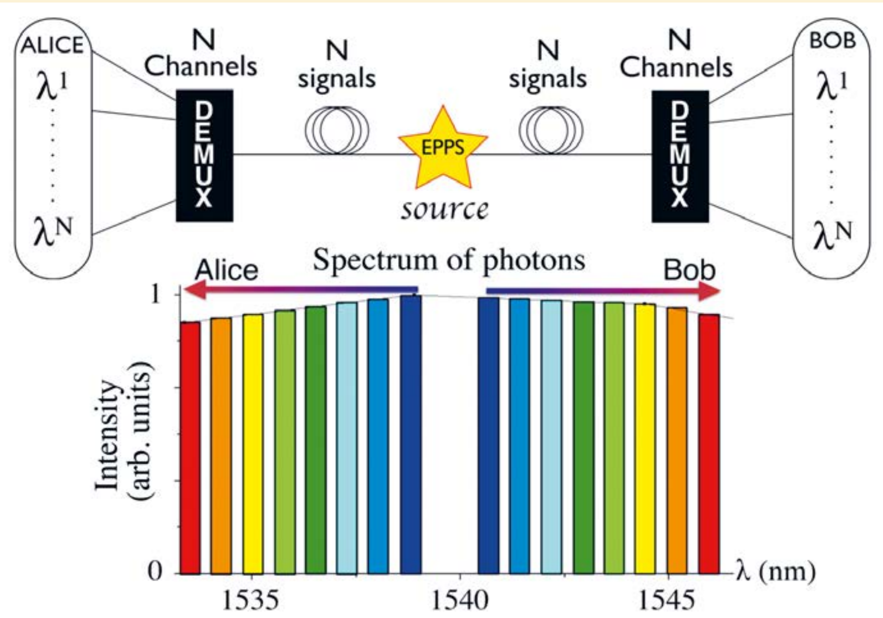

Figure 1. Operating principle of a quantum cryptography link over a distance of 150 km with a spectral demultiplexer at either end (Alice and Bob). The source delivers pairs of entangled photons with a spectrum covering the whole bandwidth. As the colour coding shows, the demultiplexing layers enable Alice and Bob to establish secret keys in each pair of complementary spectral channels. This strategy means that the total secret key rate is multiplied by the number of channel pairs that are used (Courtesy of Djeylan Aktas, Nice Physics Institute; see Aktas *et al.*, *Lasers & Photon. Rev.* **10**, 451-457, 2016). This figure is copyrighted and not subject to the Creative Commons license.

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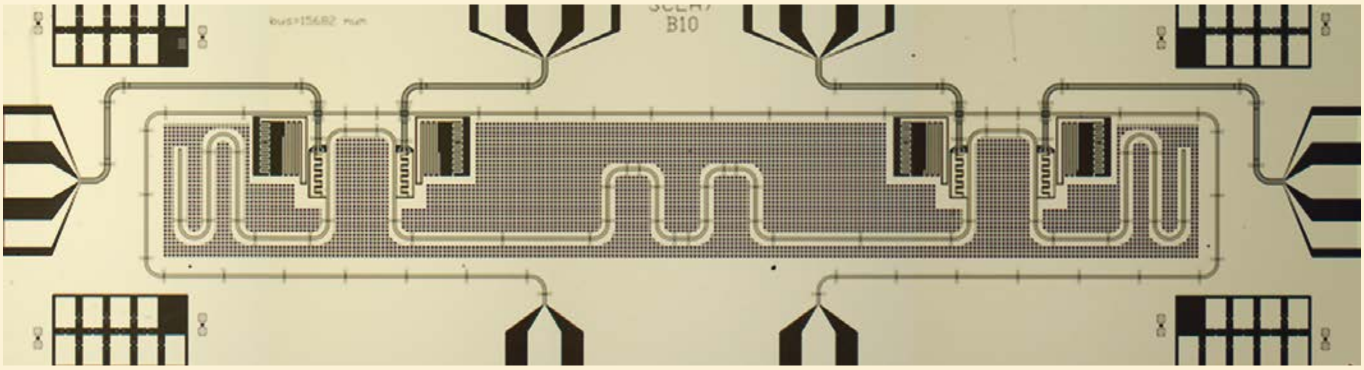

Figure 2. Prototype of a universal 4-qubit superconducting quantum processing system in aluminium that can measure individual qubits. Josephson junctions between the superconductors and microwave photons are the two key ingredients of this quantum processor, which has a total length of approximately 10 mm (Courtesy Daniel Estève, Quantronics Group, CEA-Saclay; see Dewes *et al.*, *Phys. Rev. B* **85**, 140503, 2012).

distances between them (see *Fig. 1*). Entanglement should allow for the development of officially certified cryptosystems, that is, systems that are independent of the hardware (sources and detectors) being used. There is a constant stream of new hybridization ideas, some involving the introduction of quantum cryptography into existing telecommunications systems, others the creation of post-quantum solutions based on classical cryptography that cannot currently be attacked by quantum computers. It will take years of R&D before the general public have access to a truly global quantum Internet, but the distribution of ultra-secure private keys between remote sites is already being seen as a means of defusing the threat currently posed by quantum computers to classical encryption systems.

Towards an ultra-powerful quantum computer?

The immediate goal of designing a universal quantum computer or processor is to go beyond the bounds that classical supercomputers will soon have reached. So high are the underlying stakes that a huge research effort is currently underway all over the world to build just such a quantum computer, in both academia and industry, with IT and Internet giants such as Google, IBM, Intel and Microsoft investing huge amounts of resources in it.

The idea is to perform massively parallel computing with an exponentially increasing number of operations taking place at the same time. The problem is that the applications of quantum computing rely on specific quantum algorithms that have to be implemented at the same time. So far, only a few such algorithms have proven quantum processing to be more efficient than conventional processing. The two best known ones were developed by Shor and Grover: the former can prime factorize large integers, while the latter can search an unsorted database for a single entry.

The basic underlying concept relies on the use of an entangled qubit register (see Box). The result of the computation is produced via a process of interference that depends on the initialization of the qubit register to the given problem and its evolution via logic gates. Decoherence stands as the main problem, as it tends to destroy the entanglement during the various computation operations, as a result of interactions with the environment.

A wide variety of basic building bricks have been tested in the quest to produce these qubits and construct systems capable of withstanding decoherence. In the race to set the record for the highest number of qubits in a quantum calculator (at least 50 are needed to achieve *quantum supremacy*), the most promising solutions are Josephson junctions (supercurrent; see *Fig. 2*), trapped ions (internal electronic states; see *Fig. 3*) and crystalline silicon (spin qubits). Google, IBM and Intel all recently announced that they had developed superconducting quantum computers with 72, 50 or 49 qubits, while the current laboratory record is for a string of 20 cooled calcium ions, which were used to demonstrate various elementary processes (see *Fig. 3*). Quantum processors with two-qubit logic gates have recently been demonstrated with superconducting systems using either the Josephson effect, silicon spin qubits, or integrated photonic systems.

The first hurdle facing all these potential systems is how to upscale the devices. The second one is how to control the errors introduced by the imperfect components of experimental devices, which make the system far less reliable. The number of errors increases extremely rapidly with the number of logic gates, and ever more sophisticated algorithms are being constructed (so far only theoretically) to detect and correct such errors. Programming a quantum computer is also very different from programming a classical computer, and requires new research by computing experts. In short, although it may seem extraordinarily difficult to develop technologies for quantum computers, there is no fundamental law of physics that prohibits it, and the privately held company D-Wave is already selling

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quantum computers.

Possible applications have yet to be identified. Above and beyond the threat looming over current public key encryption methods in classical cryptography, the main benefits are likely to be seen in quantum chemistry, with the discovery of new molecules, and high-temperature superconductors. Such is the power of quantum computing that it should also allow the flows of human and other resources to be optimized in the future (meshing of power and road traffic networks, etc.).

Quantum simulation of complex phenomena

It takes extremely powerful computers, or supercomputers, to design many of the complex objects and structures that fill our everyday world, such as cars, planes and public buildings. However, these computers are powerless when it comes to describing the behaviour of systems made up of more than a few dozen atoms and predicting whether they will conduct electricity, become magnetic or superconducting, or produce unexpected chemical reactions. Quantum simulation research is aimed precisely at answering these key questions, particularly in the field of condensed matter science, by applying the quantum simulation methods envisioned by Feynman, who was already talking about *"a quantum machine that could imitate any quantum system, including the physical world"* back in 1982. A range of different platforms or artificial systems can be used to gain a fuller understanding of how real-life systems made up of interacting quantum objects behave in conditions that cannot be directly observed. Theoretical and experimental scientists are working together on the design these artificial systems, which need to be flexible and adjustable (i.e., some or all of their parameters can be controlled), the general idea being that they obey the same quantum physics equations as the real-life systems they are intended to simulate.

One of the current approaches to quantum simulation involves the use of cold atoms, which offer a prime opportunity to conduct model experiments. Atoms are trapped in an optical lattice created by stationary waves from retro-reflected laser beams, ideally with one atom in each site, or held in a lattice by optical tweezers (see *Fig. 4*). Scientists can use Bosonic atoms (e.g., initially forming a Bose-Einstein condensate), Fermionic atoms (e.g., cooled to the degenerate regime below the Fermi

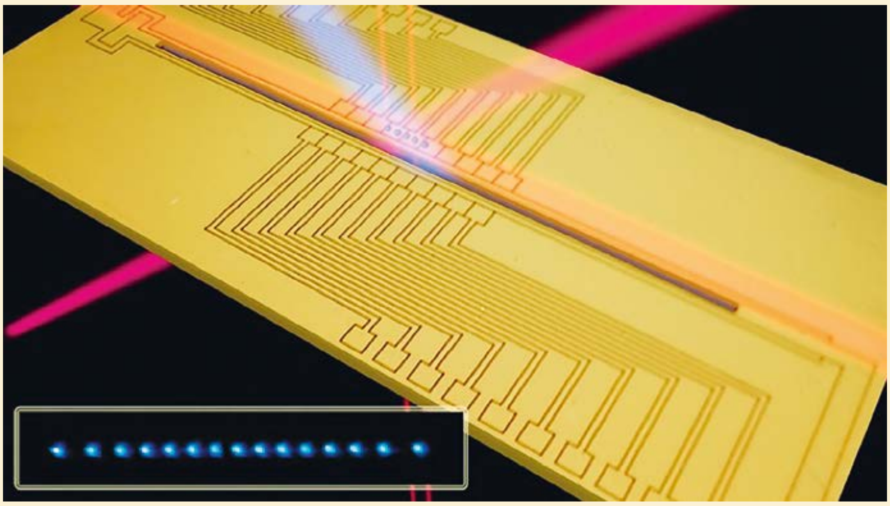

Figure 3. Image of calcium ions cooled and held in a single line in an electromagnetic trap (Paul trap). In the middle of the trap, two neighbouring ions are held 10-20 µm apart. The trap is mounted on an electronic chip where current-carrying wires create the electric and magnetic fields needed for the trap (Courtesy of Rainer Blatt, IQOQI, Innsbruck). This figure is copyrighted and not subject to the Creative Commons license.

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temperature), or both. Other types of experimental platforms for quantum simulation include cold trapped ions (see *Fig. 3*), or cold molecules, polaritons or excitons in semiconductors, networks of superconducting qubits or quantum dots, and even entangled photons in coupled waveguide arrays.

Each of these platforms allows some (but not all) of the simulation parameters to be controlled (temperature, number of particles, range and sign of the interactions, coupling with the environment, etc.).

We can therefore simulate many properties of matter, including the new low-temperature quantum phases, magnetism, nonequilibrium quantum systems (notably disorder-assisted quantum transport), topological phases, and materials. The Holy Grail is understanding the conditions needed for high critical temperature superconductivity, which remains shrouded in mystery. This would allow for the design of new materials capable of conducting electricity at ambient temperature with no energy loss, which would have huge repercussions for energy transport. Interfaces are also being developed with quantum chemistry, high energy physics and astrophysics.

Quantum sensors for high-precision metrology

Quantum state superposition is extremely sensitive to the environment, and can therefore be used to build high-precision sensors. Cold-atom accelerometers and gyroscopes

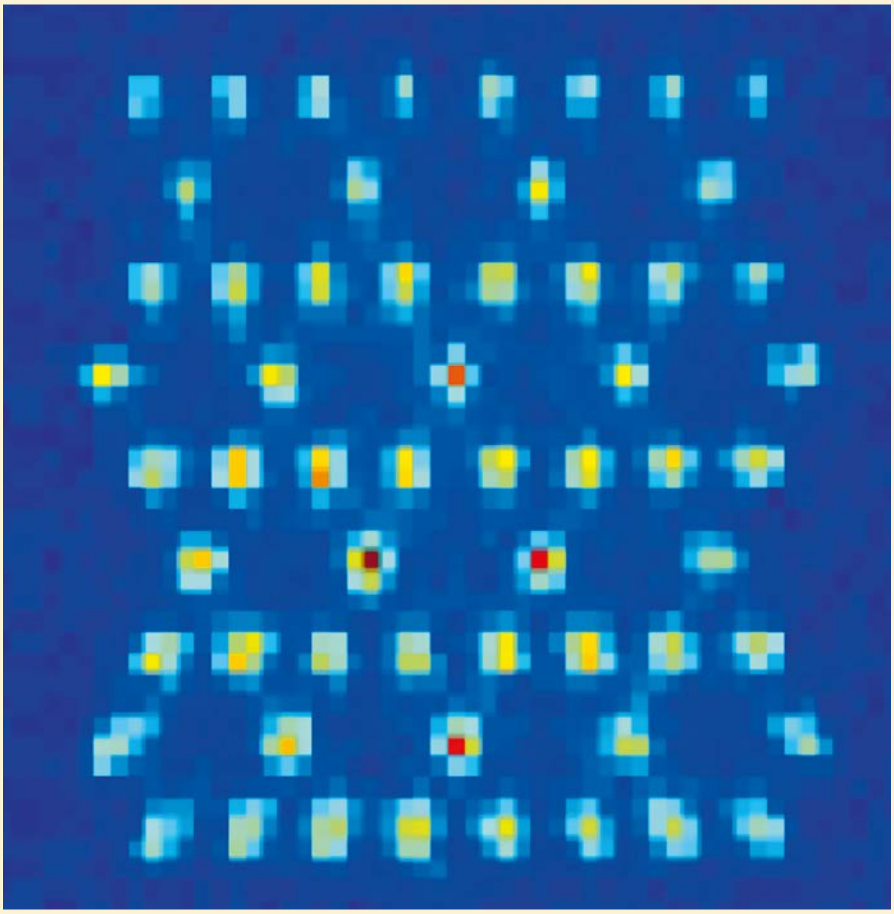

Figure 4. Image showing the fluorescence of cold rubidium atoms held in position by optical tweezers. These atoms can be used to build 2D networks with a variety of patterns (here hexagonal) and spacings (here 5 µm). The colour gradient at each site (from blue to red) indicates the probability of an atom being present (Courtesy of Antoine Browaeys, Charles Fabry Laboratory, Institut d'Optique Graduate School). This figure is copyrighted and not subject to the Creative Commons license.

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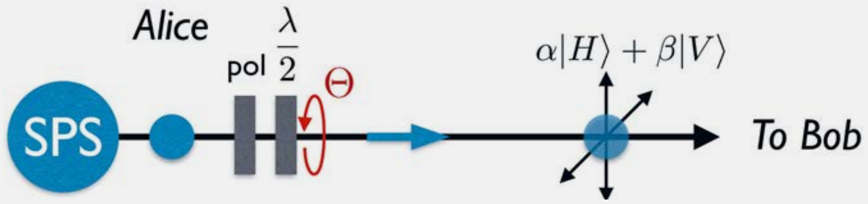
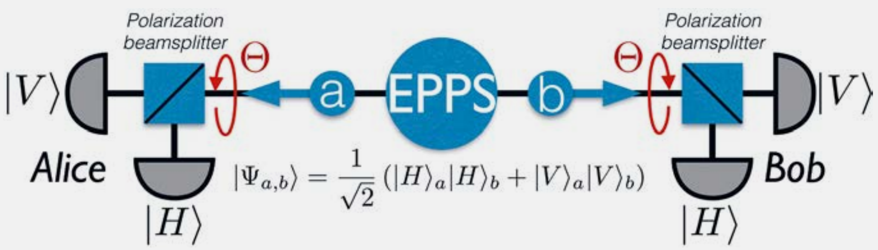
Coherent-state superposition, qubits and entanglement

Classical computing relies on bits, which can have two values (0 or 1) corresponding to states labelled by the notation $|0\rangle$ and $|1\rangle$. Quantum physics offers infinite possibilities, with all the combinations given by the *coherent superposition of two basis states* $|0\rangle$ and $|1\rangle$. For example, let us consider a photon that is horizontally polarized after passing through a polarizer (see figure, where SPS stands for single-photon source). If we add a half-wave plate and rotate it by an angle θ (shown in red in the figure), we obtain the superposition $\sin\theta\,|H\rangle + \cos\theta\,|V\rangle$ of the horizontally $|H\rangle$ and vertically $|V\rangle$ polarized states. This gives rise to a qubit in the form of $\alpha\,|0\rangle+\beta\,|1\rangle$, with the relative weights α and β varying with the angle θ while satisfying the normalization rule $|\alpha|^2 + |\beta|^2 = 1$.



Photonic qubits encoded into the polarization observable are widely used in quantum cryptography, as are those encoded into the time and frequency observables. Qubits can be based on any quantum system – whether it involves natural or artificial particles – that has two distinct states that can be superposed. They are emitted by SPSs that are located here with Alice, who encodes the qubits into the polarization observable using a polarizer (P) and a half-wave plate. The blue arrow indicates the direction of photon propagation from Alice to Bob.

Entanglement represents the generalization to two or more quantum systems of the coherent superposition of states defined for creating a qubit. Staying in the field of optics (see figure below), let us consider a source that emits pairs of entangled photons (EPPS). The usual way of creating this source is to use a nonlinear crystal, which turns a single photon from a pump laser field into a pair of photons with half the energy (not shown in the figure). The pair of entangled photons must be considered as a single quantum system, made up of two subsystems, from the moment it is created to the moment when the photons are detected, if they are far apart. When a measurement is made on one of the two photons, the result of the measurement on the other is immediately determined.



Here, an EPPS emits a pair of entangled photons where the quantum information is encoded into the polarization observable. The pair of photons is then prepared in a well-defined state $|\psi_{a,b}\rangle$, unlike the states of the individual photons. In other words, quantum information is encoded on the quantum object made up of the two photons, from the creation of the pair until its detection: we talk about entangled qubits. Experimentally, the photons are sent to two distant users, Alice and Bob, who each have a polarizing beamsplitter cube, set at an angle of 90° to each other, followed by two detectors. This enables them to project the state of the received photon into an analysis basis, here, the horizontal and vertical polarizations basis. By rotating the half-wave plate (red arrow), they can change the analysis basis. The crucial point is that until Bob has made a measurement, Alice's photon has no defined polarization, as it is solely the state of the pair that counts from the viewpoint of the information. This strategy enables the two communicating parties to reveal nonlocal correlations or to establish secret keys for use in cryptography operations.

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are based on the principle of atomic interferometry. They detect motion-induced phase shifts between matter waves that have travelled along the two paths (or *arms*) of an interferometer (see *Fig. 5*). These accelerometers and gyroscopes can measure acceleration or rotation extremely accurately, thus making them highly reliable for inertial navigation systems.

When these interferometric systems are vertically positioned, they can be used as gravimeters. The atoms fall under the effects of gravitational acceleration (*g*), which can therefore be continuously measured for an unlimited time as an absolute value, with a relative uncertainty of less than 1‰. Present and future applications for these kinds of systems lie in seismology as well as oil, gas and mineral exploration.

Interferometry is also key to the functioning of atomic clocks - quantum systems that measure electron transition frequency. Now used in the field of optics, the latest generations of atomic or cold-atom clocks achieve truly spectacular precision (drift of just one second in 14 billion years, the believed age of the universe!). They can serve many purposes, such as defining universal time (synchronization of all clocks on Earth), enhancing the current Global Positioning System, and facilitating space navigation. Their sensitivity to gravitational shift means that they can complement gravimeters, which will doubtless be used in the future to improve our knowledge of the geoid. All these laboratory quantum instruments are set to become more compact, and some are already being made market ready, such as the gravimeters designed and manufactured by the Bordeaux-based company Muquans.

Major advances in the control and reduction of classical sources of noise mean that the sensitivity of these sensors will soon reach the *fundamental limit* of the achievable signal-to-noise ratio (i.e., *quantum noise*). Current research is therefore focused on finding ways of going beyond this limit, using particular quantum states of matter or radiation (e.g., spin-squeezed states). By applying the appropriate optical method, it is possible to reduce fluctuations in the intensity of a light beam to the detriment of fluctuations in phase, or even reduce fluctuations in the position of atoms in a gas to the detriment of fluctuations in their speed. Advanced LIGO and Advanced Virgo, two giant laser interferometers that were built to detect cosmic gravitational waves, are currently undergoing squeezed light upgrades to enhance their sensitivity.

Lastly, photonics-based precision measurement techniques are also starting to emerge, notably with the use of pairs of entangled photons to determine optical material properties such as the refractive index and chromatic dispersion. Scientists are already talking about quantum white-light interferometry, which could lead to the development of new fibre optic systems operating on new wavelengths, such as lasers for medicine or molecular spectroscopy.

Benefits for society

We can start by saying that none of the quantum technologies described here could have been imagined as little as 30 years ago. Today, the long-held dreams of scientists across many different disciplines – not least physics and computer science – are finally being fulfilled, as subtle theories and sophisticated experiments give rise to exciting new technologies. Although it is too early to say how long it will be before these are commercially produced on a small or large scale, they are bound to change our daily lives. But will it be to the greater good of humanity? Given the threat of terrorism, some may wonder whether totally secure communication is really such a good thing, but then again, if it becomes possible one day to hack the classical keys to certain state secrets, then global geopolitics will be thrown into disarray. Taking this to its logical extreme, if the security of the classical Internet we all use can no longer be guaranteed, what will be the consequences for the world in which we currently live? The ethical ground rules for the responsible use of all these new quantum technologies have yet to be laid down. We can nonetheless look forward to the optimization of existing processes through quantum computing and algorithms, and the use of quantum sensors to provide increasingly accurate measurements of physical parameters. ■

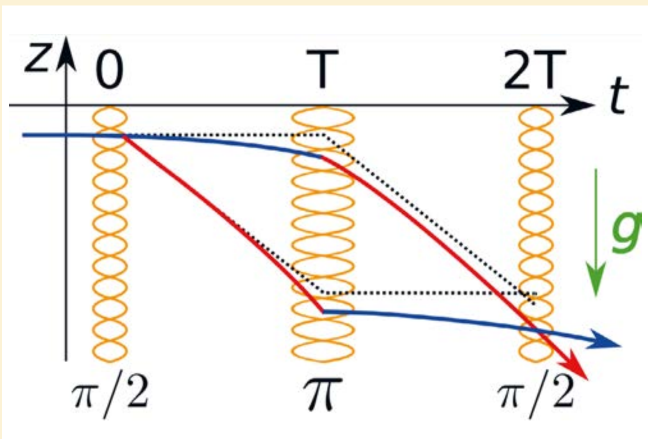

Figure 5. Diagram showing the working principle of an atom interferometer using free-falling cold atoms. The z-axis represents acceleration due to gravity (*g*) in the vertical direction. Matter waves arriving from the left interact three times with stationary laser beams that apply pulses to them. After the first pulse, the matter wave undergoes a phase shift of π/2 (referred to as a π/2 pulse), and is split into two propagation paths (shown in red and blue). These two colours represent the two quantum states paired by the lasers, which differ in their pulse state. The following π/2 pulse serves as a mirror, redirecting the two components of the matter wave. The interference produced after the final recombination π/2 pulse depends on the phase differential accumulated along the two arms of the interferometer. In the absence of gravity, there would be no interference (dotted lines). However, as the atoms fall vertically, the phase shift is proportional to *g*, which is inferred by the displacement of the interference fringes. This is how a cold-atom gravimeter is made (Courtesy of Franck Pereira dos Santos, SYRTE Laboratory, Paris Observatory). This figure is copyrighted and not subject to the Creative Commons license.

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BACK TO BASICS: Time-tagging single photons

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The analysis of time correlations between photons is the essence of quantum information processing protocols (communication, metrology and computing) presented in this special issue. These correlation measures are derived from fundamental quantum optical techniques formalised by R. Glauber in 1963 [Phys. Rev. 130, 2529] which enable the properties of electromagnetic fields to be measured, *i.e.* their fluctuations and signatures to be detected in a noisy signal. More generally, those fluctuations are the result of high order interferences and are, in certain cases, directly linked to the "traditional" coherence of the optical fields.

An analysis of the time correlations between two modes, 1 and 2, of the electromagnetic field takes the mathematical form of a normalised function such as

$$g^{(2)}_{1,2}(\tau)=\frac{\langle I_1(t)I_2(t+\tau)\rangle}{\langle I_1(t)\rangle\langle I_2(t)\rangle}=\frac{\langle :N_1(t)N_2(t+\tau):\rangle}{\langle N_1(t)\rangle\langle N_2(t)\rangle},$$

which enables to determine the degree of correlation of the fluctuations of the optical intensities $I(t)$ of the two modes, observed at two instants separated by a duration τ. It should be noted that, from a quantum standpoint, we can also express this magnitude using the numbers of photons $N_i(t)$ in a mode i. An easy interpretation of $g^{(2)}_{1,2}(0)$ can be obtained in a simple experiment, as illustrated in *Figure 1*. It consists in comparing the number of photons detected in each mode for each instant. If the time distribution of the photons in each mode is completely random and independent, then there is no correlation, which corresponds to a degree of correlation equal to 1. Conversely, if the time distributions of the photons are correlated, *i.e.* there is a photon simultaneously in each mode, then

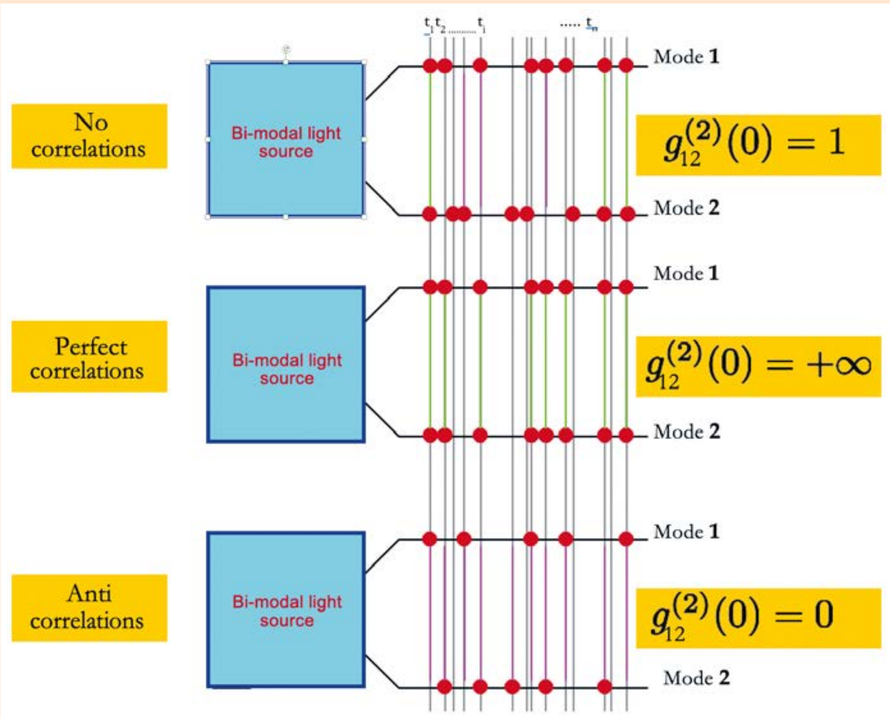

Figure 1. Analysis of correlations of the number of photons between two modes. The **correlations** (presence of a photon in each mode at instant *t*) are identified by a *green trace*, whereas the anticorrelations (presence of a photon only in one mode or the other) are identified by a purple trace. The aim in this case is to measure the correlations in the fluctuations of the light intensity between modes 1 and 2 over time. At the photon scale this corresponds to the conditional probability that a photon is present in mode 2, bearing in mind that a photon is present in mode 1. We have represented 3 (pedagogical) cases corresponding respectively to a photon pair source (perfect correlations), a coherent laser (complete lack of correlations) and a single photon source (perfect anticorrelations).

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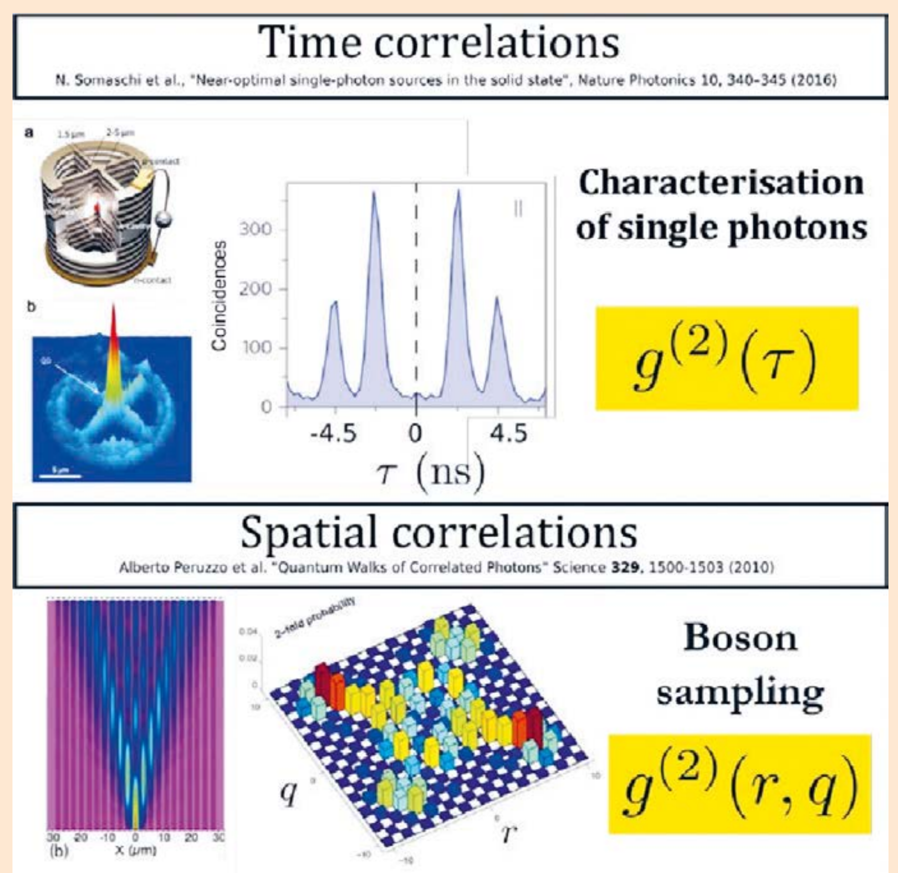

Figure 2. Two applications in quantum optics for the measurement of photon correlations. In the case of time correlations the aim is to characterise a single photon source based on a quantum dot [2] operating in the pulsed regime. In this case, it is the absence of a correlation peak at $\tau = 0$ which is significant. It reflects the fact that two photons are never produced simultaneously by the source. Conversely, the presence of correlation peaks at $\tau \neq 0$ is interpreted as the probabilities that a second single photon will be emitted in the next or previous pulses. Typically, it is the ratio of the two peaks (central to lateral) which enables the quality of a single photon source to be determined. In the spatial case, we introduce boson sampling, which consists in calculating the spatial correlations of a pair of photons at the output of a network of coupled waveguides of dimension $k \times k$ in which the coupling between the guides enables the action of beamsplitters to be simulated [3]. In this case correlated detection of photons is essential, since it enables the pairs of photons which actually travelled together (i.e. in the form of a two-photon wave packet) to be distinguished from those which travelled independently of one another (in the form of two single-photon wave packets). In fact the spatial signature at the output of the network in the two cases differs greatly, due to two-photon interference, which has no conventional equivalent.

function $g^{(2)}_{1,2}(0)$ takes a value higher than 1, which directly reflects the degree of the correlations. Finally, if the time distribution is such that there are perfect anticorrelations between the two modes, then $g^{(2)}_{1,2}(0) = 0$, showing there is only a single photon among the two modes.

Generaly speaking, the degree of correlation is expressed as a function of space and time such as $g^{(2)}(x,t)$. In practice this function is often reduced to a single variable, depending on the considered experiment. As illustrated in *Figure 2*, the "time" configuration is, for example, used to characterise single photon sources, for which we are looking for anticorrelations at $\tau = 0$ [2]. Indeed, in the case of an ideal source, one should never observe two photon at the same *time*, such that the autocorrelation function $g^{(2)}(0)$ has a value lower than 1 (ideally 0). Spatial correlations, for their part, are exploited in quantum computation, *i.e. boson sampling* for instance, which is a very difficult task for a conventional computer [3]. The aim is to analyse the spatial distribution of a pair of photons at the output of a $k \times k$-dimension

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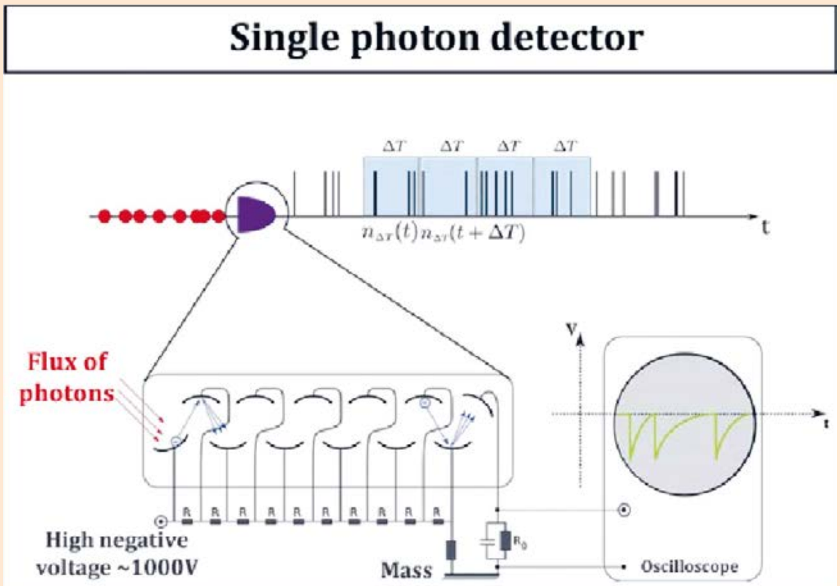

Figure 3. Principle of a photomultiplier. Incident photons produce, by cascade, electrical pulses whose time distribution reflects that of the incident photons. In practice a photon gives rise to a photoelectron which is not sufficient to obtain a signal which can be measured directly. However, after few tens of bounces the amplification is such that the quantity of electrons is high enough to allow each photoelectron to be registered. One million electrons form, indeed, an electrical charge $Q = 10^{-13}$ C, the electrostatic action of which, although low, is perfectly measurable. Arriving all together at a single instant, they temporarily charge readout capacitance C_L positioned where the last electrode was. For instance, a capacitance of 10 pF can lead to voltages of the order of $Q/C \sim 10$ mV, ~ 10 mV, which are easily observable, and can be counted with an oscilloscope. The user can then extract a magnitude *n(t)* which corresponds to a number of photons detected over a time unit *ΔT*.

network of half-silvered mirrors (each mirror reflects or transmits a photon with a probability of 50%). In this case, we are interested directly in spatial correlations (i.e. the joint probability that a photon exits the network through port r and, while the other photon leaves simultaneously through port q), through correlation function $g^{(2)}_{r,q}(0) = g^{(2)}(r,q)$.

These few examples enable us to put the issues of correlated photon detection in context, but pose several questions: how can a single photon be detected? To what type of signal does the detection of a photon correspond? What are the important characteristics which define a good "photon counter"? Which experimental methods enable the detection of a photon to be "time-tagged" accurately?

What difference is there between a detector with several photons and a single photon detector?

Let us suppose that we have an ideal source of single photons at 980 nm which emit photons on demand at a rate of 1 MHz: this corresponds to a

What detectors in practice? Conventional and less conventional single photon detectors

These are detectors operating along the principle of the photomultiplier, *i.e.* sensitive to single photons and capable of sending a conventional signal enabling the individual arrival times of these photons to be "tagged". In practice experimentalists now have access to detectors associated to a very high gain based on reverse-polarised semiconductor diodes operated near their breakdown voltage (the reverse voltage at which the diode switch to conducting states). The principle of amplification occurs as follows: the arrival of a photon gives rise to an electron-hole pair which is accelerated to the edges of the junction, and triggers an avalanche by switching the diode to the conducting state. An avalanche of electrons can then be measured at the terminals of a simple resistor. Recently, a new technology based on superconductor materials has appeared. The operating concept is related to the operation of a bolometer which is extremely sensitive to the heating of the material when a single photon is absorbed. An optical fibre delivers light to the surface of a superconducting stripe (of resistance zero to approximately 2 K), in which a direct current of several nA is flowing. The quantity of energy provided by a photon ($2\ 10^{-19}$ J) is sufficient to locally switch the material to be resistant to the passage of the current. The increased potential difference at the stripe's terminals enables the arrival of a single photon to be "seen".
Currently, the activity of research and development into superconductor detectors is progressing in leaps and bounds.

The performance of the laboratory devices shows efficiency close to 95%, time jitters of the order of 10 ps, and maximum counting rates of 100 MHz for dark counts rates of less than 10^{-9} ns. No single detector combines all these qualities for the time being, but the community has observed performance improvement of single photon detectors of a factor of 100 over 10 years.
Anecdotally the human eye could act as a photon counter. It is commonly accepted that a trained eye well accustomed to darkness is sensitive to a flux of 100 photons per second, but recent experiments show that it is, in fact, capable of resolving a single photon [5]. However, the eye must be used only with a very relative confidence, since reliability (not efficiency, which excludes the probability of believing that one has seen a photon when there was nothing) is only very slightly higher than 50% for "counting" photons.
From another angle, all detectors presented up till now are inexorably associated with absorption of the photon: measuring the photon often means losing the photon! Prolific research activity is being devoted to implementing quantum measuring techniques which are non-destructive of single photons. These measurements generally rely on an atomic interferometry assembly, and exploit the light-material interaction to cause small phase variations in the core of the interferometer. The difficulty of this technique lies in the ability to resolve these small phase jumps when a photon passes [6].

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light power of 2 10^{-13} W. Although it is true that a conventional detector – assuming that each incident photon releases one electron by photoelectric effect – can easily "accumulate" over time few hundreds of photoelectrons to obtain a charge which can be measured at the terminals of a capacitance, its low gain means that it is not capable of detecting a single photon. The appropriate solution is that of a photomultiplier tube as pedagogically represented in *Figure 3*. Few tens of electrodes subjected to increasing potentials are enclosed in a vacuum tube. The first, at the lowest potential, is a photocathode which, upon the absorption of a photon, emits a photoelectron. This electron is accelerated to the second electrode, and strikes it with a kinetic energy enabling several electrons to be extracted from the metal. When released, these new electrons are subsequently accelerated towards the next electrode, where they again extract several electrons each. The number of electrons is thus gradually increased, and a charge Q received by the last electrode is rapidly amplified by a factor of 10^6. This gain is sufficiently large to enable individual detection of the initial photoelectron at the terminals of a capacitance C. The phenomenon can be observed simply using an oscilloscope in the form of short pulses of amplitude $V_0 = Q/C$. The user therefore receives electric pulses which he can "count" over the time interval of his choice ΔT. This number can be averaged and expressed in Hz in certain circumstances, but the information contained in the instant of arrival of the photon would be lost [4].

The difference between "photon detectors" capable of measuring light fluxes of several hundreds of photons and true "photon counters", capable of resolving the arrival time of a photon, is substantial. These are two completely different devices which do not supply the same signal, and which must not be confused. Quantum technologies require the photons to be detected one-by-one.

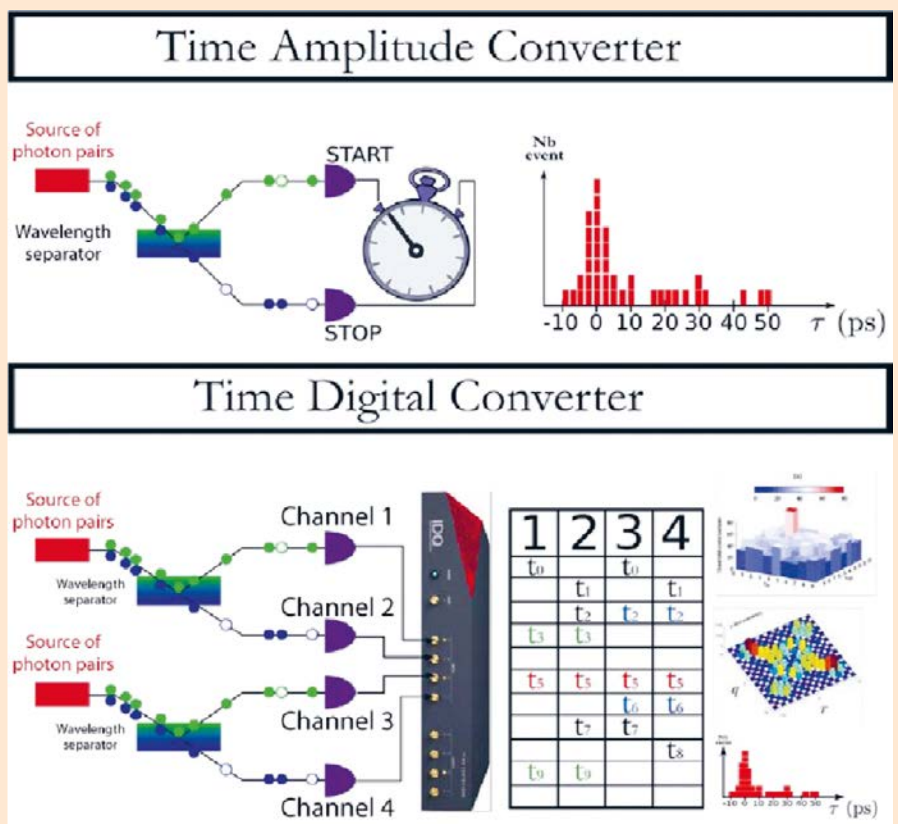

Figure 4. Principle of photon time-tagging. There are two ways of processing the data associated with the detection of single photons. The first consists in measuring time intervals between two events using a time-amplitude converter. The second is more sophisticated and more flexible since it consists in associating a label with precise time information with each detection.

Systems for dating electric signals

Surprinsingly, the first correlation devices were derived from research in particle physics, but did not enable an arrival time to be attributed to the photons. These were two-channel correlators (*time to amplitude converter*) which measured only the relative time which elapsed between two events received in each channel. In other words they were simple, but high-precision, chronometers, with a "start" channel and a "stop" channel, coupled to an analog-digital converter. This type of device then enabled bar charts to be produced showing the coincidences as a function of time τ separating the start and stop events such as the one shown in *figure 4*. It is easy to show that this diagram is directly related to time correlations function $g^{(2)}(\tau)$ presented at the beginning of the article. Their time resolution is now unequalled (~1 ps). However, the fact that they operate only using two channels limits any use in experiments using more than two photons.

Progress in the field of electronics has led to the appearance of high-precision dating systems (*time digital converters*). In this case it is simply an ultra-precise clock (between 10 and 100 ps) which enables a time label to be attributed to each detection, which is then kept in memory. Its strength lies in the number of accessible channels and in the richness of the possible post-processing analyses.

Application to observation of energy-time entanglement of pairs of photons

In the case of quantum technologies based on photonic solutions, pairs of entangled photons are a widely exploited resource. These pairs are commonly generated by parametric

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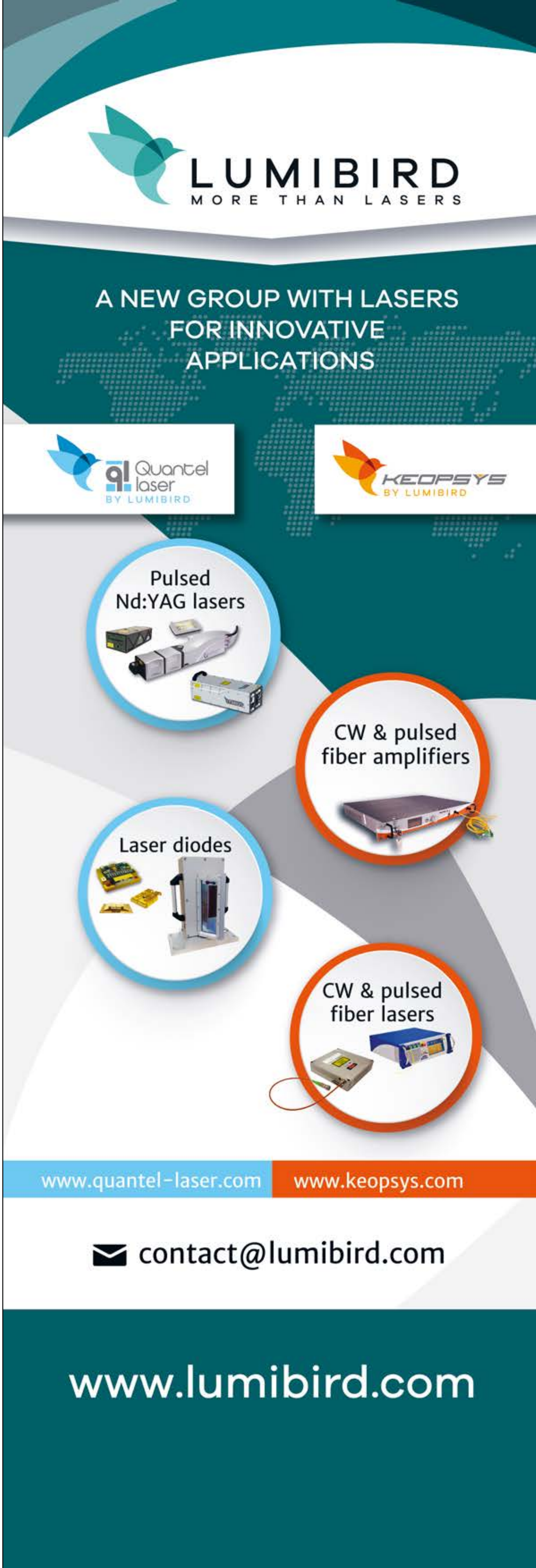

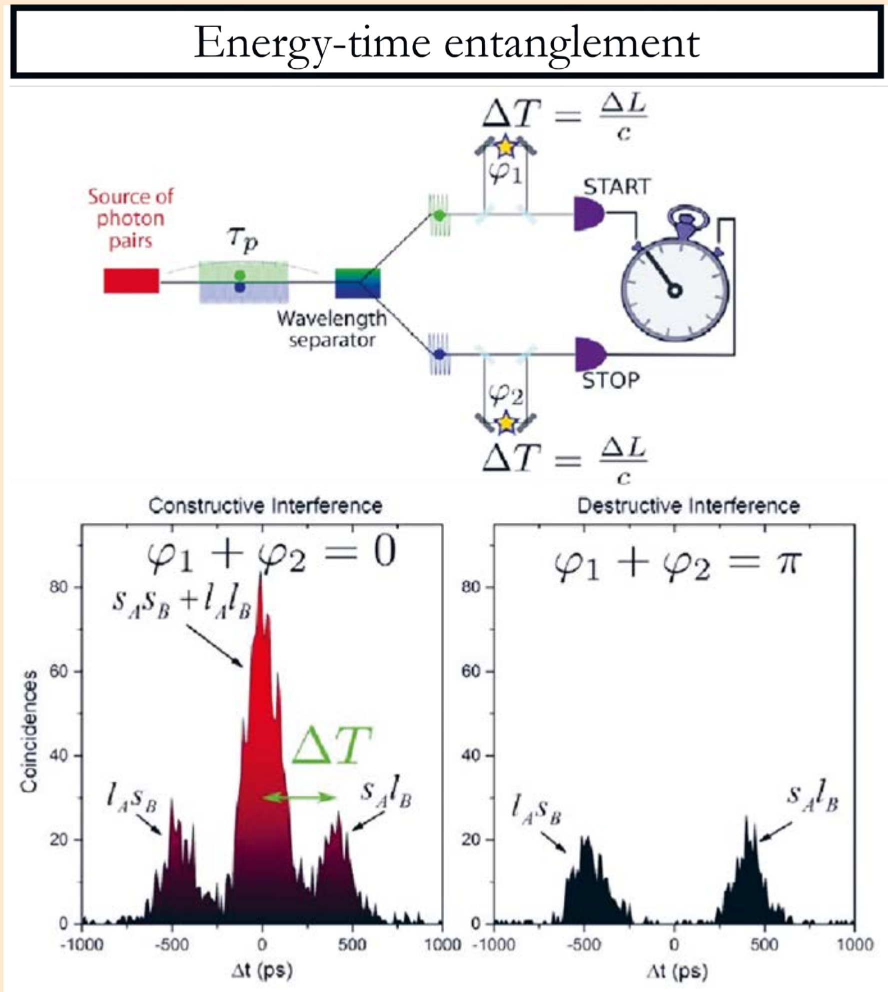

Figure 5. Measurement of energy-time correlations of pairs of entangled photons via an « Franson -type » interferometric setup. The key point of this device consists in observing the coherence of the pairs of photons via a phenomenon of interference, whilst avoiding observation of the single photon interferences. To accomplish this, the experimental conditions require highly unbalanced interferometers and a time tagging unit enabling the separation of the pair of photons contributions (central peak) from that of the two individual photons (lateral peaks). It is thus possible to observe interference patterns (not represented) which oscillate with the sum of the adjusted phases (φ_1 et φ_2) in the long arms of the interferometers. By imagining the interferometers separated by several tens of km, we can predict "the distance influence" of a choice of phase (φ_1 ou φ_2) on the result of the joint measurement. This is a manifestation of the quantum correlations non-locality.

down conversion of a pump photon into a pair of photons in a nonlinear crystal. This process respects the principle of energy conservation, which imposes strong correlations between the photons of a given pair. Bearing in mind that the paired photons are necessarily generated simultaneously, but that the instant of emission of a pair is coherently delocalised in according to the coherence time of the laser, one then speaks of *energy-time entanglement*. An experimental assembly enabling these correlations to be revealed has been proposed by J.D. Franson [7] and requires to observe photon pair interferences, strictly avoiding single photon interferences. To do so, two highly unbalanced Mach-Zehnder interferometers $\Delta T = \Delta L/c$, but which are identical to one another, are used as presented in *Figure 5*. After the interferometers, the state of a photon pair is written as the coherent superposition of 4 configurations:

$$|\psi\rangle = e^{i\varphi_2}|s_1 l_2\rangle + |s_1 s_2\rangle + e^{i(\varphi_1+\varphi_2)}|l_1 l_2\rangle + e^{i\varphi_1}|l_1 s_2\rangle$$

where *s* and *l* correspond respectively to the "short" or "long" paths followed by the photons of each mode (1 and 2) and 1, 2 are the phase shifts introduced in the long arms of both interferometers. The time correlation trace of such a state corresponds to three peaks, and it should be noted that the central peak is the result of the superposition of two indistinguishable paths $|s_1 s_2\rangle$ and $|l_1 l_2\rangle$ when coherence τ_p of the pair of photons (which is linked to that of the pump laser) is indeed higher than $\Delta L/c$. It is therefore possible to observe a phenomenon of (nonlocal) interference which takes the form of a disappearance of the central peak under certain conditions of the sum of phases $\varphi_1 + \varphi_2$. Only counting of time-correlated photons, *i.e.* using photon counters associated with a time correlations analysis device, enables this quantum phenomenon to be observed experimentally. ■

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PURCHASING a femtosecond oscillator

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What is the purpose of a femtosecond oscillator? The answer cannot be a very short one, in light of the multiple applications developed around this type of instrument, in the fields of microscopy, metrology, not to mention micro-machining or surgery, and including applications in the field of fundamental physics.

Femtosecond laser systems are almost as varied as their applications. So before choosing such a system it is important to carefully assess the determining parameters for the experiments which are to be performed. The first question one should ask oneself is, naturally: which oscillator should I choose? Although the oscillator is sometimes integrated in an amplified chain and its characteristics do not impact the overall performance of the global system, some of its specific features should be considered. The operating range of femtosecond oscillators is quite broad in terms of wavelength (typically in the red and near-infrared ranges), of duration (from several hundredths of fs to sub-10 fs), of repetition rate (tens of MHz to several GHz) and of energy (nJ to µJ). In addition to these criteria it must be borne in mind that they are not all mutually compatible, and that many options can be added, such as carrier envelope phase stabilisation (CEP), wavelength extension by non-linear effects, pulse picking, etc. We shall try to shine some light on these matters by providing – non-exhaustively – a few ways to approach the problems involved in purchasing one.

Technical analysis of femtosecond oscillators

For a good understanding of the anatomy of a femtosecond oscillator, let us start from this truism: it is a laser cavity designed to produce ultra-short pulses. To achieve this, three functions must be inserted in the cavity: laser gain, clearly, a non-linear effect of the saturable absorbent type (in the widest sense), to favour the pulse regime, and control of group velocity dispersion to guarantee satisfactory propagation and stability of the ultra-short pulses in the cavity. Let us now analyse these various points to assess their impact on the product.

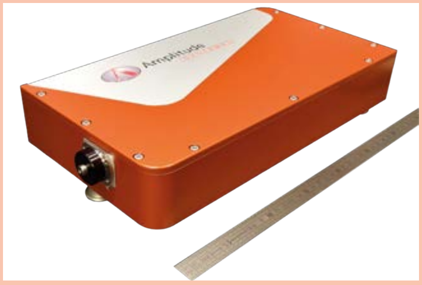

Figure 1. Photograph of industrial fs oscillator, based on a crystal doped with ytterbium (photographic credit Amplitude Systemes).

The primary purpose of the laser material is to amplify, but it is responsible for most of the characteristics and the potentials of the femtosecond laser. It is thus the choice of the laser material which will impose the central wavelength and the tuning range. It will also determine the accessible minimum duration[1]. The choice of a fibre-based oscillator will also be an important choice in terms of ease of integration and cost. From another standpoint, crystal oscillators enable higher energy levels to be obtained. Finally, the choice of the material will (or will not) allow the use of direct pumping by power laser diode, allowing lasers of high average power, which are efficient and less expensive.

The choice of the non-linear effect which will play the role of saturable absorber is important above all for the system's reliability and reproducibility. From this standpoint it is generally preferable to choose Kerr lens mode-locking (KLM) or locking by the semiconductor-based saturable absorber (SESAM), with the disadvantage that the first does not operate for all types of materials (e.g. fibres), and that the second tends to restrict the spectral bandwidth.

Dispersion compensation can be accomplished using prisms or mirrors for crystal systems, and using gratings or dispersion-controlled fibres for fibre-based systems. With a view to simplification and greater compactness, systems with prisms or gratings are sold increasingly rarely. The cavity[2], for its part, will determine the repetition rate of the oscillator. It is sometimes advantageous to choose low frequencies (20-40 MHz) to favour pulse energy and/or reduce the constraints for a possible pulse picker.

The choice of oscillator must be made in light of the fact that extensions or options can be associated with it. These are a few examples:

- The repetition rate can be reduced by adding an acousto-optical or electro-optical modulator. Even if the modulator's efficiency is generally satisfactory, this decimation greatly reduces the average power and often implies post-amplification.
- Wavelength extension can be accomplished by adding a non-linear module. Let us cite, for example, access to the visible wavelengths by generation of second or third harmonics (SHG, THG). The use of optical parametric oscillators (OPO) after the lasers is also often advantageous. Indeed, even if the energy is generally reduced by an order of magnitude the use of OPOs and of SHG allows access to wavelengths covering several octaves.
- Dispersion compensation modules can be added to the oscillators' outputs to pre-compensate for group velocity dispersion in the analysed samples (e.g. in microscopy).
- Finally, femtosecond lasers can also include control systems which finely tune the optical length of the cavity to create new functions. This is useful, for example, to guarantee synchronisation of the sequence of pulses (synchrolock) or to stabilise the envelope phase (carrier-envelope phase, CEP). As shown by *figure 2*, this type of control greatly increases the complexity of the oscillator's architecture.

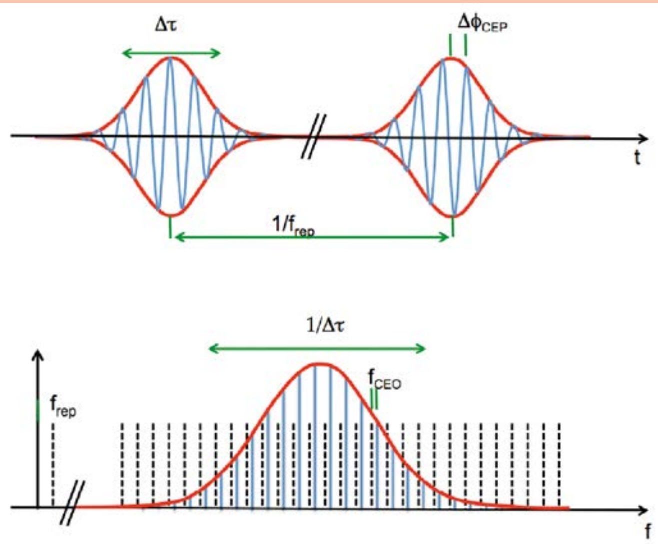

Figure 2. Time-frequency correspondence. Definition of repetition frequencies frep, of the offset between the carrier and envelope fCEO (CEO carrier envelope offset), and the CEP (carrier-envelope phase) of the laser.

The major families of oscillators

Commercial femtosecond lasers can, globally, be divided into three major categories according to the gain material, or then into two types of architecture (crystal-based or doped fibre-based).

Crystal-based femtosecond lasers

Systems based on sapphire doped with Ti (Ti:Sa), which emit between 700 and 1100 nm (with more or less spectral tuning), are very dominant in the niche of 7-30 fs ultrafast lasers. This constitutes their main benefit. The oscillators' average power is typically between 100 mW to few watts. Their main disadvantage is their pumping in the green, which leads to complex and expensive systems. Mode-locking uses KLM. These lasers are very widely used in non-linear microscopy (even though they are tending to be replaced by Yb+OPO laser systems), or to seed high peak power laser chains (TW and PW lasers). Ti:Sa oscillators can be stabilised in CEP and can be used in the field of metrology.

For their part, the main advantage of crystal lasers doped with Yb^{3+} is that they are able to supply very

[1] More technical details will be found on the subject in *New laser crystals for the generation of ultra-short pulses*, Comptes Rendus de l'Académie des Sciences, Recent advances in crystal optics, C.R. Physique 8 153-164 (2007) and in *Systèmes femtoseconde, optique et phénomènes ultra-rapides*, pp 13-49.
[2] By adjusting its length and the pulses roundrip time.

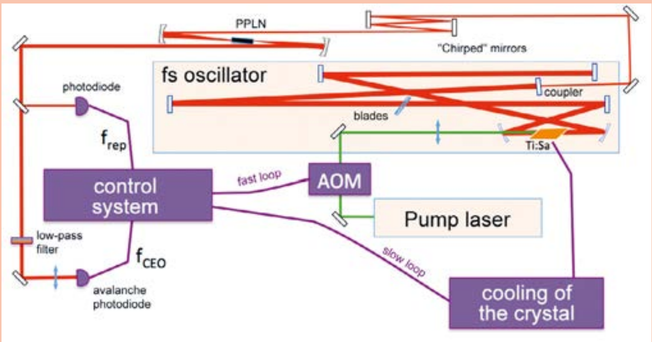

Figure 3. Example of CEP-controlled Ti:Sa laser (CEP: carrier-envelope phase) (source Rainbow of Femtolaser/SpectraPhysics). The Ti:Sa oscillator is stabilised using two control loops. The PPLN non-linear crystal enables a frequency difference to be made between the two extreme parts of the spectrum, which are then made to interfere with the original spectrum to measure fCEO (CEO: carrier-envelope offset). AOM: for acousto-optical modulator.

high average power levels (up to several tens of W) and energy levels (up to µJ) since they are pumped directly by diodes. However, their duration generally remains in the range of 100-800 fs and their emission is restricted to around 1030 nm. These systems generally use a SESAM. Finally, Yb-based oscillators are *de facto* compatible with Yb amplifier technology, which allows record average powers and efficiencies.

Fibre-based femto lasers

The advantage of fibre lasers is that they can prevent any propagation in free space, making these systems extremely robust to external conditions. They can also be coiled in cassettes and compacted. To lock the modes in phase, they generally use SESAMs, or alternatively take advantage of the strong non-linear effects in the fibres (typically non-linear polarisation rotation). The main disadvantage of fibre-based oscillators is that they are limited in terms of energy/power by the fact that the laser is confined in the small fibre core. However, it is possible to add amplification modules to increase power performance without greatly increasing complexity (cf. *Fig. 4*).

The two main technologies of fibre-based oscillators are those based on fibres doped with Yb or Er. Lasers with Yb fibre typically emit in the range of 1030 nm for durations of 200 to 300 fs with several tens of mW. They are widely used to seed very high power fibre-based systems. Lasers with Er fibre enable durations of 30 to 100 fs to be obtained at around 1550 nm (telecoms wavelength). Their robustness makes them advantageous for low-noise systems and/or CEP, with applications in particular in the field of metrology.

3 For example, for applications such as micro-machining or surgery, durations of several hundreds of fs are sufficient to guarantee athermal ionisation.
4 Peak power is the ratio of energy to pulse duration.

What should I choose?

With all these criteria it can be helpful to highlight several characteristics in order to help to choose the "right" fs oscillator for a given application.

The duration, which is the eponymous characteristic of femtosecond lasers is, paradoxically, the parameter which is least used directly, and indeed it is often its relationship with the peak power or the broad spectrum which is most important. Oscillators' durations can range from a tenth to several hundreds of fs. Sub-20 fs durations can be essential if a very high time resolution is sought, or when one is interested in phenomena sensitive to the electric field (e.g. generation of attosecond pulses). However, duration has a cost in terms of complexity, and maintaining it is a difficult challenge. Attention will therefore be paid to this parameter in oscillators integrated in ultrafast chains, always bearing in mind that sometimes it is possible to strive too hard to achieve perfection[3]. A few applications in which duration must be taken into account are pump-probe experiments, experiments involving time-resolved spectroscopy or luminescence, metrology of semiconductor wafers, or photo-acoustics, THz or attosecond experiments, etc.

Peak power is probably the primordial parameter of femtosecond lasers since it is behind non-linear optics applications. This parameter is closely related to energy[4]. With typical energy values of one nJ to one µJ, this gives peak power values of between 100 W and 100 MW, but generally they are around

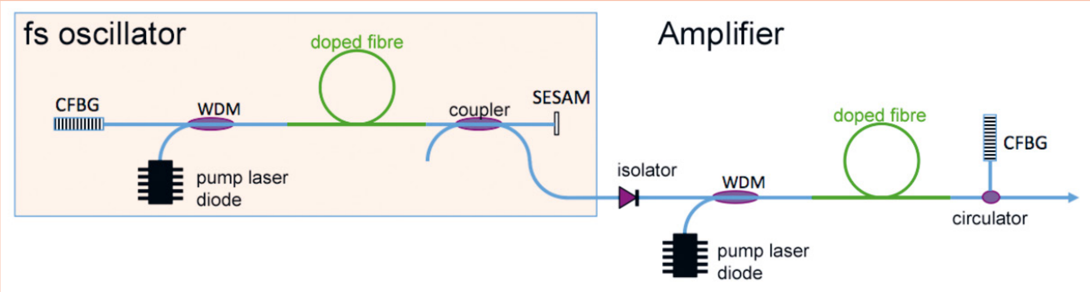

Figure 4. Example of fibre-based amplified laser without alignment, which is ultra-compact. The CFBG (chirped fiber Bragg grating) controls dispersion. WDM (wavelength division multiplexing) allows multiplexing of the pump and the laser.

one MW. The peak power values can be increased in amplified systems up to several GW for high-frequency systems (typically fibre-based systems), or to one PW, with crystal-based record systems. There are nonetheless applications for which oscillator output energy is sufficient, such as non-linear microscopy (2PEF, CARS, etc.) or generation of THz.

Since lasers' spectra are inversely proportional to pulse duration, the spectra of ultrafast lasers are the broadest. This bandwidth can be used advantageously in certain cases: for frequency combs in which the stabilisation system (CEP and CEO) requires extended spectra, or for optical coherence tomography (OCT) applications for axial resolution problems.

The spectral range of the laser (colour and tuning) is also a parameter which can be important, in particular to correspond to the spectra of the fluorophores (in particular in non-linear microscopy), or simply to be suitable for amplifiers.

Finally, repetition rate is a parameter which is acquiring increasing importance when choosing oscillators, in particular due to the appearance of systems doped with Yb ions, which allow a very great gain in terms of average power and recurrence of the processes[5]. With oscillators, it should be noted that low frequencies are of greater interest for systems requiring a pulse picker, and high frequencies in order to have a broad frequency comb.

Conclusion

There is a wide choice of different femtosecond oscillators. It is therefore of interest to examine certain properties which are more critical than others, depending on the application. We have shown a number of important – and not exclusive – parameters. It should also be noted that stability, reliability and compactness are also essential for many applications. ■

[5] This is true above all for amplified systems.

GUIDE TO OSCILLATORS

SUPPLIER	MAKES	PRODUCTS	CONTACT
Coherent	Coherent	Ti : Sa, Yb	Jean-Luc Tapié - jean-luc.tapie@coherent.com +33 1 80 38 10 11 / +33 6 09 17 40 72
Microcontrole Spectra Physics	Spectra -Physics High-Q	Ti : Sa, Yb	Dalila Ait-Amir - dalila.aitamir@newport.com +33 1 60 91 68 45
Amplitude Systemes	Amplitude Systemes	Yb	Vincent Rouffiange - vrouffiange@amplitude-systemes.com +33 5 56 46 40 62
Acal Bfi	Ekspla Onefive	Fibre Er Fibre Yb	Dadi Wang - dadi.wang@bfioptilas.com +33 1 60 79 59 84
Optoprim	Ligthconversion Fianium M-Squared	Yb Ti:Sa Ti:Sa	François Beck - fbeck@optoprim.com +33 1 41 90 33 77
Opton Laser	Advalue Photonics Laser Quantum Toptica	Fibre Er Fibre Yb	Vincent Aubertin - vincent.aubertin@optonlaser.com +33 1 69 41 04 05
Novae	Novae		Nicolas Ducros - n.ducros@novae-laser.com +33 6 58 09 12 89
KMLabs Lasers	KMLabs Lasers		Kapteyn-Murnane Laboratories Inc., USA Malcolm Warrand - mwarrand@kmlabs.com +1 303 544 9068
Imra	Imra	Fibre Er Fibre Yb Fibre Tm	Imra, USA - lasers@imra.com +1 734 930 2560
Menlo	Menlo	Fibre Er, Yb	Menlo Systems GmbH, Germany - sales@menlosystems.com +49 89 189166-0
Wavetel	Menhir Photonics		Arnaud Bout - about@wavetel.fr - +33 (0)6 83 55 19 47

IR optics

Edmund Optics teams with II-VI Incorporated to provide zinc selenide (ZnSe) optical components. **Plano-convex (PCX) lenses** offer <0.0005 cm^{-1} bulk absorption at 10.6 µm, irregularity of $\lambda/20$ at 10.6 µm and surface roughness of <50 Å. **Aspheric lenses** feature diffraction-limited performance for minimum focused spot sizes. **CO_2 beam expanders** collimate and improve the energy distribution of high power CO_2 laser beams at 10.6 µm. **Lens stress analyzers** utilize cross polarization to identify mechanical stress, thermal stress, and contamination.

www.edmundoptics.com

Laser white light

The Albalux FM laser white light module provides bright and highly directional fiber optic output for precise and contrast-rich illumination in next-generation medical and machine vision applications. A key component of Albalux FM is the LaserLight technology from SLD Laser. Based on GaN semi-polar blue laser diodes, LaserLight generates brilliant white light that is more than 10 times higher in luminance than today's LEDs. Optical fibers are incorporated that enables >150 lumen CW output with sharp narrow edges.

www.lasercomponents.com

Mount flippers

MMF series optical mount flippers provide a solution for setups in which components must be selectively removed and accurately replaced in the beam path, avoiding re-alignment while ensuring repeatability (5 arcsec). MMF mount flippers are hinged platforms supplied with an array of ¼×20 and 8-32 (or M6 and M4) tapped holes. They fit various Siskiyou optical mounts and motion stages, and simply pivot by 90° to move the mounted component either in or out of the beam path.

www.siskiyou.com

UV ps laser

The UV ps laser RGH-355-45 provides high power (over 50 W at 355 nm), short picosecond pulse (~7 ps), high repetition rates (up to 8 MHz), and spatial scaling: the beam can be split numerous times to simultaneously feed multiple work stations. Applications include processing of thin films/multilayer low ablation threshold substrate materials; microelectronic FPCB or SLP (substrate-like-package) cutting and drilling, OLED cutting and drilling.

www.photonix.com

UV ps laser

The IceFyre 355-30 laser offers TimeShift ps programmable pulse flexibility, pulse-on-demand and position synchronized output (PSO) triggering. It delivers >30 W average power and up to >60 µJ pulse energy typical at 355 nm with adjustable repetition rates from single shot up to 3 MHz. It is ideal for cold micromachining in high throughput manufacturing of 5G flexible printed circuits (FPC), flat panel OLED displays, solar cells, ceramics, plastics, and other materials and devices.

www.spectra-physics.com

Alignment turning station

Trioptics ATS 100 is an automated alignment turning station dedicated to the machining of lens mounts in a way that the lens centration and the air gaps fit between the individual optical components.

www.trioptics.fr