Photoniques

N°110

LIGHT AND APPLICATIONS | EOS & SFO JOINT ISSUE

EXPERIMENT — Speckle patterns

BIOGRAPHY — Maria Mitchell

BACK TO BASICS — OPOs

BUYER'S GUIDE — Hyperspectral cameras

FOCUS ON

GREEN PHOTONICS

- Bio-based optical and photonic materials: towards nature-based production methods for photonics
- Optical spectroscopy for the detection of micro- and nanoplastics in water
- Light harnessing by Algae: from fundamental investigations to light-based biotechnologies
- Photovoltaics: towards ultimate performances

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Editorial

NICOLAS BONOD
Editor-in-Chief

Green photonics for blue horizons

The report released on August 9, 2021 by the *IPCC Working Group I* presents an increasingly accurate and realistic assessment of the climate crisis. It alerts us once more to the urgency of decarbonizing our societies. This report predicts an increase in the earth's average temperature of at least 1.5°C or 2°C during the 21st century. One month after the publication of this report, the *IUCN World Conservation Congress* was held in Marseille. Here again, their report is devastatingly worrying, with an alarming drop in biodiversity all over the world.

The challenges to be met in order to address these climatic and environmental issues are immense and will require a thorough-going transformation of our industries and ways of living. But these challenges also present great opportunities for photonic technologies which are strategically positioned to contribute to the development of green and low-carbon technologies. This is the reason why many companies in photonics are benefitting from this new momentum as they step up efforts to maximize their potential in the emerging field of green technologies.

Solar energy, bio-inspired materials and biomaterials, plastic detection, waste sorting, pollution sensors, UV treatments... the fields are vast and photonic technologies are well adapted to invest in these multiple domains and environments. Photonic technologies have gained in efficiency, reliability and ergonomics. They must now, with the help of decision-makers and investors, accelerate their development and deployment to embrace these different fields.

Courses in photonics must continue to gain momentum across European universities and schools so that students are being trained in these technologies. Graduate students will find themselves in the numerous positions of technicians and engineers in optics and photonics that will open up. They will also comprise the new generation of scientists and decision-makers who will govern the rise of green technologies.

In addition to the harmful impact they have on the climate, the capacity of greenhouse gases to absorb infrared radiation prevents telescopes on Earth from detecting infrared spectrum from space. One solution is to bypass the Earth's atmosphere by placing the telescope in space. The launch of the James Webb Space Telescope from Kourou scheduled for December 18 is certainly one of the major events of this year. The deployment of its 6.5 m mirror after its launch promises to bring space exploration into a new era. On Earth and in space, photonic technologies continue to open our eyes to blue horizons.

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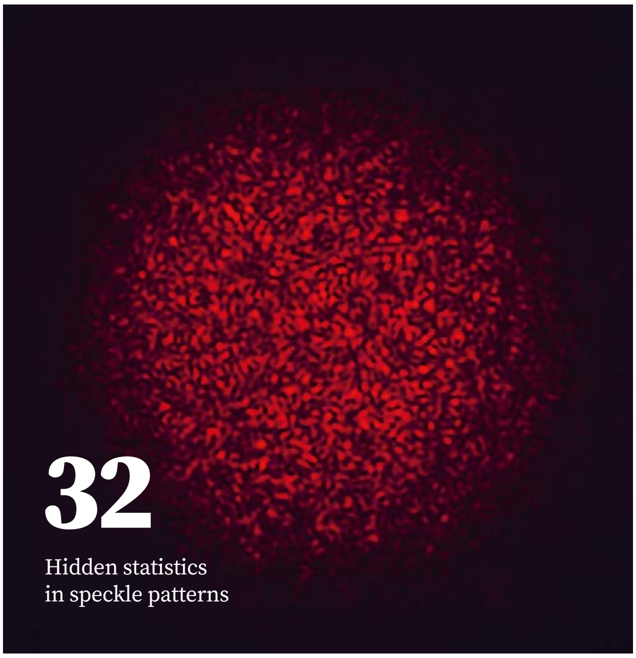

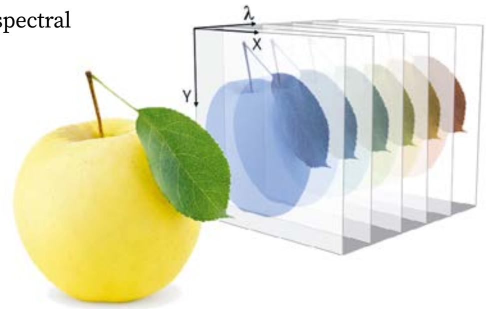

Advertisers

SFO/EOS forewords

PHILIPPE ADAM
President of the French Optical Society

After the summer deadlines, the French Optical Society (SFO) is gradually back to its normal rhythm. A great moment in our associative life is the holding of the General Assembly, scheduled for October 18, whose objective is to make an annual report on the SFO activity.
Indicators are good: building on the dynamics of OPTIQUE Dijon, 2021 saw an increase in the number of members, by more than 30%. It is also a proof of our dynamism and of the interest through the diversity of the projects proposed.
The financial situation is also improving thanks partly to the OPTIQUE Dijon 2021 event. Of course, efforts are still needed, but we are on the right track.
Our contacts with our national community have grown. The SFP is a privileged partner and exchanges are frequent. The scientific editor EDP is also a very present partner. It helps us in the distribution of our PHOTONIQUES magazine and SFO participates in the Scientific Advisory Committee.
Internationally, we note the reactivation of the Territorial Committee France at ICO. The five members, all from the SFO Board, are now clearly identified; they recently participated in the election of the new ICO board. At this occasion, Nathalie WESTBROOK was nominated as Vice-President of the ICO.
EOS is a historic partner. SFO and EOS work in close collaboration to federate the driving forces of optics in Europe. EOSAM 2021 in Rome was a great success. The SFO is delighted and notes the solidity of the link and the expression of a clear dynamic.
Finally, every two years, part of the SFO Board is renewed. In 2021, five elective seats were renewed. The next Board, scheduled for November 18 will work with this new team. I will then ensure the handover with Ariel LEVENSON who will then chair the destinies of the SFO for the next two years.
Two years is both long and short: long because the period has been complicated. Short because the task was exciting. Ariel will take over: no doubt that a new dynamic will be put in place, with new ideas and this for the greater well of our Learned Society.
Thank you all for your listening, your initiatives and your help.
Optically yours

GILLES PAULIAT
President of the European Optical Society

Face-to-face seminars and conferences have finally resumed! Our photonics community has responded overwhelmingly and enthusiastically to theses in-person meetings. This underlines our need to exchange in order to develop new ideas for the future. The first EOS in-person meeting since 2019 was EOSAM 2021, organized on September 13-17 in Rome Italy. EOS organized it in close co-operation with the Societat di Ottica e Fotonica, SIOF, the Italian optical society Branch member of EOS, and the Universita di Roma La Sapienza. For the first time, EOSAM was held in a hybrid format mixing on-line attendees with on-site participants. With over 350 on-site attendees and 180 on-line attendees, from 33 countries worldwide, this hybrid format was a real success and worth to be repeated in the future! On-site participants benefited from an exceptional venue. The meeting was held in the premises of Universita di Roma La Sapienza, in the center of Roma. Among the EOSAM highlights, was the ICO award ceremony, the prize winner being M. Guizar-Sicairos. The awarding of this prize during EOSAM underlines once again the cooperation between the many learned societies around the world. Isn't the slogan of ICO, the International Commission for Optics, "The place where the world of optics meets"?
This need to exchange and communicate is a necessity and lies at the heart of our scientific activities. EOS was created by the learned National Societies in Europe to strengthen our links; and EOS is currently exploring new ways to reinforce this cooperation at the European level. Research is indeed about pushing the boundaries of knowledge. This is done, within each field, by an ever deeper understanding of physics. Other frontiers can be crossed by confronting our knowledge with the demands of society. This issue of the journal is an opportunity to reflect on this approach. Typically, green photonics is the answer of our community to a societal problem (energy, pollution...). This suggests that many other frontiers exist that we are probably not even aware of, in forestry, agriculture, food, health...
This is the role of our learned societies to build bridges to these other fields; EOS is working on this year.
Enjoy your reading!

SFO - ELECTIONS 2021

Results of the SFO board of directors Members elected for the period 2021-2025 (Alphabetical order)

Yannick DUMEIGE
Institut FOTON
University of Rennes 1

Claude FABRE
The Kastler–Brossel Laboratory

Aurélie JULLIEN
Institut de Physique de Nice

François SALIN
CEO of Ilasis Laser Bordeaux

Marie-Claire SCHANNE-KLEIN
École Polytechnique

MEMBERS ELECTED FOR THE PERIOD 2019-2023

- ✓ **Nicolas BONOD** (Institut Fresnel, Marseille)
- ✓ **Arnaud BRIGNON** (Thales R&T, Palaiseau)
- ✓ **Sébastien CHÉNAIS** (LPL, Université Paris 13)
- ✓ **Agnès DESFARGES – BERTHELEMOT** (XLIM, Université de Limoges)
- ✓ **Sylvain GIGAN** (LKB, UPMC Paris)
- ✓ **Ariel LEVENSON** (C2N, Université Paris Saclay)
- ✓ **Inka MANEK - HÖNNINGER** (CELIA, Université de Bordeaux 1)

Results of ICO Bureau Elections 2021

Congratulations to our dear Nathalie, she is elected as ICO vice president.As you know, Nathalie Westbrook is Professor at Institut d'Optique and at the head of the Biophotonics group at Laboratoire Charles Fabry. She has been an elected member of the SFO executive Board for several years as vice-president.

OPTIQUE DIJON 2022: VENEZ À NICE

Save the date! The mobilization is strong around the OPTIQUE Nice 2022. This congress will take place in Nice from the 4th to the 8th of July 2022.

We have the commitment of more than 13 clubs and committees of the French Optical Society :

1. Guided Optics, Optical Fibers and Networks (JNOG Club)
2. Lasers and Quantum Optics (COLOQ club)
3. Crystals for Optics (JNCO club)
4. Nanophotonics
5. Optics and Photonics diagnostic (CDOP club)
6. Photonics and life science (PSV club)
7. Optics horizons (HORIZONS club)
8. Adaptive Optics (JRIOA club)
9. Lidar
10. Organic Photonics (JNPO club)
11. Physics and optical imaging (PIO club)
12. Teaching committee
13. Women in optics committee: to promote parity in optics

N.B. PAMO club of SFP (Atomic, Molecular, and Optical Physics) is invited

The congress facilities at Saint Jean d'Angély campus are well located and easy to reach. Université Côte d'Azur is ideally located between the coast and the mountains in a region known for its quality of life. At the heart of Europe, with easy access to the Nice Côte d'Azur International Airport, it is an open door to the photonic-optics community, academic and industrial world. The local organizing committee orchestrated by **Sébastien TANZILLY** is very happy to welcome hundreds of participants.

We invite you to submit and present your research and to make friendships in friendly atmosphere. Welcome to OPTIQUE Nice 2022!

Follow us: https://www.sfoptique.org/

OPTIQUE Nice 2022 in few figures

- 9th edition of the SFO congress
- 600 expected attendees
- 40 stands of compagnies in the ecosystem of optics and French photonics
- 10 educational stands
- 7 hours of plenary session
- 70 hours of specific sessions in parallel
- 5h30 dedicated to the industrial sector.
- 10 Thematic sessions

SFO and International Commission Optique sans frontière

Solar workshop for professional training in Ouagadougou from July 2 to 4, 2021.

The workshop went very well with 25 persons attending (university lecturers and high school teachers). The aim of the workshop was to build solar panels from solar cells and to characterize their performances. A second workshop will take on battery charge with application to led lighting and smartphone charge.

Arouna Darga, Lecturer at Sorbonne University organized this training.

This first "Experiment action" in Burkina Faso, was carried by SFO - Optique Sans frontière.

NewSkin project : apply for the Open Calls and get free access to the upscaling and testing facilities!

Launched in April 2020, the Horizon 2020 NewSkin project brought together 35 European partners, including the ALPHA-RLH cluster. Dedicated to nanotechnologies, the project is devoted to the development of technological platforms. The objective of these platforms is to provide SMEs and research laboratories with services to develop and test new nanotechnological products and processes on prototypes and thus improve the performance of surfaces (including metals, polymers, ceramics, graphene etc.). They will allow the industrialization of nano-structuring processes by laser, CVD, PVD, HiPIMS technology and others. Finally, organizations developing new nanotechnological solutions will be able to test them via the NewSkin's testing facilities (Antifouling, Anti-icing, Antimicrobial, testing in aggressive industrial environments, etc.). Register on the project platform: https://platform.newskin-oitb.eu/ and apply for the open calls before 31 December to take part in the NewSkin project, obtain free access to our facilities and accelerate the industrialization of innovative nanotechnologies.

CONTACT: Romain Herault
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UPCOMING INTERNATIONAL EVENTS

- **Formnext exhibition**
  November 16-19 in Francfurt (Germany)
- **Webinar "NewSkin Project"**
  November 23 (online)
- **Webinar "Choosing Canada in your international development priorities"**
  November 25 (online)
- **EMAF exhibition**
  December 1-4 in Porto (Portugal)
- **Photonics West exhibition**
  January 25-27, 2022
  in San Francisco (USA)

A UNIQUE EUROPEAN TRAINING PROGRAMME DEDICATED TO PHOTONICS TECHNOLOGIES!

PhotonHub Europe project*, whose ALPHA-RLH is one of the partners (linked third party), just launched the European Photonics Academy, a unique training programme dedicated to photonics technologies.

Several technical centers among Europe offer a wide range of photonics training courses, adapted to newcomers as well as more skilled professionals. The objective is to support the companies in the adoption and development of innovative photonics-based solutions to some of society's biggest challenges.
Three types of training courses are available: a half-day online training, geared towards new entrants to the photonics sector, one-day training courses on-site with a focus on applications, and three-day or five-day training courses, with a strong focus on lab-based activities and hands-on working.
Training catalogue direct link: https://ecosystem.photonhub.eu/trainings/?filter_empty
Introduction to PhotonHub Europe training courses:
https://www.photonhub.eu/our-services/#Training
Join the platform community: https://spaces.fundingbox.com/c/photonhubeurope/

* *Launched last 24th February 2021, PhotonHub Europe gathers 54 partners from 15 European countries for a total budget of €19M for 4 years.*

Advanced materials for Defence

Electronics, Photonics and Materials are key technologies for the Defence sector. They offer a huge potential, notably for propulsion, as well as high-performance ballistic protection for missiles, aircraft, helicopters, land vehicles and combatants.

ALPHA-RLH and the European ceramics cluster "Pôle Européen de la Céramique" co-organized, on September 9th, in Limoges, an event dedicated to the challenges of materials for defence which gathered around 100 attendees.
The programme included presentations by large companies such as Dassault Aviation, Saint-Gobain Aerospace, Nexter, MBDA and CEA, as well as pitches by SMEs offering cutting-edge technologies. 110 BtoB meetings were organized and should lead to future collaborations and projects!

Launch of the Women Leadership Programme

To further support the role of women in innovation and tech, the European Innovation Council (EIC) is offering a skills enhancement and networking programme for EIC-supported women entrepreneurs and researchers: the "Women Leadership Programme" officially launched in October.
A call for applications was brought out in March to select mentors. Isabelle Tovena Pécault, PhD, Head of International & European projects at ALPHA-RLH, has been selected to be one of the European Mentor in this new EU programme.

Photonics Online Meetings: Registrations are open!

Following the success of our first three events in 2020 and 2021, the fourth edition will be held on 23 November with the stated objective of targeting Europe and the international market.
Targeting this time mainly major industrial contractors, this edition has a clearly defined theme: MANUFACTURING.
The ambition is to offer our participants the opportunity to meet new companies, and to create or strengthen their business with European partners.
In a single day, key accounts, technology and service providers, investors, institutions, public and private partners will meet through the organisation of qualified BtoB meetings completed by conferences and product & service webinars.
More than 350 entities are expected !

MORE INFORMATIONS AND REGISTRATION AT:
www.onlinemeetings.photonics-france.org

Start-ups in the spotlight at Photonics France

On the occasion of the BestForm21, Photonics France highlights the start-ups that have joined them since 2020. And no less than 13 French start-ups in the photonics industry have joined the federation in less than two years to promote and highlight their expertise:

ALEDIA, GLOPHOTONICS, GOYALAB, GREENTROPISM, HUMMINK, ICON PHOTONICS, MICROLIGHT, NEOVISION, PHASELAB INSTRUMENT, QUANDELA, TRIDIMEO, UV BOOSTING et VISIONAIRY.

Website "Orientation Photonics"

We will soon launch our website to promote photonics to young French people.
Presentation of photonics, web series on the use of photonics in pop culture, educational resources and interviews on jobs.
If you have educational resources, conferences, videos, testimonies, teaching tools, please contact us! contact@photonics-france.org
Project supported by the Ministry of Employment

AGENDA

- **"Les RDV Carnot", partnership business convention**
  Lyon - November 17-18
- **Photonics Online Meetings #4,**
  Online - November 23
- **Business Meeting "Environment",**
  Paris - December 7
- **Photonics West, exhibition partnership**
  San Francisco - January 25-27
- **Photonics Europe, exhibition partnership**
  Strasbourg - April 3-7
- **Laser World of Photonics, Pavilion**
  Munich - April 26-29

NEW MEMBERS

Photonics France now has 177 members! Welcome to : ALEDIA – ALTIMET – BM-OPTO – EXYTE – GLOPHOTONICS – HEPPELL PHOTONICS FRANCE – HUMMINK – ICON PHOTONICS – MATHYM – MERSEN BOOSTEC – MITUTOYO – ORANGE LABS – PRYSMIAN – STERIXENE – TELEDYNE – UV BOOSTING.

TO CONTACT PHOTONICS FRANCE

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

Diplôme d'ingénieur: Institut d'Optique's flagship degree in Optical science and egineering

Institut d'Optique Graduate School is a leader in France for research and higher education in optical science and engineering, based on 3 campuses: Paris-Saclay, Bordeaux and Saint-Etienne. Its flagship degree is the "Diplôme d'ingénieur", a highly selective and demanding integrated Master degree, translated to 'Master of Science in Engineering' (MScEng). In France, this kind of programme usually recruits students after two years of undergraduate studies at least, for the 3-year long MScEng programme itself, covering the equivalent of final year of bachelor and two years of master.
The main feeder for Institut d'Optique's MScEng programme is the scientific Classes préparatoires system (www.scei-concours.fr/concours.php). After 2 years of intensive undergraduate education in Maths, Physics and Engineering sciences, students sit for nation-wide competitive exams to enter the Grandes Ecoles, among which Institut d'Optique. Institut d'Optique has also developed an alternative admission scheme, enabling students from regular bachelor or master programmes in French universities to join its MScEng. Applicants are selected by screening their application materials, and if applicable by sitting exams at Institut d'Optique, including oral exams and interviews. Bachelor students can apply for an admission in first year whereas master students can apply directly for an admission in second year.
For this Diplôme d'ingénieur (MScEng) programme, Institut d'Optique Graduate School has developed, in addition to its traditional student admission schemes in France, an international recruitment for students from foreign universities. This is enabled by the offer of courses taught in English in our Master level years. Abroad, Institut d'Optique recruits students through its own double-degree schemes, such as the 3+3 double-degree programme with Huazhong University of Science and Technology in China. Additionally, Institut d'Optique participates in the ParisTech admission programme where 7 French Grandes Ecoles in Science and Engineering join forces to offer a common platform for applicants from abroad. ParisTech operates admission programmes in China, Brazil, Russia, Argentina, Colombia, and since 2021 several Asian territories. This enables Institut d'Optique to recruit students who are finishing their Bachelor into its 2 final years of the MScEng programme. The most represented nationalities are China, Brazil and Russia.
Students from the MScEng programme at any of Institut d'Optique's 3 campuses can also follow MSc programmes from local universities in parallel and get both degrees in the end. Around 1 graduate out of 3 chooses to continue towards a PhD, while the others join directly companies with an employment rate exceeding 87% two months after graduation, in France or abroad.

Amphitheater university Paris Saclay

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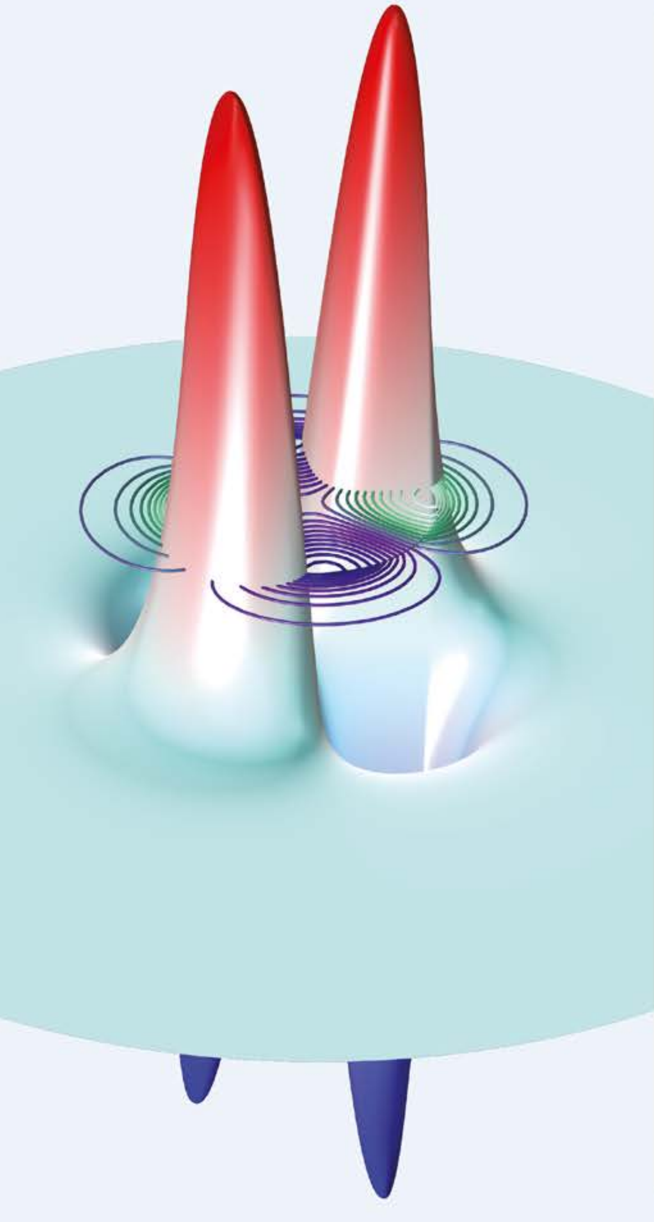


Le Verre Fluoré is part of the Horizon 2020 European project PASSEPARTOUT

The objective of this project is to develop and deploy a network of miniature, hyperspectral optical based sensors, mounted on drones, vehicles and stationary devices, in order to monitor environmental air quality in urban areas. The project will help in combating climate change by monitoring pollution and forecasting air quality to the public. LVF will develop for the project fibers designed for ICL and QCL pigtailing and will contribute to the development of fibre combiners for the multiplexing of the multiple laser sources.

Prolann creates Luzilight, new member of Photonics Bretagne

The Covid crisis forced Prolann to adopt a strategic repositioning of the company. Based on corporate know-how, it has defined three axes to energize the activity: more robots, new product development proper to the infrasound section and glass machining operations. Within this context, Prolann has created Luzilight (new member of Photonics Bretagne), a company specializing in glass and ceramics machining intended for photonics and the military Defense market.

AGENDA

- **Photonics PhD Day**
  2 December 2021, Lannion (France)
- **Photonics West**
  25-27 January 2022, San Francisco (United States)
- **Laser World of Photonics**
  26-29 April 2022, Munich (Germany)

Focus on quantum technologies at Photonics Bretagne General Assembly

Another great annual meeting for Photonics Bretagne with the general assembly of the association which took place in Trébeurden on the 24th of September. 88 attendees were captivated by the focus on quantum technologies including a presentation of Neil Abroug, National Coordinator of the Quantum Strategy, detailing the last news on the French Quantum national plan, and Eleni Diamanti from the Sorbonne University who presented some hints of the future European Quantum telecommunication network. Most of the 7 new members who joined the cluster (gathering now 118 members) at this occasion had the opportunity to pitch in order to briefly present their activity. Punctuated by many networking sessions, the event was a success and allowed the photonics community to finally meet face-to-face!

Photonics for Agrifood in the spotlight of a Bretagne-Netherlands webinar

In the context of the Dutch-French Innovation Mission 2021-2022, Photonics Bretagne and Photonics Netherlands co-organized last September a webinar on Photonics for Agrifood. The program included skilled speakers from Breton and Dutch companies/institutes which shared their experiences in the field of agrifood in order to initiate collaborations between parties on this emerging topic. These European developments are an engine of growth and financing for the Brittany ecosystem including Photonics Bretagne currently partner of 8 Europeans projects: H2020 (PROMETHEUS, BESTPHORM21, PHOTONHUB), Interreg (OIP4NWE, STEPHANIE), Eurostar (HARMONY), the recently accepted COSME (PHOTONICS4INDUSTRY), and the bi-regional project CAFCA co-funded by Wallonia and Brittany regions.

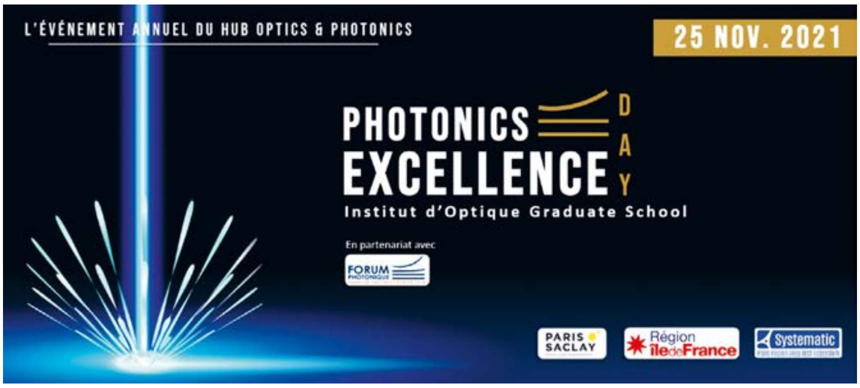
A PIONEER LOW LATENCY HOLLOW-CORE CABLE
TO SAVE NANOSECONDS IN HIGH-SPEED TRADING APPLICATION

IDIL and Photonics Bretagne launch a new range of anti-resonant Hollow-core fiber optic cables. They combine low latency data transmission, high bandwidth connections and low loss; three features highly sought after by high frequency trading. The cable was presented at the ECOC Exhibition in Bordeaux which gathered the whole telecom community from Brittany (Photonics Bretagne, IDIL, iXblue Photonics, Cailabs, BKTEL PHOTONICS, Ekinops, Idea Optical, EXFO, WAVETEL TEST SOLUTIONS, Orange Labs, CNRS Foton....)

Photonics Excellence Day 2021: November, time to register!

For its 3rd edition, we are very pleased to announce the return of the Photonics Excellence Day in person!
Organized in partnership with the Photonics Forum, we invite you to join us on November 25, 2021 for the annual Photonics Excellence Day at the Institut d'Optique Graduate School in Palaiseau.
Discover the new uses of photonics through exclusive demonstrations, discuss the latest innovations with key players in the industry and build your network, these are just some of the great promises this day has in store for you!

-> Program online and registration open.



100% EUROPE:
CLUSTERS AT THE HEART OF EUROPE'S CHALLENGES

If you are an actor of the European research and innovation landscape, please join us on Thursday 18 November for an exceptional event with high value-added conferences and B2B meetings featuring Systematic's growing European ecosystem!
Systematic, European Deep Tech cluster, invites you to its latest edition of 100% Europe, with two major sequences:

10:00 - 13:00 | CONFERENCE - Clusters at the heart of Europe's challenges
- the twin transition - green and digital transition - under Horizon Europe
- hear about experiences with EU-funded projects from your peers
- have a chance to present for the next phase of Horizon Europe topics

14:00 - 18:00 | 1 TO 1 BUSINESS MEETINGS with our bespoke matchmaking platform

-> Program online and registration open.

At a glance

Lytid – New Member
Lytid develops commercial cutting edge photonics products for science and industy. Applications range from medical imaging, NDT for industry 4.0, industrial sensing or ultra-broadband telecom. From SWIR to Terahertz don't wait to discover their products!

Nanovation – New Member
World leader in the manufacture of thin-layers, nanostructures and oxide-based semiconductors, Nanovation joins the cluster and brings its expertise in fire/UV detection and space environment control, welcome!

PSHA – New Member
Located in the heart of Paris-Saclay, the PSHA Accelerator is a key player in industrial innovation. From idea to solutions, including design, prototyping, industrialization, pre-poduction, or simply take a step back in your project they will be the perfect partner for your innovative projects.

AGENDA

- **100% Europe**
  November 18, online
- **Photonics Online Meetings**
  November 23, online
- **Photonics Excellence Day**
  November 25, 9h30-17h30, Palaiseau, France

www.systematic-paris-region.org/evenements/

Want to join the Optics & Photonics Hub of Systematic? Don't wait any longer and contact:
Lola Courtillat, Hub Coordinator

lola.courtillat@systematic-paris-region.org

AGENDA

■ **Upcoming events**
EPIC is organising meetings on various topics.
See below an overview of some upcoming events.
For a full overview of events, please visit www.epic-assoc.com

■ **EPIC Online Technology Meeting on White Lasers and Supercontinuum Generation**
1 November 2021

■ **Product Release November**
2 November 2021

EPIC Online Quantum Technology Meeting on Ion Traps, Gravitometers and other Quantum Sensors
3 November 2021

EPIC Online Technology Meeting on 3D Printed Optics: State of the Art and Applications
15 November 2021

EPIC TechWatch on Laser and Photonics Applications at COMPAMED HIGH-TECH FORUM by IVAM, MEDICA
16 November 2021

EPIC Online Technology Meeting on Advanced Laser Manufacturing for Automotive
22 November 2021

EPIC Virtual Company Tour – Canada Special I (in cooperation with OPTONIQUE)
23 November 2021

EPIC Online Technology Meeting on Mid-IR Technologies for Security & Surveillance (in cooperation with MidIR Alliance)
24 November 2021

Product Release December
30 November 2021

EPIC Online Quantum Technology Meeting on Large Scale Qubit Generation
1 December 2021

EPIC Online Technology Meeting on Medical Devices
6 December 2021

EPIC Virtual Company Tour – Canada Special II (in cooperation with OPTONIQUE)
7 December 2021

EPIC Online Technology Meeting on Challenges for LED/ MiniLED/MicroLED
13 December 2021

EPIC Online Technology Meeting on Photonics for the Food & Beverage Industry
20 December 2021

Shaping the New Future

EPIC continues their virtual journey and slowly restarts physical events

It's been a busy closing quarter of 2021 for EPIC - European Photonics Industry Consortium. Currently, in the middle of the Season 5 of the very successful EPIC Online Technology Meetings, we have a full calendar filled with both online and physical events until the end of the year. The new season of online technology meetings started strong in September with the largest meeting to date: the first event after the summer break – the Online Technology Meeting on New Developments in FMCW LIDAR, attracted more than 200 registrations.

In this period, the world's largest photonics association introduced a series focussing on mid-infrared technologies at all levels of the supply chain. Shortly after the official launch of the Mid-IR Alliance in May, three EPIC online technology meetings on Mid-IR technology were announced. Additionally, EPIC members and end-users joined meeting on Industrial Manufacturing in July and a meeting on Environmental Monitoring in September.

On 24 November the EPIC Online Technology Meeting on Mid-IR Technologies for Security & Surveillance will take place. The key aim of this and previous events is to provide a platform to exchange ideas among laser and detector manufacturers, developers of Mid-IR cameras and sensors, manufacturers of Photonic Integrated Circuits and software for modelling and packaging services.

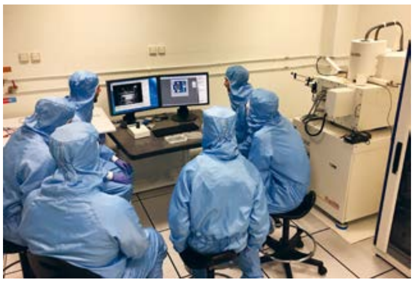
As the travel restrictions eased internationally in the second half of 2021, EPIC finally took part in several European photonics exhibitions. The first show of 2021, attended in-person by the EPIC team, was ECOC 2021 in Bordeaux, France. EPIC was able to reconnect with their member companies after busy 18 months of online activities and organized the Association's annual TechWatch and VIP Party in conjunction with the ECOC event. There was a lot of positive energy in the exhibition hall in the South of France and all visitors and exhibitors were looking forward to face-to-face exhibitions and conferences finally becoming more frequent.

EPIC team as the dissemination partner of PIXAPP and JePPIX Pilot lines at ECOC 2021 in Bordeaux, France

A Graduate School of excellence "Nano-optics & Nanophotonics" recently opened in France

Interested in a degree program to jumpstart a career in a high-tech company or an academic institution that is interested by light and associated innovation? There's a new graduate school in France 100% taught in English that could be right for you.

Nano-optics and Nanophotonics are rapidly growing and, given the connections to the fields of energy, telecommunications, security, health and environment, nanophotonics is at the crossroads of different key enabling technologies defined by the European Commission as *a priori*ty of its industrial policy. A new international graduate school "NANO-PHOT" opened in 2020. It is an "Ecole Universitaire de Recherche" supported by the French government within the frame of the "programme d'investissement d'avenir (PIA)". NANO-PHOT offers an unparalleled 5-year program of excellence (master + PhD), with an international dimension and in direct contact with scientific and socioeconomic stakes related to the use of light, on a nanometric scale. NANO-PHOT aims at training the next generations of researchers and professionals at the cutting edge of nanophotonic's sciences and technologies, bringing a genuine structuration in the Champagne area of France (region Grand-Est) by providing a new coherence to photonics and nanotechnology courses and involving several research units.



Partners and network

The leading partner is the University of Technology, Troyes (UTT, www.utt.fr) founded in 1994. Its 5 laboratories address most of the current technological and scientific challenges. Among these laboratories, the L2n leads NANO-PHOT (Light, nanometerials, nanotechnologies). More than 90 people work on new concepts and approaches on nanoscale optics. The main local partner is the multidisciplinary University of Reims Champagne Ardenne (URCA, www.univ-reims.fr) involving more than 25 000 students. Six of its laboratories (LRN, BIOSPEC, FARE, MEDYC, SEBIO, ITheMM) offer complementary domains of science and application in nano-optics: biotechnology, cellular biology, nanoelectronics, environment, materials for building engineering, etc... The French National Centre for Scientific Research (CNRS), an official partner, is among the world's leading research institutions. Its scientists explore the living world, matter, the Universe, and the functioning of human societies in order to meet the major challenges of today and tomorrow.

Program

The program consists of 2 year-master and 3-year PhD. The last master semester is dedicated to a research internship. Each semester gathers interdisciplinary and specialized/tailored courses, as well as research projects and soft skills, and includes the participation of world-class experts. The NANO-PHOT program consists of lectures, tutorials, practical works and projects, all taught in English and awarded by ECTS credits.

Research activities are structured by four scientific main themes: i) Emerging materials for nano-optics, ii) Nano(spectro)scopy, nanosensors & and nanodevices, iii) Fondamental phenomena in nano optics, iv) Nanofabrication for nano-optics.

NANO-PHOT promotes international mobility and multilingual training environments and activities. The involvement of students in research projects starts from the first semester of the master program, until the thesis defense. Through its control at the nanoscale, light can be fully exploited within a sustainable development approach, based on the latest and major scientific and technologic progress to which the students will contribute in real time.

Recent updates

The first student promotion has been recruited: 20 master students including 35% of foreigners. The official inauguration of NANO-PHOT took place at UTT on Sept 20, 2021. Many world-renowned persons attended. Among them: Prof. Naomi Halas (Rice University, USA), patron of NANO-PHOT and UTT doctor honoris causa, and Prof. Peter Nordlander (Rice University, USA), new member of the NANO-PHOT international advisory board.

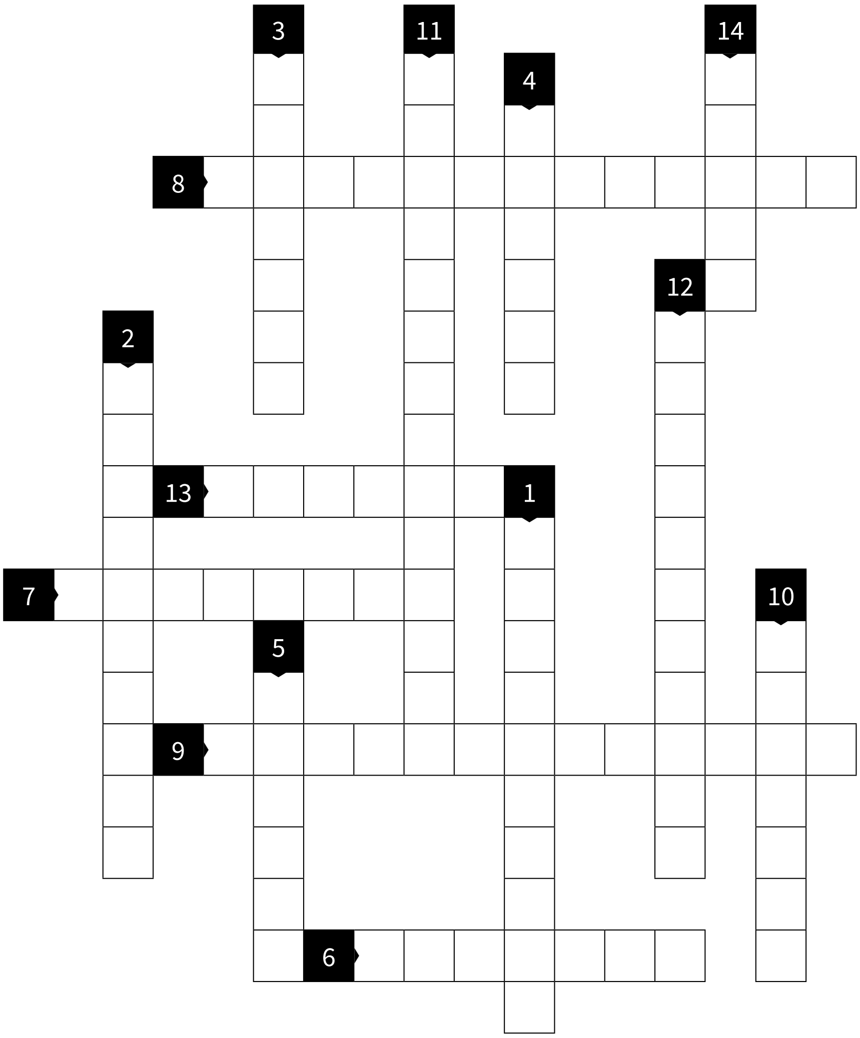
Should you wish to join the NANO-PHOT graduate school? get detailed information? start a win-win collaboration with NANO-PHOT?

CONTACT NANO-PHOT:

Go to nano-phot.utt.fr
or contact us at nanophot@utt.fr

CROSSWORDS
ON BEAMS AND MATERIALS

By Marie-Claire Schanne-Klein (LOB-CNRS)



1 Rayleigh or Mie?
2 Bends light
3 At a metal-dielectric interface
4 Beam carrying OAM
5 Self-healing beams
6 Aberrant polynoms
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11 Broadband and similar to incoherent light
12 Unavoidable with waves
13 Optical resonator
14 Thinnest width of a beam

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Parametric driving of cavity solitons

Optical pulse trains are currently attracting a lot of attention because they provide a link between the optical and microwave domains. In particular, pulse trains formed by time localized nonlinear solutions that propagate unperturbed in driven optical resonators – Kerr cavity solitons - have been intensely studied recently. In the frequency domain, they correspond to an optical frequency comb, or optical ruler, the inventors of which were awarded the Nobel prize in 2005. Their wide range of applications include atomic clocks, astronomy and high precision metrology. So far, the focus has been on cavity solitons (CSs) driven at their natural oscillation frequency, *i.e.* with a driving laser at the carrier frequency of the soliton. But nonlinear systems can also be parametrically driven, which consists in driving the system by varying one of its parameters. The simplest example of so-called parametric driving is a pendulum which can be excited by periodically changing its length. Importantly, in that case the driving must be at twice the oscillation frequency.

A team of researchers at ULB (Brussels) has demonstrated that cavity solitons can also be driven at twice their carrier frequency. To achieve it, they used an all-fiber optical parametric oscillator that incorporates both second and third order nonlinearity. This special feature confers a totally random character to the sign of the cavity soliton's amplitude. The measurement of this sign allows the generation of a binary random number, paving the way to a new type of all-optical computer such as the Ising machine.

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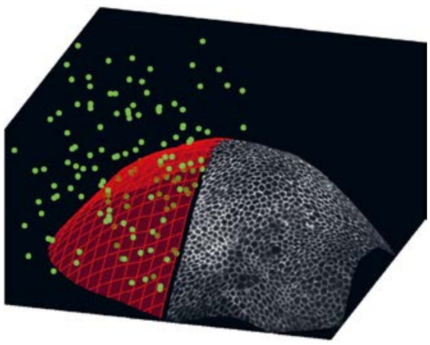
A SMART SCANNING MICROSCOPE FOR BETTER OBSERVATIONS OF CELL SHEETS

Modern biology is based on the observation of living cells, made possible within model organisms by the latest advances in optical microscopy. The widely used confocal fluorescence microscope generates volumetric images with high spatial resolutions, by scanning the volume point by point with a laser beam. However, current techniques are confronted with a problem of toxicity due to the illumination necessary for the excitation of fluorescent markings: prolonged illumination affects and slows down the growth of cells. Nevertheless in many situations, in particular in the case of embryos and developing tissues, cells are organized along sheets lying on curved surfaces. Conventionally, such objects are imaged by scanning the entire volume plane by plane, which is highly inefficient in terms of photon budget.

A team of researchers at Institut Fresnel in Marseille developed a new microscope that automatically estimates the surface on which these cells are distributed from a small number of random acquisitions (~0.1% of the voxels). The microscope can then concentrate the illumination around the surface of interest, allowing cell sheets imaging by scanning typically less than 5% of the volume. Additionally, it can also restrict illumination along the fluorescent cell contours by alternating acquisitions and prediction steps, further reducing the scanned volume up to 1%. The corresponding reduction in light dose on the sample had a profound effect on fluorophore stability and will improve viability of living samples over prolonged imaging.



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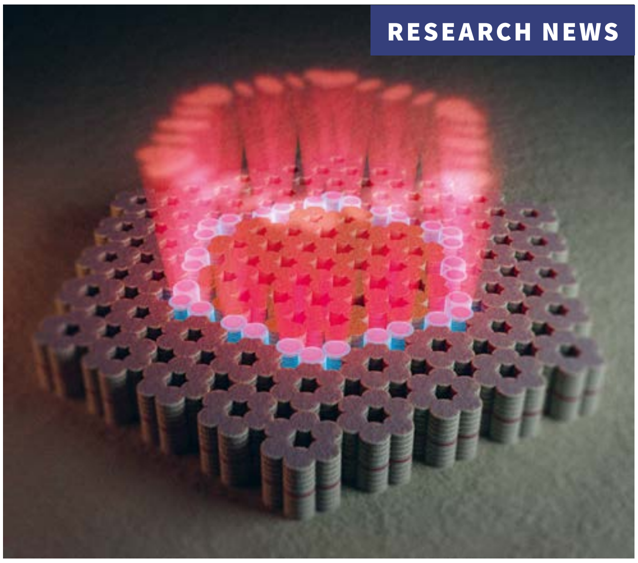


TINY LASERS ACTING TOGETHER AS ONE: COHERENT ARRAY OF VERTICAL LASERS

Topological insulators are revolutionary quantum materials that insulate on the inside but conduct electricity on their surface - without loss.

Several years ago, the Technion group led by Prof. Mordechai Segev has introduced these innovative ideas into photonics, and demonstrated the first Photonic Topological Insulator, where light travels around the edges of a two-dimensional array of waveguides without being affected by defects or disorder. This opened a new field, now known as "Topological Photonics", where hundreds of groups currently have active research. In 2018, the same group also found a way to use the properties of photonic topological insulators to force many micro-ring lasers to lock together and act as a single laser. But that system still had a major bottleneck: the light was circulating in the photonic chip confined to the same plane used for extracting the light out. That meant that the whole system was again subject to a power limit, imposed by the device used to get the light out, similar to having a single socket for a whole power plant.

The current breakthrough uses a different scheme that was developed by the groups of Prof. Moti Segev from Technion in Haifa and Prof. Sebastian Klembt from the University of Würzburg: the lasers are forced to lock within the planar chip, but the light is now emitted through the surface of the chip from each tiny laser and can be easily collected. In the new joint research paper published in Science the authors present coherent laser emission from an array of 30 coupled microresonators. The groundbreaking research has demonstrated that it is in fact theoretically and experimentally possible to combine VCSELs to achieve a more robust and highly efficient laser.

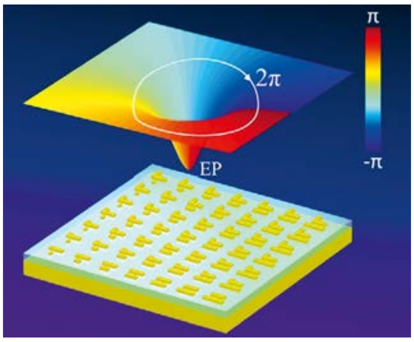
REFERENCE

A. Dikopoltsev *et al.*, "Topological insulator vertical-cavity laser array," Science **373**, 1514-1517 (2021) - https://doi/10.1126/science.abj2232

A new technique to manipulate light properties **with ultraflat optical components**

Metasurfaces are today considered as the next-generation of ultra-flat optical components. They consist of assemblies of thousands, or even millions, of nanostructures with various geometries disposed at interface to modify the light characteristics, namely its amplitude, phase and polarization.

The optical functions of a given metasurface, for example the ability to focus a light beam, are entirely controlled by the light scattering properties on each of these nanostructures. To date, only three mechanisms have been investigated to manipulate light with meta-optics: 1) light scattering by resonant nanostructures, 2) the geometric phase or Pancharatnam-Berry phase and 3) the propagation phase in nanopillars with controllable effective refractive index. Researchers from the Center for Research on Hetero-Epitaxie and its Applications (CRHEA CNRS, Université Côte d'Azur) in collaboration with the "Electrical Engineering and Computer Sciences" department (Berkeley, University of California) have demonstrated a new technique to address the phase of light beam with nanostructures. It relies on the presence of a topological singularity occurring by varying the parameters defining the nanoparticle final geometry (length, width, height, optical index, etc...). The singularity corresponds to an extinction of a given channel connecting input and output light beams (considering transmitted T, reflected R, scattering S or polarization converted channels J matrices). The amplitude of the light wave being zero, *i.e.* R=0 for example, its phase is no longer defined. Remaining within the parameters of the singularity, in fact encircling the singularity in the space of the parameters, it is possible to draw antennas whose characteristics give the desired phase, between 0 and 2π. Encircling singularity gives full phase control of the wavefront and confers reflected, transmitted light beams exceptional properties, such as non-reflection behavior, perfect absorption on certain light channels, transmission or reflection, anomalous polarization scattering, etc. This work was published in the journal Science.



Such components are expected to replace some of the conventional optical devices, such as lenses or mirrors used to control light beams in cell phones, onboard cameras and other miniaturized portable systems. Several breakthrough innovations, including systems requiring wavefront control such as LiDARs or virtual and augmented reality devices, should also benefit from this new technology. In the longer term, these components will find applications in quantum photonics, polarimetry, and for holographic image projection.

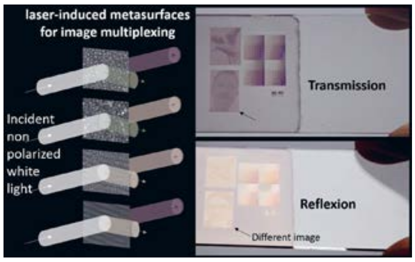
REFERENCE

Q. Song *et al.*, "Plasmonic topological metasurface by encircling an exceptional point", Science Vol **373**, Issue 6559 pp. 1133-1137 (2021). https://doi/10.1126/science.abj3179.

IMAGE MULTIPLEXING WITH LASER-INDUCED QUASI-RANDOM PLASMONIC METASURFACES

Encoding several images in a single thin layer in such a way that they could be revealed independently by altering the conditions of observation of the layer has great potential for high-end anti-counterfeiting applications. Recently, the high contrast and dichroic properties of plasmonic colors have been soundly used to develop image multiplexing. Based on perfectly controlled anisotropic metallic nanostructures produced by e-beam lithography, the techniques developed so far have however some drawbacks. The images are too small to be observed by naked eye and the demultiplexing requires either monochromatic or polarized light.

Researchers at Laboratoire Hubert Curien and HID Global CID have developed a laser processing technique that allows printing large multiplexed images at low cost, with a high flexibility, and within very short times. The laser beam tunes the statistical properties of the nanoparticle assemblies, like their size-distribution, their shape anisotropy, and their average spatial distribution through self-organization mechanisms. Yet, the laser processing reproducibly controls the macroscopic optical properties of these random plasmonic metasurfaces and interestingly creates optical properties that are not accessible by other means. The team has demonstrated two- and three-image multiplexing under non-polarized white light, making the technology useful for real applications where an authentication is expected in few seconds.



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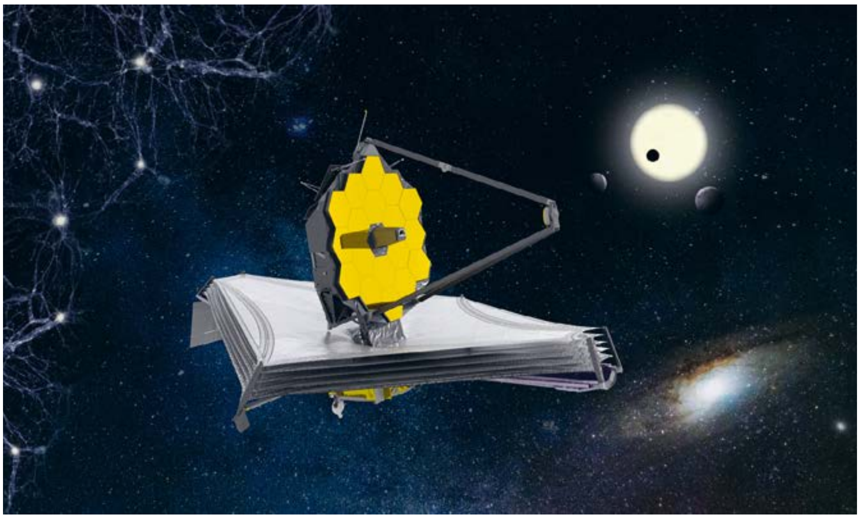
N. Destouches *et al.*, Laser-Empowered Random Metasurfaces for White Light Printed Image Multiplexing. Adv. Funct. Mater. 2021, 2010430. https://doi.org/10.1002/adfm.202010430

Webb: Largest space telescope ready for launch

Pierre Baudoz, LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris



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On December 18th 2021, the largest space telescope ever built will be launched from Kourou on Ariane 5. Following the Hubble Space telescope as the next great space science observatory, the James Webb Space Telescope (Webb) is designed to answer outstanding questions about the Universe and to make breakthrough discoveries in all fields of astronomy.

This new space telescope is designed to operate in the infrared to explore four major science themes: the early universe when stars and galaxies formed, the evolution of black holes and galaxies, the lifecycle of stars and planetary systems, the exoplanets and the origins of life.

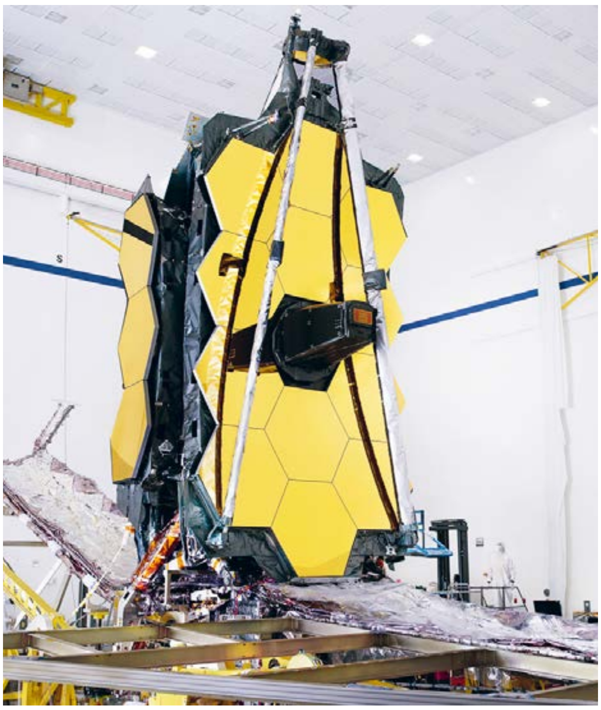
The large size of the telescope and spacecraft systems require to be folded to fit the Ariane 5 fairing, and then deployed after launch. Even its 6.5 m primary mirror has to be broken up into 18 hexagonal segments folded in three parts to fit the rocket fairing. To restore the primary mirror after launch and unfolding, each segment is supported by seven actuators to co-phase them with a precision better than 50 nm.

Webb will orbit the second Lagrange point (L2), 1.5 million kilometres from Earth in the direction away from the Sun. At L2, the telescope can operate at cryogenic temperature (40 K) required for infrared observations. This passive cooling is achieved using a large deployable sunshield that provides thermal isolation and protection from direct illumination from the Sun and Earth. To reach such a low temperature, the sunshield is built with 5 layers of coated polyimide film (Kapton), each of them with a size of a tennis court (21.2 m x 14.2 m) when unfolded and a thickness of less than 50 micrometers.

A suite of instruments will provide the capability to observe over a spectral range from 0.6 to 28 µm wavelengths with imaging and spectroscopic configurations. The European Space Agency (ESA) contributed two of Webb's four

© NASA's Goddard Space Flight Center.

science instruments: NIRSPEC developed by ESA with Airbus Defence and Space as the prime contractor and MIRI, jointly developed by the US and a nationally funded European Consortium (EC).
NIRSPEC provides spectroscopic observations with resolutions of 100, 1000, and 2700 in the near-infrared (from 0.6 to 5.3 micrometers). The instrument features about a quarter of a million individually addressable micro-shutters, covering a field of view of 9 arcmin^2 for multi-object spectroscopy (MOS mode), an integral field unit with 3×3 arcsec^2 field of view, and five fixed slits, for high-contrast long-slit spectroscopy. The MOS mode allows slit-spectra of about 100 sources to be recorded simultaneously. NIRSpec will be the first spectrograph in space that has this capability.
The Mid-Infrared Instrument (MIRI) provides photometric imaging in between 5 µm and 27 µm over a 2.3 arcmin^2 field of view, low spectral resolving power (R ~ 100) slit-spectroscopy between 7 and 12 µm, coronagraphy in 4 wave-bands between 10 µm and 23 µm and medium spectral resolution (R ~ 1500 to 3500) integral field spectroscopy over a 13 arcsec^2 field of view between 5 and 28.5 µm. The wavelengths where MIRI operates are particularly promising since Webb can detect very faint astronomical sources like galaxies and exoplanets in comparison with the limited sensitivity of even the largest ground-based telescopes due to Earth's thermal radiation.
After 6 months of instruments testing, routine science operations should begin with great discoveries to come. Stay tuned!



Folding and packing the Webb before launch (© ESA).

The advent *of X-ray free electron lasers*

Free Electron Lasers (FEL) use free electrons in the periodic permanent magnetic field of an undulator as a gain medium. They extend from far infrared to X-rays, they are easily tunable and provide a high peak power. The advent of tunable intense (few mJ) short pulse (down to the attosecond regime) FELs with record multi GW peak power in the X-ray domain enables to explore new scientific areas. These unprecedent X-ray sources come along with versatile performance.

https://doi.org/10.1051/photon/202111022

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Vacuum tubes in which free relativistic electrons interact with electromagnetic waves were rapidly developed last century. First observed in particle accelerators in 1947, the synchrotron radiation emitted by accelerated charged particles, in bending magnets for example, is collimated in a narrow angular cone ($1/\gamma$ with γ the Lorentz factor) and spectrally expands from far infra-red to X-rays. High intensity is achieved with alternated magnetic poles, as in undulators, that create a periodic permanent magnetic field: The radiation from the different periods N_u can constructively interfere and emit on-axis a spectrum of sharp lines at the resonant wavelength and its n^{th} order odd harmonics $\lambda_n = \lambda_u(1+K_u^2/2)/2n\gamma^2$, with λ_u the undulator period, B_u peak magnetic field, K_u the deflexion parameter $= 0.94\ \lambda_u$ (cm) B_u(T). First observed in 1951, undulator radiation is well collimated, adjustable in polarisation and is tunable by a change of the electron energy or by the undulator magnetic field. A. Einstein first discussed the stimulated emission from excited atoms in black-body studies in 1917. The MASER achieved in 1954 by C. Townes, replaced the electron beam amplification of vacuum tubes by stimulated emission of excited molecules introduced in a microwave cavity resonant at the molecule transition frequency. A. Schawlow and C. Townes proposed to use a Fabry-Perot type resonant cavity to extend the radiation to the optical spectral range [1], giving birth to "optical lasers", later named LASER (Light Amplification by Stimulated Emission of Radiation) and underlined limits in wavelength reduction for which new approaches are needed.

J.M.J. Madey from Stanford University searched for a Free Electron Radiation mechanism that could be coupled to the optical cavity approach of the lasers. He opted for Stimulated Compton Scattering process and replaced the counter-propagating photon beam by a virtual one with the radiation from high charge electrons in a strong periodic transverse magnetic field, for being more efficient. The scheme (see Fig.1) includes the electron beam in the undulator field as the gain medium and the laser type optical resonator. After Madey's first gain calculations in quantum mechanics, a classical theory was found to be applicable in most cases. The undulator synchrotron radiation, stored in the optical resonator, exchanges energy with the electrons, leading to an electron energy modulation that is gradually transformed into microbunching at λ_n separation. Electrons set in phase thus radiate coherently, the light is then amplified to the detriment of the electron kinetic energy. The gain of the medium is proportional to the electronic density, the cube of the undulator length and the inverse of the cube of the electron beam energy. FEL wavelength is merely tuned by the electron beam energy of the magnetic field of the undulator. Short wavelength operations require high electron beam energies according to the undulator resonance condition, and thus require high electron beam performance and high undulator lengths. Saturation takes place by enhancement of energy spread, or by unsatisfied resonance condition due to electron beam energy decrease to the benefice of the optical wave. The undulator length is also limited by the slippage of the radiated photons travelling slightly quicker than the electrons, for not the radiation to escape from the electron bunch.

Low gain FELs

J. M. J. Madey pursued at Stanford University on a superconducting linear accelerator with FEL experimental demonstration in 1976 of the amplifier regime and in 1977 of the oscillator one at 3.4µm [2]. Six years later, FEL oscillators were produced on the ACO (France) storage ring in the visible, in the infra-red again at Stanford and at Los Alamos (USA) linac (9-11µm). Coherent harmonic generation (see Fig.1), with a seed laser tuned on the undulator resonant wavelength extended to the UV and VUV. Linac based FEL output power was enhanced by undulator tapering (i.e. adjusting the magnetic field value along the longitudinal coordinate), in maintaining the FEL resonance condition with the electron beam energy decrease. The FEL oscillators, also installed on Van de Graafs, microtrons, energy recovery linacs, were largely developed, and cover from infra-red to VUV spectral range (190nm on the ELETTRA storage ring FEL). They offer a very high degree of coherence (the transverse one thanks to the optical resonator and the longitudinal approaching the Fourier limit thanks to multi-passes). The short wavelength operation is limited by the gain value compared to the mirror losses submitted to drastic irradiation conditions.

High gain FEL development

Along with high gain FEL studies, the production of coherent radiation from a self-instability, in the Self Amplified Spontaneous Emission (SASE) regime without optical cavity was discovered (see Fig.1) [3]. The FEL starts from the undulator spontaneous emission shot noise : electrons communicate together through the radiation and the space charge field and "self bunch" on the scale of the radiation wavelength periods. They emit collectively coherent synchrotron radiation in areas with nearly equal phases driving for a collective instability. After a "lethargy" period required for the initial pulse to build up, the light is amplified exponentially with a gain length L_g depending on the

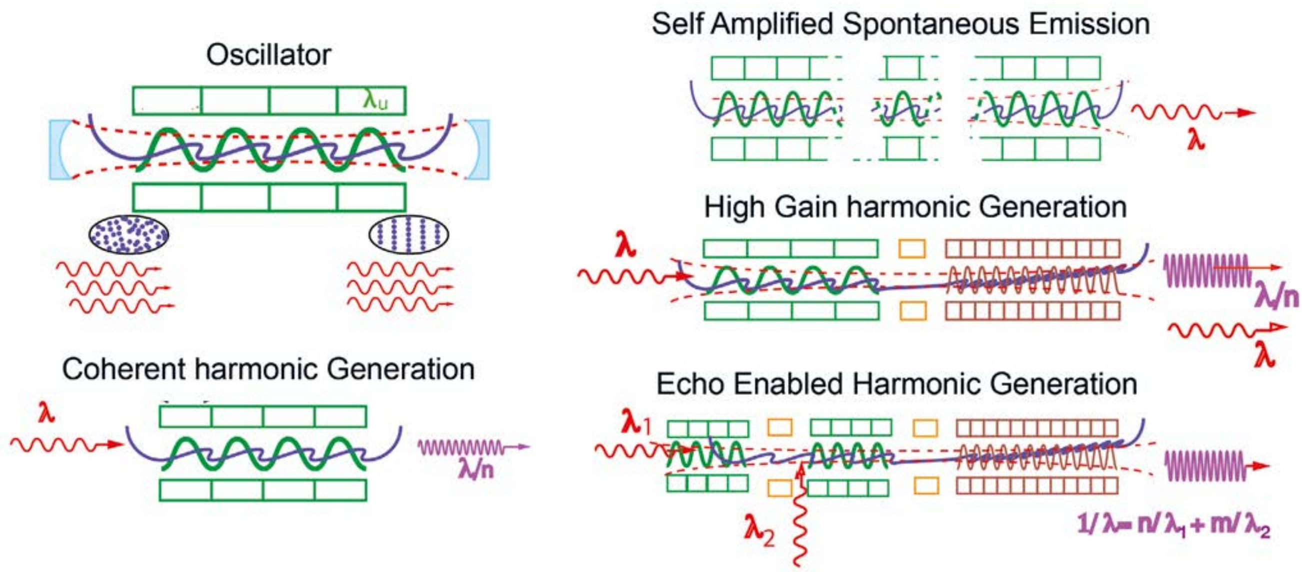

Figure 1: FEL gain medium (relativistic electrons (trajectory in blue) in the undulator (in green)) for the different configurations: oscillator (spontaneous emission stored in an optical cavity, with a sketch of the energy modulation and electron bunching), harmonic generation with an external laser (red) tuned on the undulator resonant wavelength, SASE (undulator spontaneous emission amplified in a single pass), High Gain Harmonic Generation, Echo Enable Harmonic Generation with two electron / laser interactions.

Pierce parameter ρ_{FEL}, that also characterises the FEL efficiency and gain bandwidth. Saturation is typically reached after $20L_g$. The interaction between the electrons is only effective over a cooperation length (slippage in one gain length). The uncorrelated trains of radiation lead to spiky longitudinal and temporal distributions and poor longitudinal coherence, apart from single spike operation.

SASE was first experimentally demonstrated in the mid-eighties in the far infrared where the gain is more favourable in view of the electron beam quality available at that time and then in the infrared one decade later. Thanks to the accelerator developments for future colliders, a major step was crossed with the use of a photo-injector with improved electron beam properties with respect to thermionic guns, on the Los Alamos experiment, demonstrating five orders of magnitude amplification and saturation at 12µm. The beginning of the 21st century saw the advent of the saturated SASE in the visible and UV on the Low-Energy Undulator Test Line (LEUTL, Argonne National Laboratory, USA) (530 and 385nm) in 2000, VISA SASE FEL (USA) (423 - 281nm) in the VUV on FLASH (Germany) (109nm) with a low emittance high charge photo-injector in 2001, *i.e.* 25 years after the FEL invention. Tunability in the 80-120nm range was demonstrated, with a very high degree of photon beam transverse coherence. With higher peak current, the GW level (~1µJ) had been reached in the 95-105nm spectral range [4]. These SASE results competed the shortest wavelength achieved on a storage ring FEL oscillator, making a turning point in

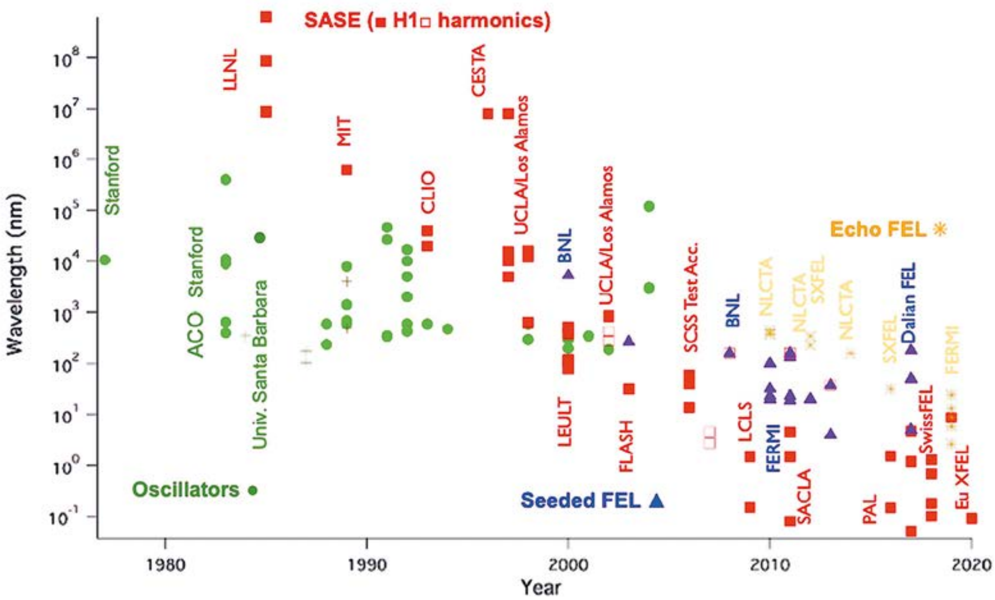

Figure 2: FEL evolution versus years: achieved FEL wavelengths versus year for various configurations (oscillators (non exhaustive), coherent harmonic generation, SASE, seeding).

the choice of the FEL accelerator driver (from storage rings to linear accelerators) and configuration (from oscillator to single pass) for short wavelength FELs. 2000 appeared to bring a transition where VUV was reached both by oscillator and SASE configurations (see Fig.2).

The XFEL advent

The path towards the X-ray domain with SASE radiations was paved with new achievements in the soft X-ray region on the SCSS Test Accelerator (Japan) (60-40nm, 30mJ), FLASH (6.5, 4.1 and water window), which was established as a user facility in 2005. Then, the advent of hard X-ray FELs opened a new area, one decade later, with LCLS in Stanford (USA) at 0.15nm, with saturation after 60m of undulators [5] in 2009, more than forty years after the first FEL in the infra-red in Stanford, SACLA (Japan) in 2011 down to 0.08nm, PAL FEL (Korea) in 2016, Swiss FEL (Switzerland) and European XFEL (Germany) at high repetition rate in 2017 [6] (see Fig.3). European XFEL, an international facility, is driven by a 17.5GeV superconducting linear accelerator with up to 5000 electron bunches per second that serves different FEL branches and experimental stations, providing 2mJ pulses and 6W average power. High repetition rate XFELs enabling multi-users operation are also under preparation on LCLSII (USA) and SHINE (China) projects. In order to alleviate for SASE pulse jitter, spiky spectral and temporal distributions that are prejudicial for use, several configurations are employed: Single spike mode with low-charge short electron bunch regime, chirped electron bunch associated with an undulator taper, seeding with an external laser spectrally tuned on the undulator fundamental radiation, that enables to reduce intensity fluctuations, saturation length and improve the longitudinal coherence (see Fig.1) [7]. Direct seeding has been extended to short wavelengths with High order Harmonics generated in gas (HHG). Nonlinear harmonics can also be applied for efficient up-frequency conversion with cascades of "modulator"/ "radiator" undulators ("modulator" insuring electron modulation with the seed, "radiator" emitting FEL on fundamental and harmonics wavelength), the first cascade using the external seed, the second using the harmonic emitted by the previous radiator with a conversion order up to ~15th order per stage. FERMI@ELLETRA (Italy), the first seeded FEL user facility with two FEL branches: FEL1 (100 - 20nm single cascade) and FEL2 (20-4nm, double cascade harmonic generation), has reached an up-frequency conversion by 192. The seeded Dalian FEL (China) covers the 50-150nm range. For the X-ray domain where seeds are not available, seeding is performed with the FEL itself: a monochromator installed after a first undulator series spectrally cleans the radiation before the last amplification in final undulators. The Echo Enabled Harmonic Generation scheme that imprints a sheet-like structure in phase space via two successive electron-laser interactions in •••

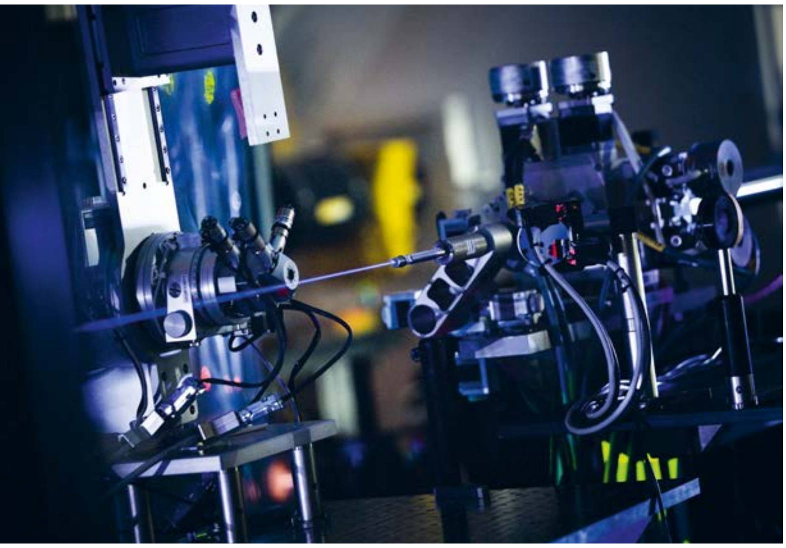

Figure 3: Picture of the European X FEL.
Copyright European XFEL / Jan Hosan

two undulators has demonstrated efficient up-frequency conversion. Coherent emission down to harmonic 101 and lasing down to harmonic 45 at FERMI [8], with enhanced stability as compared to HGHG configuration, multi-colour operation (5.7 and 5.9nm), radiation could be extended to the water window. Hard X-ray FELs employ high beam energies for reaching the resonant wavelength, long undulators (0.1-1km) and high electron beam density (small emittance and short bunches) for ensuring a sufficient gain. These intense XFELs largely benefited from the improvements of the electron beam performance, thanks to the development of photo-injectors and future colliders.

User applications of XFELs

Since the laser invention, the FEL advent in the X-ray domain half a century later opened new areas for matter investigation (structure and dynamics) on unexplored domains with higher temporal resolution [9]. Ultra-intense XFELs give access to the unexplored domain of X-ray nonlinear optics under extreme conditions. In addition, the femtosecond XFEL can be combined to an optical laser for pump (manipulating the internal electronic state)/probe experiments, enabling to provide molecular movies (tracking of structure and electronic states) and process dynamics. Besides, taking advantage of the coherence and of the femtosecond FEL duration, and considering that the diffraction can take place before the destruction of the sample, coherent diffraction imaging can be applied to tiny, fragile crystals in solution even at a high repetition rates (serial crystallography) and single particles such as virus with very good spatial resolution below 1nm. XFELs permits the imaging of living cells and the dynamics of proteins (for example, conformation change of the chromophore in the photoactive yellow protein) can be followed by pump-probe measurements.

Versatile performance of the XFELs facility

Various advanced manipulations enable to XFEL properties to be adapted to the user needs. XFELs provide ultra-short single spike SASE pulse using various electron beam manipulation shaping or FEL specific regime. Single 280 (480) attosecond pulses at 0.9 (0.5) keV [10] with a peak power exceeding 100GW have been recently achieved and used. These features, unlikely to be reached by HHG in a near future, open the path to unique exploration of electron dynamics with X-ray nonlinear spectroscopy and single-particle imaging [16]. After the early two-colour FEL oscillators, XFELs are also operated with two different pulses delayed in time and spectrally shifted for pump-probe experiments, using various schemes (use of one single bunch and differently tuned undulators, pulse splitting combined with chirp or twin bunches). Polarization is controlled on demand and optical vortices can also be produced. FEL oscillators come back into play for the X-ray regime for high repetition rate low bandwidth XFELs or for driving kW average power EUV lithography.

Prospects with new accelerator concepts

FEL is also adequate to qualify new alternative accelerator concepts (dielectric acceleration, inverse FEL, plasma acceleration) for which electron beam performance still does not meet those achieved by conventional accelerators. An amplification of two orders of magnitude at 27nm was recently achieved on the laser plasma accelerator at SIOM (China) [11].

Conclusion

The advent of X-ray Free Electron Laser implemented on conventional linear accelerators, 40 years after the FEL invention constitutes a second laser revolution, enabling to decipher unexplored area of structure and dynamics of matter and biological samples. The unprecedent combined XFEL performance, combining single attosecond pulse, multicolour, GW power and high repetition rate make them unique tools in the landscape of X-rays light sources. ●

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Maria Mitchell

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Maria Mitchell was a pioneer in many aspects: first observer of a comet with a telescope, she received the Gold Medal from the King of Denmark and became the first female astronomer and astronomy professor in the United States of America. But she also got involved in feminism, participating in the foundation of the *Association for the Advancement of Women* in 1873 as well as promoting the access to higher education for women and their inclusion in science.

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 Picture by H. Dassell – Sweeper in the Sky: The Life of Maria Mitchell, First Woman Astronomer in America by Helen Wright, 1914-1997, New York: The Macmillan Company, 1949 (public domain)

First years

Maria Mitchell was born on August 1st 1818 on the Nantucket Island in Massachusetts. At this time, women did not have many opportunities to access proper education, but her situation was uncommon: her parents, Lydia Coleman Mitchell, a library employee, and William Mitchell, a teacher and amateur astronomer, were educated and raised their 10 children according to the Quaker religion, valuing women education as much as men education. As a teenager, Maria Mitchell assisted her father both at school and during night observations≤: she quickly learnt to use a telescope and became passionate about astronomy. At 17 years old, she founded her own school where she applied non-conventional teaching methods and allowed African-American students despite of the ongoing segregation in public institutions. She then became librarian at the Nantucket Atheneum, which enabled her to study on her own and, almost every night, she climbed on the Pacific Bank rooftop, where her father was working, to observe the night sky with a telescope provided for them by the Coast Survey.

Miss Mitchell's comet

It was during one of these night observations that, on October 1st 1847, at 29 years old, she discovered the comet C/1847 T1 (named 1847 VI back then), a so-called telescopic comet since it is invisible to the naked eye and can only be detected with a telescope. With this finding, she became the third woman to discover a comet after Maria Margarethe Kirch (comet of 1702) and Caroline Herschel (8 comets from 1786 to 1797) and the first American person, among both men and women, first detecting one. Two days later, Father Francesco de Vico in Rome (Italy) observed the same comet. Since he published its coordinates before Maria Mitchell did, he temporarily received credit for this discovery, resulting in a short argument

KEY DATES

August 1st 1818:
Birth (Nantucket Island, Massachusetts)

October 1st 1847
Discovery of the *Miss Mitchell's Comet*

1865:
Astronomer and professor at the Vassar College (New York State)

between the two astronomers: indeed the question of the prior settlement was particularly crucial since the previous King of Denmark, Frederik VI, had promised a Gold medal to the first observer of a telescopic comet. Once the credit of her discovery established, the Gold medal was eventually awarded to Maria Mitchell by the king Christian VIII of Denmark and the comet was named after her: *Miss Mitchell's comet* [1]. Her career then took an unexpected turn with an immediate international recognition.

The scientific Maria Mitchell

After this discovery and her novel fame, Maria Mitchell was welcomed in several American institutions. In 1848, she was elected member of the *American Academy of Arts* and Sciences, becoming the first woman to join it. Female admissions were officially not allowed before 1943, a promotion that included, between others, Cecilia Payne-Gaposchkin (see Photoniques **100**, 24-26 (2020)). In 1850, Maria Mitchell was also the first woman to enter into the *American Association for the Advancement of Science* and, in 1869, she joined in particular Mary Somerville and Elizabeth Cabot Agassiz at the *American Philosophical Society*.

In 1849, she accepted a position as a researcher and human computer at the US Nautical Almanac Office of the U.S. Coast Survey, becoming the first female professional astronomer in the USA. Her work consisted in studying the motion of the Venus planet and in arduously computing its position to guide navigators over seas. She worked eight years as a computer before travelling to and through Europe, where she visited numerous observatories such as the ones of Caroline and Sir John Herschel and of Mary Somerville. In 1865 and despite her inexistent degree, she was hired at the Vassar College, a young university for women only back then, and was even named director of the Vassar College Observatory. Once again, Maria Mitchell remained a pioneer since she became the first female professor in astronomy. Her teaching methods were as eccentric as in her younger years: she refused to give marks for evaluations and asked for reduced classes to provide personalized support for her students. She also allowed them to come to the university by night to observe with the telescope and organized missions away for astronomical events such as the total solar eclipse of 1869, defying once again social protocols for women of the XIXth century. Within her students, one can find Vera Rubin who would also become a famous astronomer and Elizabeth Williams Champney who would dedicate her novel In the *Sky Garden* (1877) to her. Some time after having begun to teach and despite her director responsibilities, she discovered that she and Alida Avery, her only female colleague, received wages lower than male professors: they both demanded higher wages, which they were granted with.

Maria Mitchell left the Vassar College in 1888 to retire to her sister to Lynn, in Massachusetts. She died there the following year from a brain disease, on June 28th 1889, and was buried at the Prospect Hill cemetery, on the Nantucket Island that witnessed her birth.

1873:
Co-foundation of the
Association for the Advancement of Women

June 28th 1889:
Death
(Nantucket Island, Massachusetts)

The activist Maria Mitchell

All along her lifetime, her various social and political convictions appeared in her activities and friendships: in particular, Maria Mitchell was a strong advocate against slavery, refusing to wear clothes made of cotton coming from Southern states and opening her school to African-American students.
However, her feminist activism is still nowadays more recognized. In first place, she actively advocated for women right to vote and befriended several suffragettes such as Elizabeth Cady Stanton and Lucretia Mott. During her life, she also promoted the access of women to education and work, particularly concerning the scientific field. Allowing her students to observe by night at the observatory or during missions was already non-conventional for this epoch, but she even encouraged them to work, arguing they should remain independent and competitive at work.
In 1873, she co-founded the *Association for the Advancement of Women* (AAW) that aims to set up and promote the access and the advancement of women in all intellectual and cultural domains, mainly through education. If the AAW was directed, the first year, by Julia Ward Hore, Maria Mitchell became its president the following year and for two years. In 1876, at the fourth AAW congress hold in Philadelphia, she pronounced a speech that still remains known under the name *The Need of Women in Science* and that contains these words: "*Does any one* suppose *that any woman in all the ages has had a fair chance to show what she could do in science? […] until able women have given their lives to investigation, it is idle to discuss the question of their capacity for original work*" [2].

Figure 1. Maria Mitchell's portrait - Nantucket Historical Association Research Library (public domain)

Scientific contributions

Maria Mitchell's research is complex to perceive with certainty for the contemporary perspective. First, her archives are spread between a few scientific articles, outreach articles, notes, poems, her journal, and letters. In addition, if the XIX[th] century witnessed the advent of spectroscopy and photography, two inventions mentioned in Maria Mitchell's writings (she used a chronograph during her observations), part of her measurements were made by eye, which she outlined in some of her articles ("*I have taken great pains to notice the colors of the stars before my eye was fatigued*"). In addition to tiredness, she mentioned measurement uncertainties that are also witnesses of the difficulty to observe at that time ("*The color is peculiar*", "*reddish*").
Maria Mitchell was also curious and her researches spread between very diverse topics. The famous *Miss Mitchell's comet* [1] is nowadays known as a non-periodic comet with a hyperbolic orbit. In addition to Venus that she focused on as a human computer, she observed for a long time Jupiter satellites ([3], in which she refers to Io, Europe, Ganymede, and Callisto as numbers, as the norm back then required) and Saturn satellites ([4], where she explicitly names Tethys, Dione, Rhea, Encelade, and Titan). Maria Mitchell also focused on the Sun and suggested that solar patterns could be due to surface irregularities like holes instead of clouds. Eventually, she observed several double stars, thoroughly reporting her coordinates and characteristics [5].

Honors

From the discovery of the comet that holds her name, Maria Mitchell was internationally recognized. Her celebrity was meteoric and allowed her to join many associations both during her lifetime and posthumously. Thirteen years after her death, the Maria Mitchell association was founded to honor her memory, to perverse her works as well as to stimulate everyone's curiosity towards science. The association notably manages the Maria Mitchell's Observatory, on the Nantucket Island.
She entered into the *Hall of Fame for Great Americans* in 1905, *i.e.*, the first year a woman could integrate this gallery, and into the *National Women's Hall of Fame* in 1994.
In addition, many tributes are dedicated to her: a World War II *Liberty Ship* boat was named *SS Maria Mitchell*, a New York train is called *Maria Mitchell Comet*, and, probably more importantly to her view, one of the moon craters holds her name.
For the most curious readers, several books mention her or tell her story, such as *Figuring* from Maria Popova (2019), *What Miss Mitchell Saw from Diana Sudkya and Hayley Barrett* (2019) and *Maria Mitchell and the Sexing of Science: An Astronomer among the American* from Renée Bergland (2008). Last but not least, we have to cite her own biography, *Maria Mitchell: Life Letters and Journals*, posthumously published in 1896 by her sister, Phebe Mitchell [6].

Fig. 2. Buildings of the Maria Mitchell Liones Observatory on Nantucket Island, Massachusetts – Bersageek.

Nowadays

Still today, Maria Mitchell would be a revolutionary. Her curiosity brought her to the observation of various objects and made her a pioneer in astronomy: first observer of a telescopic comet, first female professional astronomer in the USA, first female professor in astronomy, first woman elected in numerous science organizations... She also rapidly became a main figure of feminism, opening the path to women recognition in science and getting actively involved in access to education and science for women.
Her own words best summarize her impact on society and astronomy : "*do not most persons, even of the intelligent classes, believe that above all other things a woman's first duty is to be useful in the kitchen and ornamental in the parlor? It belongs to women themselves to introduce a better order of things. [...] "Society" is certainly fashioned by women*"[7].

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HIDDEN STATISTICS IN SPECKLE PATTERNS

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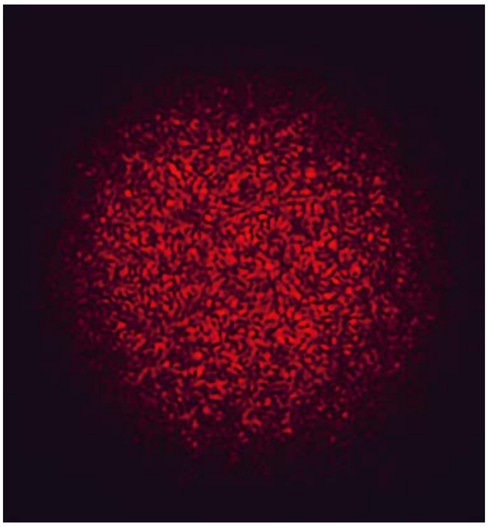

Scattering of coherent light from a disordered material produces a complex distribution of intensity known as a speckle pattern. Speckle patterns are not as random as they appear at first glance. Their statistical properties exhibit universal features, as already recognized in the first paper on laser speckle. The existence of short-range and long-range spatial correlations in speckles has been shown to be fundamental in wave physics. It has also led to the emergence of novel approaches for imaging through scattering media.

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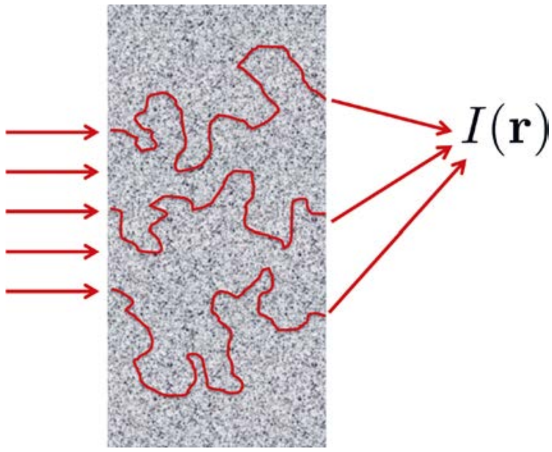
A HISTORICAL PAPER ON LASER SPECKLE

In 1963, shortly after the laser was invented, Robert Langmuir reported on a curious phenomenon in a Letter entitled *Scattering of Laser Light* [1]. By illuminating a piece of paper with a helium-neon laser, he observed a pattern of dark and bright spots, which could be seen both in transmission and reflection. Without using the word, Langmuir described what we now call a speckle pattern, and his Letter seems to be the first report on laser speckle produced by scattering. After a brief qualitative description of the phenomenon, Langmuir assumes that the observed behaviour "must surely be related to the coherence and extreme monochromaticity of the light emitted from the laser". Using an analogy with radar wave propagation, he borrows a known result in this domain to deduce that the probability distribution of the intensity I in the speckle pattern must be of the form $exp(-I/I_0)$.

Although intuitively introduced by Langmuir in his paper, this result actually reveals the existence of fundamental statistical properties in speckle patterns. This negative exponential distribution, known as Rayleigh statistics, is more precisely written as $exp(-I/<I>)/<I>$, where $<I>$ is the average intensity. Its universal character, independent of the nature of the scattering object generating the speckle pattern, is remarkable. In fact it can be shown that the distribution follows from an application of the central-limit theorem, under very general assumptions that are quite robust in practice (see insert 1).

RAYLEIGH STATISTICS

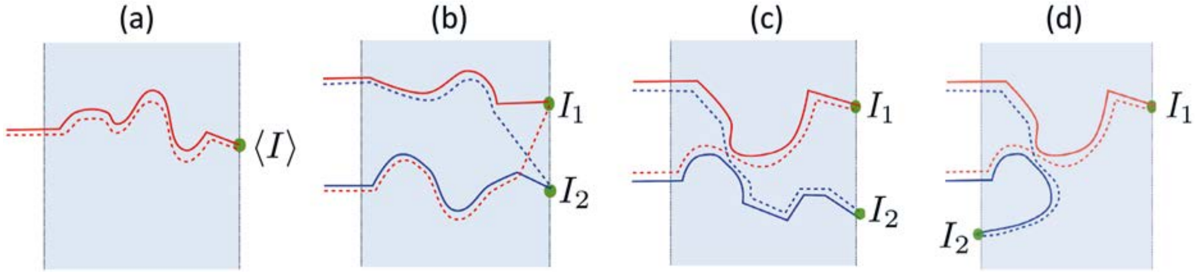
In a speckle pattern, formed by shining monochromatic light on a scattering medium, the complex field amplitude E(*r*) is the superposition of partial waves emerging from all possible scattering paths inside the medium. Three of such paths are represented in the figure. In the simplest model, one assumes that the partial waves are statistically independent with their phases uniformly distributed (roughly speaking, the waves are "as random as possible") [2]. The amplitude E(*r*) being the sum of a large number of independent random amplitudes, its real and imaginary parts follow a Gaussian statistical distribution by virtue of the central-limit theorem. The intensity $I(\mathbf{r})=|E(\mathbf{r})|^2$ therefore follows a negative exponential distribution, also known as Rayleigh statistics.



NOISE OR SIGNAL?

With the advent of the laser, the observation of speckle in optics has become commonplace, and integral to the development of coherent detection and imaging techniques. Many book chapters, and even dedicated textbooks, are devoted to speckle [2]. At first sight, the granularity of speckle creates some noise superimposed on signals or images, and the reduction of speckle noise becomes a key issue. However, speckle being interferometric in nature, its high sensitivity to the scattering medium can be used, for example, to detect a deformation or to probe the internal dynamics of a medium in which the scatterers are in motion (such as particles in suspension in milk or a blood flow). In this case a statistical property is used, such as a spatial or temporal correlation function of the detected intensity, to measure a parameter on which it depends (in this case, the chosen statistical property has to be non-universal). From noise, the speckle becomes a signal.

ORIGIN OF LONG-RANGE CORRELATIONS IN SPECKLE PATTERNS

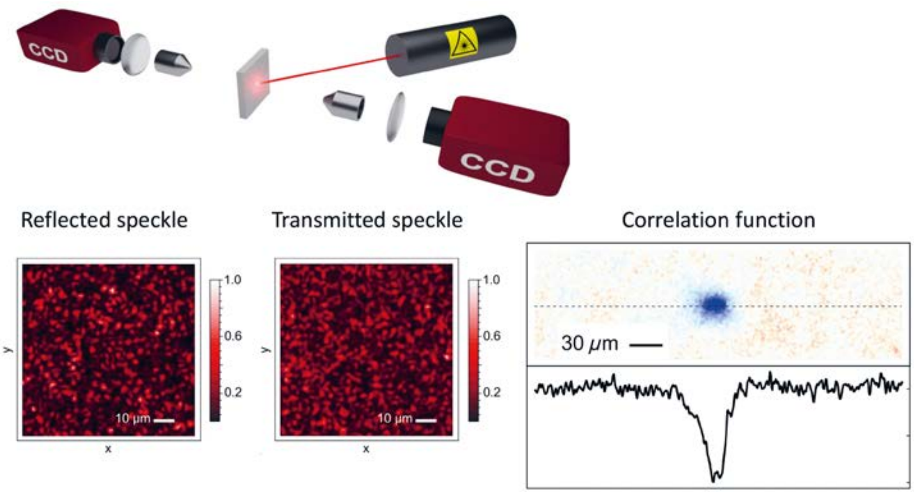


A wave in a disordered medium propagates along scattering paths, schematically represented as wavy lines. To form the intensity $I = |E|^2$, one needs to pair two scattering paths corresponding to E (shown as a solid line) and to its complex conjugate (shown as a dashed line). In multiple scattering theory, one shows that the leading term in the average intensity $<I>$ corresponds to a field and its complex conjugate following the same scattering paths (other pairings vanish after averaging due to destructive interferences) [6]. One uses the representation in (a) for the average intensity, with the double line known as a "ladder". Observing now the intensities I_1 and I_2 at two different points, a correlation between them can be created by crossings between ladders (two independent ladders would simply lead to $<I_1 I_2> = <I_1> <I_2>$). If the crossing occurs at the last scattering event, followed by ballistic propagation towards the observation points as represented in (b), one creates a short-range correlation characterizing the size of the speckle spots. If the crossing occurs deep inside the medium, followed by diffusion as shown in (c), one creates long-range correlations. This mechanism can also generate intensity correlations between two observation points on opposite sides of the scattering medium, in the reflected and transmitted speckle patterns. This kind of correlation has been observed only recently [7].

MULTIPLE SCATTERING AND THE CONNECTION TO MESOSCOPIC PHYSICS

The traditional description of speckle in optics has long been based on a physical optics approach, assuming a single scattering regime, in which the different points of the object are illuminated by the incident wave and scatter towards the detector, without interaction between them. From the mid-1980s, the emergence of multiple light scattering as a full-fledged research topic gave a second wind to the study of optical speckles. This emergence was stimulated on the one hand by applications in imaging through strongly scattering media (such as biological tissues), and on the other hand by fundamental questions in mesoscopic physics. Indeed, the expected analogies between quantum transport of electrons in condensed matter, and multiple scattering of coherent light in disordered media, have allowed to revisit the statistical properties of optical speckles.

Figure 1. Measurement of the reflected and transmitted speckle patterns produced on both sides of a scattering medium. A statistical correlation between them persists even when the medium is opaque due to multiple scattering. Adapted from [7].



The spatial correlation function of the intensity in a three-dimensional speckle has been predicted, showing a universal short-range component characterizing the average size of a speckle grain [3]. More surprisingly, the existence of long-range intensity correlations (well beyond the size of a speckle grain) has also been predicted [4] (see insert 2). These long-range correlations can be demonstrated by measuring the intensity correlation function at two different points, or at two different times or frequencies [5], which is possible in optics but not for electrons in condensed matter. The study of optical speckles became more and more fundamental in wave physics, with an impact far beyond the field of optics.

MORE SURPRISES WITH LONG-RANGE SPECKLE CORRELATIONS

In principle, the mechanism responsible for the long-range correlations in a speckle pattern should allow one to generate correlations between speckle patterns measured in reflection and transmission on both sides of a turbid scattering medium (see panel (d) in insert 2). After a theoretical study showed the possibility, the existence of such a statistical link has been demonstrated experimentally [7]. The experiment and the result are summarized schematically in figure 1. The existence of a statistical correlation between the intensities measured at two points on either side of the scattering medium proves that the reflected and transmitted speckle patterns share mutual information, even in a multiple scattering regime in which the medium is opaque (meaning that it is not possible to form a direct image through it).

Sometimes noise, sometimes signal, object of fundamental studies or tool for new optical techniques, speckle patterns have a long history. Today, the possibility to manipulate them using wavefront control techniques, and the use of their long-range statistical correlations, have opened new avenues for imaging and detection in or through strongly scattering media. A long story, therefore, and far from over. ●

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BIO-BASED OPTICAL AND PHOTONIC MATERIALS:
TOWARDS NATURE-BASED PRODUCTION METHODS FOR PHOTONICS

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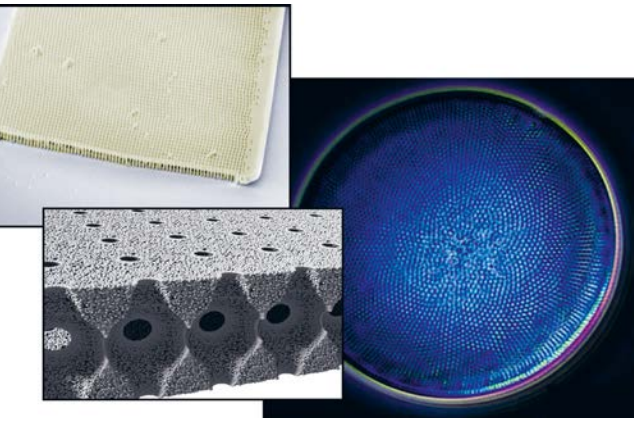
Image by Johannes Goessling

Nature has been a source of inspiration for the fabrication of new optical materials for centuries. During the last decades, the rapid developments in nanofabrication allowed mimicking the photonic properties of living organisms towards more efficient functional devices. But nanophotonics still relies on nanofabrication techniques and materials not compatible with the current environmental challenges. Bio-based optical materials have emerged as a sustainable alternative combining the best of both worlds: precise nanostructuring and unique optical properties with environmentally friendly natural production protocols.

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PHOTONIC NATURAL SYSTEMS BEYOND BIOINSPIRATION

The very urgent climate emergency demands advanced materials sustainable both in their properties and their fabrication procedures. Reducing carbon footprint is a top priority worldwide. Under this scenario, making the properties of photonic materials more efficient for a particular application is not enough. The fabrication and manipulation of those materials should be sustainable and with the smallest carbon footprint possible. In this context, Bio-based Optical Materials (BOMs), advanced optical materials produced by living organisms, have been raised as a sustainable alternative for future photonic technologies.

Indeed, natural systems can overcome man-made optical technologies [1]. And although BOMS can show extraordinary anisotropies or narrow absorptions due to their material composition, they usually present low refractive indexes reducing their possibilities as bulk photonic materials. Interestingly, natural systems can produce very complex structurations at all scales providing BOMs with advanced photonic properties. The most studied case of BOM optical nanostructures are the scales of insects and feathers of birds, responsible for bright and resilient structural colours. But in recent years, a large family of BOMs with functionalities beyond colour display such as enhanced sensitivity in vision or thermal protection have been discovered.

These discoveries triggered at first biomimetic implementations which consisted mainly of top-down approaches where, to solve a specific technological need, researchers seek into nature a "blueprint" that fulfils the device requirements. But this approach suffers from the same limitations and large carbon footprint as non-biomimetic technologies. To solve this, a new family of BOMs are being developed in which living systems are not just an inspiration but the actual source of functional photonic nanomaterials. BOMs such as silk, lignin or bacteria are already showing interesting possibilities. In the following, we discuss the three main types of photonic BOMs depending on their optical properties and their level of technology implementation.

BIOPOLYMERS IN NANOPHOTONICS

Biopolymers are natural polymers produced or derived from cells of a living organism. In a biopolymer, the monomer unit is replicated to form a larger molecule and render some of the most important molecules for life such as DNA or cellulose. Although biopolymers can vary widely in composition, their material properties have been extensively studied and exploited at both research and industrial scales. However, their use in photonic technologies has been very limited. In recent years, developments in nano and biotechnology have opened the possibility to use biopolymers as actual photonic devices in a wide set of applications, particularly for biopolymers based on proteins and polysaccharides.

One of the most studied cases of photonic biopolymers in nature is chitin. Chitin is a polysaccharide present in the exoskeletons, wings and cell walls of many organisms (Fig.1). Optically, chitin presents a homogenous refractive index (approx 1.55) with neglectable absorption in the VIS. A couple of decades from now, the seminal works in the field showed that chitin forms complex nanostructures such as 3D photonic crystals [2] which promoted the developments of biomimetic devices based on these structures (Fig.1) [3]. However, the growth of chitin photonic nanostructures in the laboratory has not yet been achieved.

Despite chitin's interesting properties, probably the most studied • • •

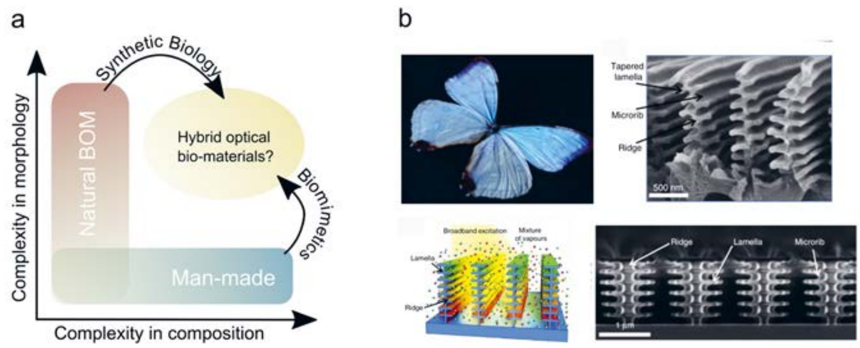

Figure 1. a) Man-made photonic nanostructures benefit from material complexity. Natural photonic materials on the other hand are often simple in composition but they can present complex morphologies with diffrent levels of structuration. While biomimetic approaches might allow to reach higher degrees of morphological complexity, the use of synthetic biology methodologies might enable similar performance with greener implementations. Figure adapted from [1]. b) Example of bioinspired photonic nanostructures. The strong blue color of the wings of a *Morpho* butterfly (left) is produced by interference at the 3D chitin nanostructures (top right). Bottom right shows the biomimetic counterpart produced by patterning PMMA polymer using e-beam lithography. The PMMA has a refractive index n=1.49 across the visible and negligible extinction coefficient (extracted from Ref. [3]). In a gas sensor implementation, different vapours fill the nanopores inducing a local refractive index change detectable as variation in the reflected color (bottom left).

example of photonic biopolymers in the last years is cellulose. Cellulose is a polysaccharide biopolymer present in plants and is also the most abundant biopolymer on earth. From an optical perspective, cellulose is a homogenous material with a relatively low refractive index (n≈1.53). However, it can arrange to form chiral structures in cell walls. The formation of such chiral photonic crystals provides these cell walls with some of the brightest colours in nature [4] (Fig.2b). In recent breakthroughs, these structures were replicated in the laboratory by inducing the self-assembly of cellulose nanofibers and nanocrystals which lead to the fabrication of large-scale, cost-less and sustainable cellulose-based photonic devices [5] (Fig.2c).

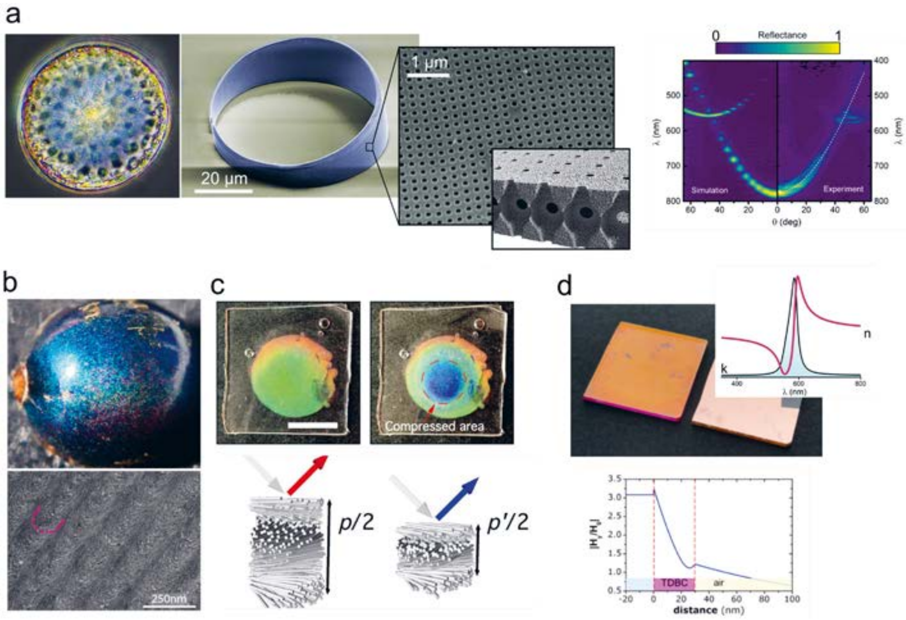

Figure 2. a) Biomineralization in diatom microalgue can produce high quality slab photonic crystals. The image shows a specimen of species *C.granii* (left), a biosilica membrane (known as girdle band) after separation from the organic material and a close up of the natural slab photonic crystal. The biosilica membrane is approximately 1 um thick and it is perforated by a square lattice of period a≈300nm well preserved among individuals of the same species. Angle resolved spectroscopy (right) shows the dispersion corresponding to a low contrast slab photonic crystal structure. Data extracted from [8]. b) In some organism (in the image fruit of *Pollia condensata*) cellulose can form Bragg-like stacks with a chiral twist as shown in the electron micrograph (images extracted from [4]). c) Encapsulation of hydroxipropil cellulose in PDMS polymer can be controlled in the laboratory to obtain chiral Bragg-like reflectors tunable through pitch selection. The central wavelength changes upon compression of the celullose multilayer (image extrated from [5]). d) Organic excitonic dyes found in nature can show narrowband highly resonant dielectric constants (inset) allowing strong reflectance and surface polariton propagation. In the image, photograh of a thin film of gold (right) and J-agregate TDBC molecule (left) embedded in a Poly(vinyl alcohol) (PVA) matrix. Note the metallic narrowband strong reflection of the organic film. Surface polariton modes are supported at both interfaces of the J-aggregate film as shown in the magnetic field calculation. Images extracted from [7].

NATURAL PIGMENTS FOR RESONANT PHOTONICS

Many organisms showing advanced optical properties present a combination of biopolymers and organic pigmentations within the same nanostructure. Interestingly, the organic dye can induce a strong resonance in the dielectric constant hence adding an extra parameter in the "design" of the natural photonic structure. Probably the most interesting case of natural pigment-protein systems is the molecular complexes responsible for photosynthesis. In these complexes, the chromophores are compactly arranged within a protein scaffold. The proximity of the chromophores in the nanostructure allows the delocalisation of excitons among them, rendering an almost unity efficiency of energy transport [6].

Interestingly, the exciton delocalisation of photosynthetic complexes can be mimicked by bio-supramolecular assemblies known as J-aggregates which are present in some molluscs, plants or fruits. The delocalisation of the exciton within the monomers forming the supramolecule provides them with narrow and strong resonances bringing up shinning colours. Noteworthy, J-aggregates can be embedded in polymer matrix allowing their incorporation into photonic nanostructures. The final composite is a strong dispersive material [7] with a resonant dielectric constant which provides these materials with metal-like optical properties and support for surface exciton-polaritons (Fig 2d). Moreover, they can be incorporated as sharp absorbers into photonic cavities for strong coupling polaritonics. These properties could open the door for the development of metal-free resonant nanophotonics and metamaterials fully based on naturally produced organic matter.

PHOTONIC MATERIALS THROUGH BIOMINERALIZATION

Biomineralization is the process by which many endos- and exoskeletons in living systems as algae, clams or plants are formed. The outcome of biomineralization is organic-inorganic composites that can show intricated hierarchical nanostructures often providing the living organism with stiffer and harder properties than biopolymers. As with biopolymers, the interest in these BOMs has drastically increased during the last few years. Firstly, the composition of biomineralized BOMs is often based on calcium salts (calcification) or silicon oxides (silicification), both compatible with current photonic technologies. In addition, they present multidimensional photonic-scale structuring with features at least as precisely defined as those obtained with complex etching and patterning techniques in the cleanroom (see Fig.2a).

In this context, diatom microalgae are one of the most interesting BOMs. They are unicellular organisms whose most characteristic feature is a silica-rich exoskeleton, known as frustule, which size can range from tenths to hundreds of microns per cell. Their photonic properties were debated for decades but it was recently demonstrated that the frustule can show slab photonic crystal features comparable to those produced with man-made nanofabrication [8]. Moreover, diatoms photonic biosilica structures can be doped during cell growth by adding organic dyes or plasmonic nanoparticles paving the way to *in-vivo* production of ad-hoc hierarchical nanostructures with specific photonic functionalities. Yet, the appropriate tailoring of the photonic properties will need a better understanding of the biomineralization processes during the morphogenesis of the diatom exoskeleton.

Interestingly, the nanostructures produced by biomineralization can be isolated from other bio-products with relatively simple procedures. In the case of diatoms, these products could be biosilica, pigments and oils. Whilst biosilica and pigments can be desirable for optical applications, the oils can be used as biofuel and/or feedstock. Therefore, photonic structures resulting from biomineralization in plants or algae might allow for circular economy approaches where all bio-products, photonic or not, could find a use enabling a zero-waste technology.

CONCLUSIONS AND FUTURE OPPORTUNITIES

The field of natural photonics was originally fuelled by human curiosity for understanding how living organisms play with light. More recently, biomimetic photonics was propelled by the search to replicate the extraordinary natural structures in the laboratory towards technological applications. Now, the rapid advances in synthetic biology [9] anticipate a completely new era for photonics where it will be possible to manipulate the biochemical processes behind the BOM formation at the cellular level enabling the production of ad-hoc hierarchical natural photonic nanostructures. This will change drastically how we design and produce photonic devices making the collaboration between synthetic biologists, chemists, engineers and physicists essential to push forward this new generation of clean photonic technologies.

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OPTICAL SPECTROSCOPY FOR THE DETECTION OF MICRO- AND NANOPLASTICS IN WATER

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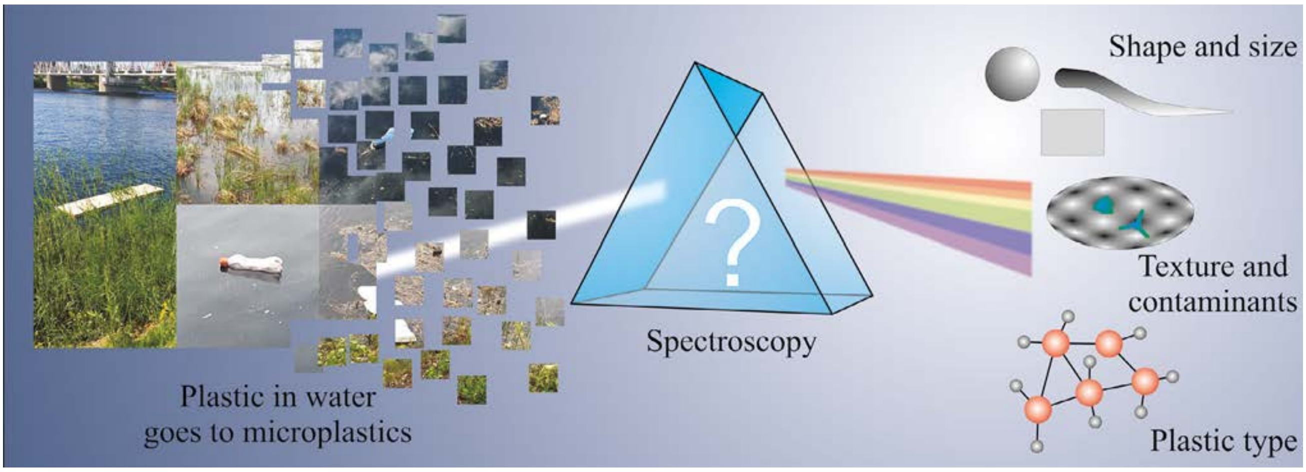

Optical spectroscopy techniques offer an additional dimension to classical methods for the detection and identification of complex particles in complex environments. We present some of these techniques applied in the frame of the fight against the plague of Micro- and Nano-plastics.

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Plastic products have much importance for human beings in our everyday life. The resulting wastes from these products are usually sent for recycling especially in developed countries. Despite the contemporary regulations and suggestions to recycle plastics, this has not been the case in the past. Moreover, in less developed countries, the recycling of local wastes is still an issue. Consequently, lots of plastic litter have been buried in soil or ended up in the seas and lakes, where light plastics are floating, and heavier ones settle at different depths in these environments. The presence of plastics and their degradation into micro- and nanoplastics (MNPs, 100nm < MP < 5mm, NP < 100nm), due to UV-radiation and weathering, for example, pose a threat to the environment. There is scientific evidence that both MPs and NPs can accumulate in Flora and Fauna. Associated health-related issues, such as the toxicity of MPs and NPs, are currently under continuous investigation. Whatsoever, the detection of MPs and NPs is still in its infancy and, probably, our current knowledge of these particles is still limited.

Optical spectroscopy or spectrophotometry is a field of Photonics for the investigation of the interaction of light with matter. It yields information on the nature of matter through spectral response, *i.e.*, how different wavelengths are transmitted, reflected, absorbed, or re-emitted by an analyte under a particular illumination. Spectroscopy represents nowadays one of the most powerful techniques of analysis in domains of medicine, pharmacology, biology, chemistry, and environment. For decades, these methods have been improved and some of them are ready to be applied for the detection and identification of MNPs.

Plastics are man-made materials mainly based on polymers, *i.e.*, very large molecules that may be petroleum derivatives. Depending on the monomer molecule composing their long polymeric chain, plastics may have different physical and chemical properties that define their use. Ranging from containers, packaging, fabric to components used in industrial processes, plastics are everywhere for about 70 years. Since then, their production is in monotonic growth and so are the wastes. In one way or another, plastic particles end up in water, which is a perfect carrier of these particles to biological organisms. In addition to the complex nature of these particles, the host medium such as open water, wastewater, or tap water, can also be complex. Further to being small, various, and capable of hiding in the complex matrix, MNPs are preferential hosts for a multitude of organisms, such as bacteria or viruses, and other materials, such as heavy metals. Besides biological organisms, MNPs are also considered dangerous to human health. With all these complexities surrounding these particles and their hosts, spectroscopic techniques can reveal some relevant information about the particles elusive to other detection techniques.

There are some basic features of interest to characterize and identify MNPs. These include their size, abundance (especially in aquatic environments), and type. Although the problem is recent, there is already quite extensive literature reporting on the different detection and analysis methods for MPs [1]. For NPs, the situation is different since these particles are more difficult to detect; thus, identification and monitoring methods are still under development. A review focused on the different optical detection methods and the outlook of in-situ methods is presented in our recent paper [1]. While the size and shape of MNPs are typically obtained by imaging and microscopy, the identification of MNPs is principally based on optical spectroscopy. Thus, we deal with the current knowledge of MNPs detection by exploiting optical spectroscopy methods. Examples of optical spectra on transparent and translucent plastic particles, that are obtained from a municipal wastewater treatment plant, are presented.

OPTICAL SPECTROSCOPY FOR THE DETECTION OF MICROPLASTICS

Among the numerous variants of optical spectroscopy methods, we describe in this article only the most used ones in laboratories for the identification of MNPs. It is to be understood that most of these methods require sample preparation, which can be cumbersome for an inexperienced researcher or in-the-field measurements. This sample preparation usually starts by the collection of enormous amounts of water sediments and its filtering to isolate ultimately only a few particles. Then, samples are analyzed using the spectroscopy methods described in the following. Examples of methods (Raman microscopy, FT-IR, and transmission spectroscopy) are illustrated in Fig.1.

A very common technique is the Fourier transform infrared spectroscopy, FT-IR. This method is based on the measurement of the energy absorbed by molecules at the specific frequencies •••

We deal with the current knowledge of MNPs detection by exploiting optical spectroscopy methods. Examples of optical spectra on transparent and translucent plastic particles, that are obtained from a municipal wastewater treatment plant, are presented.

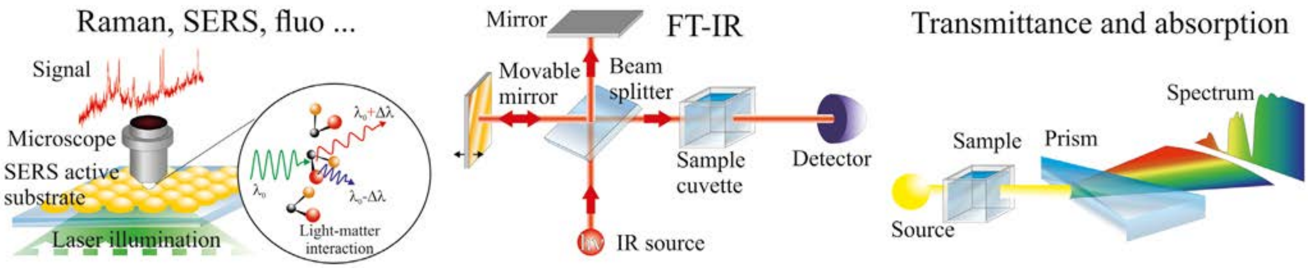


Figure 1. Illustration reproduced from [1] showing the principles of some optical spectroscopic techniques used in the detection and identification of micro- and nanoplastics.

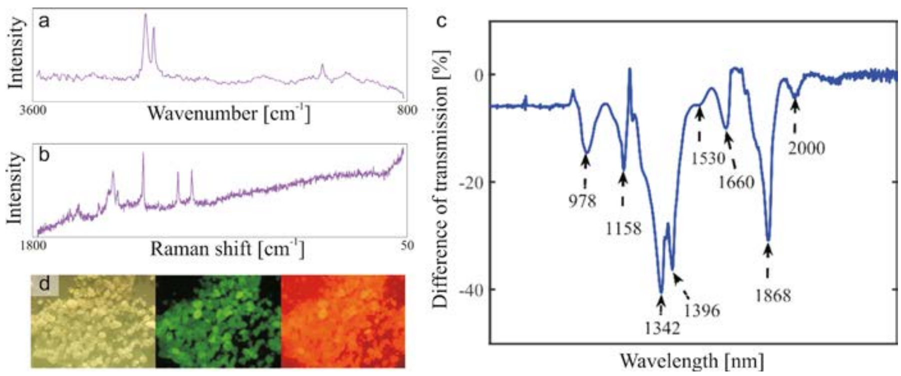
corresponding to the bonds linking atoms together. Very characteristic absorption peaks (Fig.2a) of plastics are certain in the infrared region of the electromagnetic spectrum, which makes FT-IR a suitable method for the identification of plastics. By measuring the position and shape of these peaks, one can identify, by comparison with a previously established database, the different types of MP particles. A limitation in size, however, exists, but by integrating a microscope with an FT-IR, the detection limit can be improved to detect particle sizes down to 10µm. Extensive details are given in the review article by Veerasingam *et al.* [2].

Another important technique used in the identification of the MNPs is the so-called Raman spectroscopy [3], which assigns a unique signature to a particular molecule, see Fig.2b. Based on the elastic scattering of photons by matter, a Raman spectrum gives the difference in energy between absorbed and re-emitted photons. This is quantified by the Raman shift, which depends on the vibrational state of each bond in a molecule. A Raman spectrometer can also be coupled to a microscope, which enables the detection of smaller particles (< 1µm). Raman spectroscopy is probably the most precise method for MP analysis since it provides reliable results over a relatively large (~ 50cm^{-1}) spectral range. However, the resulting weak Raman signal from this spectroscopic method and the difficulty in sample preparation reserves the method for experts only.

A third type of spectroscopy used in MPs identification is based on the study of the simple transmission spectra of samples [4,5]. Unlike FT-IR and Raman spectroscopy, the result of such a measurement does not provide a quantitative identification of the plastic types. Usually, peaks or dips of a transmission spectrum may overlap hiding some features important for the determination of the constituents. Typically, the spectral data is analyzed by combining the knowledge on the complex refractive indices of pristine plastics and that of the environment and performing advanced data processing of the spectral response of the analyte, such as investigating the difference of transmission, see Fig.2c. Once the protocol is set, transmission spectroscopy becomes a fast and easy-to-implement method to determine the composition of samples. No sorting is necessary, and a lower level of filtering is required.

One of the challenges in detecting MNPs in water environment is the low concentration of these particles. Therefore, it is typically needed to filter large quantities of liquid before obtaining a significant amount of MNPs to be characterized. For low concentration samples, fluorescence spectroscopy is very efficient especially at the counting phase of the sorting. This method is improved by using dyes, for instance, Nile Red, enabling easier observation as shown in Fig.2d. A technique recently applied in the detection and identification of MNPs involves the use of hyperspectral imaging allowing simultaneously the measurement of the shape (imaging) and the determination of the type (spectrum) of the particle. The data processing of the huge data files collected by such cameras is the key to providing relevant results. This

Figure 2. Examples of results obtained with different spectroscopic methods applied on microplastics identification. a) FT-IR [1], b) Raman microscopy [1], c) Transmission spectroscopy [1,5], d) Fluorescence microscopy [6].



processing is often based on machine learning including algorithms such as principal component analysis or other classification methods. The method is used for monitoring large geographical areas, *e.g.*, coastal monitoring [7]. This is a promising method for the detection of large microplastics (> 100µm).

In most of the methods described in this article, samples must be filtered, sorted, and then analyzed. It represents a huge work and therefore a need for fast and portable devices, which has emerged in the recent past years. Several techniques based on optical spectroscopy can be combined into handheld apparatus. However, the integration of laboratory-based techniques into smaller devices leads to a decrease in device resolution and sensitivity, unfortunately. However, in return, a large number of samples can be analyzed.

CONCLUSION

For all methods developed so far, the drawback comes from the matrix, *i.e.*, the environment surrounding the plastic particle. It may indeed contain all types of other particles that may perturb the identification of the MNPs. Typically, organic materials in wastewater or freshwater lead to fuzzy results, which makes filtering an important part of the analysis process.

Micro and nano-plastics are already everywhere, and their amount increases considerably at every moment. Many years of research and individual effort on limiting our usage of plastic are needed to achieve a significant change in this trend. Our duty as researchers is to now provide the tools to understand the problem deeply. Monitoring, detecting, and identifying MNPs is crucial as an initial step. However, the removal of these particles is even more important, and efforts are currently directed towards the development of techniques for such a task.

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LIGHT HARNESSING BY ALGAE: FROM FUNDAMENTAL INVESTIGATIONS TO LIGHT-BASED BIOTECHNOLOGIES

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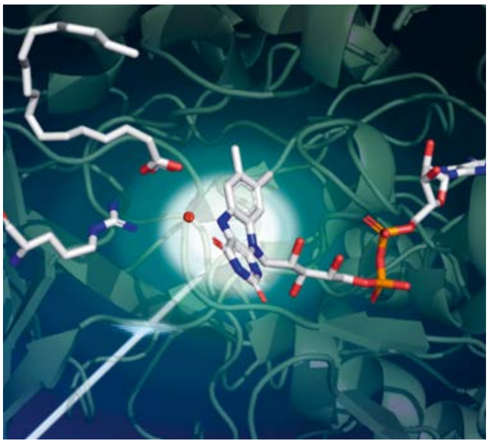

Light is the most abundant source of energy on earth and is used by photosynthetic organisms to drive the synthesis of organic molecules. Light also allows the catalysis of few enzymes, the photoenzymes. Among them, the fatty acid photodecarboxylase (FAP) isolated from microalgae converts fatty acids into hydrocarbons. We present here our understanding of the role of hydrocarbons produced by FAP *in vivo*, the catalytic mechanism of the FAP and its potential biotechnological applications.

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Sunlight powers all life processes, warming our planet and providing energy for photosynthetic life. In photosynthetic organisms, light is harvested by the photosynthetic chain that allows the conversion of photon energy into chemical energy, which can then be used by the Calvin cycle and cellular metabolism to fix CO_2 and generate the organic compounds essential for growth. Among the photosynthetic organisms, we find plants, algae, cyanobacteria, and microalgae. It is not surprising that we find in these organisms, biological systems allowing the perception and the use of the light. However, known enzymes capable of directly using photon energy for their catalysis are still very rare. With the exception of photosystems, to date only three natural photoenzymes have been identified, DNA photolyase involved in DNA repair, light dependent protochlorophylide oxidoreductase, and FAP that convert fatty acids to hydrocarbons [1] (figure 1). All these photoenzymes are found in microalgae but FAP is the only photoenzyme of obvious biotechnological interest. In this perspective, we will address our current understanding of the role of hydrocarbons produced by FAP in microalgal cell, the catalytic mechanism of the FAP and its potential biotechnological applications.

FATTY ACID PHOTODECARBOXYLASE IS A PHOTOENZYME SPECIFIC TO ALGAE

We have previously shown that various species of microalgae naturally produce hydrocarbons and that this production is strictly dependent on the presence of light [2]. The hydrocarbon-forming enzyme present in

Figure 1 : Chemical structures of fatty acid and a hydrocarbon.

the microalgae *Chlorella variabilis* has been identified by partial purification of the activity and a proteomic analysis. The enzyme allows the direct conversion of fatty acids into hydrocarbons plus CO_2. This enzyme contains a light-absorbing FAD cofactor and we have shown that excitation of FAD by light is required for each catalytic cycle. This photoenzyme was named fatty acid photodecarboxylase (FAP). FAP belongs to a family of enzymes that is present in a wide array or organisms, from animals to bacteria. However, the FAP subgroup seems only present in algae and most algal genomes known to date possess a gene encoding a FAP protein [3].

The biological function of the hydrocarbons produced by FAP in microalgae is still not clear but a function linked to photosynthetic membranes is likely. Indeed, in the model microalgae *Chlamydomonas reinhardtii*, it has been shown that all fatty-acid derived hydrocarbons are produced by FAP and >90% of them are localized to the membrane fraction of the chloroplast, the subcellular organelle that harbors the photosynthetic membranes [3]. Besides, in a *Chlamydomonas reinhardtii* mutant in which the gene encoding FAP has been knocked out, the photosynthetic activity of the algae has been found to be reduced under specific conditions (namely after cold acclimation when light intensity varies). Moreover, a phylogenetic analysis in algae indicates that the gene encoding FAP was mostly conserved during evolution of algal lineages but was always absent when the photosynthetic capacity was lost. Hypotheses about the role of hydrocarbons produced by FAP in photosynthetic membranes include the regulation of the overall fluidity of the membranes in response to specific conditions of light and temperature, a role in the association/dissociation between specific proteins of the photosynthetic apparatus or the action as a chemical signal in membranes.

MECHANISM OF A HYDROCARBON-PRODUCING PHOTOENZYME

Photoenzymes offer the possibility to study ultrafast processes taking place in living organisms, by allowing a synchronization of the whole sample by light. We can therefore study reactions such as proton transfer, electron transfer, bond breakage [4]. A recent study has improved our knowledge of the enzymatic mechanism of FAP by studying the wild type enzyme as well as mutants by numerous biophysical approaches such as static spectroscopy, time-resolved spectroscopy, and cryotrapping approaches associated with spectroscopy, as well as static and time-resolved crystallography. Combined with quantum mechanics approaches, the researchers proposed the mechanism illustrated and detailed in figure 2 [5].

This work has provided important results regarding the catalytic mechanism of FAP but other questions arise. FAP has a certain substrate specificity. And to date, we don't know if this substrate specificity is related to the binding in the active site or to a difference in quantum yield. Other questions arise concerning CO_2 and its conversion to bicarbonate, the researchers were surprised by the conversion of CO_2 to bicarbonate within the enzyme by a catalytic process [5], we still do not know how the bicarbonate will leave the protein.

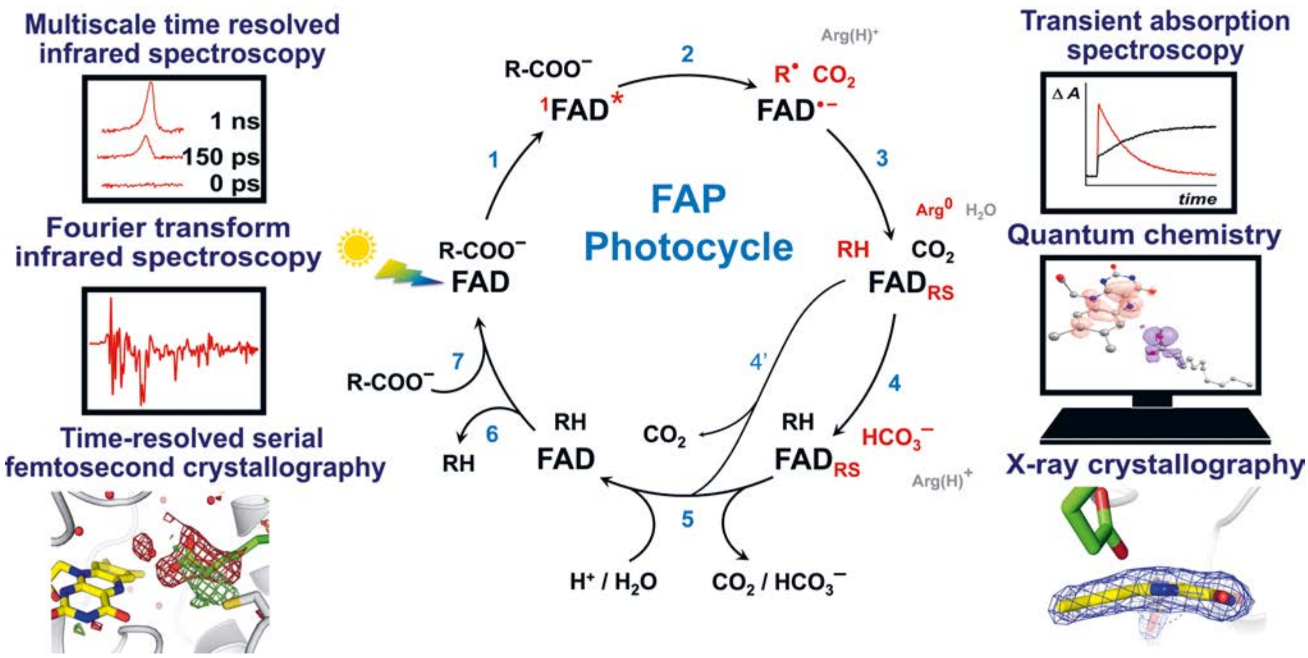
Finally, it has been shown that the lifetime of FAD RS is associated with a proton transfer in the protein, identifying the amino acids involved in this proton relay would also be an advance in the understanding of the mechanism.

We hope that in the near future, these questions can be answered by different biophysical approaches.

POTENTIAL BIOTECHNOLOGICAL APPLICATIONS OF FAP

Hydrocarbons are at the heart of our economy. Produced from the distillation of petroleum, they are used in most sectors, from chemicals to cosmetics and transport. This exhaustible resource is unequally

Figure 2: Upon light excitation (1), forward Electron Transfer occurs in ~300 ps from the fatty acid anion to 1 FAD* (observed by ultrafast fluorescence and transient absorption spectroscopies) and leads to its quasi-instantaneous decarboxylation (2), as observed by Time Resolved Infrared spectroscopy and Time Resolved Serial Femtosecond crystallography and supported by the computed absence of an energy barrier. Back Electron Transfer occurs in ~100 ns from FAD•– (presumably to the alkyl radical) and results in formation of red-shifted (re-) oxidized flavin FADRS; the Hydrogen/Deuterium Kinetic Isotope Effect suggests that back Electron Transfer is coupled to and/or limited by a Proton Transfer. Cryotrapping Fourrier Transform Infrared spectroscopy experiments suggest arginine as the final proton donor to the alkyl (3). Concomitantly, most CO_2 (~75%) is transformed (4) to bicarbonate as indicated by Time Resolved Infrared spectroscopy and cryotrapping Fourrier Transform Infrared spectroscopy. FADRS disappears in ~3ms (5) with a Hydrogen/Deuterium Kinetic Isotope Effect > 3, indicating coupling to Proton Transfer. Upon alkane release (6), new substrate binds (7). About 25% of the formed CO_2 is not transformed to bicarbonate, likely because it migrates away from the active site within 100 ns, leaving the protein in ~1.5ms (4'). In this minor fraction, arginine (R451) should reprotonate at latest in the ~3ms step (5). Changes after individual steps are marked in red; time constants are for RT.



distributed on the surface of the globe and variations in oil prices have a strong impact on the economy. Chemically, hydrocarbons are made solely of carbon and hydrogen. Alkanes are saturated hydrocarbons, alkenes are unsaturated hydrocarbons. The combustion of these hydrocarbons in thermal engines produces CO_2 and is associated with global warming by amplifying the greenhouse effect. It is interesting to note that global warming is not only related to the emission of CO_2 during combustion but rather to the natural resource used, renewable or not. Fossil petroleum was formed from the accumulation of organic matter (mainly plants and phytoplankton, *i.e.* microalgae and cyanobacteria) that was buried underground and due to pressure and temperature conditions was transformed into petroleum. Formed between 20 million and 350 million years before our era, the carbon contained in petroleum remained trapped until the 19^{th} century. Since then, this carbon has been massively released into the atmosphere by industry and transports.

An alternative to fossil fuels could be the production of hydrocarbons directly by photosynthetic organisms as hydrocarbons can directly replace the fossil compounds. Numerous studies on FAP have shown its ability to act on fatty acids substrates from 4 to 20 carbons allowing the production of hydrocarbons ranging from propane to nonadecane. Moreover, enzymatic cascades have been realized and by combining FAP with a lipase, it is then possible to directly convert lipids (triolein) into fatty acids (octadecenoic acid) and then fatty acids into hydrocarbons (heptadecene). With a two-step cascade using homogeneously dissolved triolein and lipase, production of heptadecenes was observed in presence of FAP [6]. Finally, using structure-based engineering researchers identified regions in the natural substrate binding channel of FAP. With targeted mutagenesis they generate enzymes variants with an increased activity on short chain fatty acids. These enzymatic mutants that produce propane and butane from butanoic and pentanoic acids respectively was finally express in a photosynthetic microorganism thus allowing a direct conversion of CO_2 into Hydrocarbons [7].

CONCLUSION

In conclusion, FAP is an excellent enzymatic model for biotechnology research. Although the best hydrocarbon productions have been observed in non-photosynthetic organisms, we hope that the use of FAP in photosynthetic organisms and in particular in oleaginous algae will be able to develop and allow a more direct conversion of CO_2 into hydrocarbon. For the fundamental research on enzymatic catalysis, the understanding of the mechanistic details will bring new knowledge of enzymatic reactions. We imagine that it will facilitate the development of more efficient enzymatic variants allowing to bring alternative solutions to the use of fossil compounds.

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PHOTOVOLTAICS:
TOWARDS ULTIMATE PERFORMANCES

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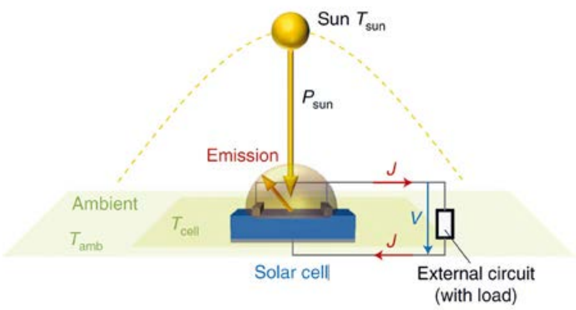

Photovoltaic conversion has made impressive progress since its discovery, but as will be discussed here, much can still be done. It is of interest to investigate what are the intrinsic limits of the technology. We call here ultimate performance those that could be limited only by intrinsic properties of the devices. This point will be discussed along three lines: ultimate limits for energy conversion, ultimate limits for material usage and ultimate limits for device stability.

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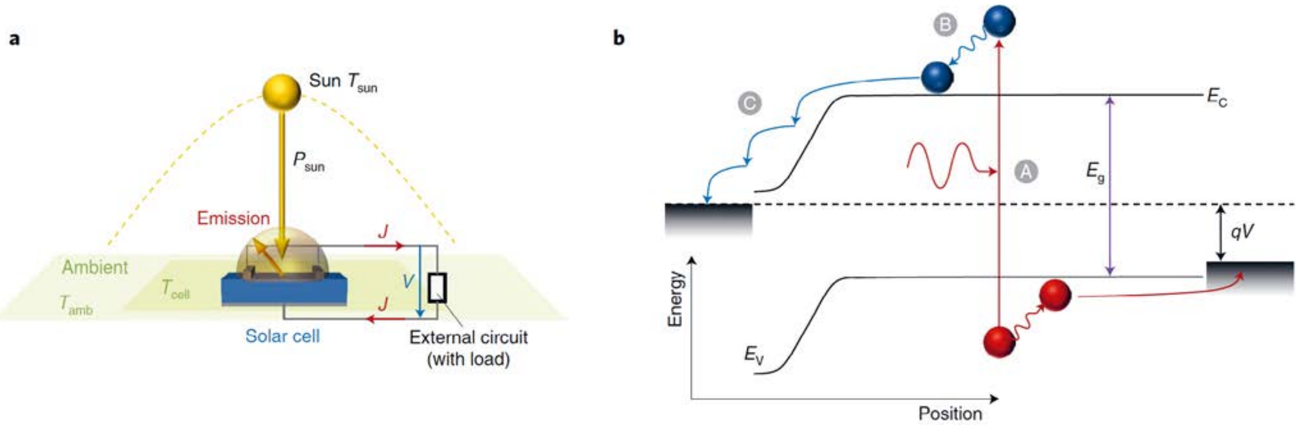
Solar energy, because of its abundance, availability everywhere, and innocuity, is considered among the main sources of renewable energy and an important pillar in the current energy transition. Indeed, Photovoltaic effect, discovered in 1839 by E. Becquerel [1], has made impressive progress from being a laboratory curiosity to contributing about 3% of the world electricity production in 2021. Progress have been made on conversion efficiency (now commercially above 20%),

Figure 1: Solar cell operation (from [2]). (a) A solar cell absorbs the light from the sun and emits electrons in the external circuit, the load, while excess energy is rejected in the ambient. (b) Energy diagram of an operating solar cell: an absorbed photon promotes an electron from valence to conduction band (A), the excess energy is dissipated (B) and some potential energy, that depends on the operating voltage V, can be collected (C).



mass production (now close to TW capacity installed), cost (one of the cheapest energy in sunny places, with LCOE near 1 ct/kwh), reliability (20 to 30 years' warranty on lifetime), energy return on energy invested (about 20 times), etc... That is not to say there are no impediments to large scale use of solar energy. Some preeminent issues today: the supply is variable and with the current technology, it would require large amounts of materials. These issues are subject to intense research, and could be solved. I will not discuss them further here, but will rather discuss another question: can we define some intrinsic limitations to photovoltaic conversion, and if so, which? By intrinsic, I mean that are deeply rooted in physics, and would not depend on the specifics of the operation conditions.

I will shortly discuss below three such limits. First, there is certainly a limit to energy conversion efficiency, how far is the state of the art from that point? This question has a bearing on cost and on how cheap solar electricity could ultimately become, but also on the environmental footprint of the technology and on the opening of a larger range of applications. It depends on the quality of the semiconductors used, but also on the architecture of the devices, ... Second, there is a limit on the amount of material that has to be mobilized to make efficient devices. This question may have a bearing on cost (if expensive materials are used), footprint (if scarce materials are used). As will be seen, some device concepts may require a tiny amount of active materials only.

Third, as p/n junctions, widely used for this application, are kinetically stable, but not intrinsically stable, it is an open question whether that would set a limitation on the time of use of solar cells. This question could also have a bearing on ultimate cost and footprint of the technology.

LIMITS TO EFFICIENCY

As surprising as it is, efficiency limits of photovoltaic conversion are ultimately set by optical properties. As there is an energy threshold (or gap energy, Eg, Fig. 1b) for light absorption in a semiconductor, in a process that promotes an electron from the valence band into the conduction band, only the fraction of the incoming photons having an energy above Eg (more precisely the fraction that is effectively absorbed, determined by the optical properties (n,k) of the device) can be used: it determines the photogenerated current. Most of the carriers' excess energy, above threshold, is quickly degraded into heat and given away to the lattice by fast, activationless processes, till carriers have an average kinetic energy on the order of kT, k being the Boltzmann constant, so that the energy per photogenerated carrier is slightly above Eg. Therefore, the energy threshold limits at the same time the amount of photons that can be absorbed (and therefore the photocurrent), and the energy available per carrier (see Fig. 2a): this gives an optimal value for a diode with Eg about 1 eV and 44% efficiency, an efficiency that is independent of source and sink temperature, and of illumination intensity, therefore a crude model. A much improved model was proposed by Shockley and Queisser [3], that considered also the impact of temperature, illumination intensity and operating bias on the efficiency.

In simple terms, a solar cell works by absorbing solar photons that generate excited electrons. Some of these would be eventually collected at one electrode and after having performed some work in the external circuit, would be reinjected at the other electrode (see Fig. 1).

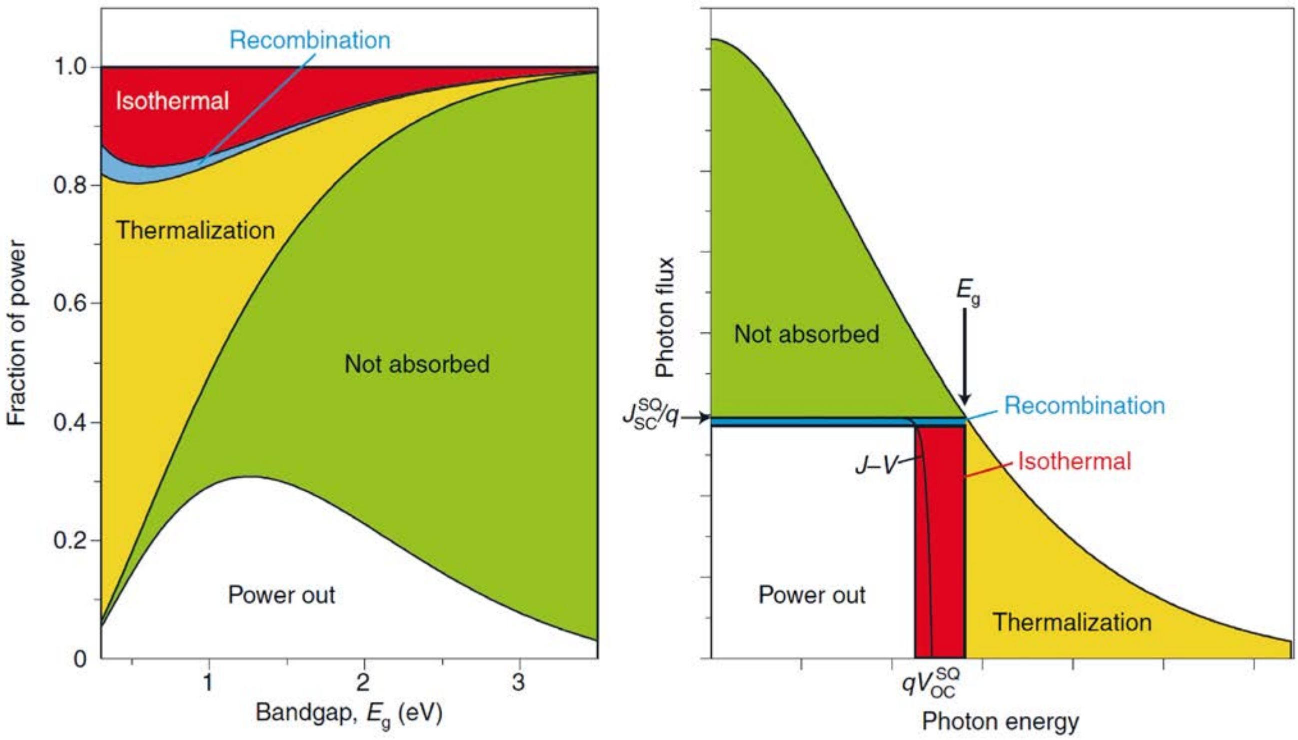
In its simplest form, a photovoltaic device is composed of a semiconductor and two selective contacts, one for holes (exchanging carriers with the valence band mostly), and the other for electrons holes (exchanging carriers with the conduction band mostly): a typical example of such a device is a semiconductor p/n junction. The efficiency of any such device depends on its operation point, that is light intensity, temperature and terminal voltage (or equivalently, load impedance). Let's start with the temperature: like any conversion device, a solar cell is subject to the laws of thermodynamics. A solar cell is an engine that converts a heat flux coming from the sun (almost a black-body source at 5800 K) and dumped at ambient temperature (the cold sink) into electrical work (Fig. 1a). Put in these terms it should be bounded by the Carnot efficiency (about 95%). Clearly, when the cold sink temperature rises, the efficiency is expected to decrease. Indeed, a complete analysis of a solar cell yields a Carnot efficiency factor in its terminal open circuit voltage.

Turning now to the terminal voltage: under forward bias, electrons are extracted through the electron selective contact but in doing so they work against the electric bias (conversely, when the diode is reverse biased, photogenerated carriers are quickly extracted from the solar cell, but at the price of an extra work). This work is then available in the load (driving a motor, the charge of a battery, ...). The fact that photogenerated carriers have to go against an electric bias to be extracted increases the chances that they relax to their fundamental state (a process called recombination): as the forward voltage V increases, so does the available potential energy per extracted carrier, while the flux of carriers (intensity I) goes down. At zero bias, the current (so called short circuit current) is close to the absorbed photon flux in state of the art devices. For some terminal voltage (called open circuit voltage, Voc) the output current is zero (Fig. 2b). Now, because the power output of the device is P=I.V, it will reach a maximum between zero bias and Voc: this is the optimal working point of the device (for a given temperature and light flux).

Finally, the efficiency depends also on the light intensity. At high light intensity, the concentration of photogenerated carriers is larger (for a given bias and temperature), and therefore the cell voltage is larger. Because the work delivered per collected carrier depends on the carrier concentration, light concentration is beneficial.

Because of these effects, at 300K working temperature, and standard solar illumination, the optimal diode would yield an efficiency of 33%, with about 30% of non-absorbed light, the rest being lost in heat during the initial thermalisation process or during the collection process. A single semiconductor cannot optimally make use of the broad solar spectrum, but it can be optimized for a narrow band of the solar spectrum. A collection of semiconductors with adjusted band gaps can be used to cover more optimally the conversion of the full solar. This is the main technological route to achieve high efficiencies, as the bottleneck is essentially engineering. In 2021, such devices, called multijunctions, using up to 6 diodes (each with adjusted Eg), have achieved conversion efficiencies of 47% [4] which is quite an impressive achievement already. Pushed to the limit, with essentially a diode for each narrow wavelength range,

Figure 2: Shockley Queisser limit (from [2]). a) fraction of power optimally converted as a function of band gap of an idealized solar cell (Shockley-Queisser model). Non-absorbed and thermalized power are explained in text. There is an irreductible fraction of carriers that recombines emitting photons before being collected (b), and a usually larger fraction still that recombines by non-radiative processes, thereby reducing available current, while the entropy produced, called here isothermal losses, during the recombination processes also reduces the available voltage (details in [2b]).



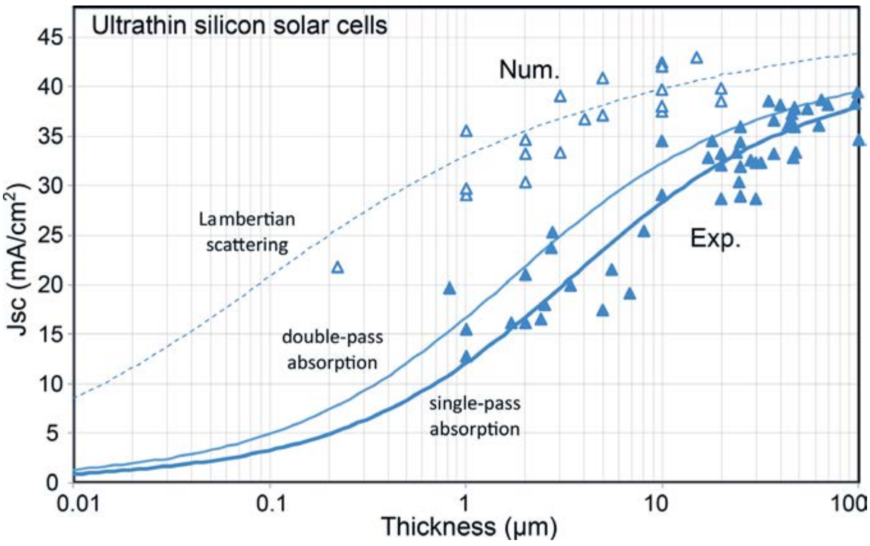


Figure 3: Dependence on thickness of the maximal photogenerated current, experimentally (filled triangles) and theoretically (empty triangles) for Si cells. The lower curve is obtained by absorption from Beer's law , and the top curve from Lambertian light trapping. From [6].

such devices could reach the ultimate photovoltaic efficiencies of 68% under one sun of 87% under maximal solar concentration achieved when the solar cell "sees" the sun over a 4π solid angle).

A variety of device architectures have been proposed and tested. As effective as it is, these devices require many technological steps, and are very complex and expensive to make, especially for the most efficient designs. Other research directions are being pursued to reach similar efficiencies as the multijunctions, but with much simpler device architectures. For instance, hot carrier solar cells would work at the same time as a photovoltaic and a thermoelectric engine [5]. First proofs of principle have been made but there are still many issues on the way related to photonics, and materials and device engineering.

LIMITS TO MATERIAL USAGE

Even if solar cells were approaching their limiting efficiency, current technologies would require large amounts of active materials (semiconductors), often in a highly pure form. But yet another expectation on solar cells is that they should be produced with minimal environmental impact.

Using solar concentration (the limit being 45000 times standard illumination, when the solar cell "sees" the sun over a 4π solid angle), the amount of active material needed could be reduced by the concentration factor. A less recognized way of reducing material use is to reduce the thickness of solar cells. Using photonic concepts, again ultimately, a factor in thickness reduction close to 2 orders of magnitude as compared to standard technology could be gained. For instance, Silicon solar cells, today 200 µm thick, could in principle be a couple of µm thick (*figure 2*), this direction of research is only in its infancy, but is very promising. As this approach has already been developed [6], the details will not be repeated here.

Taken together, concentration and thinning enable a conversion process by a very small amount of active materials, ultimately down to few grams for GW production capacity . Of course, to this reduced amount of active materials, one needs to add a significant quantity of metals, for the electrical contacts, of optical materials to collect the solar illumination and channel it to the device, and structural materials for mechanical and environmental integrity).

LIMITS TO DURABILITY

Another aspect of the operation of a solar cell, is that it should produce with minimal degradation during decades, in spite of environmental aggressions.

Solar cells do wear out in outdoor conditions, especially as thermal cycling may induce cracks, as water could ingress in the modules and corrode the contact, encapsulation polymers could degrade and absorb part of the incoming light, ..., but some devices have been working since their fabrication, decades ago, without trouble. Light absorption does produce excited electrons, and there is a small, but non-zero possibility that defects will be created in the absorbing material, reducing efficiency over time. Moreover, p/n junctions are intrinsically unstable since they result from a gradient in doping concentration that are subject to both Fick's law and the built in electric field as forces opposing the existence of the gradient. This causes a fundamentally limited intrinsic device stability [9], especially in the case of ultrathin devices, where this effect would be exacerbated.

Presently, device stability is ensured either by reducing the kinetics of damage, or by halting damage, possibly by selecting materials with high activation barriers to damage. A potentially more robust way of achieving the same goal would be to design self-healing devices, and a proposal to achieve that is to design thermodynamically stable devices.

Interestingly, the advent of intrinsically stable p/n junctions is possible as thermodynamically stable homo- and hetero-junctions have been discovered. An example of this is given by silver-doped MCT (Mercury Cadmium Telluride), where homojunctions, smeared out by application of a strong field or high temperature would spontaneously reform [8]. This system is an example of a dynamically stable device (likely the result of a spinodal decomposition between n and p regions), as opposed to say, silicon homojunctions, that are kinetically stable (frozen non-equilibrium).

Other semiconductors appear to have an intrinsic defect population that, at equilibrium, is optimal or close to optimal for PV conversion, and when perturbed, appears to spontaneously return to their functioning state. This seems to be the case of CIGS [7], and could be the case of the quickly emerging halide perovskites. This property does not only allow the device to work for long, but also enables the device to operate in specific environments, like space, where end of life is determined by radiation hardness.

Even if possibilities appear to emerge in the far distance, it should be reckoned that today's solar cell are not limited in use by their intrinsic stability but rather by the impact of environment mostly on the structural elements that protect the active material.

CONCLUSIONS

When looking closely to the physics of solar cells, quite general conclusions could be made on intrinsic possibilities offered by this category of energy conversion devices, and what could be achieved ultimately. Specifically, the ultimate conversion device could be extremely efficient (over 80%), using very little of hard-to-produce active material (few g/GW) and could be used for indefinitely long time and in a variety of environments, thanks to self-healing properties that could be imparted to the device.

As for today, as these fundamentals topics are an active research topic, other more pressing issues are actually impeding today the use of Photovoltaic devices, such as the ability to be integrated in diversified usage, which is also subject to intense R&D. Nevertheless, the conclusion of the above is that the ultimate cost and footprint of the technology has a very low limit, and therefore is likely to further progress for quite some time in the future.

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OPTICAL PARAMETRIC OSCILLATORS

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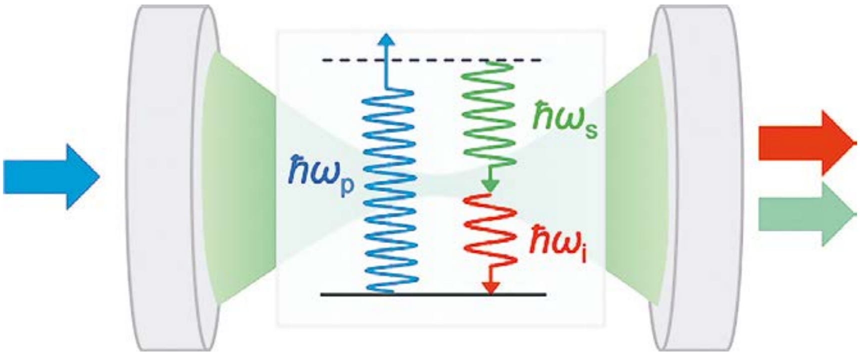

Optical parametric oscillators are versatile devices for generating a tunable coherent radiation from an incident laser beam. They rely on nonlinear frequency conversion to cover spectral ranges that are poorly or not covered by direct laser emission. This article presents a short overview of the optical parametric oscillators principles of operation, main implementations and related applications.

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Despite the various developments of wavelength tunable lasers, their spectral coverage remains incomplete, especially when a high peak power is required. Nonlinear optical processes, which arise from the non-harmonical response of electric dipoles in dielectric media when submitted to an intense electrical field, allows to convert the frequency emitted by a laser to another frequency, while preserving various properties of the original laser emission, namely its temporal and spatial coherences. More interestingly, the generated frequencies can be tuned by controlling the so-called phase-matching condition, which relies on the dependence of the indices of refraction upon the crystallographic orientation, temperature, light polarization, and even mechanical strain.

Optical parametric generators (OPGs) and oscillators (OPOs) are devices • • •

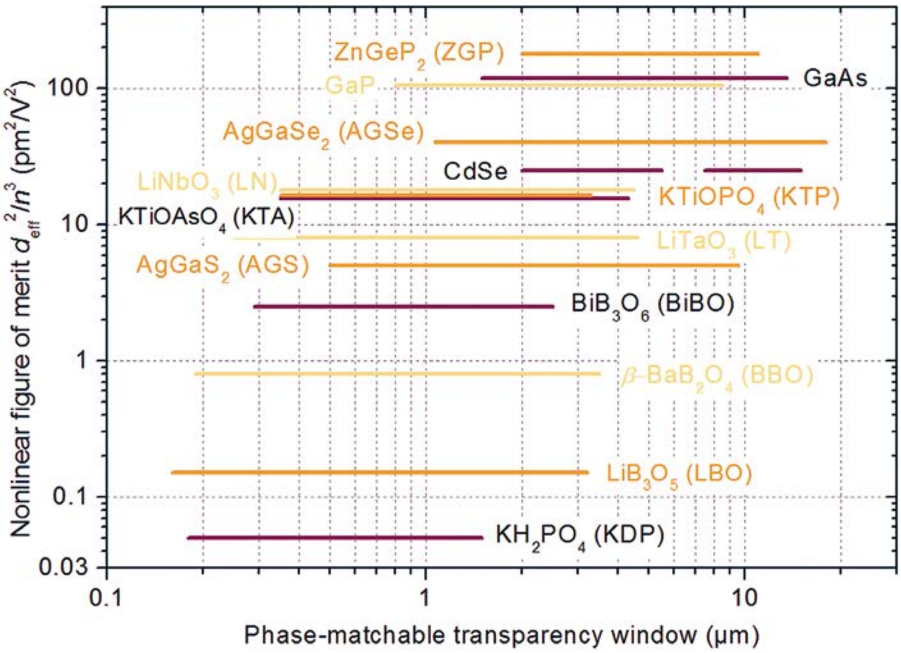


Figure 1. Major nonlinear crystals, organized according to their useful spectral window and their nonlinear figure of merit (based on data from [1]).

that efficiently generate such tunable coherent radiation from an incident laser beam.

OPTICAL PARAMETRIC AMPLIFICATION AND GENERATION

Parametric interaction is a three-wave mixing phenomenon arising in a non centro-symmetric medium, such as a crystal (figure 1). The most intense beam, with the highest angular frequency ω_p, is called the pump. When the signal wave of frequency ω_s is incident together with the pump on the nonlinear crystal, the signal is amplified while the pump is depleted. At the same time, an idler wave is generated at the difference frequency $\omega_i = \omega_p - \omega_s$ (by convention one usually assumes $\omega_s > \omega_i$). From a corpuscular point of view, this is equivalent to considering that each pump photon is split into a pair of photons respecting the conservation of energy: $\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$.

An efficient energy transfer requires that the waves propagating along the crystal are in phase with the nonlinear polarization generating them. This is called the phase matching relation (see insert). Unlike energy conservation, phase matching does not need to be strictly satisfied: it actually defines the spectral and angular acceptances of parametric interaction.

Three-wave mixing is a non-resonant, energy conservative, coherent process: phase information is preserved, and the signal and idler beams are generated at the same location while their momentums are anti-correlated in the transverse plane. From the point of view of quantum optics, the signal and idler photons are generated as a pair of entangled states. These properties have enabled applications in phase control of optical fields, imaging with undetected photons, quantum communications and computing [2].

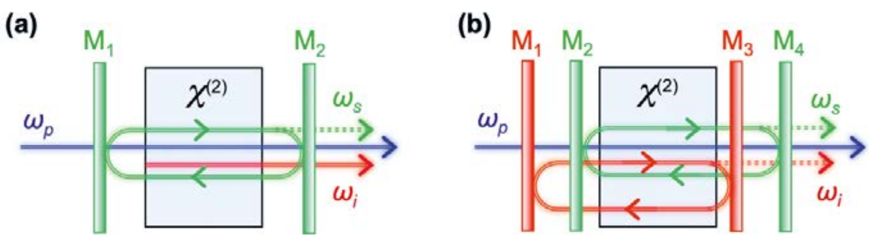
To a first approximation, the parametric gain is proportional to the power density (in W/cm^2) of the pump wave inside the nonlinear medium, and to the square of the nonlinear coefficient d_{eff}, which depends on the crystal, the direction of propagation, the wavelengths, and the type of phase matching. High gains are achieved by confining the energy in space and time, with shorter laser pulses, tightly focused laser beams, and optical cavities.

OPTICAL PARAMETRIC OSCILLATORS

Similarly to a laser oscillator, it is possible to realize an optical parametric oscillator (OPO) by inserting the nonlinear crystal in an optical cavity. Parametric generation builds up on quantum noise, and the signal and idler waves are further amplified during each round trip in the optical cavity. Due to the simultaneous presence of three interacting waves, the possible configurations of optical resonators are more varied than in the case of a laser oscillator.

The closest configuration to a laser oscillator is the singly resonant OPO illustrated in figure 2(a): the mirrors of the optical cavity reflect only one of the generated waves (signal or idler), while the other is totally coupled out. This configuration has the advantage of leading to simple and robust systems. On the other hand, the oscillation threshold can be quite high (several watts in continuous-wave regime), which may require the use of a bulky pump laser.

Figure 2. Drawing of a singly-resonant (left) and of a dual-cavity, doubly resonant (right) OPO.



It is also possible to find a condition for which the signal and the idler waves are both resonant (see figure 2b). This is called a doubly resonant OPO. This configuration, which has no equivalent among laser oscillators, reduces the oscillation threshold by at least one order of magnitude compared to the singly resonant configuration. In the case where the two resonant waves share the same cavity, the operation may become unstable because it is necessary that the signal, ω_s, and idler, ω_i, frequencies each correspond to a mode of the optical resonator, while satisfying $\omega_p = \omega_s + \omega_i$. A solution to avoid this problem is to decouple the signal and idler cavities, *e.g.*, by using the dual-cavity OPO scheme illustrated in figure 2b.

OPO cavities often require low-loss custom dielectric coatings for the mirrors and the nonlinear crystals, which generally represent a challenge for suppliers, especially in the mid-infrared. The parametric gain is directly related to the intensity of the waves that depends strongly on the duration of the pump laser pulses. This is why it is common to distinguish the applications of nonlinear optics according to the temporal regime of operation.

CONTINUOUS-WAVE REGIME

Reaching a sufficient parametric gain in the continuous-wave regime typically requires a pump laser delivering several watts in a diffraction limited beam. This is now routinely done with commercial products such as diode pumped solid state lasers and fibre lasers. Besides, the nonlinear coefficient has been increased thanks to the development of quasi-phase matched crystals such as periodically poled lithium niobate (PPLN), with the added benefit of being virtually free of adverse effects such as photorefractive focusing, grey tracking, and optical absorption.

In a continuous-wave OPO, the photon conversion efficiency is only limited by passive losses and gain saturation at the center of the Gaussian beams. It is therefore possible to approach a quantum efficiency of 100% [3]. Due to the homogeneous nature of the parametric gain (all the longitudinal modes of the cavity share the same gain), oscillation naturally converges to the longitudinal mode closest to perfect phase matching. Thereby, continuous-wave OPOs have found application in high resolution spectroscopy.

PULSED REGIME

Since parametric oscillation starts from quantum noise, several cavity round-trips are necessary before the pulses can be detected: this is called the build-up time. During this time, amplification is very high for the oscillating pulses, but pump depletion is negligible, *i.e.* a significant fraction of the pump energy passes through the crystal without being converted. Hence the quantum conversion efficiency is lower than that obtained in the continuous-wave regime.

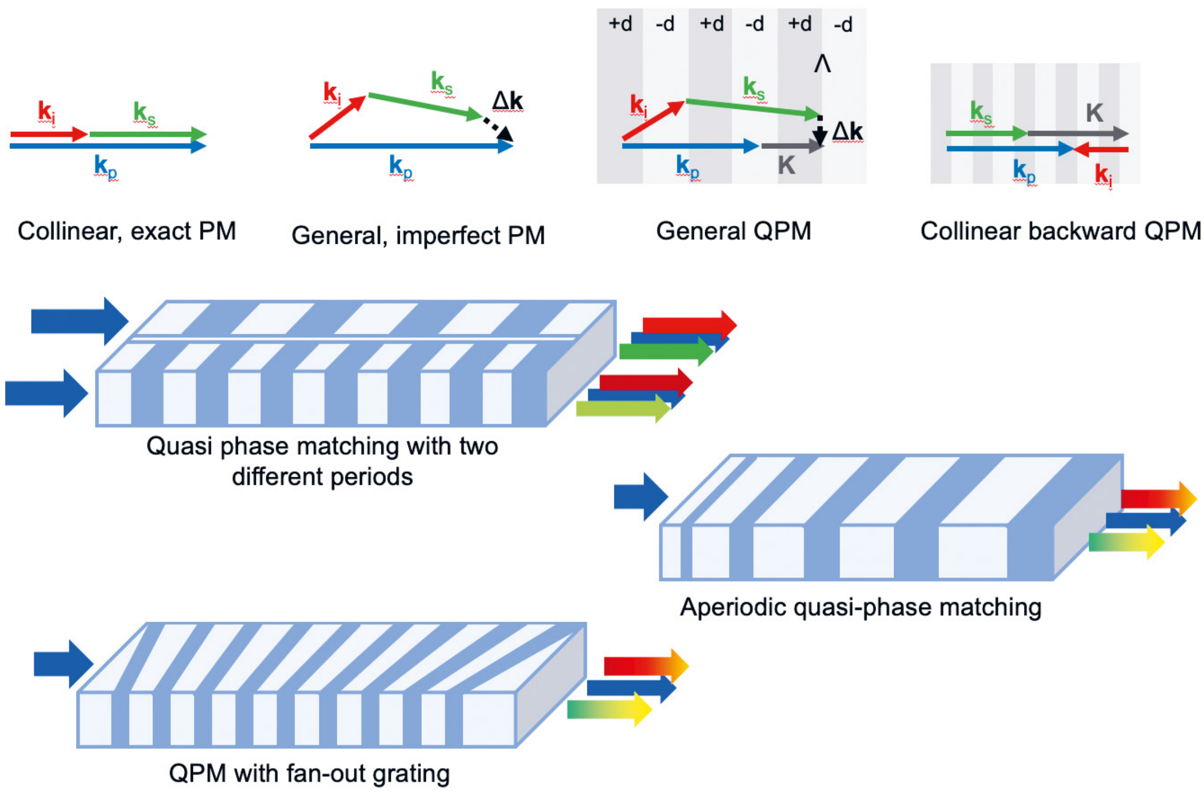
The pulsed regime has been widely used to pump OPOs because of the large availability of efficient, compact Q-switched pump lasers, emitting nanosecond or sub-nanosecond pulses with several kilowatts of peak power. The high peak power relaxes the need for a high finesse cavity, so that pulsed OPO cavities are usually shorter and more rugged than those used in other temporal regimes. Short pulse duration enables time-resolved measurement, while the Fourier-Transform-limited spectrum of nanosecond pulses is typically less than 100 MHz, which is compatible with spectroscopic analysis of gases at atmospheric pressure. Hence nanosecond OPOs have been used in telemetry, remote gas analysis, optical countermeasures, and active imaging.

In the pulsed regime, selection of a longitudinal mode by the phase matching condition cannot reach steady state. It is thus necessary to resort to line-narrowing technics to force a monochromatic spectrum. In singly resonant OPOs, the usually implemented technics are inherited from lasers; *e.g.*, the use of an intra-cavity spectral filter or injection of narrow-linewidth continuous-wave seed radiation. In doubly resonant OPOs, a very efficient filter can be synthetized by combining the Fabry-Perot responses of signal and idler cavities of different optical lengths, a technique referred as nonlinear Vernier-effect spectral filtering (figure 3) [4].

ULTRA-SHORT PULSES GENERATION

With ultrashort pump pulses, in the picosecond and femtosecond ranges, peak intensities reach the megawatt range, enabling amplification above detectable power levels with a single-pass through the crystal. The required crystal length is typically one order of magnitude shorter than in the nanosecond range, increasing the spectral acceptance tenfold. Thus, nonlinear crystals have been extensively used to amplify wideband ultrashort pulses, especially with a technique called optical parametric chirped-pulse amplification (OPCPA), which is the nonlinear optics analog of the chirped-pulse amplification (CPA) for which a Nobel Prize in Physics was awarded in 2018. Such ultrashort, high-intensity parametric sources are mainly developed for high-field physics [5].

Regarding parametric oscillators, since the spatial extent of ultrashort pulses is shorter than the crystal itself, amplification of light reflected by the cavity during the same pump pulse is not possible. One then has to resort to a technique called synchronous pumping, that shares similarities to gain mode locking in lasers. In this case, the round trip time in the OPO cavity is matched to the repetition rate of the



The phase-matching relation usually writes: $\overrightarrow{\Delta k} = \vec{k}_p - \vec{k}_s - \vec{k}_i \rightarrow 0$, using the wavevectors $\vec{k} = \frac{n(\omega,\vec{u})\omega}{c}\,\vec{u}$, where $\vec{u}$ is the unitary vector perpendicular to the wavefront. The maximum tolerable phase mismatch corresponds typically to $|\Delta k|_{max} = \pi/L$, where L is the length of the nonlinear medium. Because Δk depends on the frequency through the index of refraction, it determines the spectral acceptance of the three-wave mixing process, *i.e.* the parametric gain bandwidth. Because of chromatic dispersion, which generally leads to $n_p > n_s, n_i$, exact phase matching is only possible in birefringent materials in which the dependence of the index to the direction of propagation $\vec{u}$ is used to compensate for dispersion. Another method is to use modal birefringence in waveguides. However, the most popular method is to periodically structure the nonlinear response of the material, which is usually done by electric field poling. The resulting grating of period Λ contributes to phase matching through a wavevector $\vec{k} = \frac{2\pi}{\Lambda}\vec{u}_z$. This so-called Quasi Phase Matching (QPM) method offers many more features than birefringent phase matching, because the crystallographic domains can be oriented and structured to different aims [7]: selecting the highest coefficient among the nonlinear tensor d, generating more than two wavelengths, shaping the gain spectrum, generating a wave in the backward direction, generating a perpendicular THz wave, etc. QPM can also be used with isotropic crystals, such as GaAs.

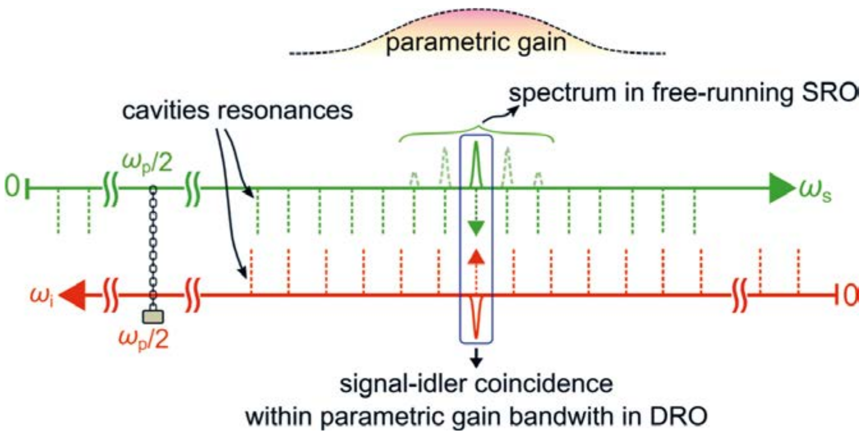


Figure 3. Mode selection by the dual cavity scheme.

pump laser, so that the signal and/or idler pulse generated by a pump pulse is amplified by the next pump pulse after a cavity round trip. If the pump laser is a mode-locked laser, the constant phase relation between pump pulses also means that the signal/idler pulses are in phase: the OPO emits a train of mode-locked pulses at two new wavelengths. In the spectral domain, this train of mode-locked pulses is a frequency comb, at the heart of the Nobel Prize in Physics in 2005, which, thanks to the very large spectral acceptance of the parametric gain, can span more than an octave (ω-2ω). This property enables to measure the phase-carrier offset that defines the fundamental frequency of the comb, and stabilize it in time. This step has been the cornerstone of high resolution dual-comb spectroscopy in the mid-infrared [6].

CONCLUSION

Rephrasing Maiman's citation on lasers, we can say that the optical parametric oscillator has originally been "a solution seeking a problem". Today, it is a fundamental component for controlling the properties of coherent light in any part of the spectrum, with a sufficient optical-to-optical efficiency. Laser companies now propose products dedicated to OPO pumping. While candies can come in many flavors, OPOs can take very different forms, from table-top servo-locked cavities for demanding laboratory experiments, to semiconductor waveguides and monolithic mirrorless cavities for industrial applications. These unique properties make them highly relevant for various applications such as gas sensing or infrared countermeasures as well as for fundamental science spanning from quantum optics to strong-field physics.

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VIS-NIR HYPERSPECTRAL CAMERAS

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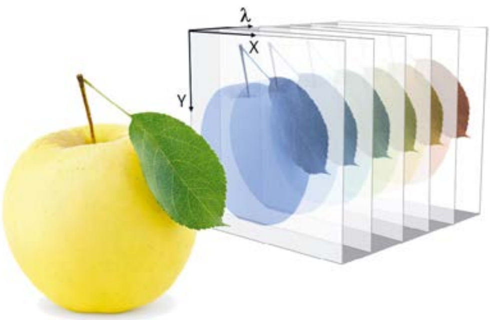

Hyperspectral and multispectral imaging can record a single scene across a range of spectral bands. The resulting three-dimensional dataset is called a "hypercube". A spectrum is available for each point of the image. This makes it possible to analyse, quantify or differentiate the elements and materials constituting the scene. This article presents the existing technologies on the market and their main characteristics in the VIS/NIR spectral domain (400–1000 nm). It then focuses on a specific multispectral technology called *snapshot* multispectral imaging, combining CMOS sensors and pixelated multispectral filters (filtering at the pixel level).

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Hyperspectral imaging is usually distinguished from multispectral imaging based on the number of spectral bands captured by the instrument. As a general rule, hyperspectral cameras can record over 100 spectral bands, while multispectral cameras typically capture fewer than 25. This article covers products providing at least 8 spectral bands. The commercially available hyper/multispectral cameras on the market are based on a wide range of different technologies. Their respective performance levels, advantages and disadvantages suit them for a variety of uses and markets.

In the first part of this article, we propose to review the main technologies available and prepare a table listing their characteristics to guide users in their choice. The second part of the article emphasizes on one of these technologies: *pixelated filter snapshot* multispectral cameras. This section presents the performance levels of the cameras available on the market.

The technologies described below on the VIS/NIR domain (400-1000nm) have equivalents in the SWIR, LWIR and MWIR ranges. The main advantage of the VIS/NIR range is the use of silicon-based sensors (i.e. CMOS technology), which are simple to implement at a low cost as they are produced in large volumes. Prices of equivalent systems in the SWIR, LWIR and MWIR regions, using more "exotic" sensors (InGaAs, HgCdTe, etc.) are much higher (2 to 20 times).

A WIDE RANGE OF TECHNOLOGIES

Hyper/multispectral camera technologies can be divided into three categories: *pushbroom* technologies, *snapshot* technologies and intermediate technologies. The main characteristics of these technologies are summarized in table 1.

PUSHBROOM TECHNOLOGIES (EXTERNAL SCANNING)

Like filter wheel technology (which is not covered in this article), pushbroom is a long-established technology. Its best-known application is probably multispectral Earth observation from satellites. Conventional pushbroom technology involves a 2D sensor that records spatial data along one dimension of the sensor (y) and spectral data along the other (x). The wavelength dispersion of the signal (or separation of different spectral components) is obtained with either a diffraction grating or a one-dimensional band filter. The second spatial dimension is

Category	Technology	Number of bands	Spectral Resolution	Spatial Resolution per band	Volume of data	Hypercube registering time	Optical system complexity	Footprint	Robustness	Level of price	Industrialization scalability
Push-broom with external 1D scanning	Grating	100 to 400	2 to 6 nm	up to 3000 px (1D)	High	Long	Specific	Medium/ large	"Sensible (fine aligment)"	Medium to high	Low
	1D Filter	100 to 150	10 to 15 nm	2048 px (1D)	High	Long	Specific	Very low	Robust	Low	Very High
Push-broom with internal 1D scanning	1D Filter	100 to 200	7 to 15 nm	0.25 to 7.5 Mpx	High	Medium-long	Specific	Very low	"Sensible (moving parts)"	Medium	Medium
Snapshot 2D with spectral scanning	Tunable filter	300 to 600	5 nm	2.3 Mpx	High	Medium-long	Standard	Medium	"Sensible (tunable parts)"	Medium	Medium
Snapshot 2D with sub-images	"2D filter (sub-images)"	150 to 200	10 nm	0.17 Mpx	Medium	Short	Specific	Low/ Medium	Robust	Medium	High
Snapshot 2D with macro-pixels	2D filter (macro-pixels)	8 to 25	10 to 40 nm	0.07 to 0.5 Mpx	Low	Short	Standard	Very low	Robust	Low	Very High

Table 1: Key features of hyper/multispectral technologies in the VIS/NIR range.

obtained by displacing the sensor relative to the scene, in the direction perpendicular to the indicatrix of the grating or to the filter bands (figure 1). This displacement can be achieved by moving the camera (mounted on a drone or a satellite, for example) or by moving the object below the camera (objects on a conveyor belt, for example). This case can be described as *external* pushbroom scanning.

The main advantage of push-broom technology is its capacity to generate a hypercube with a very high spatial and spectral resolution. Spectral resolutions below 10nm can be obtained in the 400–1000nm range. From a spatial viewpoint, these systems ●●●

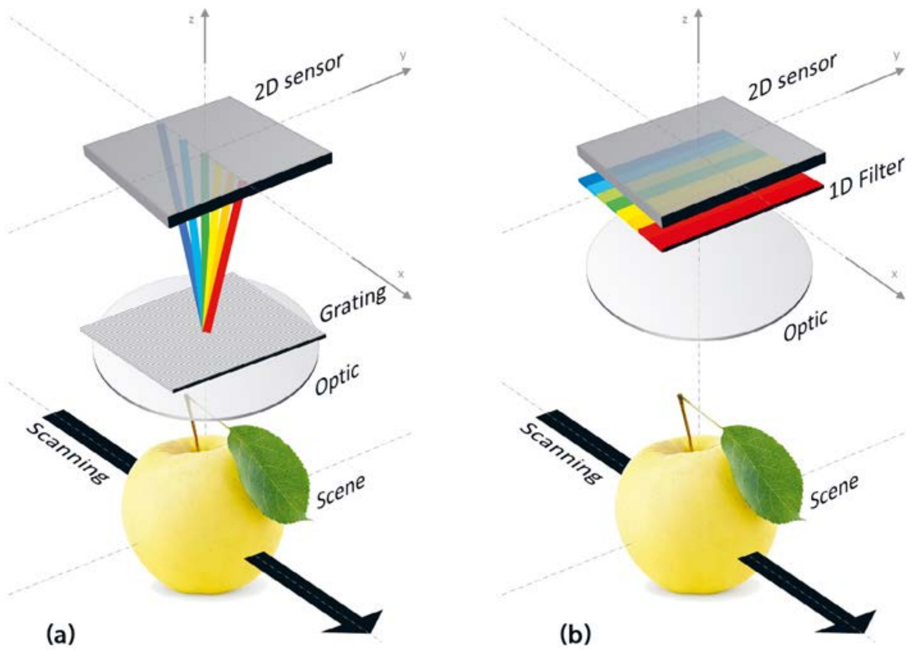


Figure 1. Hyper/multispectral pushbroom technologies based on a grating (a) or on a 1D multiband filter (b). The scanning is external (either the camera or the scene is moving).

use sensors that frequently offer over 2,000 pixels in their largest dimension. The resolution of the second spatial dimension depends on the speed of the camera's movement relative to the object and the rate of image capture. This wealth of information comes at a price: the amount of the data. The resulting hypercube is extremely large. Consequently, these high-performance systems, whether fixed or embedded, are often used as laboratory tools. They are designed for advanced scientific research and are frequently deployed in preliminary studies to determine the reduced set of spectral bands that is essential to address a sorting, discrimination or quantification problem that will then be performed industrially by systems with a lower spectral resolution (see snapshot technologies).

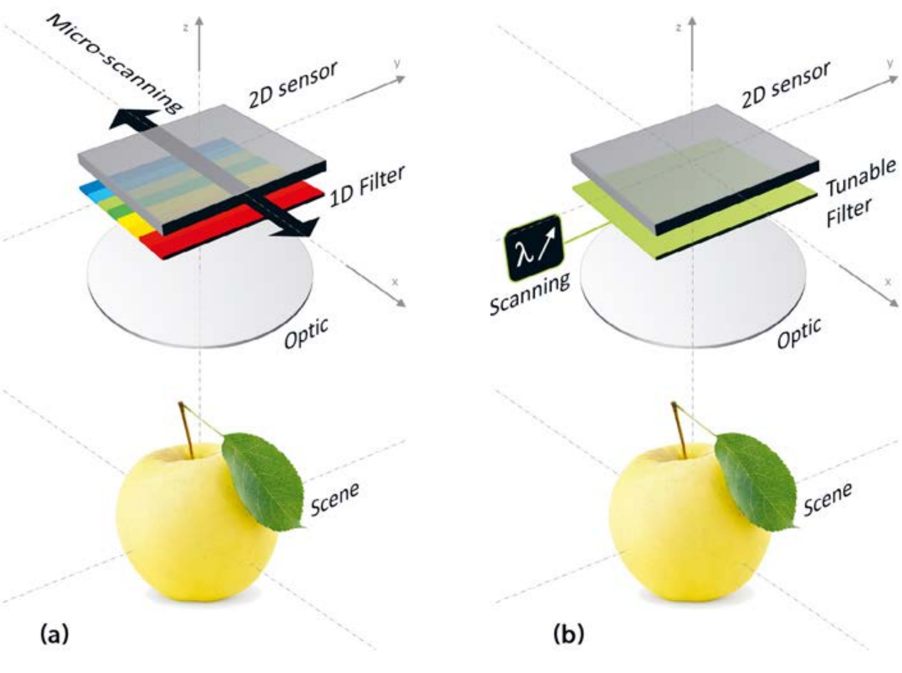
The main disadvantage of pushbroom technology arises from its image recording principle. Unlike snapshot technologies, the image is captured sequentially. The whole 2D scene is not recorded instantaneously; it is captured by scanning. Only static scenes or scenes in which the kinetics of the movement are negligible compared with the time taken to capture the image are suitable for these systems. This limits the scope of possible applications.

The number of manufacturers of hyperspectral cameras based on this principle is quite large. Here is a non-exhaustive list: *Brimrose, Bruker Corporation, Corning, Headwall, Hyspex, Itres, Middleton Spectral Vision, Norsk Elecktro Optikk, Resonon, Senop, Specim, Spectral Engine, Surface Optics, Telops* (see table 3).

INTERMEDIATE TECHNOLOGIES (INTERNAL SCANNING)

To mitigate the complexity of traditional pushbroom systems, newer technologies have emerged. These attempts to move towards a more conventional snapshot-type capture mode. The principle involves performing the scanning inside the camera itself. Moving the sensor on a miniaturised plate makes it possible to sweep the scene and recover the missing second spatial dimension (figure 2). This means there is no longer any need to move the camera relative to the scene. Another approach involves sweeping through the spectral

Figure 2. Intermediate hyper/multispectral technologies based on the scanning of a 1D multiband filter (a) or the λ scanning of a tunable filter (b). The scanning is internal.



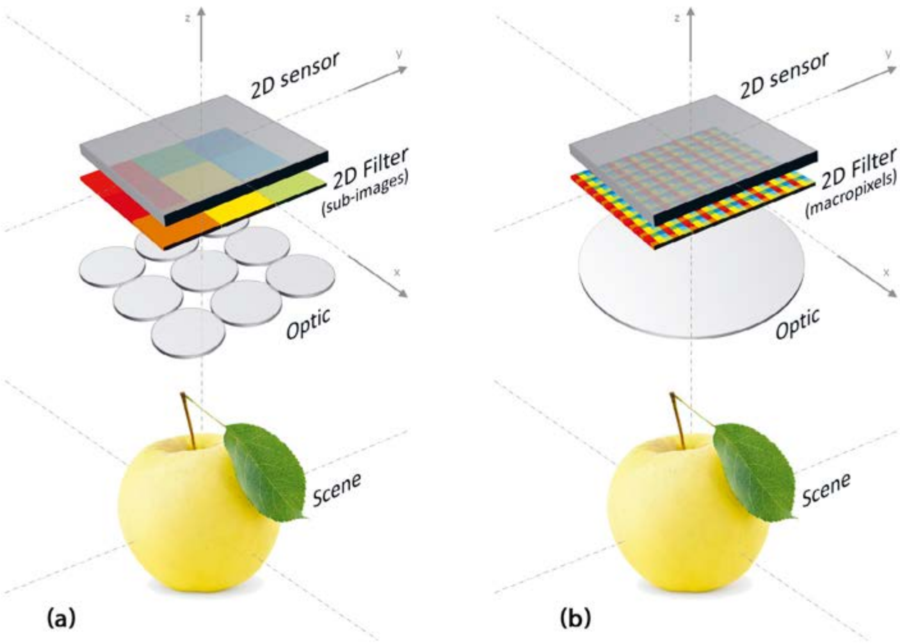


Figure 3. Multispectral snapshot technologies based on a sub-image 2D filter (a) or a pixelated 2D filter (b). There is no scanning.

dimension, using a tunable filter in front of the sensor for example.

The capture is then similar to a snapshot approach, greatly simplifying its implementation. However, the recording of the hypercube is still based on capturing a sequence of images over time. In other words, the hypercube is not acquired in a single shot. Consequently, most of the disadvantages of the capture method described in section 1.1 remain. Like conventional pushbroom systems, these systems can achieve high performance levels in terms of spatial and spectral resolution. As a result, the hypercube is again very large.

These intermediate technologies produce less bulky systems than most traditional pushbroom systems, while still providing high levels of performance and also simplifying the data capture mode for the user. To our knowledge, the main manufacturers of products based on these intermediate technologies are: *IMEC (Snapscan technology), HINALEA, PHOTON etc and SPECIM (IQ camera)* (see table 3). This list is probably not exhaustive.

SNAPSHOT TECHNOLOGIES (NO SCANNING)

The so-called snapshot technology allows the hypercube to be captured in one single shot, without any scanning. The principle is based on capturing all the spectral and spatial data at the same time. The 2D sensor is partitioned with a 2D spectral filter (figure 3), filtering by sub-images (or thumbnails) or at a pixel level (macropixel organization). We note that sub-image filtering is fairly uncommon due to the complexity of the multi-optic system required to capture the scene. Filtering at the pixel level, on the other hand, allows standard optics to be used (mounting type C or CS, for example). In terms of advantages, these snapshot systems are particularly compact, robust and often more affordable. Their manufacturing methods, derived from the semiconductor and microtechnology sectors, make them suitable for low-cost, high-volume production (see section 2). The major disadvantage of these systems is the loss of performance compared to the hyperspectral systems presented in sections 1.1 and 1.2. The numbers of spectral bands and/or ●●●

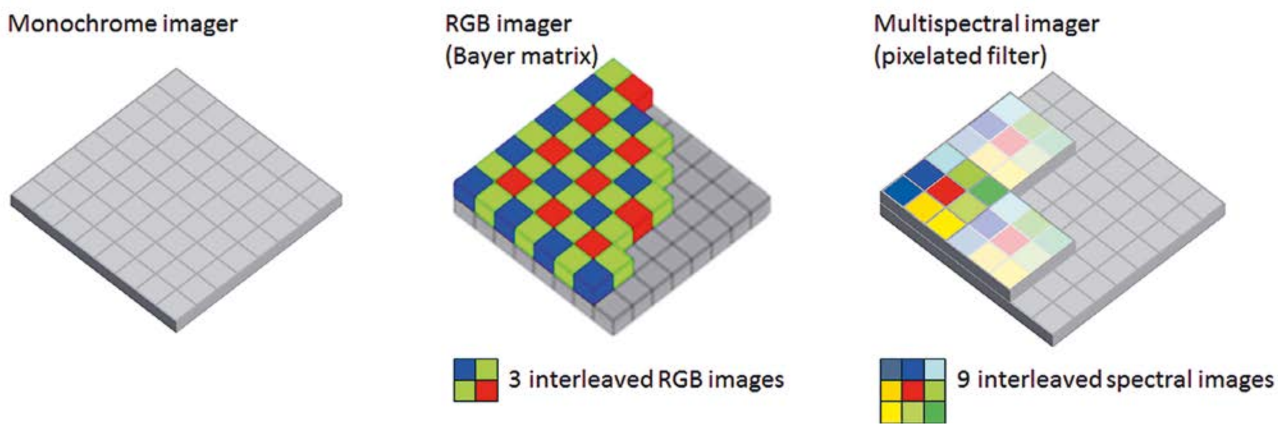


Figure 4. Bayer filter principle and example of a 3×3 multispectral macropixel.

the spatial resolution are significantly lower. The spatial resolution of each spectral image falls to less than 0.5 Mpx (between 0.07 and 0.47 Mpx) compared to 1 to several Mpx for the above technologies. However, if the application is able to accommodate this level of performance, the snapshot solution is the best choice on the basis of price, robustness, compactness, integrability, volume manufacturing etc.

To our knowledge, the manufacturers of snapshot cameras are for the thumbnails filtering: Cubert and for macropixel filtering: *XIMEA (with IMEC sensors), Photon Focus (with IMEC sensors), Spectral Devices and SILIOS Technologies* (see table 3).

PIXELATED FILTER SNAPSHOT MULTISPECTRAL CAMERAS

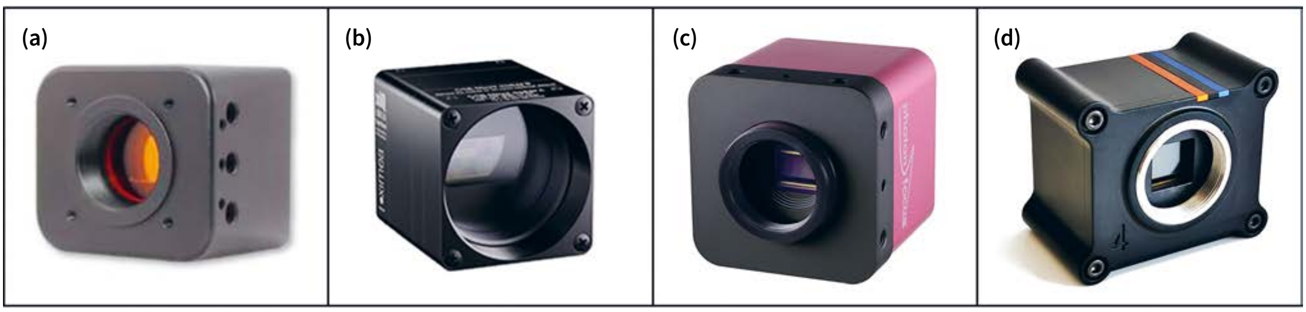
This multispectral technology is based on the well-known principle of the Bayer filter mosaic, which is used to convert monochrome sensors into colour sensors. The Bayer filter consists of a macropixel (or kernel) of 2×2 pixels as shown in figure 4. Snapshot multispectral cameras use more complex macropixels of 3×3, 4×4 or even 5×5 pixels. Each pixel in the macropixel filters a specific band, offering a breakdown into 9, 16 or 25 bands. Several technologies have emerged, each offering specific abilities. The pixelated mosaic filter is either applied to the sensor itself (the CMOS sensor wafer for IMEC, or individual sensors for Spectral Devices), or produced on a separate substrate that is then cut up and assembled (hybrid transfer) on the sensor in its commercial housing (COLOR SHADES® technology from SILIOS Technologies). The IMEC technology, based on semiconductor tools and processes, offers high-volume production capacity, while the technologies developed by Spectral Devices and SILIOS have the unique ability to adapt to any commercial sensor and any multispectral configuration the customer may require and this starting from a very low volume of production. This means both companies can produce custom multispectral cameras at very affordable prices in addition to their catalogue cameras.

Other differences relating to the production technologies for the bandpass filters used provide to the cameras distinct characteristics.

SPECTRAL BANDWIDTHS

The width of the spectral bands depends on the technology used. An analysis of the commercial

Figure 5. Snapshot multispectral cameras. (a) Spectral Devices (MSC-VIS8/MSC-NIR8), (b) Ximea (MQ022HG-IM-SM4X4-VIS/ MQ022HG-IM-SM5X5-NIR) – IMEC sensor, (c) Photon Focus (MV1-D2048x1088-HS02-96-G2/MV1-D2048x1088-HS03-96-G2) – IMEC sensor, (d) SILIOS Technologies (CMS/CMS4/TOUCAN).



products reveals two families of cameras (see table 2, column 6): narrowband cameras, *i.e.* cameras with FWHM widths between 10 and 15 nm (XIMEA and Photon Focus – IMEC sensor), and wider bandwidth cameras, with FWHM widths between 20 and 45nm (Spectral Devices and SILIOS). The formers offer the advantage of a significant spectral finesse. This makes it possible to have a larger number of spectral bands within a given spectral region. Cameras based on IMEC sensors can offer 16 or 25 spectral bands. This means the sampling of the spectrum is relatively high. Spectral Devices and SILIOS cameras are limited to a maximum of 16 bands to avoid too much overlap between bands. However, wider bands offer other advantages compared with narrower bands. (i) They offer a lower level of attenuation, allowing more flow to pass through. (ii) These broad filters also have much greater tolerance in terms of angular incidence (lower angular sensitivity) than narrow filters. A wide range of apertures can thus be used with these cameras without the need for dedicated calibration in advance.

SPATIAL RESOLUTION - NUMBER OF BANDS.

The spatial resolution of each spectral sub-image in the hypercube depends on the native resolution of the sensor (table 2, column 7) and the number of spectral bands being measured (number of pixels in the macropixel - table 2, column 3). The native resolutions of the sensors range from 1 to 4Mpx. The resolution of the spectral sub-images is equal to this native resolution divided by the number of bands. The highest spatial resolution per sub-image is obtained with SILIOS CMS4 cameras using a 4Mpx sensor and a macropixel of 3×3 pixels (8 bands + 1 PAN), *i.e.* $682 \times 682 px^2$. With Spectral Devices, the same conditions (4Mpx and a macropixel of 3×3 pixels) result in a resolution per sub-image of only $256 \times 256 px^2$. This is because Spectral Devices considers only alternate lines and columns of the sensor to space out the pixels of the macropixel and to reduce the effects of crosstalk. The raw signal from each pixel becomes less sensitive to crosstalk pollution but at a price of a weaker spatial resolution. Digital crosstalk correction methods based on a spectral calibration of the camera can also be applied but these are beyond the scope of this article.

SPECTRAL EXCURSION RANGE

Unlike products based on internal or external scanning technologies, none of the Bayer-type snapshot cameras fully covers the VIS/NIR spectral domain (400–1000 nm). Rejection thin film filters in a domain of 600nm are complex and their structure at the pixel level (a few microns) is difficult to reach with conventional fabrication technologies. Preference is thus given to simpler filter structures that restrict the spectral excursion range. Analysing all the cameras on the market shows that this excursion is limited to below 300 nm (see table 2, column 5). This width allows the visible (400–700nm), the near infra-red (700–1000nm) or any other intermediate domain to be addressed separately. Only one commercial camera (the TOUCAN model recently launched by SILIOS) gives access to an excursion of 450 nm, covering the visible and part of the near infra-red (420–870nm).

PAN PIXEL

Finally, some cameras (CMS and CMS4 from SILIOS) include a panchromatic (PAN) or neutral pixel in the macropixel. This pixel is not selective in terms of wavelength. Its optical density prevents neighbouring pixels being blown out by too high a signal level (reprendre). It provides a simple broadband photometric reference for the scene. An equivalent can of course be obtained on all cameras without panchromatic pixels by summing the responses of all the pixels.

PRICE

The cheapest cameras on the market are available in the €5k to €7k range while the cost of the most performant cameras ranges between €12k and €18k. ●

Camera manufacturer	Camera ref.	Number of bands	Spectral range (nm)	Spectral range width (nm)	Bandwith (nm)	Sensor (native resolution)	Spatial résolution (HxV)	Web site
SPECTRAL DEVICE	MSC-VIS8-1-A	8	474 to 640	166	20 to 35	CMV4000 (4.2Mpx)	256 x 256	www.spectraldevices.com
	MSC-NIR8-1-A		720 to 980	260	18			
XIMEA/PHOTON FOCUS (IMEC HSI sensor)	MQ022HG-IM-SM4X4-VIS3 (XIMEA) / MV1-D2048x1088-HS03-96-G2 (PHOTON FOCUS)	16	460 to 600	140	10 to 15	CMV2000 (2.2 Mp)	512 x 272	"www.ximea.com www.photonfocus.com"
	MQ022HG-IM-SM4X4-RN2 (XIMEA) /	15	600 to 860	260	10 to 15		512 x 272	
	MQ022HG-IM-SM5X5-NIR2 (XIMEA) / MV1-D2048x1088-HS02-96-G2 (PHOTON FOCUS)	24	665 to 960	295	10 to 15		409 x 217	
SILIOS TECHNOLOGIES	CMS-C	"8 + 1 PAN"	430 to 700	270	25 to 45	RUBY (1.3 Mpx)	426 x 341	www.silios.com
	CMS-V		550 to 830	280	25 to 35			
	CMS-S		650 to 930	280	25 to 35			
	CMS4-C	"8 + 1 PAN"	430 to 700	270	25 to 45	CMV4000 (4.2Mpx)	682 x 682	
	CMS4-V		550 to 830	280	25 to 35			
	CMS4-S		650 to 930	280	25 to 35			
	TOUCAN	10	420 to 870	450	25 to 45	CMV4000 (4.2Mpx)	512 x 512	

Table 2: Main characteristics of commercial snapshot multispectral cameras (above 8 bands)

Manufacturer	Web Site	Technology
BRIMROSE	www.brimrose.com/aotf-hyperspectral-imaging-system	Pushbroom
BRUKER CORP.	www.bruker.com (see : HI90)	Pushbroom
CORNING	www.corning.com (see : spectral sensing)	Pushbroom
HEADWALL	www.headwallphotonics.com	Pushbroom
HYSPEX	www.hyspex.com	Pushbroom
ITRES	www.itres.com	Pushbroom
MIDDLETON SPACTRAL VISION	www.middletonspectral.com	Pushbroom
NORSK ELECKTRO OPTIKK	www.neo.no	Pushbroom
RESONON	www.resonon.com	Pushbroom
SENOP	www.senop.com	Pushbroom
SPECIM	www.specim.com	Pushbroom
SURFACE OPTICS CORP.	www.surfaceoptics.com	Pushbroom
TELOPS	www.telops.com	Pushbroom
IMEC	www.imechyperspectral.com	Internal Scanning
HINALEA	www.hinaleaimaging.com	Internal Scanning
PHOTON Etc	www.photonetc.com	Internal Scanning
SPECIM	www.specim.com	Internal Scanning
CUBERT	www.cubert-gmbh.com	Snapshot (Thumbnails)
PHOTON FOCUS	www.photonfocus.com	Snapshot (macropixels)
SILIOS TECHNOLOGIES	www.silios.com	Snapshot (macropixels)
SPECTRAL DEVICES	www.spectraldevices.com	Snapshot (macropixels)
XIMEA	www.ximea.com	Snapshot (macropixels)

Table 3: Main manufacturers in the field of hyper/multispectral imaging systems (non-exhaustive list).

ULTRASTABLE LASER

The rack-mountable ORS-Mini Ultrastable Laser System delivers ultra-narrow linewidth laser light with excellent frequency stability. The system's centerpiece is a high-finesse Fabry-Pérot cavity (cubic spacer with a length of 5 cm) serving as a reference for a CW laser. The reference cavity is acoustically isolated allowing for excellent performance also in rough laboratory environments.

https://www.menlosystems.com/products/ultrastable-lasers/ors-mini/

Compact multispectral camera

The TOUCAN Multispectral camera (SILIOS) is specially designed to allow high integration of VIS+NIR multispectral systems. This lightweight (less than 180g) and very small footprint (52×63×40mm) camera splits the image into 10 spectral bands on a very large range (400-900nm). Made by hybridization of a custom Bayer-like mosaic filter on a commercial 4.2 MPixel CMOS Sensor, it allows extracting the spectrum on each point of the image.

https://www.silios.com/toucan-camera

Multiple color laser

Prima is a compact laser module offering 3 individual emission wavelengths that can be operated in picosecond pulsed and continuous wave (CW) mode. The picosecond pulses can be triggered either by the module's internal clock or by an external oscillator at up to 200 MHz. Prima provides laser light at three wavelengths: 635, 510, and 450 nm. Each color can be generated individually, one at a time.

https://www.picoquant.com/products/category/picosecond-pulsed-sources/prima-stand-alone-3-color-picosecond-laser

HIGH-POWER LED LIGHT SOURCE

The SLED 1000 Series is a super-luminescent LED light source with high output power, large bandwidth and low spectral ripple. It comes in various wavelength models to address applications in the telecom and datacom markets. The SLED is a single-slot PXIe module and is ideal for building a customized optical testing platform that delivers reliable and repeatable results in manufacturing or R&D environments.

https://www.quantifiphotonics.com/products/lasers-amplifiers/pxi-sled-1000-series/

In-vivo NIR hyperspectral imaging and spectrometer

The *in-vivo* hyperspectral imaging system for the NIR II SWIR domain (800-1700nm), IR VIVO Photon etc., is now available with an infrared microplate reader, VladimIR™, and an infrared spectral probe, IRina™. VladimIR captures full fluorescence spectra from 900 nm to 1600 nm and the transmittance spectrum from 500 nm to 1600 nm while IRina™ is an in-vivo NIR-II spectrometer ideal to quantitate bio-photonic emissions and visualize spectral shifting of activity-based sensors in real-time.

https://www.photonetc.com/products/irina