N°128

Photoniques

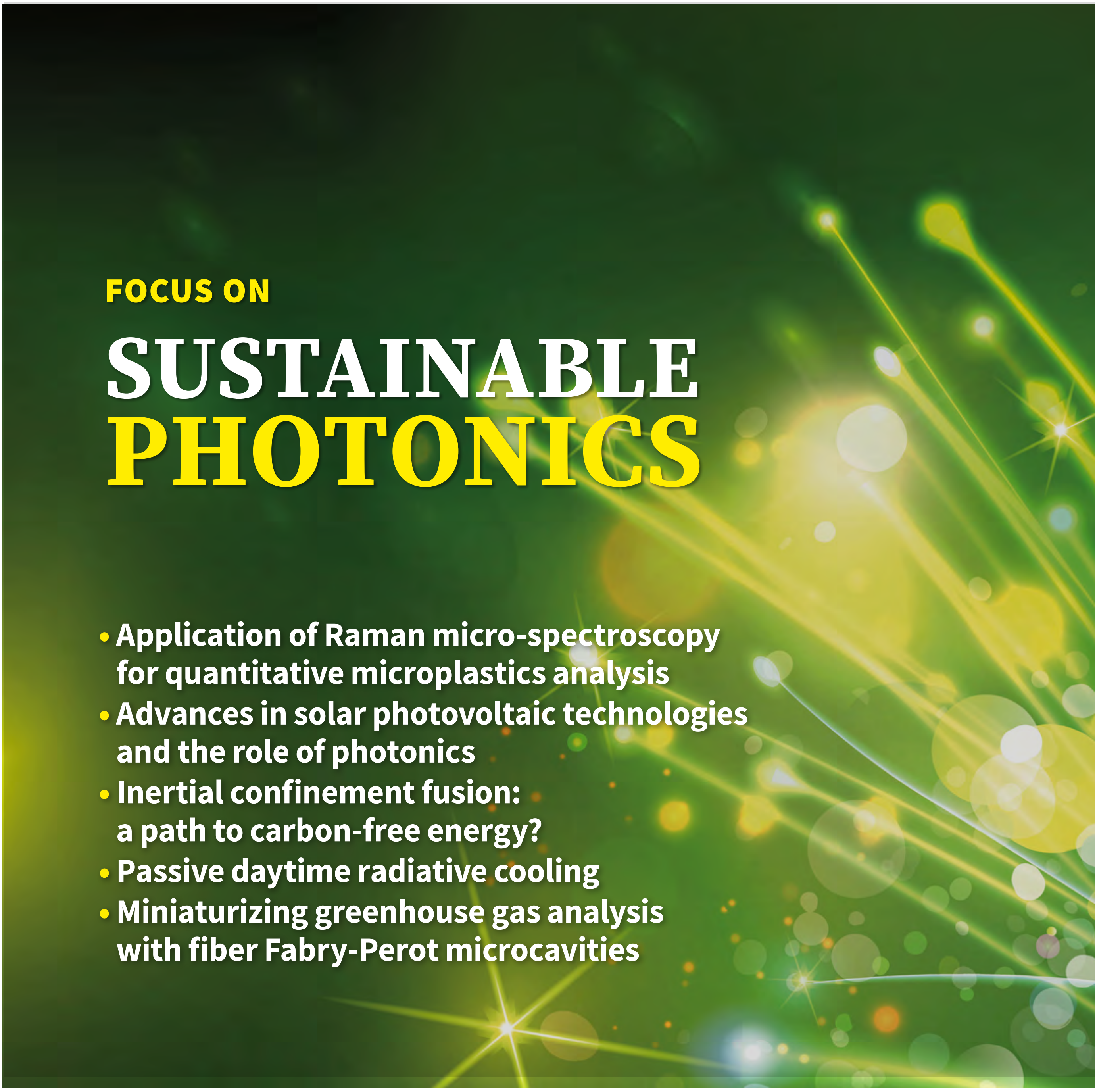
LIGHT AND APPLICATIONS | EOS & SFO JOINT ISSUE

INTERVIEWS
Wilhelm Kaenders
Nathalie Picqué

ZOOM
Photonics
in Germany

LABWORK
Telescope farms
in Chile

BACK TO BASICS
Molecular
strong coupling



FOCUS ON

SUSTAINABLE PHOTONICS

- Application of Raman micro-spectroscopy for quantitative microplastics analysis
- Advances in solar photovoltaic technologies and the role of photonics
- Inertial confinement fusion: a path to carbon-free energy?
- Passive daytime radiative cooling
- Miniaturizing greenhouse gas analysis with fiber Fabry-Perot microcavities

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Editorial

NICOLAS BONOD
Editor-in-Chief

Sustainability : Lighting the Way with Photonics

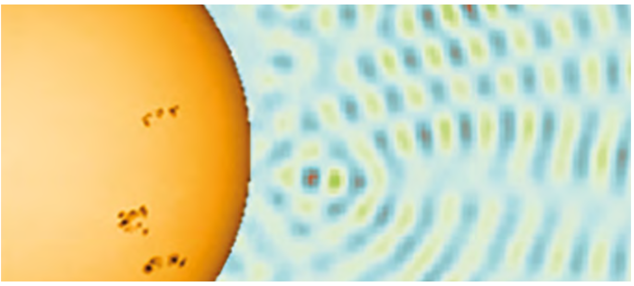
According to the World Meteorological Organization, 2024 is likely to become the warmest year on record with warming temporarily hitting 1.5°C, marking the period from 2015 to 2024 as the warmest decade. The acceleration of ice melting, sea-level rise, and ocean heating is alarming. Despite some reductions in greenhouse gas emissions in a few countries, overall greenhouse gas concentrations continue to rise. Additionally, biodiversity is declining with a significant drop in the aggregate Red List Index. It is clearer than ever that efforts must be intensified and transformations towards sustainable industries accelerated.

Optical processes play a crucial role in global warming through the increased concentration of greenhouse gases, and photonics in turn emerges as a natural technology to address the climate crisis. Light-driven technologies offer numerous solutions in energy production, light harvesting, photocatalysis, energy saving, green manufacturing, environmental monitoring, pollution detection, waste sorting... This impressive list motivated the editorial team of Photoniques to publish an extended issue covering some of the most interesting and relevant aspects of sustainable photonics.

Let's focus on energy, a critical issue since this sector is the largest emitter of greenhouse gases. Photonics technologies can be used to heat or cool buildings through direct solar heating or radiative cooling and to produce electricity through the rapidly advancing field of photovoltaics. The optimization of light trapping and confinement in advanced materials has pushed the concept of passive radiative cooling to daytime passive radiative cooling with impressive results and progress over the last ten years; Advances in photonics and light harvesting continue to enhance the efficiencies and global performances of solar cells, accelerating their worldwide deployment.

A longstanding challenge in producing carbon-free energy has been harnessing nuclear fusion with hydrogen isotopes. While a laser-based approach was proposed and investigated as early as the 1960s, magnetic fusion confinement has since received most of the attention and funding. However, the ignition point achieved by the National Ignition Facility in 2022 evidenced the relevancy of inertial confinement fusion, spurring the formation of industry-academic consortia and the funding of ambitious programs. Although numerous difficulties remain, the goal is now clearly identified: developing carbon-free inertial confinement fusion-based electricity power plants by the mid-century.

The promising horizons offered by photonics to mitigate the climate crisis and promote sustainable technologies can boost the transformation of our industries. Light-based technologies offer innovative and relevant solutions in the quest for a sustainable economy, lighting the way to achieve carbon neutrality and build a bright future.



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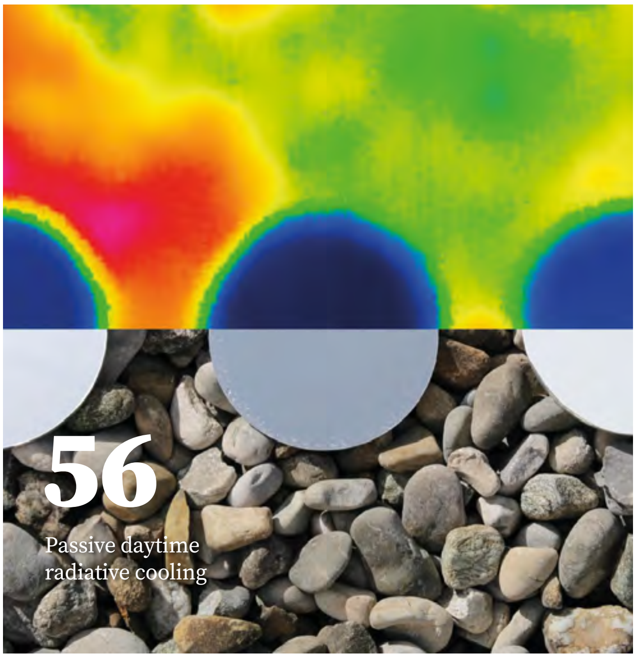

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FRANÇOIS SALIN
President of the French Optical Society

A new academic year full of action and hope!

We left off after OPTIQUE Normandie, whose preparation had drained much of our energy. Fortunately, the summer holidays allowed us to recharge our batteries. We hope you were able to do the same because this new academic year promises to be busy and exciting. But first of all, a warm welcome to Emiliano Descrovi, the new EOS president.
The Wavinaire organized October 2nd with the CNRS GdRs "Ondes" and "Complexe", to delve into the decoherence in quantum optics, was a success. Many thanks to Eliott Beraud (LP2N), Michel Brune (LKB) and David Dreon (planqc), who put the issue into perspectives. One week later, our Optical Calculation Club successfully co-organized the Freeform surfaces – ONERA scientific days.
2024 was a very successful year for the SFO, and we are already actively working on 2025. We contribute to the preparation of the C'Nano Congress in Paris-La Villette (March 18-21). In addition to the usual participation of the Nanophotonics Club, SFO will co-organize the industrial exhibition. Two residential schools are also in the target. The annual one at Les Houches (iconic physics center in the French Alps), May 12 to 23, will be devoted to LNOI. The school organized by the LIDAR Club is back at the Observatoire de Haute Provence (June 11-16).
In parallel, work starts towards the 42th edition of the guided optics Club conference, JNOG, in Sète (July 7-10), for the first time as a residential event, ideally located by the sea. Chairs Christelle Brimont (LCC) and Stéphane Blin (IES), will ensure an excellent hospitality and a top-notch scientific program. Book your spot ASAP...
As for the rest, an important change that we are hopeful for could mark a significant development in SFO trajectory. The request for public utility recognition, submitted 2 years ago, should now be able to come to fruition following our third-year consecutive positive economic balance. Let's hope and keep moving forward!

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

EMILIANO DESCROVI
President of the European Optical Society

Lights on Napoli!

The EOS Annual Meeting, held in Napoli this September, offered an amazing opportunity for the European Optics & Photonics community to meet and extend a bit longer the enjoyment of the summer weather.
In the spectacular setting of the Parthenopean city, general chairs Luca de Stefano, president of the Italian Society of Optics and Photonics (SIOF), and Raffaele Velotta, professor at the University of Napoli, supported by Elina Koistinen, Patricia Segonds and myself, offered a rich program across many branches of O&P. Outstanding plenaries covered topics from non-linear optics, biophotonics and optics in complex media. Also, the 50th anniversary of the first work on passive radiative cooling, carried out in Napoli, was celebrated with an inspiring talk. As in EOSAM2023, traditional Topical Meetings were complemented by Focused Sessions, proposing novel exciting themes. Tutorials registered a great attendance from PhD students and early-stage researchers, thanks to the broad thematic coverage offered, from 2D nano-optics to scientific communication.
With 470 accepted submissions, EOSAM2024 gathered nearly 500 attendees from 36 countries (18 outside EU), reaffirming its status as a key appointment on the European scene. The EU session, hosting representatives from the EC, Photonics21, PhotonHUB and the 360Carla project, represented a valuable moment for a lively discussion. Significant appreciation also from the industrial sector, specifically at the IMOTS sessions and the Industrial Podium that preceded the welcome party. As a follow-up, a topical issue on EOSAM2024 is launched on the EOS open-access Journal, JEOS-RP. Extended papers are welcome for submission and will be subjected to peer-review. JEOS is indexed in major databases and EOS members benefit from significant discounts on APCs. Next year, EOSAM will move to Delft, The Netherlands, August 24-28. Save the dates and stay tuned for updates on the newsletter, social media, and Photoniques! Visit https://www.europeanoptics.org/ to discover more on EOS memberships.

Emiliano Descrovi,
Professor at the Politecnico di Torino, President of EOS

AGENDA

■ **Lithium Niobate**
The Houches Physics School, France

12 - 23 May 2025

Limited to 70 attendees

■ **LIDAR**
June 15-20, 2025

OHP, Observatoire de Haute Provence, France

Limited to 40 attendees

■ **JNOG Montpellier 2025**
Sète

07 - 10 July 2025

+ 200 participants expected

■ **OPTIQUE BFC 2026**
Dijon - Palais des congrès

06 - 10 july 2026

+ 670 participants expected

SFO - THEMATIC SCHOOL 2025

In 2025, the French Optical Society reaffirms its commitment to the dissemination of knowledge in optics and photonics through the organization of two high-level thematic schools, showcasing the diversity of our community: The very first international school on the flourishing field of integrated lithium-niobate thin-film photonics in the prestigious site of Les Houches and the second edition of a thematic school on LIDAR with dedicated practical work at the Haute-Provence Observatory.

Lithium niobate on insulator integrated photonics from fabrication to classical and quantum applications

Registration is now open for this school—join our experts!

The Houches Physics School, France, May 12 to 23 – 2025

The workshop is dedicated to bring leaders in integrated photonics platform of Lithium Niobate On Insulator (LNOI) together with the aim of providing an overview on the advances that have been achieved over the last years, use this overview to speculate about future opportunities of LNOI and provide recommendations on how these opportunities can be realized by coordinated research efforts.

Lecturers

- Cristina BENEA-CHELMUS, EPFL, Switzerland
- Jean BERNEY / Davide GRASSANI, CSEM : Centre suisse d'électronique et de microtechnique, Switzerland
- Ya CHENG, SIOM : Shanghai Institute of Optics and Fine Mechanics, China
- Nadège COURJAL, FEMTO-ST, France
- Aaron DANNER, National University of Singapore, Singapore
- Martin FEJER, Stanford University, USA
- Katia GALLO, KTH, Sweden
- Tobias GEHRIN, DTU : Technical university of Denmark, Denmark
- Tobias KIPPENBERG, EPFL, Switzerland
- Bart KUYKEN, Gent Univ., Belgium
- Francesco LENZINI, CNR-IFN, Italy
- Marko LONCAR, Harvard University, USA
- Amir SAFAVI, Stanford University, USA

The scientific program committee

- **Kamel BENCHEIKH** (C2N, University Paris Saclay – CNRS, France)
- **Andreas BOES** (The University of Adelaide, Australia)
- **Rachel GRANGE** (ETH Zurich, Switzerland)
- **Arnan MITCHELL** (RMIT University, Australia)

Lidars: from fundamentals to geophysics and industrial applications

Organized by the Club LIDAR
OHP, Observatoire de Haute Provence, France, June 15 – 20 2025

The Summer School **"LIDARS: From Fundamentals to Geophysics and Industrial Applications"** is dedicated to Master students, PhD students, young researchers and engineers who want to acquire theoretical and technical know-how on Lidar systems from experts in the Lidar community.
We look forward to welcoming you to OHP from June 15 to 20, 2025!

Lecturers

- **Nicolas CEZARD**, ONERA/DOTA, Université de Toulouse
- **Sandrine GALTIER**, Institut Lumière Matière (ILM), CNRS, Université de Lyon
- **Alain MIFFRE**, Institut Lumière Matière (ILM), CNRS, Université de Lyon
- **Fabien GIBERT**, Laboratoire de Météorologie Dynamique (LMD), CNRS, Ecole Polytechnique, Palaiseau
- **Romain CEOLATO**, ONERA/DOTA, Université de Toulouse
- **Alain DABAS**, Centre National de Recherches Météorologiques (Météo-France/CNRS), Toulouse
- **Philippe KECKHUT**, LATMOS/IPSL, UVSQ Université Paris-Saclay, Sorbonne Université, CNRS, Guyancourt
- **Laurent LOMBARD**, ONERA/DOTA, Université Paris-Saclay, Palaiseau
- **Patrick FENEYROU**, Thales Research & Technology France, Palaiseau
- **Hervé DELBARRE**, Laboratoire de Physique et Chimie Atmosphériques (LPCA), Université du Littoral Côte d'Opale, Dunkerque
- **Myriam RAYBAUT**, ONERA, Palaiseau
- **Jean-Baptiste DHERBECOURT**, ONERA, Palaiseau
- **Stéphane VICTORI**, CIMEL, Paris
- **Julien TOTEMS**, LSCE, Gif-sur-Yvette

JEOS-RP: the European Optical Society at the service of authors and readers of the photonics community

The Journal of the European Optical Society-Rapid Publications, JEOS-RP, is an open-access journal wholly owned by the European Optical Society. EOS is thus fully responsible for its scientific policy and quality.
To better meet the needs of our scientific community, both authors and readers, five learned societies, from Spain (SEDOPTICA), Italy (SIOF), Germany (DGaO), Portugal (SPOF), and Belgium (PromOptica), have now joined the EOS. Together, significant improvements have been achieved over the past year:
Over 2023, the median time from submission to online with DOI fell below 73 days.
The impact factor now reaches 1.9.
And the author publication fees remain at a very fair level with a large discount for EOS members.
JEOS-RP covers all the fields of photonics, and gives further focus on specific areas through its topical issues, the next of which is entitled “Using wavefronts: detection and processing”.
Discover how you can give high visibility to your research work by publishing in JEOS- RP: https://jeos.edpsciences.org/.

CONGRATULATIONS TO THE WINNERS OF THE 2023 EOS PRIZE

The EOS Prize is awarded annually for the best paper published in the Journal of the European Optical Society–Rapid Publication. It consists of a diploma and an invitation to present a plenary lecture, the JEOS-RP Highlight, during the EOS Annual Meeting.

The 2024 Prize was awarded to the paper titled: “Terahertz nondestructive stratigraphic recon- struction of paper stacks based on adaptive sparse deconvolution”, By Min Zhai, Alexandre Locquet, and David S. Citrin, J. Eur. Opt. Society-Rapid Publ. 2024, 20, 4.

Enjoy your reading at:

Alexandre Locquet (right) receiving the EOS Prize from Gilles Pauliat, the EOS Past-President (left), on behalf of his co-authors prior to his plenary presentation at the EOS 2024 Prize Ceremony at the EOS Annual Meeting in Naples, Italy.

125th anniversary of IOP Optical Group

The IOP Optical Group, as the UK & Ireland Branch of the European Optical Society, EOS, seeks to engage the Optics and Photonics community both nationally and internationally. Its core motivation is to be an effective medium of exchange on issues that impact the technical and cultural aspects of human endeavour.
https://iop.org/

Optics and Photonics Days Finland 2025

Annual Meeting of Photonics Finland, OPD2025, will be held at Oulu Music Center 3 – 5 June 2025, Oulu, Finland.

DGaO 126th Annual Meeting in Germany

Annual Meeting of DGaO will take place from 10 to 14 June 2025 at the University of Stuttgart, Germany.

EOSAM 2025 moves to the picturesque Delft

Each year, EOS organizes its Annual Meeting in different locations across Europe, making each EOSAM a unique event. In 2025 EOSAM moves to the idyllic city of Delft and is co- organized with The Delft University of Technology, TU Delft. Around 500 attendees from all over the world are expected, for presenting their most recent results, networking and catching up. Sessions will also be organized to facilitate connections among industrial and research communities along with an industrial exhibition.

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In brief

Congratulations to Léa Dubois, former PhD students at Laboratoire Charles Fabry (Institut d'Optique / Université Paris-Saclay / CNRS), who is one of the 35 laureates of the 2024 L'Oréal-UNESCO For Women in Science Young Talents Award ! In her PhD, Léa studied "Non-equilibrium dynamics of a 1D Boson gas », focusing on the study of ultra-cold atoms.

CONTINUING EDUCATION AGENDA :

- **CO1 - Optical design of imaging systems with Zemax® / OpticStudio – Introduction**
November 19 to November 22, 2024
- **EF1 - Optics without calculation**
December 3 to December 5, 2024
- **CO2VIS - Optical design of visibe imaging systems with Zemax®/OpticStudio - Advanced**
December 16 to December 18, 2024
- **SC2 - Optical manufacturing and optical metrology**
March 4 to March 6, 2025
- **EF2 - Basics of optics**
March 11 to March 14, 2025 and March 25 to March 28, 2025
- **SC7 - Wavefront sensing**
March 20 to March 21, 2025

CONTACT

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Head of communication
clementine.bouye @institutoptique.fr

Inauguration of the 503,
center for entrepreneurship and innovation of Institut d'Optique

Tuesday, October 1st marked a magical moment for Institut d'Optique: after two years of renovation work financed by the French government, the Region Ile-de-France and the Département de l'Essonne, the 503 was inaugurated on a memorable day.


© photo credits : Corinne Hameau

After the famous ribbon-cutting ceremony, the 300 participants - academic, industrial and institutional partners of the 503 and the Institut d'Optique - enjoyed a rich and varied program.
Institut d'Optique's new Innovation Department - Audrey Durand, Johan Boullet, David-Olivier Bouchez - led a series of lectures and round tables on sourcing innovation in labs, student entrepreneurship, investment, collaborative research, innovation in large industrial groups...
During the breaks, the public could stroll through the Photonics and Innovation Village, which showcased representatives of the photonics industry and the innovation ecosystem. Participants also enjoyed a photo exhibition, created especially for the occasion, combining archive photos of the 503 before renovation with photos of the renovation worksite. Throughout the afternoon, tours of the building were offered to meet companies, students from the Filière Innovation-Entrepreneurs and to (re)discover the Photonic Fablab. The day ended with a convivial cocktail reception.
While retaining a link with its scientific history and its expertise in training and transfer to industry, Building 503 has been transformed to provide a showcase for the ambitious vision of innovation espoused by the Institut d'Optique.
This day marks the beginning of a new era for Institut d'Optique, and many exciting projects are already in the pipeline at 503.

INAUGURATION OF THE ALAIN ASPECT AMPHITHEATRE

During the inauguration of the 503, the building's amphitheatre was named "Amphithéâtre Alain Aspect"!
Rémi Carminati, General Manager of Institut d'Optique, in the presence of Alain Aspect, laureate of the 2022 Nobel Prize in Physics, proudly unveiled to the public the inscription permanently installed in the amphitheatre (see photo). With emotion, Alain Aspect recalled the period during which he carried out his research in this building, and in particular, the day he defended his « Thèse d'Etat » in 1983 in the amphitheatre that now bears his name.

© Photo credits: Daniel Madac
Annie and Alain Aspect in the "Amphithéâtre Alain Aspect" of the 503.

PIMAP4Sustainability project
is coming to an end

The PIMAP4Sustainability Eurocluster-project which aimed to support SMEs in the photonics value chain to innovate and develop new projects is drawing to a close.

Coordinated by ALPHA-RLH, the project distributed €1,050,000 to 70 European SMEs through 13 innovation projects, 36 training projects and 8 financial supports for SMEs wishing to participate in the international mission to Japan that took place in Tokyo in June 2024.

Several ALPHA-RLH members directly benefited from these support tools: ALPhANOV, BLOOM Lasers, Canoe, Emulseo, GLOphotonics, Polyrise and VLM Robotics.

The PIMAP4Sustainability consortium is now fully engaged in finalizing the last administrative elements of the project and is already looking ahead to the next Eurocluster-call to continue supporting the photonics value chain!

SOTER:
TOWARDS ENHANCING VISITOR EXPERIENCE AND IMPROVING SAFETY AT FESTIVALS

SOTER is a multidisciplinary project funded by the European Union, aiming to transform the experience of visitors at music festivals and large gatherings.

The project brings together experts in computer vision/AI from IkanoVision, Prime Cognition World providing gamification expertise and the Motocultor association organising the renowned music festival in France.

The consortium is dedicated to building technology for analysing the presence and movement of crowds and identifying behaviours of interest. These insights are leveraged by means of a gamified solution for visitors and can be used to improve safety. Notable examples include the presence and ambience detected at stages and waiting times in queues. The ambition of SOTER is to build technology that can be adapted to audiences at trade shows, exhibitions…

The technology is developed using crowd data collected from cameras deployed at the 2024 edition of the Motocultor festival.

SOTER pursues its international expansion and participated in the Tokyo Game Show 2024, as part of a learning expedition in Japan organised by ALPHA-RLH.

This project has indirectly received funding from the European Innovation Council and EISMEA, European Commission COSME-SMP-2021- CLUSTER. FRIEND CCI PROJECT.

Pôles de compétitivité and European clusters gathered in Strasbourg, France

ALPHA-RLH took part in the C2Lab event in Strasbourg on 25-26 September 2024, organised by the European Cluster Collaboration Platform (ECCP), in collaboration with the Association Française des Pôles de Compétitivité (AFPC).

The C2Lab interactive workshops provided an opportunity to meet new partners, discuss project ideas and initiate collaboration between European clusters on various topics: meta clustering, interregional investments, mobility, health and construction.

AFPC organised 2 parallel events during these two days:

- **The AFPC annual Europe Committee with all the Pôles de Compétitivité,**

- **The « Pôles pour l'Europe » awards ceremony. These awards aim to illustrate the commitment, creativity and contribution of French Pôles de Compétitivité to Europe and reward the best European initiatives. ALPHA-RLH was nominated in the "Best collaborative initiative" category for the NewSkin project, dedicated to surface nanotechnologies.**

UPCOMING INTERNATIONAL EVENT

- **Photonics West 2025**
  January 28-30, 2025 in San Francisco (USA)

News in Brief

- **25 new master students** have joined NANO-PHOT in September
- **NANO-PHOT attended the "forum des Entreprises UTT"** https://www.utt.fr/actualites/forum-utt-entreprises-126-entreprises-a-la-rencontre-des-etudiants-et-diplomes-de-lutt
- **NANO-PHOT** is a new member of Photonics France (https://www.photonics-france.org/)

Within the context of NANO-PHOT, a 21-page review article has been published in ACS Photonics on hybrid plasmonic nanosystems based on strong and weak coupling: https://lnkd.in/ezf9ZjHz. The first author, Minyu Chen is a NANO-PHOT PhD student who will soon defend her thesis and look for a good postdoc in nanophotonics from January 2025.We hope this review will be useful to members of the nanophotonics community (researchers, professors, students, engineers, technicians,.) who are interested in hybrid plasmonic nano-emitters and nano-absorbers.

AGENDA

- **Conference NFO17**
  2-6 Dec., Melbourne, Australia
  https://aipcongress2024.com/nfo-17/
- **Conference SPP11**
  19-23 May, Tokyo, Japan
  https://spp11.tokyo/

CONTACT

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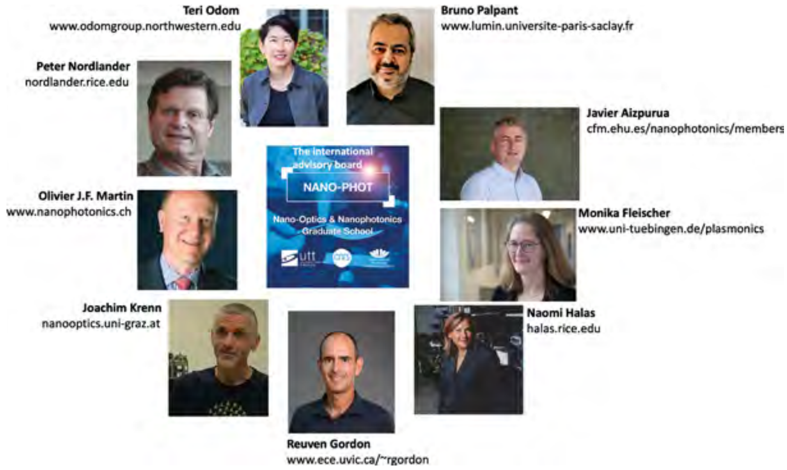
nanophot@utt.fr

Presentation of the international advisory board (IAB) of the NANO-PHOT graduate school

Nine world-class scientists help our graduate school to become better



Javier Aizpurua, Ikerbasque Professor at Donostia International Physics Center in San Sebastian, and distinguished researcher at the University of the Basque Country, where he leads the "Theory of Nanophotonics Group". He addresses theoretical aspects of light-matter interaction at the nanoscale focusing on quantum effects on nanostructures.

Monika Fleischer, Professor at the Institute for Applied Physics of Eberhard Karls University of Tübingen. She serves on the board of directors at the Center for Light-Matter-Interaction, Sensors and Analytics. Her research focuses on nanofabrication and optical spectroscopy of hybrid nanoantenna configurations.

Reuven Gordon, Professor at University of Victoria. He is a leader in nanoaperture optical tweezers, particularly for the label-free analysis of single proteins. He is Fellow of IEEE, SPIE and Optica, Deputy Editor for Optics Express and has served as chair for SPIE Nanoscience and Engineering, NFO16 and the inaugural Gordon Research Conference on Label-Free Single Molecule Sensing.

Naomi Halas, Professor at Rice University. She pursues fundamental studies of light-nanoparticle interactions and applications in (e.g) biomedicine, photocatalysis, and solar water treatment. She is a member of the National Academies of Sciences and the Engineering (USA), and member of the Royal Danish Academy of Sciences and Letters.

Joachim R. Krenn, Professor at the University of Graz. He works on the experimental research of optical phenomena on the nanoscale, including plasmonics, single quantum emitters and nanofabrication.

Olivier J.F. Martin, Professor at the Ecole Polytechnique Fédérale de Lausanne, where he conducts comprehensive research on numerical techniques for the solution of Maxwell's equations with advanced nanofabrication and experiments on plasmonic systems. Applications include optical antennas, metasurfaces, nonlinear optics, security features and optical forces at the nanoscale.

Peter Nordlander, Professor and Wiess Chair of Natural Sciences at Rice University. His research is focused on the theoretical modeling of plasmonics and nanophotonics phenomena. He is the recipient of the 2013 Willis E. Lamb Award, the 2014 Frank Isakson Prize, the 2015 R. W. Wood Prize, and the 2022 Eni Energy Transition Prize.

Teri W. Odom, Joan Husting Madden and William H. Madden, Jr. Professor of Chemistry at Northwestern University. She is an expert in structured nanoscale materials that exhibit extraordinary optical and physical properties. She is a Member of the US National Academy of Sciences and is Editor-in-Chief of Nano Letters.

Bruno Palpant, Professor at CentraleSupélec, University Paris-Saclay, France. He works on optical properties of plasmonic nano-objects in interaction with ultrashort laser pulses. His multidisciplinary projects lead to application for (e.g.) new functional materials and photonic and biomedical technologies.

NEW MEMBERS

Welcome to our new members:

CFA des Sciences is an apprentice training center within Sorbonne University, offering 20 university apprenticeships from Bac+2 to Bac+5.

NANO-PHOT Graduate School is developing a nanophotonics program for Masters and PhD students, with a focus on teaching and research.

Join Photonics France and benefit from a wide range of services to help you develop your professional network and activities. It also means contributing to the strong representation of the French photonics industry in dealings with public authorities.

Business Meeting: Photonics with CNRS

Photonics France and the National Center of Scientific Research (CNRS) organize a business meeting on November 22 at CNRS headquarters in Paris.

The CNRS draws on more than 80 years of research to foster innovation in science and meet contemporary challenges.

This day will be an opportunity to discover CNRS research on light and optics, from the emitting source to the final sensor. Find out about the latest innovations and meet key players in the sector.

Programme:

- Conferences: five scientists will share their research and partnership opportunities.
- Laboratory testimonials: feedback from Amplitude about its partnership with CNRS.
- Networking: workshops to exchange ideas with CNRS, other participants, and initiate new collaborations.

More details and registration on our website: photonics-france.org

AGENDA

- **Optical metrology and control**
  (with cluster Alpha-RLH)
  November 13-14 – Bordeaux
- **Photonics Forum**
  (with students of Institut d'Optique Graduate School)
  November 14 - Orsay
- **Business Meeting Photonics with CNRS**
  November 22 - Paris
- **SPIE Photonics West**
  January 25-30, 2025
  San Francisco

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PHOTONICS FRANCE
HELPS ITS MEMBERS WITH EXPORT CONTROL

Photonics France supports its members in their economic development at national and European level. The federation establishes lasting links with public institutions, particularly in the case of exports of dual-use goods.

Export controls for photonics technologies generate issues for many companies, whose products are often qualified as dual-use goods (civil and military). To clarify export controls for its member companies, the federation offers advanced training courses in collaboration with the Dual-use goods service (SBDU) and customs. The latest course took place on October 10 at SBDU headquarters.

Photonics France also organizes technical meetings with the SBDU and the European Commission's export control team to enable Photonics France members to be better informed about current regulations and adapt their export strategies.

ECOC Exhibition:
a Showcase for Optical Communications

From September 23 to 25, 2024, the ECOC Exhibition in Frankfurt brought together leading companies and experts in optical communications. Photonics Bretagne showcased their cutting-edge optical fibre solutions. We highlighted our range of specialty optical fibres, including hollow core, multicore, and the new bismuth-doped fibres, as well as our offer of tailored solutions for various applications. Photonics Bretagne also fostered collaborations across Europe, pointing out the potential for photonics innovation projects to benefit from funding with Photon Hub Europe. Our members were well-represented, with companies such as Orange Lannion, Ekinops, BKTEL Photonics, EXFO, OptoSigma, and Tematys contributing to a dynamic and forward-looking showcase of french capabilities.

Photonics Bretagne at SPACE 2024: Advancing Precision Agriculture and Animal Well-Being

Photonics Bretagne presented its innovative photonic solutions at the SPACE exhibition in Rennes, a leading event for agriculture and livestock professionals. Located at the INNOZH stand, the team showcased how photonics technologies can make farming more precise and sustainable. A highlight of the event was the thematic visit "Data at the Service of Precision Livestock Farming", co-organized with Images & Réseaux. This session attracted over a dozen participants, who explored how data can transform livestock farming, namely to enhance performance and animal well-being. The group visited key industry stands: itk, PIC Sensors France, iOtee, Anses, AIHERD, and Adventiel. Photonics Bretagne also presented funding opportunities from Photon Hub Europe with subsidies of up to 85%, encouraging the integration of photonics into agriculture. This event further solidified the role of Photonics Bretagne in promoting the vast potential of photonics in agricultural innovation.

KWAN-TEK SIGNS A PARTNERSHIP TO ADVANCE QUANTUM METROLOGY

After raising 1.2 m€, Kwan-Tek signs a strategic partnership with HiQuTe Diamond to develop quantum metrology solutions for industry and research, strengthening Europe's diamond-based quantum sensor ecosystem. HiQuTe Diamond will supply state-of-the-art, quantum grade diamond doped with Nitrogen Vacancy centres for integration by Kwan-Tek in demanding products for Education, Research and Industry applications. Kwan-Tek will provide its expertise and services in the characterization of the quantum properties of diamond for quantum sensing, helping to establish standards for CVD diamond qualification. This collaboration will accelerate innovation in quantum metrology and combine the strengths of both companies.

Photon Lines Launches New Imaging Brand "eye4you"

Designed to open up new perspectives in image acquisition and processing, eye4you offers a cutting-edge range of imaging benches and platforms for academic research and a variety of industrial applications. This new launch reflects Photon Lines' commitment to providing high-quality solutions tailored to the demands of imaging, with four first technologies:

- **eyeMOTION:** a universal image acquisition and processing software, compatible with a wide range of cameras.
- **eyeSTREAM:** a platform based on eyeMOTION, which enables several cameras to be used simultaneously, parameterised and synchronised with a very high degree of precision.
- **eyePIV:** an eyeMOTION plug-in for instantly calculating 2D2C velocity fields in real time or in post-processing from flow images.
- **eyeSPICE:** a spectral imaging software platform with total and intuitive control over spectral imaging cameras and acquired data.

AGENDA

- **SPIE Photonics West**
  January 25-30, 2025, San Francisco (United States)
- **OFC**
  April 1-3, 2025, San Francisco (United States)
- **Laser World of Photonics**
  June 24-27, 2025, Munich (Germany)

Nobel Prizes awarded to AI-Pioneers:

The Deep link between Computing and Physics (and Chemistry)

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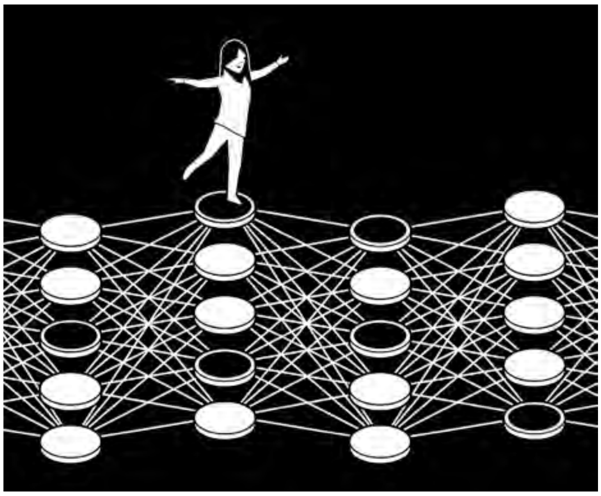
The 2024 Nobel Prize in Physics has been awarded to John J. Hopfield and Geoffrey E. Hinton for their pioneering contributions to harnessing principles from physics to establish foundational methods in machine learning. Their work catalysed ground-breaking computing concepts, establishing the basis for unconventional computing architectures that directly exploit the physics of their underlying hardware. Today, these novel paradigms promise to drive next-generation hardware with enhanced performance and efficiency, while advanced neural network architectures open doors to transformative scientific discoveries. In this review, we outline the broader context of their contributions to unconventional computing and emphasize the integration of physics-based concepts in modern machine learning architectures.

https://doi.org/10.1051/photon/202212812

The human brain, a biological marvel, has inspired the development of physical computers with extraordinary capabilities. Notably, it is highly energy-efficient, capable of complex problem-solving, supports creativity and can solve certain problems with remarkable reliability. Research into brain function has long had two interwoven goals: to understand the brain itself, and to develop technologies that mirror its capabilities. This dual interest has influenced generations of scientists, including the 2024 Nobel laureates in Physics, Geoffrey Hinton and John Hopfield, whose work has highlighted the profound link between brain-inspired computing and fundamental physical principles [1, 2].
Early computing began with special-purpose devices that leveraged analogue physics to perform calculations, usually with a rather direct mapping of the computational task onto the physical laws of the machines. This approach, though relatively simple to implement, limited such devices in their ability to evaluate/solve/compute/mimic specific functions to the ones embedded in their physical construction. The breakthrough in general-purpose computing emerged with Alan Turing's concepts, which abstracted computation using binary logic [3]. By reducing computation to simple, hence more readily reproducible operations, Turing's model made computing robust against physical imperfections, enabling the development of reliable hardware that operated largely independent of the specifics of the underlying physics.
However, this direct task-mapping approach, linking computational objectives to Turing algorithms, diverges

John J. Hopfield and Geoffrey Hinton © Niklas Elmehed - Nobel Prize Outreach



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significantly from the mechanisms underlying human intelligence. This discrepancy has intrigued researchers seeking to bridge the gap between conventional computing and brain function. Santiago Ramón y Cajal's pioneering studies in neuroscience (for which he received the Nobel Prize in Physiology or Medicine in 1906) provided an initial view of the brain's network structure, hypothesizing how neural connections could grow to support learning [4]. Later, McCulloch and Pitts associated neural function with computation using Boolean logic, interpreting neurons' binary firing patterns as a justification for representing neural activity in symbolic terms [5]. While this approach integrated computer science with networked computation, it failed to capture the deep connections to physics.

Improved understanding of the distributed, interactive nature of brain function started to increasingly highlight the parallels to physical systems. In the 1980s, a seminal analogy connected fundamental computing operations to atomic spin-spin interactions [6, 7]. Early researchers recognized that Ising models, where spins could point up or down, evolve toward stable configurations through the minimization of free energy. The resulting spin patterns are influenced by the topology of interactions, the initial spin states, and random fluctuations akin to the effects of a temperature, yielding highly robust configurations. John Hopfield extended this concept to memory storage in neural networks. In these binary memory systems, each memory corresponds to a specific spin configuration [2] and a spin network can store a variety of memories due to multiple stable configurations. Hopfield showed how to design these spin-spin interactions, or the network topology, such that inherent physics establish these memories as stable points positioned at local minima within the system's energy landscape [8], c.f. Fig. 1A. When the system is initialized from a partial state, it naturally relaxes to the closest stable configuration, restoring the intended memory. Hopfield networks thus enable memory retrieval ●●●

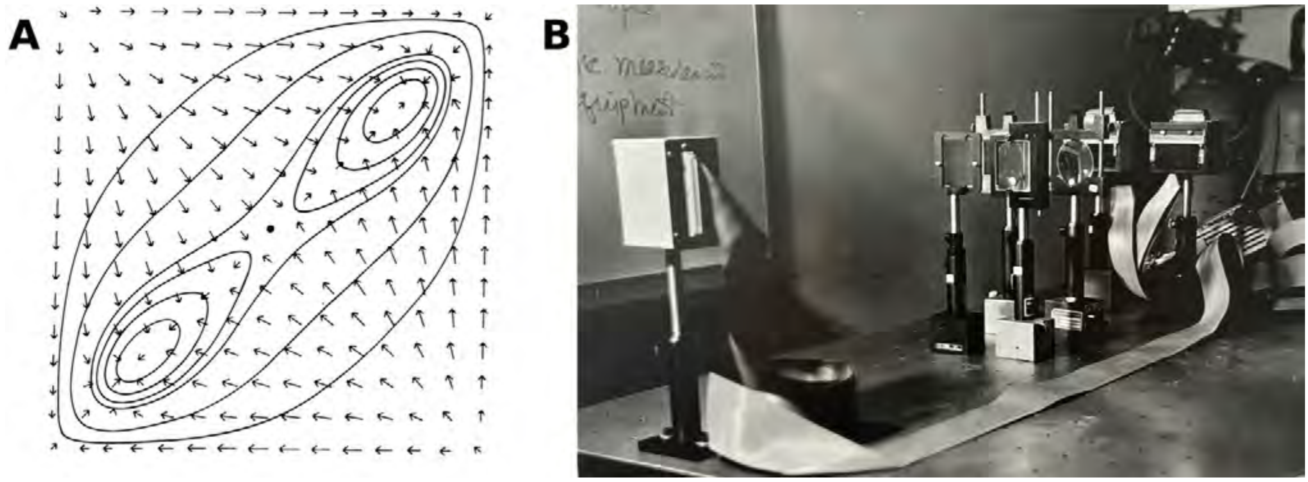

Figure 1. A The energy contour map for a two-neuron network, *i.e.* two-spin Ising model. Arrows indicate the relaxation-direction towards the two memories stored in the Hopfield network's energy minima. Picture reproduced with permission from J.J. Hopfield. B The almost immediate implementation of a Hopfield network demonstrates the legacy of Hopfield's work: connecting computing and physics. Photo: courtesy D. Psaltis. See also Ref. [10]

from incomplete inputs, offering a unified framework for neuro-inspired memory reconstruction, Ising spin system dynamics, and bistable network interactions. This achievement underscores the deep link between neuro-inspired computing, memory dynamics, and physical systems [9].

Geoffrey Hinton's Boltzmann machine expands the use of these concepts by leveraging concepts of statistical mechanics. The Boltzmann machine is also based on an Ising system connected in such a way that it searches for low-energy configurations to represent meaningful content again as stable configurations. Drawing on the idea of an energy landscape, each stable network state corresponds to a point with an associated energy level. The machine seeks configurations that minimize this energy, akin to how physical systems settle into stable, low-energy states. However, Boltzmann machines incorporate a "temperature" concept, using simulated annealing to explore network configurations by initially allowing more randomness (high temperature) and then gradually cooling (lowering randomness). This process helps avoiding poor solutions by enabling the system to escape local energy minima. The Boltzmann machine exemplifies how the principle of energy minimization combined with thermal fluctuations can bridge the gap between physics and artificial intelligence in the context of probabilistic learning models, and the approach has been foundational for deep learning architectures, particularly in unsupervised learning.

The legacy of Hopfield networks and Boltzmann machines has significantly motivated the fields of artificial intelligence, machine learning and unconventional computing using physics. Their work contributed to the development of deep neural networks that are now widely used. In particular, Hopfield's initial publication was pivotal, sparking interest in optical neural networks and leading to the first experimental realization of a Hopfield network [10] just two years later – using optics (c.f. Fig. 1B). Driven by the urgent need for new and efficient neuro-inspired physical computing engines, optical neural networks flourish again today. The 2024 Nobel Prize in Chemistry awarded to Demis Hassabis and John Jumper for their work on AlphaFold highlights the importance of Hinton's and Hopfield's work for novel computing concepts. Including an energy landscape model of protein folding, AlphaFold 2 exemplifies the application potential of the computational techniques pioneered by the early neural network architectures. Beyond this, neural network methodologies permeate nearly every scientific discipline, driving advancements in automated optical design, enabling the rapid simulation of complex optical systems and creating breakthroughs in computational imaging. Thus, the combined legacy of Hopfield networks and Boltzmann machines continues to inform advancements in artificial intelligence, illustrating the profound connections between physics and computational intelligence. ●

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UNIQUE NANODISK PUSHING PHOTONIC RESEARCH FORWARD

Photonic applications harness the power of light-matter interactions to generate various intriguing phenomena. This has enabled major advances in communications, medicine, and spectroscopy, among others, and is also used in laser and quantum technologies. Now, researchers at Chalmers University of Technology have succeeded in combining two major research fields – nonlinear and high-index nanophotonics – in a single disk-like nanoobject.

The effect arises as a combination of material and optical resonances with the ability to convert light frequency through crystal's nonlinearity. In its fabrication, the researchers have used transition metal dichalcogenide (TMD), namely molybdenum disulfide, an atomically thin material that has outstanding optical properties. The problem with the material is however that it is challenging to stack without losing its nonlinear properties due to its crystalline lattice symmetry constraints. A nanodisk of specifically stacked molybdenum disulfide (3R-MoS2) that preserves the broken inverse symmetry in its volume, and therefore maintains optical nonlinearity, was fabricated for the first time. Such a nanodisk can maintain the nonlinear optical properties of each single layer.

The material has a high refractive index (n>4.5), meaning that light can be more effectively compressed in this medium. Furthermore, the material has the advantage of being transferable on any substrate without the need to match the atomic lattice with the underlying material. The nanodisk is also very efficient in localising electromagnetic field and generating doubled frequency light out of it, an effect called second-harmonic generation. Thus, this nanodisk combines extreme nonlinearity with high-refractive index in a single, compact structure.

The significance of this work lies in the disk's extremely small size. Second-harmonic generation and other nonlinear processes are used in lasers every day, but the platforms that utilise them are typically on the centimetre scale. In contrast, the scale of this nanodisk is only about 50 nanometers, yet it is a very efficient light frequency converter. It is approximately 10,000 times more efficient than the unstructured material of the same kind, proving that nano structuring is the way to boost efficiency.

In future, TMD materials' incredibly compact dimensions, combined with their unique properties, could be used in advanced photonic applications. Specifically, one could dramatically reduce the size and enhance efficiency of optical devices for applications in e.g. nonlinear optics and the generation of entangled photon pairs. ●

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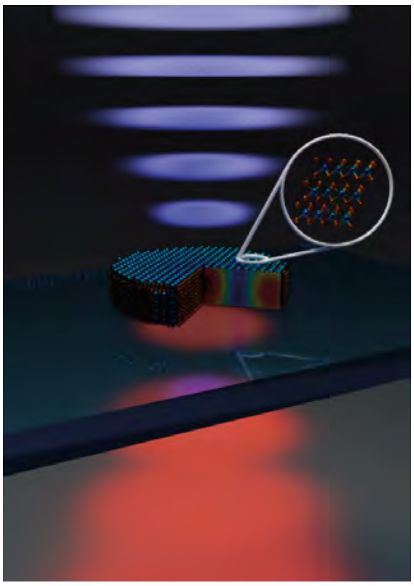
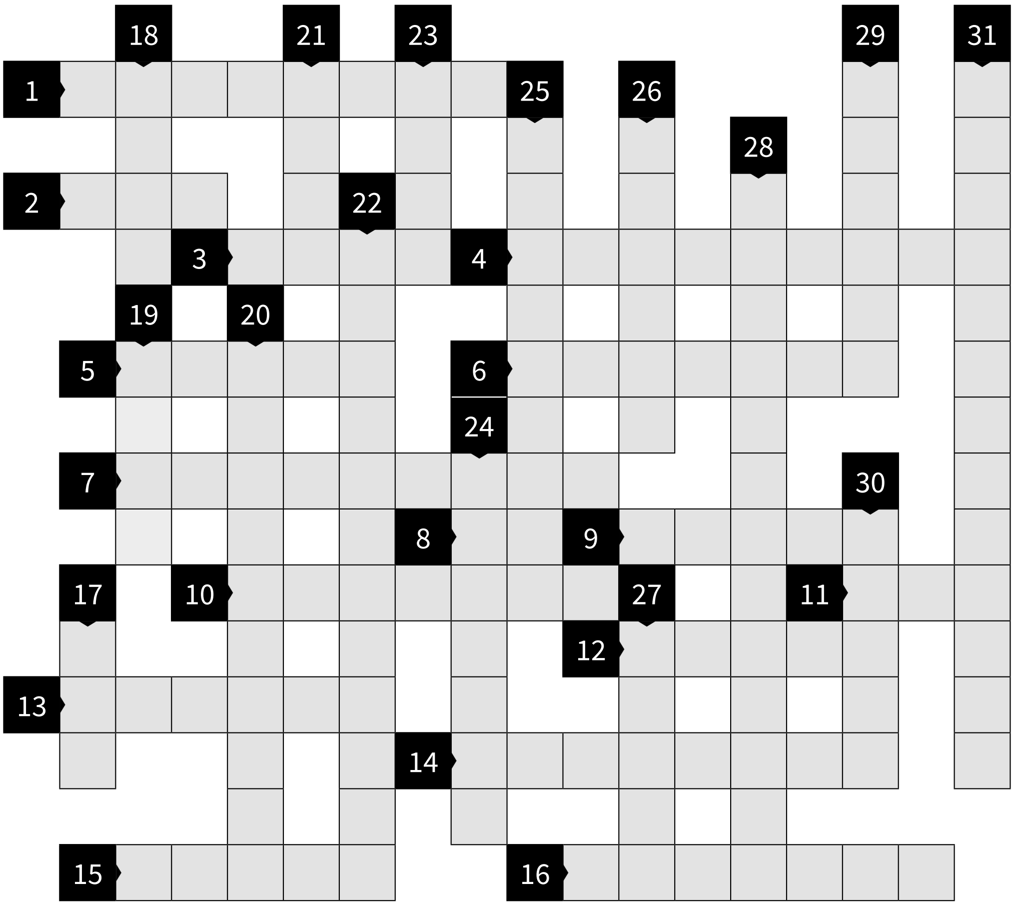
https://doi.org/10.1038/s41566-024-01444-9



Schematic of the optical experiment: Excitation near-infrared laser (red bottom one) - excites the nanodisk fabricated from the 3R-MoS_2 flake, standing on a glass substrate. © Georgii Zograf

CROSSWORDS ON SUSTAINABILITY

By Philippe ADAM

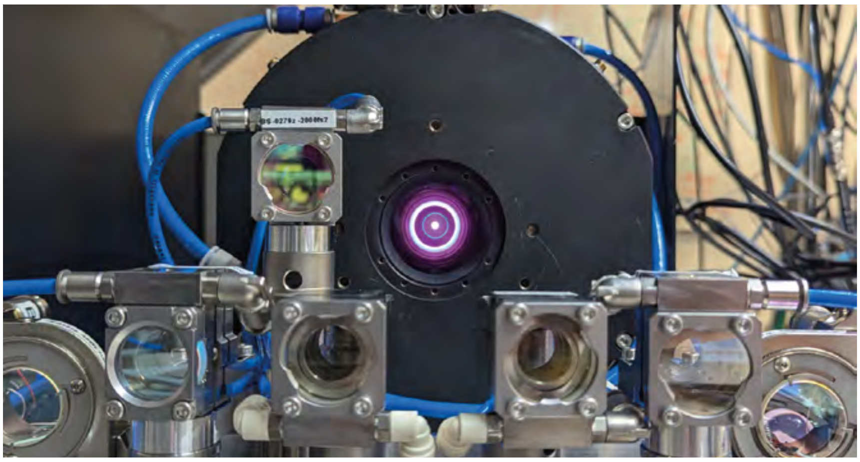


SOLUTION ON PHOTONIQUES.COM

1 Improved by using laser technology in combustion, lightweight construction or monitoring
2 Key Enabling Technology as defined by EC
3 For optical components, the smaller the better
4 That of carbon is critical for the environment
5 Satellite-based laser tool to monitor atmospheric pollution
6 Could be radiative
7 For automotive industry, laser technologies could increase their efficiency
8 Among others (AL, Fe, Zn …), compound called a greener metal
9 That kind of panel produces electricity by sunlight conversion
10 Its changes could be dramatic in the future
11 International Agency working to shape energy policies for sustainability
12 Optoelectronic devices, reducing power consumption and therefore considered as ECO-friendly
13 Devices to call your colleagues, family or friends, or simply, to give a call
14 A sustainable approach to treat e-waste and heavy-metal pollution
15 The symbolic colour of sustainability
16 Devices for monitoring environment or medium from physical signal variations
17 Surface Plasmon Resonnance
18 Technology to manufacture efficient hard and flexible displays
19 Laser technology allowing to sort materials
20 Large infrastructure using optical technologies to reduce energy consumption
21 Wireless optical network based on Light Fidelity
22 The graal for overall human activities
23 Renewable and highly predictable natural energy generation
24 Optical devices to improve sustainability and greening radiology
25 Qualifying a high conversion rate device
26 Quantum of light energy
27 Made in silicon instead of graphite, boosts the capacity of batteries
28 Optical devices with a minimal carbon footprint
29 Dimensioning request for future energy consumption
30 That kind of industrial operations should be drastically reduced
31 For converting solar energy

Breaking records with high-power ultrafast lasers to enable new physics measurements

Ultrafast high-power lasers are needed in many areas of science and industry, from driving beam lines generating attosecond pulses and providing insights into fundamental physics to machining of materials such as glasses with great accuracy.



In a recent Optica publication, researchers from ETH Zurich have presented a new record for ultrafast laser pulses directly from a laser oscillator. Using a so called thin-disk laser, they were able to achieve 550 W of average power which surpass the previous power maximum by more than 50 percent. Lasting less than a picosecond, pulses are emitted from the laser at a rate of more than five million per second, which is much higher compared to conventional amplifier-based systems. These short pulses reach peak powers of 100 megawatts.

This breakthrough is based on two innovations made by the researchers. Firstly, using a special arrangement of mirrors inside the cavity allows the laser to pass through the gain medium several times before leaving the oscillator through an outcoupling mirror. This arrangement allows to amplify the light without the laser becoming unstable and the intracavity power getting too high. Secondly, the element at the heart of the modelocked laser, a special mirror made from semiconductor materials was improved. This mirror, commonly called a SESAM, has the special property that its reflectivity depends on the strength of light hitting it. This allows the favoring of pulses inside the laser cavity over continuous operation. The researchers developed a new process of bonding this semiconductor structure to a sapphire, which improves the thermal and optical characteristics.

With this laser, the researchers show that high-power oscillators are a good alternative to more complex amplifier-based systems. The fast and strong pulses made possible by the new laser could also see applications in frequency combs in the ultraviolet or X-ray regime, which opens new precision measurement applications or the development of even more precise clocks. In the future this laser could be combined with a pulse compression setup, providing even higher peak powers of the laser pulses. The high repetition rate together with the high peak powers achievable make it very interesting for the generation of high-harmonics or terahertz radiation.

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Interview with Wilhelm Kaenders, Chief Technical Officer (CTO), Founder & President of Toptica

https://doi.org/10.1051/photon/202412818

What was the topic of your PhD thesis?
Coming from the scientific field of atomic physics, I defended my diploma in 1995, focused on autoionization resonances triggered by light. A group from Imperial College was collaborating with us at the University of Bonn on the synchrotron to build laser-based replacements for VUV sources. We were developing a tunable record-high power Lyman-alpha laser source taking advantage of Four Wave Mixing in phase-adjusted krypton-argon gas mixtures. This work led me into the field of lasers, and I became acquainted with Theodore Hänsch's group in Munich. The former postdoc there, Dieter Meschede, was establishing a new laboratory in Hanover for his newly gained professorship, and one of my PhD tasks was to transfer diode laser-based technology for cold atom physics and helping to build a new group there.
I worked on laser cooling, an exciting time when the first magneto-optical trap from the gas phase was invented independently in 1990 by Carl Wieman and Jean Dalibard. Specifically, I focused on chirped laser cooling, slowing down a thermal atomic beam with resonant laser light to allow for imaging atomic beams using permanent magnets. We built various magnetic field configurations (quadrupoles, hexapoles, etc.), aiming to ultimately create a "racing track" for cold atoms. Hexapoles for example can be treated nearly as "classical lenses" for atomic beams and their trajectories, allowing focusing and imaging. While pursuing these objectives, I had to build multiple diode lasers and a lab environment, replacing titanium-saphire and ring dye lasers by low-noise electronic laser diode-based alternatives. By the way, this exciting period saw hydrogen nearing Bose-Einstein condensation, but ultimately, affordable laser diodes

matching rubidium and cesium resonance lines opened new avenues. This environment spurred me to start Toptica later, initially focusing on external cavity diode lasers (ECDL) for laser cooling in scientific fields.

Toptica was initially related to fundamental science
Yes, and fundamental science remains a core part of our activities, constituting about half of our business today. We proudly show at least 14 Nobel laureates in our customer list since we started. There might be more that we do not know about whether they are using our tools or people that are still on the path of becoming "Nobel", who knows in such a vivid field.

How did you choose between pursuing a post-doc position or funding your own business?
I was applying for postdoc positions, trying to synchronize plans with my then-fiancée. However, at that time, I received an offer to start and direct a new business with a budget of DM50,000 flat and three months to be allocated between salary and equipment. After that, our work quickly garnered public funding and interest because of the features of our laser products: tuning, narrowband, and cost-effectiveness. And compared to the academic world, I enjoyed the business environment from day one, as it allows building "ownership" in a different way. Improving technology over many cycles with qualified engineers in the background allows to generate value when sold back into research.

Was the market clearly identified?
I initially worked within an existing company focused on ophthalmology lasers, which helped me discover the independence and field I enjoyed. But my interest was atomic physics and spectroscopy, while my co-founders envisioned medical applications, leading to a mismatch in our goals. After two years, we realized I was better suited to pursue my vision, leading to the foundation of Toptica as an independent entity.

When did you create this spin-off company?
In 1998. We're now celebrating our 26th year. At the time, there was no Venture Capital interested in this field and we might have failed their ambitions. So the only opportunity was to actually use an existing framework, an umbrella and then move it out with a colleague and with significant personal financial participation.

What have been the main motivations to develop your products?
Our slogan "All wavelengths" reflects our open collaboration style with scientists, who often requested specific product adaptations. Whenever we made something, a scientist came the next

moment to require a similar product but with another given specificity. "Can you match your laser wavelength with strontium?" "Can you also match that with ytterbium?" "Or maybe barium would be better?" The company today has been evolving quite a bit since. Toptica fabricates still the broadest range of diode-based lasers, in addition to fiber lasers, but in addition, also fibre lasers in the shape of ultrafast picosecond and femtosecond lasers, and there is also a new line of CW fibre lasers. We bought a company fabricating semiconductor lasers, called Toptica Eagleyard, which now gives access to our own semiconductor packaging. Last not least, we run a world-leading subsidiary producing most powerful laser guide stars for adaptive optics for astronomy and other fields.

Is Toptica a large company today?

Yes, in total we have about 600 employees and revenues in the order of €140 million in 2024, and have enjoyed steady growth since 1998. We recently acquired the company Azur Light Systems in France for their lowest intensity noise (RIN), and to be closer to the French photonic community. We have founded subsidiaries in Japan, China, and the US, the latter developing a range of its own products while all of them are reselling locally.

How did you start addressing the sector of biophonics?

We bought a company which was in our same building called Till Photonics. This company was doing microscopy for life science, in particular fluorescence confocal microscopy. We naively thought that we could integrate our lasers into a microscope much better than all the other big companies. The microscope instrumentation field is not very large and there are not many companies in the world that can fabricate world-class microscope objectives. And they implement lasers to what we considered to be falling short to the their full potential capabilities. Today, we pursue in addition multi-photon microscopy with ultrafast fiber laser using unique modulation and fiber delivery options.

What have been the main steps in the growth of Toptica?

When we started, we aimed to complement our scientific business with industrial applications. This led us to produce optical disc testing equipment, which was a completely different and new market for us. We leveraged our optoelectronics expertise to test CDs, DVDs, and next-generation formats like Blu-ray and holographic data storage. We pursued this activity for some time, but eventually, we realized that Blu-ray would not achieve the same market success as DVD. Despite this, our production test equipment proved valuable for Sony and Microsoft, just to name a few, but more importantly, it allowed us to build an internal highly professional electronics team.

In 2011, we commercialized our first multi-color diode laser source, which delivers four colors of single-mode laser diodes combined into one single-mode pm fiber. This innovation is again used in confocal microscopy for fluorescence microscopy. This was a significant step as it marked our first industrial multi-color unit, which we produce today in several hundred units of various kinds also for OEM customers.

What have been the latest achievements in term of technology?

Today, our products are becoming increasingly powerful and integrated. In 2020, we began selling complete integrated rack systems that combine multiple of our external cavity diode lasers, femtosecond lasers, and optical frequency combs, in many cases actively frequency-locked to suitable atomic transitions or even optically phase-locked to each other or high finesse cavities allowing linewidths of 1 Hz. These integrated systems are essential for quantum computing applications. Companies working with atoms and ions in the •••

quantum computing industry rely heavily on our devices to make their quantum computers function.
Currently, in our Quantum Technology Solutions group, we are developing a highly precise atomic clock as a substitute for hydrogen masers, using a single ytterbium ion as the optical reference. This requires eight different laser sources to store the ytterbium ion and interrogate it in a quadrupole clock, then investigate and derive an optical frequency from it. In a last optical step, an optical frequency comb then connects this frequency to the current international time standard, cesium 9 GHz rf line. We are the only company in the world which can offer all the required subunits out of one hand.

What are the main application domains that you address with your products?
In general we work in three well-identified markets: quantum technologies and spectroscopy, measurement and processing, and finally, biophotonics. Atomic physics was the first and still important target market, as today it is coined quantum technology. We also address precision interferometry, metrology, non-destructive testing in a market segment that we call "materials" and last not least, we support optical lifecell microscopy. Laser technology is a solution to many problems that do not yet know about its potential and will be explored only if the handling of the laser devices becomes easier and their costs go down. At Toptica, we like relatively small market niches that are fitting our company size and our in-depth level of expertise.

How much do you invest in research and technology?
Our R&D efforts represent between 13 to 15% of revenue annually. This effort is executed by more than 120 physicists, engineers and technicians mainly in Munich. We are proud that we have the full spectrum of engineering qualifications ready in house for our targeted markets.

When did you start working on frequency comb generation?
In 2003, we developed an independent approach to frequency combs. The Optical Frequency Comb is a significant achievement by the groups headed by Theodore W. Hänsch and John L. Hall, who were awarded the Nobel Prize in Physics in 2005 for their discovery. Their method involved stabilizing the carrier-envelope phase by working on the pump system, using an extra control loop. We pursued a different stabilization method that did not require an extra control loop. Instead, we used a scheme based on difference frequency generation, which naturally eliminates the carrier-envelope offset phase through the physics of the process.

TOPTICA Photonics AG Headquarters in Graefelfing near Munich / Germany

What is the main feature of Toptica?
Our main feature is what we call "All wavelengths". The various technologies we implement into our products enable us to cover a broad range of wavelengths or energy bands. This capability is unique. I don't know of any other company that can span such a wide optical frequency band. While this breadth is advantageous, it also presents challenges: these markets are mainly niche and it's extremely difficult to scale-up technology in numbers across such a wide spectrum. Although there is competition in specific subunits of our technology, there is no company that competes with us across the full spectrum of what we offer.

Where are located your headquarters?
TOPTICA Photonics is headquartered near Munich, Germany, where our main development and manufacturing facilities are located.

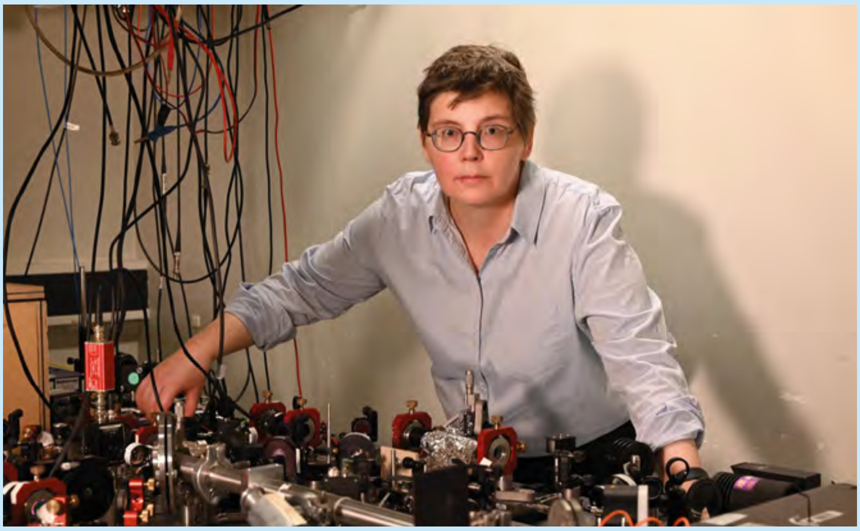
Are you focusing your sales efforts in Europe or worldwide ?
The company has a global reach with a focus on laser sales for scientific and industrial applications, including dedicated teams in North America, Japan, France, UK, and China.

What are the main assets of Europe for photonics companies ?
Europe stands out as a key region for photonics companies, largely due to its advanced research ecosystem and significant investments in high-tech industries. Germany, together with other European countries are leaders in scientific research and development with world-class laboratories, academic institutions, and large-scale collaborative projects, providing an environment that fosters technological advances in laser and photonic technologies. The region's strong support for innovation in industries such as automotive, aerospace and healthcare also drives demand for photonic applications, making it an attractive market.

Interview with Nathalie Picqué

Specialist in laser frequency combs, scientific director at the Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy - Berlin, Germany.

https://doi.org/10.1051/photon/202412821



Charlotte Huber, Max Planck Institute of Quantum Optics

How did you become interested in science?
When I was in secondary school, I was passionate about archaeology. My parents were scientists and they managed to get me an appointment with an archaeologist. They told me that it was almost impossible to secure an academic position in that field and my dream collapsed. I decided to study science by default, thinking it would open me opportunities. I took my science high school leaving exam (baccalaureate series C), then went on preparatory classes to the Lycée Saint-Louis, and then to the Ecole Normale Supérieure in Paris for a magistere degree in chemistry. Meanwhile, I realised that I was more attracted in the physics side of chemistry and decided to switch to physics. That's why I enrolled in the Masters in “Lasers and Matter” at the Pierre and Marie Curie University, École Polytechnique and the University of Paris-Sud.

Did this Master in Lasers and Matter strongly influence the rest of your career?
Yes, I really enjoyed the lectures. For the first time, I started to really engage with the material being taught instead of having my own agenda. I was particularly interested in quantum mechanics, non-linear optics and lasers, and molecular spectroscopy. Part of the training involved studying research papers and presenting them to others, and this was my favourite activity. I did a short internship at an institute called the Laboratoire de Physique Moléculaire et Applications in Orsay (now merged with other institutes as ISMO). My internship focused on pushing the limits of the precision of a Fourier transform spectrometer, a widely used spectroscopy technique based on the Michelson interferometer.

Did this experience lead you to pursue a PhD?
It seemed to me that by developing instrumental concepts, I might be able to measure something that had never been measured before. I developed a passion for the high-resolution Fourier transform spectrometer I was developing and decided to pursue my doctoral thesis in the same team. The ideas were to develop measurement techniques combining high temporal and spectral resolution to observe unstable molecules, or selective techniques to preserve only transitions of paramagnetic or ionic species. My supervisor was Guy Guelachvili, a pioneer in Fourier spectroscopy. He had been involved in the first high-resolution Fourier spectroscopy in the 1970s at the Laboratoire Aimé Cotton under the direction of Pierre and Janine Connes. My graduate research has been one of the happiest times of my life. The team was very supportive and I had great freedom to carry out original research projects. Our aim was to explore new topics, but we did not try to publish our results in high-impact journals. I defended my thesis in December 1998.

What did influence your choice for finding your post-doctoral position?
I wanted to learn new things, especially about frequency metrology and precision measurements with lasers. That's why I joined Massimo Inguscio's group at LENS in Florence as a post-doctoral fellow, where the fine structure splitting was being measured more and more precisely in order to better determine the fine structure constant. I learnt a lot during my 1.5 year stay and it was there that I first heard about frequency combs from Theodor Hänsch. In 2001 I was offered a position at the CNRS (French National Centre for Scientific Research), which was ideal for me as I was very keen to explore my own ideas on optical frequency combs for Fourier spectroscopy. I joined the Laboratoire de Photophysique Moléculaire in Orsay (which has since merged with other institutes to form ISMO).

What was your CNRS research project?
I wanted to develop experimental spectroscopy techniques that combine lasers and Fourier spectroscopy. Fourier spectroscopy offers a wide spectral range, while lasers offer high resolution and high sensitivity. My aim was to combine the two to have all these features in a single instrument. At that time, I was already ready to work with optical frequency combs and had come up with the dual comb scheme for Fourier spectroscopy, among other crazy ideas. But I was part of a team that had no laser and no expertise in ultrafast optics. My applications for funding were systematically turned down. Broadband spectroscopy with frequency combs was a very bold idea. It was a time when people were suspicious of frequency combs as frequency rulers, so proposing to use two of them for interferometry was obviously ahead of its time. My projects couldn't start as I wanted them to because of a lack of funding. I started to build the lasers myself, in my spare time in addition to pursuing other, less intriguing but funded, projects. In 2006, graduate student Julien Mandon and I saw our first femtosecond pulses from our home-built mode-locked oscillator. Out of ignorance, I had chosen to build a Cr:YAG laser, which turned out to be a complex system to build and work with. Nevertheless, it was a great way to learn about ultrafast laser physics and I had managed to attract some excellent students who contributed greatly to the success of the project.

How did this home-made laser source impact your work in spectroscopy?
Once the frequency comb generator worked, we were able to analyse it with our Michelson interferometer and quickly demonstrated the feasibility of our approach. We obtained the first experimental results on a technique now called frequency comb Fourier transform spectroscopy. The first paper reporting these results was published in Optics Letters in early 2007. At the same time, another group in the US was starting to explore similar ideas. I became painfully aware that we were not alone and did not have an infinite amount of time to explore our ideas, that it was necessary to publish quickly, and that without dedicated funding I could not compete with groups in the best US institutions. At the end of 2006, I contacted Theodor Hänsch, whom I knew from my post-doc in Italy and who had just been awarded the 2005 Nobel Prize in Physics for the invention of frequency combs as frequency rulers in metrology. In early 2008, I went on a six-month sabbatical to his institute, the Max Planck Institute of Quantum Optics (MPQ) in Garching near Munich, with two PhD students. This stay significantly accelerated our work, as we were able to benefit from the infrastructure and expertise at MPQ. We were able to greatly improve the dual-comb interferometer we had first developed in Orsay, and we were the first to measure spectra with resolved comb lines over the full span of the combs. Ironically, I received my first dedicated funding in France for this project in 2008.

Was it during this period that you considered moving to Germany?
I realised that the working conditions and the scientific environment at the Max Planck Institute for Quantum Optics were exceptional. At the end of my sabbatical, Theodor Hänsch offered me a position at the MPQ and I was very excited about the opportunity. There was a transition period where the CNRS allowed me to go back and forth, followed by a secondment from the CNRS. I moved to Garching full-time in 2011. This has certainly greatly evolved my approach to research, as it is unique to get to know two very different institutions such as the CNRS and the Max Planck Society so closely. This has made me think a lot about how I organise myself and what I prioritise.

This opened up a very stimulating period for your research activities.
Yes, it was an incredible time, with many directions to explore and abundant resources. Frequency comb interferometry turned out to be a great platform for exploring new insights. Initially there were only a few groups involved in this research, but there was intense competition. Now the community has grown, with more than two hundred groups contributing.

What were some of your most significant scientific results during this time?
It all started out of curiosity. I had noticed that by using two frequency combs with slightly different frequencies, the time delay between pulses in a pulse pair, one from each comb generator, would increase from pulse pair to pulse pair. This mimicked the effect of a scanning Michelson interferometer, where you send a pulse train while scanning one of the two arms. So it was obvious to me that you could do Fourier transform spectroscopy with such a system. Initially, I saw the main advantages of the dual comb interferometer as being the absence of moving parts and the ability to scan the delay between pulses much faster than with a mechanical interferometer. So that was the aim of our first demonstrations. Once we had the comb sources, it produced results incredibly quickly. However, we recognised that the frequency comb sources we needed weren't exactly the same as those needed for metrology. We had to develop sources that emitted in regions of interest for molecular spectroscopy, particularly in the mid-infrared, because no sources were available. We then became involved in the development of frequency comb sources in this spectral region. We also realised that the methods for measuring interference in dual comb spectroscopy required long coherence times between the two combs. Fast feedback loops are required. There was a lot of groundwork to be done to make the technique efficient, and after the first convincing proofs of principle, it took years to explore different variants that would allow high quality spectra to be obtained, especially in the mid-infrared and, more recently, in the near-ultraviolet

What were your main scientific projects?
I had originally planned to work on linear absorption spectroscopy, where the spectrum of small molecules is sampled by the narrow lines of the comb. When the combs are stabilised and the dual-comb

spectrometer resolves the comb lines, the frequency scale becomes self-calibrated and the signature of the spectrometer, which we call the instrumental line shape, becomes negligible compared to the molecular profiles. I thought it would be exciting to explore this potential. Then other insights followed in quick succession: because the laser sources we used emit ultrashort pulses, we can exploit nonlinear phenomena at the sample, and we played with several schemes using two-photon excitation or coherent Raman effects. With two-photon excitation, we were able to largely cancel out the Doppler broadening of the lines. In dual-comb spectroscopy, as in other techniques of Fourier spectroscopy, all spectral elements are recorded on a single detector. Another intriguing idea was to replace the detector with a matrix of detectors. We could then perform hyperspectral imaging and even digital holography.

You were recently appointed scientific director at the Max Born Institute in Berlin.

Yes, and I currently spend a lot of time commuting between Munich and Berlin because the new laboratories in Berlin are not yet ready. I now have exceptional resources to carry out my research, with ample space for state-of-the-art laboratories, positions for collaborators and generous funds for equipment and consumables. This is extremely exciting and, in the meantime, creates some new challenges: I have always spent a lot of time in the lab; my schedule was organised to spend every afternoon with the students in the lab, and I will need to organise myself to maintain a strong involvement in the lab.

Have you developed international collaborations?

Over the years, our work has benefited greatly from collaborations with specialists all over the world. For example, in our work on integrated optics, we have had fruitful collaborations with Jelena Vučković's group at Stanford, Kerry Vahala at Caltech, Alex Gaeta and Michal Lipson at Columbia, Bart Kuyken at Ghent University and Marko Lončar at Harvard. I have also kept in touch with French scientists and, just to give an example, we have interesting ongoing work with my brilliant former post-doc, Lucas Deniel, who is now a "maître de conferences" in Lannion.

What scientific challenges do you want to address in the framework of your new position?

There is nothing I love more than exploring new insights and ideas, setting up new experiments and exploiting the interplay between fundamental physics and photonics technology. I love the intellectual rollercoaster ride that is the uncertainty in the early stages of an experiment, when we gradually discover all the problems to be solved and oscillate between doubt, excitement, confusion and hope. This guides my endeavours. In each new project I try to add ingredients that are new to me, so that I am out of my comfort zone.

I have been surprised to find that frequency combs and dual-comb interferometry have been a rich enough platform to continually fuel new ideas, and I now feel that the most interesting ones are yet to come. Dual comb interferometry is the only broadband spectroscopy technique where the resolution depends only on time. This is fundamentally different from all spectrometers where the resolution depends on length. I realised this only some years ago, and the consequences have not yet been exploited. For me, this opens up new questions such as: Can we bridge the gap between broadband spectroscopy and frequency metrology? Can we perform frequency metrology over a wide spectral band? What are the accuracy limits of these techniques? Can we contribute to fundamental physics tests? Can we search for new physics by pushing the limits of precise laser spectroscopy of simple molecules? We are currently developing Doppler-free dual-comb spectroscopy and ultraviolet dual-comb spectroscopy to answer these questions. Another consequence is more relevant to applied physics: our instruments can be very compact. But how compact can they be? Can we put high-resolution spectrometers on a chip? More generally, what other interferometric techniques would benefit from a dual-comb system?

Photonics in Germany

Germany has established itself as a global leader in photonics, excelling in optical and laser technologies. This article examines the country's photonics industry, which accounted for €51.7 billion in 2023 and is essential to sectors such as healthcare, Industry 4.0 and, more recently, quantum technologies. Key contributors include companies such as ZEISS, TRUMPF and hundreds of SMEs, supported by robust educational institutions and research organizations such as the Fraunhofer Institutes. Government initiatives like "Photonik Forschung Deutschland" and the Research Program "Quantensysteme" have ensured continuous innovation. Emerging trends in quantum systems, laser fusion and ultrafast lasers further secure Germany's position at the forefront of global photonics advances.

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History of photonics in Germany

The history of optics and photonics in Germany dates back to the early 19th century, when pioneers like Joseph von Fraunhofer, a physicist and optician, laid the foundation for modern optical technology. Fraunhofer's advancements in spectroscopy and precision optics, including the invention of the diffraction grating, established Germany as a leader in optical research. In the late 19th and early 20th centuries, German companies like Carl Zeiss, founded in 1846, revolutionized optical instruments, particularly for scientific and medical applications. Zeiss's collaboration with Ernst Abbe and Otto Schott resulted in groundbreaking innovations in lens design and glass production.

After World War II, Germany's optics and photonics sectors experienced rapid growth, driven by advancements in industrial applications and scientific research. Research institutes like the Max Planck Institutes and the Fraunhofer Society became world leaders, fostering strong collaborations between academic research and industrial development. A key focus was laser technology, which became integral to the country's industrial and scientific progress. German companies such as Atlas Laser, Lambda Physics, TUI Laser, Rofin-Sinar - these and a number of others acquired by Coherent - and the family-owned machine manufacturer TRUMPF became pioneers in laser technologies, developing cutting-edge solutions for precision manufacturing, medical devices and scientific instrumentation. TRUMPF, in particular, gained prominence for its high-performance industrial lasers, which revolutionized manufacturing processes. This emphasis on laser innovation propelled Germany to the forefront of the global photonics industry.

German photonics market: current status and growth

Germany continues to lead Europe in photonics production, contributing to 39% of the continent's total photonics output (Fig. 1). Within Europe, Germany's photonics industry accounted for €51.7 billion in 2023, representing significant growth from €40.8 billion before the pandemic in 2019.

This industry is essential for the German economy, contributing 3% of Europe's total manufacturing output and employing more than 188,500 people across over 1,000 companies. These companies, ranging from large corporations like ZEISS and TRUMPF to dynamic SMEs, forming the backbone of the country's technological prowess in photonics.

Key industry segments in german photonics

Germany's photonics industry spans numerous sectors, but some key areas dominate in terms of both innovation and production (Fig. 2). According to the most recent market reports,

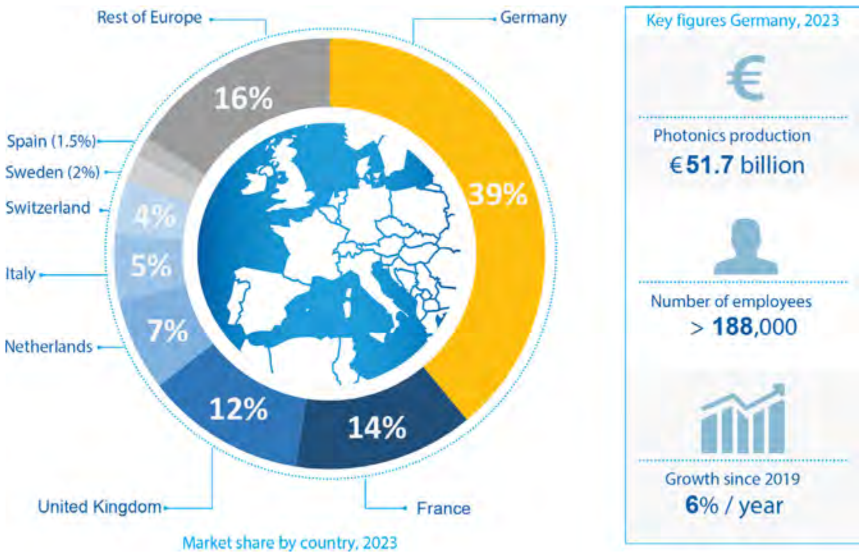

Figure 1. Germany in the European photonics market (Source: TEMATYS/ SPECTARIS)

components and materials, smart factories/Industry 4.0 and healthcare are particularly strong segments.

Components and Materials: Germany plays a crucial role in the development and production of high-performance photonic components and materials. These include optical lenses, lasers, fiber optics, and photonics integrated circuits (PICs). German companies are at the forefront of precision optical components for industrial, medical, and scientific applications. Additionally, advanced materials such as semiconductors and specialized glass used in photonic applications are areas where Germany excels.

Photonics for Industry 4.0: Germany leads the global market in industrial photonics, with a 38% share of the world's photonics technologies for manufacturing. This includes laser-based precision systems used in production, optical metrology, and machine vision technologies, which are essential for smart factories and automated processes in the context of Industry 4.0.

Healthcare and Biophotonics: In the healthcare segment, Germany holds a 21% share of the global photonics market. Key innovations include biophotonics, which covers diagnostic equipment like imaging systems and laser surgery tools. Companies such as Carl Zeiss Meditec and Karl Storz are global leaders in this field, producing cutting-edge medical devices and systems.

The role of quantum systems in Photonics

A crucial aspect of Germany's leadership in photonics is its integration with quantum systems, a joint research initiative that combines quantum technologies and photonics to harness their synergies. The "Forschungsprogramm Quantensysteme" (Fig. 3), launched by the Federal Ministry of Education and Research BMBF, strategically •••

Figure 2. Sales of German photonics by product segments (Source: TEMATAYS/ SPECTARIS)

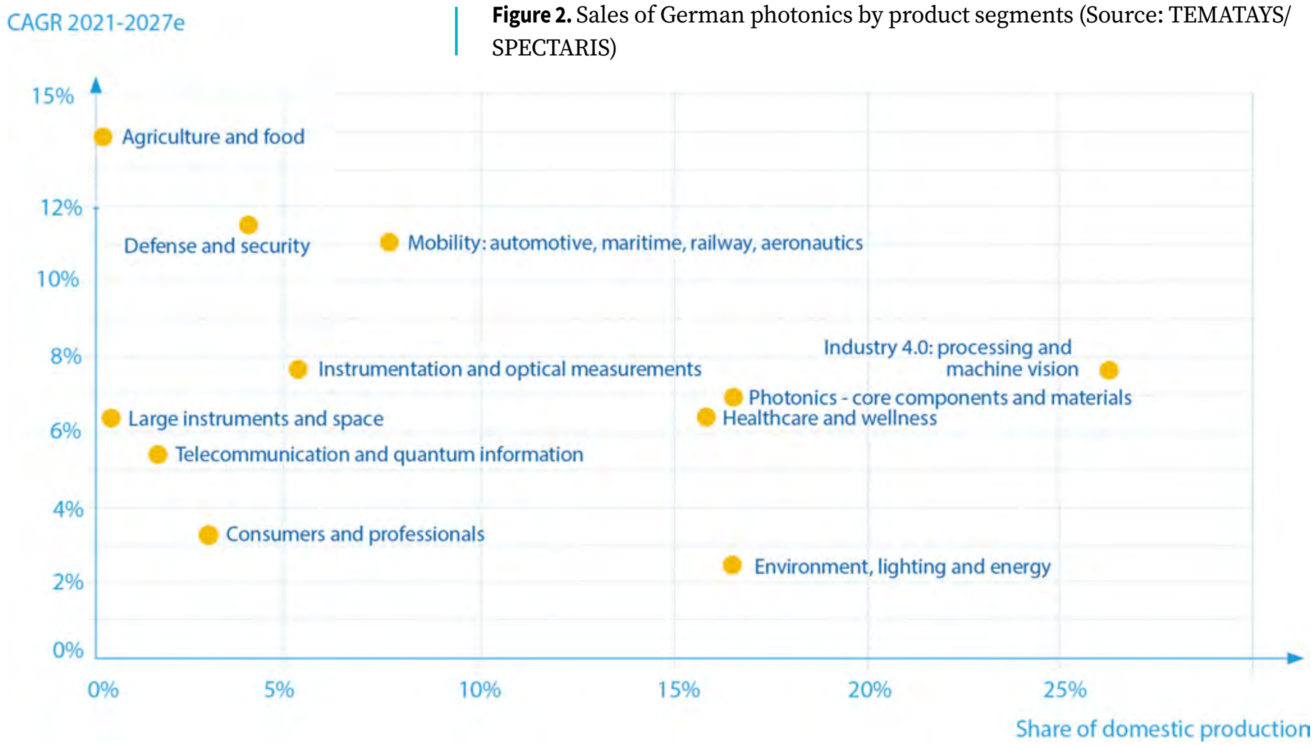

Figure 4. Germany's Quantum Systems Research Program.

unites these two fields to propel Germany to the forefront of quantum innovation.

Quantum systems utilize quantum mechanics' principles, such as superposition and entanglement, to create new technologies like quantum computers, quantum sensors, and quantum communication systems. Photonics is indispensable in this initiative, as it provides the foundational technology necessary for many quantum applications, such as photon-based qubits in quantum computing and quantum-enhanced optical sensors.

The goal of the quantum systems program is to make Germany a global leader in quantum computing and quantum sensing by 2030. The program fosters technological innovation across a range of industries, including healthcare, telecommunications, and manufacturing, where precise measurements, secure communications, and advanced computational capabilities are becoming increasingly essential.

Photonics acts as a critical enabler in these advancements, particularly in the development of quantum-enhanced imaging, sensors, and integrated photonic circuits. Through this joint program, Germany aims to unlock the potential of quantum technologies while expanding the applications of photonics in real-world scenarios, leading to significant technological breakthroughs.

Educational framework and research ecosystem

Germany's photonics excellence is supported by a robust education and research infrastructure. Universities such as RWTH Aachen, the Friedrich-Schiller University Jena, and the Karlsruhe Institute of Technology (KIT) and more than a dozen other educational institutions offer specialized programs in optics and photonics. These institutions collaborate with Germany's renowned Fraunhofer Institutes and the Max Planck School of Photonics (MPSP), ensuring that research and industry are closely linked.

Max Planck Institutes are focused on fundamental photonic research laying the foundation for an continues flow of discovery and inventions in photonics and quantum physics. The Nobel prize winners Theodor Hänsch and Stefan Hell are evidence for the highest standards of photonic research in the Max Planck Institutes.

Research institutes like the Fraunhofer Institute for Applied Optics and Precision Engineering IOF in Jena, the Fraunhofer Heinrich Hertz Institute HHI in Berlin and the Fraunhofer Institute for Laser Technologies ILT in Aachen are at the forefront of technological advancements, working closely with industry to translate research into commercial products. These collaborations foster innovation in emerging fields such as quantum optics, high-power lasers and biophotonics.

Government Support and Funding

The German government plays an active role in supporting the photonics industry through funding initiatives and innovation clusters. The photonics research program "Photonik Forschung Deutschland", launched by the Federal Ministry of Education and Research BMBF, has provided significant financial resource to support innovation in photonics for many years, focusing on areas such as healthcare, optical communication, and industrial technologies. Since 2017 the photonics program has been an essential part of the research program Quantum Systems.

Additionally, European programs like Horizon 2020 and Horizon Europe fund collaborative research projects in photonics, with Germany being a major beneficiary. Public and private investments in R&D are crucial for sustaining Germany's competitive edge in photonics and ensuring its global leadership in this key technology.

Photonics associations and quantum clusters in Germany

Germany's photonics sector is supported by a dense network of associations, innovation clusters, and research hubs that bring together industry, academia, and government institutions.

SPECTARIS
German Industry Association for Optics, Photonics, Analytical and Medical Technologies

SPECTARIS, the German Industry Association for Optics, Photonics, Analytical and Medical Technologies, is the representative of the German photonics industry. The photonics membership consists of large companies like ZEISS, Jenoptik and SCHOTT, but also of more than 100 SMEs that are often world-market leader in their specific photonic niche. Permanent topics of SPECTARIS are the support of its corporate members in the areas of international trade, governmental regulations, market research and attraction of young talents. Also outreach activities belong to the portfolio like the publishing the books "Photonics Infographics" to get students, politicians and the general public interested in photonics.

PHOTONICS GERMANY

Figure 5. Logo of the German photonics alliance

At the regional level, there are a number of vibrant photonics clusters such as OptecBB in Berlin and Optonet in Jena, as well as Bayern Photonics and Photonics BW in the southern federal states. They are all part of the umbrella organization OptecNet Deutschland, which represents some 600 companies, universities and other photonics stakeholders, making it the largest photonics network in Germany.

In 2020, SPECTARIS and OptecNet Deutschland have started the alliance PHOTONICS GERMANY (Fig. 4) to bundle their large membership and expertise for an even stronger voice of photonics in the German economic discourse.

Future trends in german photonics

The future of photonics in Germany is bright, driven by key emerging trends:

- Quantum Systems: As quantum technologies evolve, Germany is heavily invested in developing photonics for applications in secure communications, quantum computing and quantum sensing.

  A vibrant network of stakeholders in quantum technologies is growing with excellent interlinked regional clusters, and a growing number of startups are commercializing the latest inventions of academic research.
- New generation of powerful ultrafast laser systems: So far, ultrafast laser systems are limited in power. The goal of a large consortium of Fraunhofer institutes and collaborating German companies under the name CAPS is on the way to develop and industrialize new systems in the multi-kilowatt range offering a wide range of new applications in industry and research.
- Research on laser fusion has gained momentum in Germany, following fundamental advances in international basic research. New initiatives have been launched to develop and establish the necessary infrastructure, with particular emphasis on high-power lasers and precision optical components.
- Photonics in Agriculture and Food: A rapidly growing segment, photonics in agriculture is becoming more important for ensuring food security and enhancing sustainable farming practices. Although small (around 1% of the total market), this segment is growing at an impressive 11.8% CAGR. German specialists in optical sensors like the Nynomic corporation and dozens more German photonics companies benefit from this trend.

Conclusion

Germany's leadership in the global photonics industry is built on a strong foundation of research, innovation, industrial expertise and a unique network of all those photonics stakeholders. The country's photonics sector is expected to continue its growth trajectory, driven by advances in healthcare, Industry 4.0 technologies, and quantum systems. With a well-developed educational system, significant government support, and a dynamic industry (see Fig.5) , Germany is poised to remain a global powerhouse in photonics for years to come.

Figure 6. New headquarters of German photonics flagship ZEISS under construction in Jena (Source: ZEISS)

Telescope Farms in Chile and the History of the Hacienda of Stars

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The popularization and exceptional improvement of amateur astronomy equipment has democratized astrophotography, making it possible to achieve nearly professional-quality shots. Some enthusiasts even install internet-controlled telescopes under the world's most beautiful skies, such as those in Chile.

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Chile boasts one of the world's most stunning skies, as evidenced by the numerous scientific observatories, such as Cerro Tololo, La Silla, Gemini South, the VLT at Cerro Paranal, and the 39-meter ELT currently under construction at Cerro Amazones. This concentration of large telescopes is due to Chile's unique geography: the proximity of the Pacific Ocean and the Andes mountain range results in very low turbulence at high altitudes, above the cloud layer.
The explosion in the number of remotely controlled amateur telescopes in recent years has been enabled by the internet and increasing automation of telescopes accessible to amateurs. While some astrophotographers invest significantly (some even owning two observatories, one for each hemisphere!), a visit to the Astronomy Picture of the Day website reveals stunning images of galaxies and nebulae that rival professional work in aesthetics.
It is now possible to own fully automated instruments at reasonable costs. Many enthusiasts have embarked on the adventure of remote imaging. However, finding a suitable location for the equipment, with necessary prerequisites like an internet connection, security, and technical support for adjustments or repairs, is still required. Hence, numerous "telescope farms" have been established, particularly in Chile.
Nadine Roux and Raymond Christian are among the pioneers, with their installation in the Andes dating back to the early 2000s. Initially, their idea was to welcome visitors to discover the beauty of the Chilean sky, but the installation of remotely controlled telescopes began in 2017. Here's a look back at this life adventure!

Figure 1. Nadine Roux and Raymond Christian in front of some telescopes of the Hacienda of Stars.

Figure 2. The lodge perched at an altitude of 1800 meters

Arriving in Chile

The meeting between Nadine Roux and Raymond Christian sparked a desire for change, a return to a simpler life closer to nature. In 2000, they packed their bags for a long journey in search of the best place for this new life. The journey began in Texas, where they bought a van, which became their mobile home.

First, they explored Mexico and Central America, starting a project to import Native American crafts and trade gemstones such as Mexican opals, amethysts, aquamarines, and Colombian emeralds. They established a successful import and sales business in France, gaining a good reputation among jewelers in southwestern France.

After deciding to leave their business, they set off for Latin America at 53, visiting Mexico and Costa Rica. Their journey continued along the Pan American Highway, encountering challenges like flat tires, unsettling encounters, and finding themselves in a dump at night. But these were outweighed by magnificent landscapes and interesting meetings.

After a brief return to France to replenish funds, they resumed their quest in Nicaragua and Guatemala, taking various jobs like grape picking and apple harvesting. Their search led them through Peru and Machu Picchu, finally arriving in Chile in 2002. They found the country different, with a European feel, • • •

Figure 3. The setup of a Dobsonian telescope for visual observation

less poverty, and warm hospitality. The marked four seasons and the beauty of the Chilean sky convinced them to pursue their astronomy project here. They needed to find the ideal spot.
Using their van, they explored every nook from Arica. San Pedro de Atacama didn't appeal due to its tourism. After visiting La Serena, a charming coastal town, they headed to the Andes for clearer skies. Eventually, they found a spot by the Rio Ponio near Monte Patria. A local shepherd woman suggested a remote family-owned land unused by its owners. After some discussions and a return trip to France, they secured ten hectares of land in 2003.

Building the Hacienda of Stars

Upon returning to Chile with tents and backpacks, they visited the remote site with the shepherd's son. Finding a water source under thorny bushes, they realized the place's potential. They bought a 4x4, rented a bulldozer to create an access road, and started building their retreat, living in a tent and dining under pear trees. By winter 2004, they completed a pavilion with two bedrooms, bathrooms, and a kitchen.
Their first guest was a French amateur astronomer from Santiago, accompanied by his wife and three-year-old daughter. They built the first observatory for a 14-inch telescope without outside help, as no company wanted to go that far up the mountain. Today, the Hacienda of Stars features four pavilions for astronomers or nature lovers, offering limited stays for up to 8 people to maintain tranquility.
The Hacienda of Stars Today: For those unable to visit Chile, Nadine and Raymond built shelters for a small number of robotic telescopes, allowing remote observation of the stunning Chilean sky. Over the years, the Hacienda of Stars has welcomed enthusiasts despite the pandemic, modernization, and climate change. Initially enjoying 320 clear nights a year, now it's about 280 due to increasing cloud cover.

Setting up a Dobsonian Telescope for Visual Observation

The robotic telescope park expanded post-pandemic in 2021 with new installations. Despite changes, the Hacienda remains a haven for Nadine and Raymond, living semi-self-sufficiently with a vegetable garden, chicken coop, fruit trees, and close ties with local shepherds. They've ensured top-notch internet access for remote users, recognizing Chile's sky remains among the world's finest for astronomy.

Conclusion

Amateur and professional astronomy has surged, with remote telescopes proliferating in Chile at sites like Deepskychile, Obstech eL Sauce, and eL Pangue, near the Hacienda of Stars. Despite initial establishment challenges, they value friendship over business, with connections to renowned astro-photographers and clubs.
While initially remote, the Rio Hurtado area now hosts several telescope farms, leading to some light pollution. Given the choice, they might prefer higher, less polluted areas like Paranal or La Silla. Still, the Hacienda remains relatively protected, maintaining its appeal with 260 clear nights annually.
Despite challenges like light pollution and Starlink satellites, Chile remains a premier astronomy destination. Raymond remains devoted to the stars, proclaiming, "Love the stars, love the planet, the Earth is our homeland, astronomy is our religion!"

Copyright for photos of the Hacienda of Stars: Nadine Roux and Raymond Christian.

Figure 4. Sh2-308 (emission nebula and an HII region). Mosaic of 2 images with a total exposure time of 40 hours for each image: 20 hours on the Ha layer and 20 hours on the OIII layer. Newtonian telescope with a 520mm diameter, F/D=3.5, ZWO6200 camera, sampling at 0.4 arc seconds per pixel. Image captured from the Hacienda des Étoiles (copyright: Team Janus: Laurent Bernasconi and Michel Meunier)

CHARLES TOWNES AND INFRARED HETERODYNE INTERFEROMETRY

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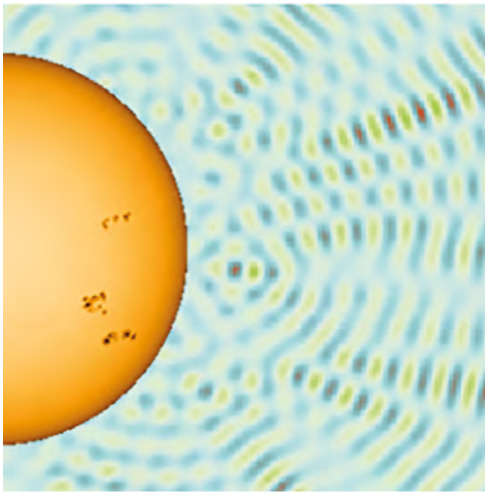

Nobel laureate Charles Hard Townes is well known for his work in quantum electronics, which led to the invention of the maser and lasers. He was also a notable figure in astrophysics and astronomy, particularly recognized as the architect of the first high-resolution optical stellar interferometer.

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Is there a scientific life after winning the Nobel Prize in Physics? For American physicist Charles Hard Townes (1915-2015), the answer is a resounding yes. Townes, who was awarded the prestigious prize in 1964 for his pioneering work in quantum electronics that led to the development of maser and laser technologies, later made significant contributions in a completely different field: astrophysics and infrared astronomy. In 1969, Townes and his collaborators detected ammonia (NH3) and water (H_2O) molecules in interstellar space. Then, in the 1990s, they discovered fast-orbiting gas clouds around a massive object, now identified as Sagittarius A*, the supermassive black hole at the center of our Milky Way. In 2009, Townes' team published the results of 15 years of observations of the red supergiant star Betelgeuse, revealing that its diameter had unexpectedly shrunk [1]. The star's sudden fluctuations in brightness—visible to the naked eye during the winter of 2019-2020—generated headlines and sparked false concerns about an imminent supernova [2]. This long-term study was made possible through the use of a heterodyne detection interferometer with extremely high angular resolution, a technical marvel combining starlight and laser light, and a true scientific and engineering feat.

Measuring the diameter of distant stars

The apparent angular diameter of stars—the tiny fraction of the celestial vault they occupy—is incredibly small. For instance, the angular diameter of Betelgeuse, one of the closest largest star, is estimated at around 45 milliarcseconds (mas), which is comparable to the angle at which a €1 coin would appear if placed about 100 km away—a challenging feat even for today's telescopes. As both amateur and professional astronomers know, most modern optical instruments cannot resolve the surface of stars. This is ●●●

due to two main factors: atmospheric turbulence and optical diffraction. While the effects of atmospheric turbulence can sometimes be corrected (using adaptive optics), reduced (through observation at longer wavelengths), or avoided altogether (with space-based telescopes), optical diffraction remains a fundamental limitation. Diffraction restricts the theoretical angular resolution to approximately 1.22 λ/D, where λ is the observation wavelength and D is the diameter of the telescope's aperture. In practical terms, a telescope with a diameter of several tens of meters is required to measure Betelgeuse's angular diameter, while a telescope on the scale of hundreds of meters would be needed to resolve details on its surface.

Aperture synthesis

An alternative to direct imaging, first proposed by Fizeau in 1864 and demonstrated by Michelson and Pease in 1920, is indirect imaging through aperture synthesis, more commonly known as interferometry in the optical domain. To fully appreciate the revolutionary originality of this counterintuitive approach, it's essential to revisit the fundamentals: a star is an extended source composed of many independent points, each emitting its own wave. However, because the star appears under an extremely small angular diameter, these waves interfere constructively (by symmetry), forming a common wavefront – a quasi-plane wavefront - near the observer's line of sight. Despite this, the star's large and incoherent surface is revealed through random spatial variations in this quasi-wavefront. The characteristic scale of these variations depends on the star's angular size (Figure 2). The smaller the apparent diameter of the star, the larger this characteristic distance becomes, as we approach the case of a perfect point source, which behaves like a true plane wave. The van Cittert–Zernike theorem formalizes this principle, stating that, under certain conditions commonly met in astronomy, the inverse Fourier transform of the spatial coherence function corresponds to the intensity distribution of the source—in practical terms, the image of the source.

How can the spatial coherence function be measured? Conceptually, the solution is straightforward: it requires a differential approach. Using two telescopes, for instance, one remains fixed as a reference while the other 'samples' the wavefront at varying distances from the first. Ideally, this sampling should occur in a plane orthogonal to the observation plane. However, due to the inclination of the observed star relative to the local vertical and the Earth's rotation, this is generally not feasible. Geometric corrections, however, allow for these effects to be accounted for—or even exploited.

Figure 1. Charles Townes at ISI in 2008, cleaning one of the siderostats with a jet of compressed carbon dioxide. [Cristina Ryan]

What is the physical observable in this case? Generally, it is the degree of correlation between the temporal fluctuations in the amplitude (or intensity) of the electric fields detected by the telescopes. At first glance, this seems rather simple to retrieve: simply measure these fluctuations and then calculate the correlation mathematically, repeating the process for different relative positions of the telescopes. However, in practice, measuring these fluctuations is challenging because they occur over time scales that are too short to be captured by electronic systems. There are a few exceptions to this limitation, such as relatively low-frequency radio waves (up to a few tens of GHz), which can be sampled, processed, transmitted, and correlated in real time using fast electronic systems. This advantage is extensively utilized in radio astronomy, where aperture synthesis is the standard imaging technique.

From radio astronomy to heterodyne interferometry

Charles Townes was no stranger to radio astronomy. As early as 1956, he had used his first tunable maser as an amplifier for radio astronomy. In fact, most of the technological building blocks of radio astronomy have optical counterparts—or almost all of them—and it was this challenge that Townes would overcome. A key method in radio astronomy is heterodyne detection, which reduces the frequency of the electromagnetic carrier wave while preserving the information carried by the field envelope. This frequency reduction is crucial for enabling electronic systems to amplify, detect, and correlate the signals. Technically, heterodyne detection relies on mixing the incoming signal with a reference wave known as the "local oscillator." The very principle of aperture synthesis assumes that all heterodyne detections across the radio telescope array use the same ultra-stable local oscillator. In practice, this requires a clock based on a frequency reference—often a hydrogen maser. This was another intersection with Townes' earlier work, particularly since the optical equivalent of a radiofrequency local oscillator is a laser, of which Townes was also the co-inventor!

Shortly after receiving the Nobel Prize, Townes decided to step down from his administrative role and return to fundamental research. He joined the Department of Physics at the University of California, Berkeley, and, with his students, began adapting radio interferometry techniques to optical wavelengths. Instead of using electronic oscillators, they employed CO_2 lasers with a wavelength of 10.6 µm. This choice was driven by both technical and scientific reasons: these lasers were readily available, the effects of atmospheric turbulence were reduced, and there was good atmospheric transparency between 9 and 11 µm. Additionally, this wavelength allowed better observation through interstellar dust clouds.

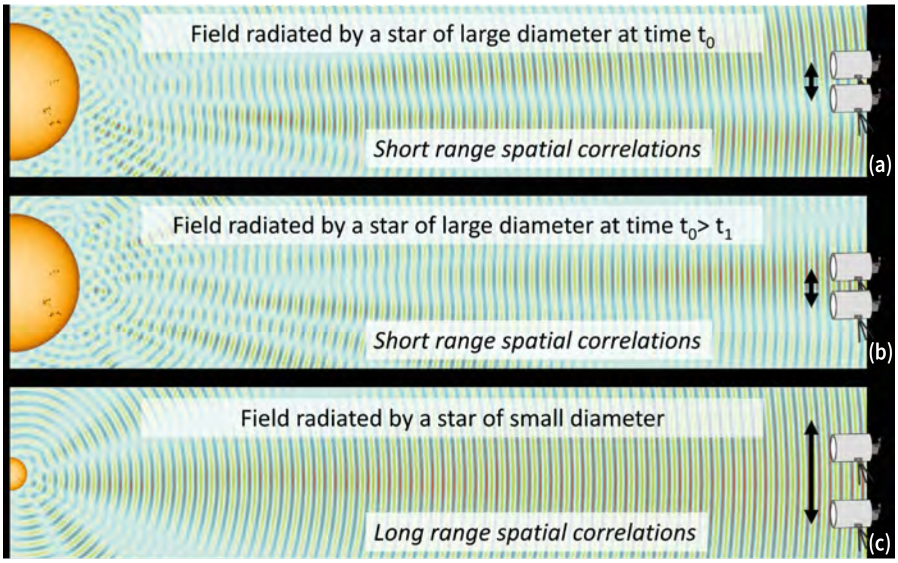

Figure 2. Numerical simulations illustrating the van Cittert-Zernike theorem and the principle of aperture synthesis. An extended incoherent source generates, at great propagation distances, wavefronts that exhibit random variations over time (Figure (a) and Figure (b)). However, the scale of the typical spatial variations, the coherence length, depends on the shape and angular dimension of the source (Figure (c)).

The Infrared Spatial Interferometer (ISI)

Following preliminary tests at the Kitt Peak National Observatory and a decade of technological development, the Infrared Spatial • • •

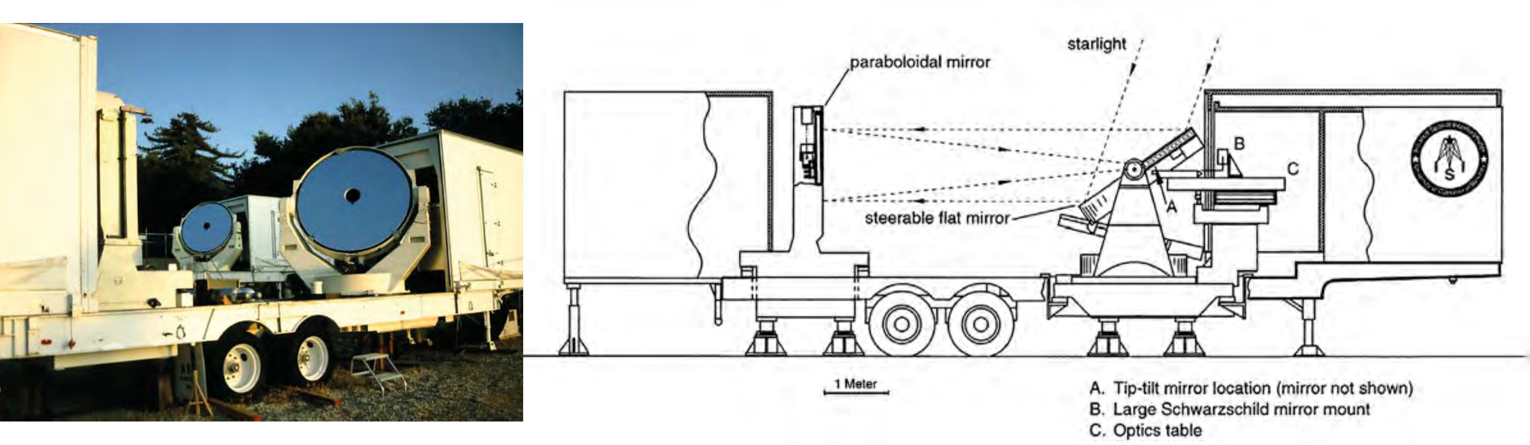

Figure 3. View and cross-section diagram of the mobile telescopes.

Interferometer (ISI) was completed in 1988 at Mount Wilson, California. The ISI is a marvel of ingenuity, combining mechanical, optical, and electronic engineering [3]. Despite its technological sophistication and complexity, users describe it as both robust and highly functional. The instrument consists of two, later expanded to three, 1.65-meter (65-inch) telescopes, which can be moved over distances of up to 85 meters. The telescopes utilize a Pfund-type optical configuration, an uncommon design that pairs a 2-meter adjustable flat mirror, known as a siderostat, with a 1.65-meter fixed parabolic mirror, operating at f/3.14. The siderostat is centrally perforated so that the parabolic mirror's focal point forms behind it, where an optical table is located (Figure 3). This compact architecture allows the telescope to be mounted on a standard semi-trailer, enabling it to be transported to different locations. At each site, the telescopes are secured on concrete pads through the trailer. The siderostat's orientation is computer-controlled, adjusting every second via an infrared camera to track the stellar target under observation. A second motorized mirror (tip-tilt) compensates for rapid directional fluctuations caused by atmospheric turbulence, making corrections several dozen times per second. To achieve this, a dichroic mirror separates the near-infrared light (used for tracking) from the mid-infrared light (used for measurements). Inside each telescope is a CO_2 laser, monochromatic and ultra-stable, tunable between 9 and 12 µm across various laser transitions. One of the cavity's end mirrors is mounted on a piezoelectric element, allowing precise tuning of the emission wavelength. A partially reflective mirror combines starlight and laser light, with their resulting interference beats detected by a fast (2.6 GHz) HgCdTe photodetector, cooled by liquid nitrogen.

The critical aspect of the ISI architecture is the wavelength and phase locking of the various CO_2 lasers. The technique chosen by Townes and his team is highly complex but remarkably effective. To give a sense of the system's sophistication, here is a brief and partial summary. The CO_2 lasers are intentionally set to operate at slightly different optical frequencies, with a 1 MHz difference between them. A portion of the 'slave' laser's beam is transmitted through free space to the 'master' CO_2 laser, where the 1 MHz beat frequency between the two is compared to a reference clock (a stabilized crystal oscillator). This comparison stabilizes the frequency and phase difference between the lasers by applying feedback to the piezoelectric mirror of the 'slave' laser. Simultaneously, the free-space optical paths are interferometrically stabilized to eliminate environmental factors from affecting the differential phase measurement. Now, imagine all of this operating between semi-trailers spaced tens of meters apart at an altitude of 1,742 meters—it's a remarkable technical challenge.

The RF signals generated by the HgCdTe detectors are dynamically resynchronized using coaxial cables of varying lengths, adjusted via an electromechanical switch, and then combined in the equivalent of a 50/50 splitter. The frequency difference between the RF signals produces a 1 MHz beat signal, whose amplitude is proportional to the product of the RF signals, and thus to the degree of correlation. This correlation signal is then demodulated, calibrated, and digitized. The sophistication of the detection system goes even further. As the Earth's rotation causes a varying rate difference between the telescopes, this is calculated and compensated for by slightly adjusting the frequency of the 'slave' laser, ensuring that the correlation signal maintains a constant amplitude modulation (100 Hz), regardless of the target's position in the sky. All of this equipment is controlled by a network of computers, including several real-time systems and Intel

486 processors – because, yes, indeed, this impressive piece of engineering dates back to the 1980s and 1990s!

The legacy of ISI – Berkeley's ISI remained the only high-angular-resolution interferometer operating in the mid-infrared for nearly two decades. Its innovative technology enabled the study of celestial objects with an angular resolution that, for a long time, was unmatched in this wavelength range (3 mas at 11 µm). However, over time, heterodyne interferometry has been largely replaced by direct optical recombination interferometry due to the latter's much higher sensitivity. The primary limitation of heterodyne detection is its extremely narrow spectral bandwidth (~2 nm), which significantly restricts the usable light flux and, consequently, the faintest objects that can be observed. Despite this, the ISI highlighted several technical and practical advantages of heterodyne detection: the lack of need for optical path stabilization on the stellar light path, the ability to accumulate data across multiple observation sessions, and the reliability of its data calibration. Perhaps most importantly, the ISI demonstrated that the modularity of the heterodyne approach is compatible with large-scale expansion. This concept is now a key focus of research in optical interferometry, where the goal is to massively parallelize detection channels to increase spectral coverage and, ultimately, the sensitivity of heterodyne detection. Emerging technologies like integrated optics and frequency combs hold the potential to overcome this limitation and could lead to a revival of heterodyne interferometry.

HETERODYNE INFRARED INTERFEROMETRY ON THE FRENCH RIVIERA

In 1974, Jean Gay (1937-2024) joined the nascent Centre for Research in Geodynamics and Astrometry (CERGA, now the Côte d'Azur Observatory) with a proposal for a heterodyne infrared interferometer, abbreviated as SOIRDETE, which stands for Synthèse d'Ouverture en Infra Rouge par Détection Hétérodyne (Infrared Aperture Synthesis by Heterodyne Detection). After extensive development efforts, which included constructing a building, developing two twin telescopes (2x 1 m), and forming a team, the project was ultimately not pursued. Jean Gay then became part of the ISI team, where he spent a year. In the early 2000s, SOIRDETE was revitalized and renamed C2PU (Centre Pédagogique Planète Univers, Planet-Universe Educational Center). It has since evolved into an active training and research center that has played a crucial role in the revival of intensity interferometry [4].

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APPLICATION OF RAMAN MICRO-SPECTROSCOPY FOR QUANTITATIVE MICROPLASTICS ANALYSIS

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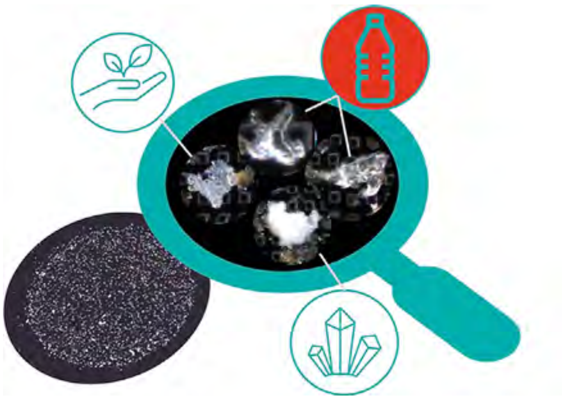

Microplastics pollution poses a significant environmental threat, highlighting the need for effective quantification methods across various matrices. This article provides an overview of measuring microplastic concentrations and emphasizes the importance of Raman micro-spectroscopy. Capable of detecting microplastics down to 1 micron, this technique targets the smallest particles that present the highest risk.

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Microplastics are synthetic polymer particles insoluble in water and measuring between 1 µm and 5 mm. They are ubiquitous, found in drinking water, food, and the atmosphere. Concerns regarding their persistence in the environment and potential health risks are increasing. Studies indicate that microplastics may accumulate in organs, trigger inflammatory responses, and cause cellular damage [1].

Measuring microplastic concentrations in various matrices is crucial for assessing pollution pathways, human exposure risks, and ecological impacts. Microplastic concentrations can be measured using two primary methods: mass-based and particle-number-based approaches [2]. Mass-based methods determine the total mass of plastic particles and differentiate various polymer types, often employing thermoanalytical techniques such as pyrolysis-gas chromatography/mass spectrometry (Py-GC-MS) and thermal desorption gas chromatography-mass spectrometry (TED-GC-MS). In contrast, particle-number-based methods provide detailed characterization of individual particles, including their number, size, shape, and chemical composition. Understanding these characteristics is critical for toxicological assessments, as smaller and more numerous particles may exhibit increased toxicity.

Vibrational micro-spectroscopy is the reference method for particle-number-based microplastics analysis, as recommended by ISO standards (ISO 24187:2023, ISO 4484-2:2023, ISO/DIS 16094-2). Techniques such as Raman spectroscopy and Fourier-transform infrared spectroscopy (FTIR) yield information regarding chemical identity, particle • • •

COMPOUND SEMICONDUCTOR ANALYSIS WITH CORRELATIVE RAMAN IMAGING
STRESS, DOPING AND TOPOGRAPHIC VARIATION VISUALIZED

Semiconductors are the materials from which the engines of the information age are built, and their advancement is among the most vital endeavors in technology. Powerful characterization tools enable researchers to comprehensively characterize novel devices in this field.

The first step in their production generally involves crystal growth and sectioning into thin wafers. The wafers are then altered using methods such as doping to give them specific electronic properties. Access to the subtlest details of these chemical and structural modifications on the sub-micrometer scale is crucial in new device development and final product quality control.

Raman microscopy is a powerful tool for semiconductor research that can nondestructively acquire high-resolution, spatially-resolved information to determine the chemical composition of a sample, visualize component distribution, and characterize properties such as crystallinity, strain, stress or doping. This is particularly valuable for compound semiconductors, which often consist of multiple elements and complex structures.

The measurements below demonstrate the insight that correlative Raman imaging can provide to researchers investigating stress, doping and topographic variation in a large-area wafer measurement.

Figure 1. Oxford Instruments - WITec alpha300 Semiconductor Edition

TOPOGRAPHIC RAMAN IMAGING OF A SIC WAFER

To meet the challenge of maintaining nanoscale-precision across the surface of a 150 mm (6 inch) diameter Silicon Carbide (SiC) wafer, an Oxford Instruments WITec alpha300 Semiconductor Edition Raman system (Figure 1) was used. The microscope's extended-range scanning stage enables the inspection of up to 12 inch (300 mm) wafers and the acquisition of large-area Raman images.

Raman imaging revealed alterations in the doping-sensitive A1(LO)-mode at 960 rel. cm^{-1} of the Raman spectrum (Fig. 2A) for a region within the wafer (Fig. 2B). Compared to the bulk wafer area (red), this region contained a higher doping concentration (blue). The sensitivity of the system enabled the detection of minimal shifts of the E2(high) mode at 776 rel. cm^{-1}, which is sensitive to material stress and strain. In comparison to the overall wafer, more central regions were exposed to compressive stress while distal regions were subjected to relatively higher tensile stress (Fig. 2C). TrueSurface compensated for height variations within the sample and allowed the recording of the wafer's topography and warpage (Fig. 2D) simultaneously along with the Raman spectral information.

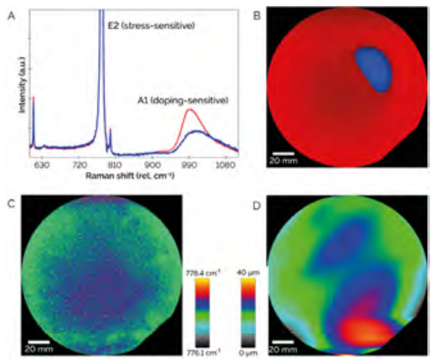

Figure 2. Raman imaging of a 150 mm SiC wafer. A: Characteristic Raman Spectra; B: Different doping concentration; C: Distribution of stress fields. D: Warpage of the SiC wafer with height variations of up to 40 µm.

SUMMARY

Researchers in semiconductor development rely on detailed, conclusive investigations such as these to achieve a comprehensive understanding of their materials and manufacturing processes. The WITec alpha300 line of Raman microscopes offer precise, versatile tools that can help accelerate their rate of advance. ●

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count, size, and shape. Notably, Raman spectroscopy can analyze microparticles down to 1 micron, making it invaluable for ecotoxicological studies and monitoring. This article gives a brief overview of the application of Raman spectroscopy in microplastics analysis.

PRINCIPLE OF RAMAN SPECTROSCOPY

Raman spectroscopy is a powerful analytical technique based on the scattering of light, which provides molecular and structural information about a sample. When laser light interacts with molecules, most of it is elastically scattered (Rayleigh scattering), but a small fraction undergoes inelastic scattering—this is known as Raman scattering. During Raman scattering, the energy of the photons is either increased or decreased due to interactions with the molecular vibrations, rotations, or other low-frequency modes of the sample. The difference in energy corresponds to specific vibrational modes of the molecules. Since each compound has a unique vibrational signature, Raman spectra are used as a fingerprint for the chemical identification of the particles.

TYPICAL WORKFLOW FOR MEASURING MICROPLASTICS CONCENTRATION

Prior to particles characterisation the sample preparation is performed aiming the efficient separation of the targeted microplastics particles from the sample matrix. Depending on matrix, different approaches can be applied such as density separation, chemical and/or enzymatic digestion and finally filtration. Nevertheless, after the final step of samples preparation, filter usually contains various particles, thus the chemical identification of each particle is the key for obtaining reliable results.

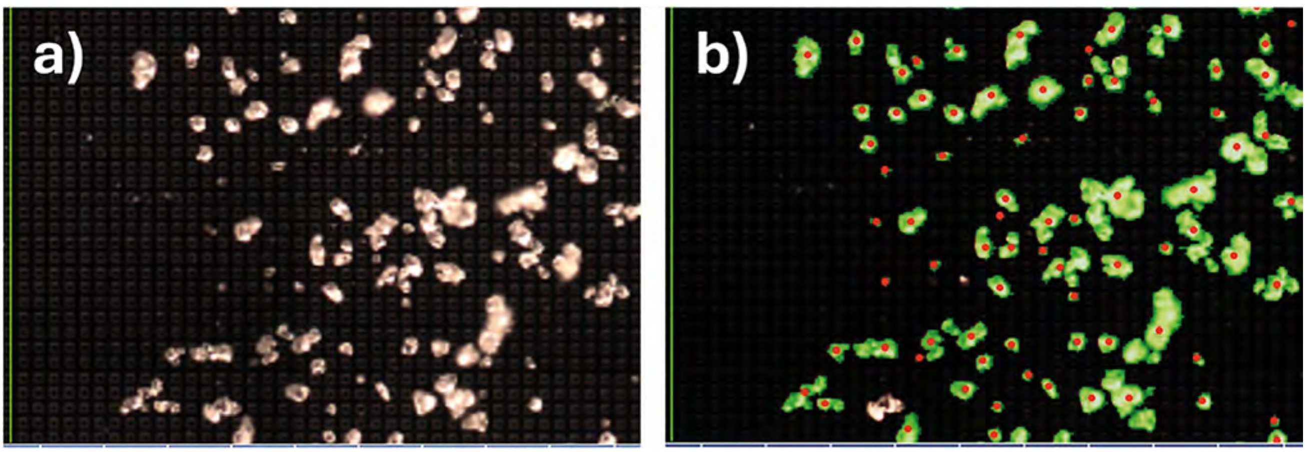
AUTOMATIZATION OF RAMAN ANALYSIS

There are two primary methods for performing automatic Raman analysis of particles on the filter. The first method involves Raman mapping, which entails point-by-point scanning of the filter surface. Although highly precise, enabling the characterization of particles even when agglomerated or overlapping, it is time-consuming. As a result, this technique is generally applied to a subset of the filter surface, relying on statistical subsampling [3].

The second approach focuses the laser beam directly on specific areas where particles are located, acquiring one spectrum per particle [4]. This method is widely adopted due to its efficiency, with commercial software available for particle localization, correlation with Raman analysis, and the measurement of particle geometrical parameters using optical microscopy images (Figure 1). However, this method requires sample preparation that enables automatic particle detection. Current algorithms depend on the optical contrast between the filter surface and the particles, making the choice of filter material and the optical microscope's illumination mode critical. For instance, silicon filters are ideal due to their flat, reflective surfaces and regular pore patterns. Particles deposited on such filters, when illuminated using dark-field mode (where the sample is illuminated from the sides by a hollow cone of light), appear bright against a dark background (Figure 1). Additionally, silicon exhibits a distinct Raman signal that does not overlap with polymer signals, simplifying data interpretation.

For spectral acquisition, several parameters must be optimized to balance the quality of spectra and the time required for analysis. Key variables include laser wavelength, laser power, exposure time, numerical aperture of the optical objective,

Figure 1. Optical image of Si filter with the particles in dark field illumination. b) Particles are located automatically on the optical image with Particle Finder ™ software. Green mask indicates the particles area, the red spot indicates where the laser will be sent to acquire the Raman spectrum of each particle



> Under optimized conditions, it is possible to analyze several thousand particles, including those smaller than 20 microns, within a few hours. This efficiency makes Raman spectroscopy an excellent tool for monitoring microplastic concentrations, particularly in matrices relevant to human exposure, such as drinking water, food, and air.

and autofocus settings. Depending on the complexity of the sample and the size of the target particles, these parameters should be adjusted to obtain spectra of sufficient quality for reliable chemical identification. For relatively large particles (> 5 µm) that have been efficiently separated from the sample matrix and do not exhibit fluorescence, analysis can be performed using a green laser and a low-NA objective, without the need for confocal mode or additional autofocus. In such cases, exposure times can be short (less than 1 second), and laser power can be increased to obtain a sufficient Raman response in a short period. To increase signal intensity, the system should offer flexibility in confocal settings, allowing the user to adjust the confocal pinhole size or fibre diameter in fibre-based optics. Under these conditions, rapid analysis of several thousand particles can be completed in a few hours, making Raman spectroscopy an excellent tool for fast monitoring of simple matrices, such as drinking water or food ingredients soluble in water, or matrices where microplastics can be efficiently separated.

In cases involving fluorescent matrices, which are common in biological or environmental samples, lasers with longer wavelengths (e.g., 785 nm) should be considered to minimize fluorescence, which can obscure Raman peaks. Given that Raman scattering intensity (I) decreases with the fourth power of the excitation wavelength (λ, $I \sim \lambda^{-4}$), higher laser power and longer exposure times are necessary to achieve a strong Raman signal. Longer acquisition times are also useful for reducing fluorescence and correctly identifying pigmented polymeric particles. Pigments often exhibit strong (pre)resonant Raman signals, and spectra collected with short acquisition times (around 1 s) may incorrectly be identified as pigment particles. Extending acquisition time can help capture the Raman signals of the polymers as well [2].

Spectral identification is a critical step in the analytical workflow [5]. A common approach is to compare the acquired spectra with a reference database. The sample spectrum is matched to the most similar entry in the database, often with a minimum similarity threshold applied. However, determining spectral similarity can be complex, and choosing an appropriate database is essential for accurate • • •

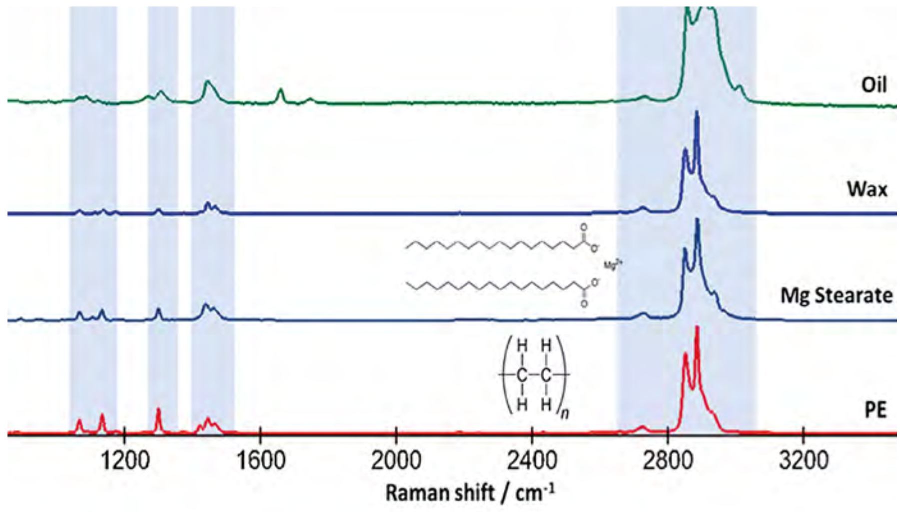


Figure 2. Raman spectra of a polymer (Polyethylene, PE) and other organic molecules (Salt of stearic acid, wax, oil) containing long C-H chain. It is important to include such spectra in the library dedicated to microplastics analysis to avoid the false positive identification.

identification. At a minimum, the database should contain spectra of various synthetic polymers (plastics) as well as other non-plastic substances commonly found in the sample or introduced during sample preparation. For simple matrices, such as drinking water, these databases should include spectra of proteins, oligosaccharides, cellulose, and typical minerals like carbonates, which are naturally present in water and may be found on the filter after filtration.

It is also essential to account for particles introduced during sample preparation. For example, salts of fatty acids, commonly used as slipping agents in laboratory gloves, have been mistakenly identified as polyethylene (PE) [6]. Additionally, spectra of detergents like sodium dodecyl sulphate (SDS), commonly used in cleaning procedures, resemble PE spectra. In principle, any organic molecule with a long C-H chain presents similar vibrational spectra to PE (Figure 2). Differentiation is possible only if adequate reference spectra are included in the database, and if the risk of confusion between substances is well-known.

Beyond traditional spectral matching, machine learning algorithms are increasingly being integrated into microplastics analysis. These models can be trained on large datasets of polymer spectra, allowing them to recognize complex patterns and subtle variations that may not be as easily detected through standard library matching. Machine learning models improve identification accuracy, particularly for microplastic particles that are weathered, degraded, or contaminated, leading to spectral changes. Furthermore, machine learning approaches enable the development of more adaptive and robust algorithms capable of handling large-scale, automated analysis of environmental samples, making them valuable tools in high throughput microplastics research.

PERSPECTIVES

Raman spectroscopy is a promising technique for nano-plastics analysis. When coupled with preconcentration methods such as flow field fractionation and advanced localization techniques like scanning electron microscopy (SEM) and atomic force microscopy (AFM), Raman spectroscopy can overcome the limitations of diffraction-limited optical microscopy [2]. This powerful combination allows for detailed chemical identification and characterization of nano-plastics.

CONCLUSIONS

Raman spectroscopy stands out as one of the reference methods for microplastics analysis. The automation of Raman analysis facilitates rapid quantitative assessments, enabling the counting of microplastic particles and their classification by chemical composition and size categories. Moreover, Raman spectroscopy is a promising method for advancing nano-plastics research, especially when integrated with other advanced techniques.

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ADVANCES IN SOLAR PHOTOVOLTAIC TECHNOLOGIES AND THE ROLE OF PHOTONICS

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Solar photovoltaics (PV) is expected to play a crucial role in achieving carbon neutrality by 2050. The past 15 years have witnessed remarkable progress in both research and industry. This review provides an overview of current technologies, including dominant silicon PV, emerging perovskite materials, premium III-V semiconductors, and alternative thin-film technologies. We also introduce the main research avenues, with a particular focus on the emerging field of tandem solar cells and the role of photonics.

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Solar photovoltaics (PV) is expected to play a key role in the deployment of the renewable energies needed to achieve carbon neutrality by 2050 and comply with the Paris Agreement adopted in 2015. Over the last 15 years, solar energy has progressed at a lightning speed that no one had predicted: the capacity of PV installations worldwide has increased tremendously and overcome 1.5 TW, representing 5.5 % of the PV electricity share. From 2010 to 2024, the efficiency of PV modules has increased by 0.3–0.4% absolute per year to reach 22-23%, their price has fallen from over 1 €/W to 0.2 €/W, and the levelized cost of electricity of large PV systems has dropped from 0.31 $€_{2022}$/kWh to less than 0.05 $€_{2022}$/kWh [1]. Thanks to these changes, solar photovoltaics is now in a position to play a dramatic role in the energy transition.

These impressive gains are the consequence of large-volume manufacturing combined with advances in the technologies and processes. There is little doubt that the silicon PV, which dominates the current photovoltaic market, will continue to be improved over the coming years. Still, the best efficiencies are approaching the theoretical limits, and new architectures will be needed to achieve efficiencies over 30 %.

The operation of solar cells can be summarised in three stages: absorption of sunlight in a semiconductor and creation of electron-hole pairs (photon energy greater than the bandgap), thermalisation of charge carriers, separation and collection of charges through selective contacts (pn junctions or heterostructures). Under standard solar illumination (the so-called AM1.5G solar spectrum), the theoretical maximum conversion efficiency is 33% for a single junction (Shockley-Queisser limit). In practice, the record is 29.1% with 1-2 µm of GaAs, 27.3% with 120-150 µm of silicon, and around 23-24% for thin-film solar cells composed of 2-3 µm of $Cu(In,Ga)Se_2$ or CdTe. 1 µm-thick absorbers are typically sufficient for materials in the emerging perovskite family, and efficiencies over 25% have been demonstrated.

Tandem solar cells are considered the most promising technology to overcome the 33%-efficiency limit. The approach consists of combining two or more solar cells: a top cell with a wide bandgap absorbs high-energy photons, enabling energy conversion with reduced thermalisation losses (heat dissipation), and is transparent to low-energy photons. A straightforward route is to build upon the silicon technology by adding a wide-bandgap solar cell on top of the bottom silicon wafer, in a two-terminal (2T, monolithically integrated cells in series) or four-terminal configuration (4T, mechanically stacked, electrically independent). Perovskite is seen as the most promising candidate for low-cost tandem devices, but it still has several challenges to overcome. Other technologies are also being developed to contribute to the advancement of tandem cells, as potential alternatives to perovskite and for specific applications.

In the following, we draw an overview of the state of the art of the photovoltaic technologies and we introduce the main current research avenues, with particular emphasis on the role of photonics.

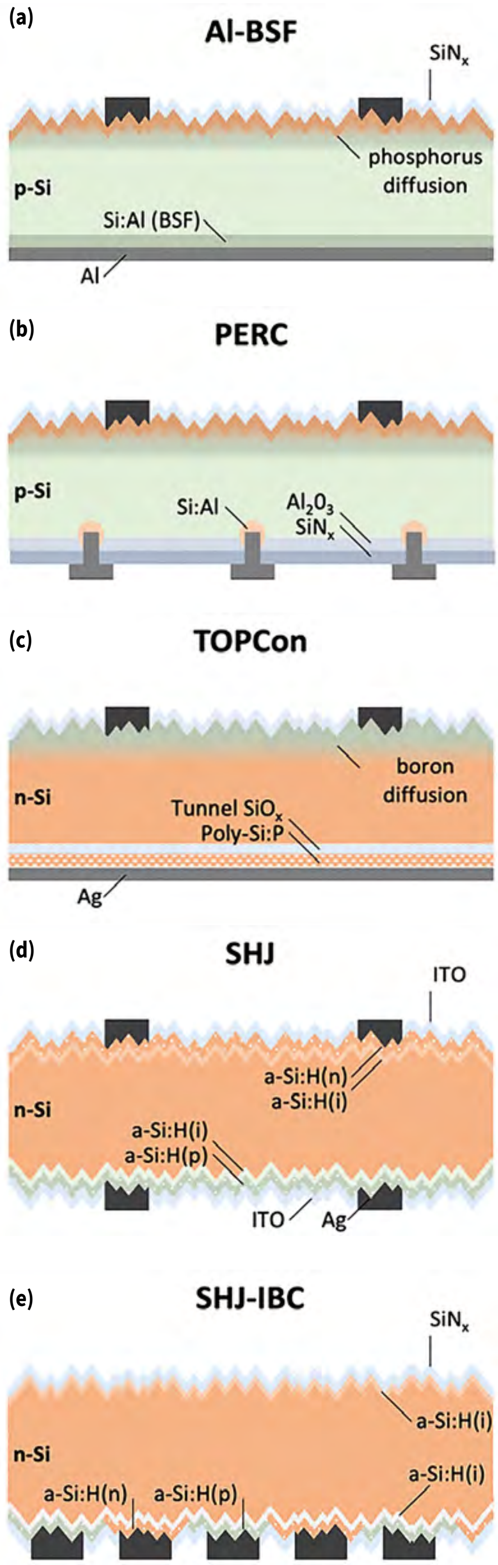

Figure 1. Main architectures for silicon solar cells: (a) aluminium-based back-surface field (Al-BSF), (b) passivated emitter and rear cell (PERC) (c) tunnel oxide passivating contact (TOPCon) at the rear side, (d) silicon heterojunction (SHJ), and (e) interdigitated back contacts (IBC) silicon heterojunction solar cell.

SILICON PHOTOVOLTAICS

Silicon is an indirect bandgap (1.12 eV) semiconductor with a low absorption coefficient, requiring typical wafer thickness of more than 100 µm for efficient absorption of near-infrared sunlight. This places strong constraints on the charge carrier diffusion length and surface recombination velocity.

For several decades and until the end of the 2010s, most silicon solar cells were made of p-type boron-doped wafers with surface texturing. A p–n junction was obtained by phosphorus diffusion at the front side, and the back contact was made with an aluminium-based back-surface field (Al-BSF) covering the full area. An anti-reflective coating (ARC) made of SiN_x:H was deposited by plasma-enhanced chemical vapor deposition (PECVD) on the front side and contributed to surface passivation.

The architecture and manufacturing processes for silicon solar cells have undergone numerous developments, gradually moving from the laboratory to industry (see Figure 1) [2]. To reduce the impact of surface recombination at the rear Si/Al interface, the contact area can be reduced, and the remaining surface is passivated by dielectric layers, leading to the passivated emitter and rear cell (PERC) configuration. With this design, the optical reflectivity at the back side is also increased, allowing for wafer thickness reduction. PERC became the dominant silicon technology in the industry from 2019.

Improved surface passivation has increased the need for higher quality silicon wafers, resulting in the progressive shift from multi-crystalline to monocrystalline silicon grown by the Czochralski method in the 2010s, the replacement of boron by gallium in recent p-type Si wafers, and now a transition to n-type wafers, which exhibit a higher minority carrier lifetime. To avoid the recombination losses still occurring at the localized metal/silicon interfaces, two main strategies have been developed to create full-area passivating selective contacts. These solutions need to provide both surface passivation (suppression of defects or field-induced repelling of minority carriers) and carrier selectivity (electrons/holes).

The TOPCon (tunnel oxide passivating contact) architecture combines a 1.0-1.5 nm thick silicon oxide layer for surface passivation and charge carrier tunnelling, with polysilicon contact layers (typical thickness >200 nm) highly-doped with boron (n-type) or phosphorus (p-type). Passivation of interfaces can be further improved using a hydrogenation treatment. For the front contact, the best compromise between transparency, passivation and conductivity is still the subject of ongoing research.

The second option is the so-called silicon heterojunction (SHJ) architecture. An intrinsic hydrogenated amorphous silicon (a-Si:H) layer (<10nm) provides excellent surface passivation and good conductivity and is topped with doped a-Si:H layers, both deposited by PECVD. The lateral transport of charge carriers towards the metal grid is partly ensured by an additional transparent conductive oxide (TCO) layer, typically indium tin oxide (ITO), which also acts as an ARC.

Both TOPCon and SHJ technologies are rapidly growing in the PV industry. The metal fingers typically have a width of less than 40 µm and are formed using screen-printing of silver pastes. To avoid grid-induced shadowing and parasitic absorption in the a-Si:H layers (bandgap 1.6-1.9 eV), interdigitated back contacts (IBC) have been the subject of long-standing developments. The IBC architecture has led to the highest efficiency; however, its industrialization still requires cost reduction and simplification. Interestingly, recent progress has benefited from laser technology, and the record efficiency of 27.3% was obtained with an IBC heterojunction silicon solar cell fabricated with an all-laser patterning process.

In addition to increasing efficiency, silicon consumption has been reduced (kerf losses and wafer thickness), from 16 g/W in 2004 to almost 2 g/W in 2023, and is one of the driving forces behind the reduction in manufacturing costs. Going further, an impressive 26%-efficiency was achieved in 2024 with a wafer thickness of only 57 µm, paving the way towards flexible silicon solar cells with high power-to-weight ratios. It is noteworthy that the remaining losses are mainly optical losses (see the section on photon management).

HALIDE PEROVSKITE

Halide perovskites are a (re-)discovered family of ionically bound compound semiconductors. Their common ground is that they share their generic crystallographic structure with $CaTiO_3$, the mineral named Perovskite in 1839 by Gustav Rose in recognition of the works of Lev Alekseyevich Perovski. In contrast to $CaTiO_3$ the class of halide ●●●

perovskite are not found in nature and were discovered as early as the 1890s, but it took another 100 years until the first semiconducting hybrid perovskites were reported. Since the first paper in 2009, reporting on halide perovskites as absorbers in solar cells, the research field has exploded and in the short time since then a plethora of new material compositions and applications have been discovered [3]. This was largely driven by the simplicity of fabrication of poly-crystalline thin-films, nano- and even single-crystals with staggering high optoelectronic quality using simple solution processing and low temperatures around 100°C.

Practically speaking the crystal structure ABX_3 can be modified to exhibit a controllably tuned bandgap anywhere in the range from 1.2 to 3.5 eV. To this end the A-site may contain cesium, or organic molecular cations such as formamidinium, methylammonium, or guanidinium, while the B-site is typically a divalent metal (Pb, Sn, Ge) combined with a halide (I, Br, Cl) on the X-site and mixtures thereof. What sets halide perovskites apart from most other semiconductors is their mix of very heavy and very light atoms, resulting in comparably low phonon energies that dampen rapid nonradiative recombination. In combination with moderate carrier mobilities in the range of 1 cm^2/Vs and comparably high absorption coefficients (10^4-10^5 cm^{-1}) due to their direct bandgap-nature, they are ideal for many optoelectronic devices and it is no surprise that highly efficient LEDs, FET, X-ray detectors (again due to the heavy atoms Pb, Sn), photodetectors and solar cells have been fabricated. In particular, solar cells have been evolving at an unprecedented speed, where efficiencies of close to 27% have been realized within 15 years of development. To put this into perspective: solar cells made from crystalline silicon or GaAs took 30-40 years of intense R&D to reach this level.

Beyond single-junctions, multi-junction devices are a natural "evolutionary step" for such versatile material systems and double- and triple-junctions have been realized with a large set of combinations (perovskite/perovskite/perovskite, perovskite/perovskite/Si, perovskite/perovskite, perovskite/CIGS, ...) with the most successful (so far) implementation being the combination with crystalline silicon (cross-sectional image of a cell from EPFL in the Figure 2).

In fact, this combo has reached an impressive efficiency of 34.6% in as little as 8 years since the first demonstration. This is a remarkable milestone since it is thereby the first dual-junction device configuration to beat the detailed balance limit of single-junction solar cells postulated by Shockley and Queisser. At the same time, the combination is of extremely high commercial appeal: crystalline silicon constitutes 97% of the global photovoltaics market share, and from an engineering point of view the perovskite top-cell could be considered little more than a few additional thin-film layers, and can likely be integrated into existing production lines.

The ionic nature of halide perovskites is, however, a double-edged sword. This property renders the material highly water-sensitive (they behave effectively like rock salt and can be dissolved in water) and prone to halide movement within the devices causing reversible (they counteract the built-in field, reducing the power output) and irreversible degradation (halides reacting with other species in the cell, *e.g.*, oxidizing the electrodes). At the same time, this is the reason for the ease of fabrication, making them comparably soft materials enabling flexible optoelectronics and resulting in remarkable self-healing effects. For example, after intense electron or proton irradiation, displaced atoms equilibrate rapidly, making them ideally suited for satellites. The remaining obstacle for this technology is – exaggeratedly speaking – it comparably low stability when in operation. With operational stability at elevated temperatures (~85°C) reaching several thousands of hours and a highly active academic and ever-growing industrial research community, it is not unlikely

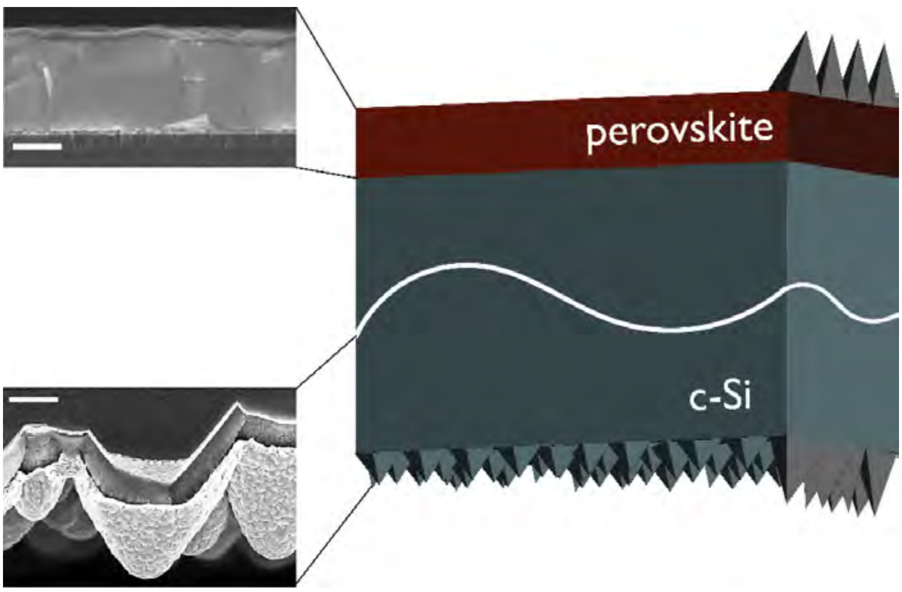

Figure 2.Simplified schematic of a perovskite tandem cell (right) with electron microscopy images of cross-sections of the perovskite top cell (top) and the silicon bottom cell rear-contact (bottom), scale bar = 500nm. Credit: Kerem Artuk & Deniz Turkay, EPFL.

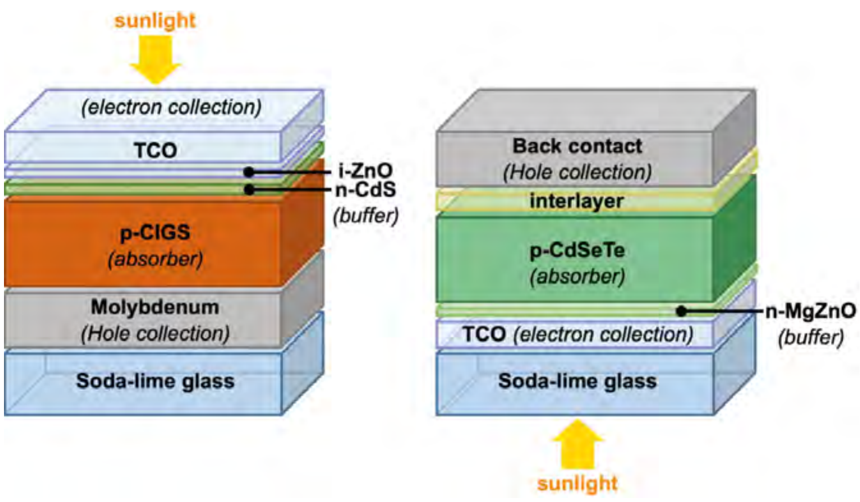

Figure 3. Sketchs of a CIGS solar cell (substrate configuration) and a CdTe solar cells (superstrate configuration).

that the remaining stability gap (compared to crystalline silicon) with a factor of 3-5x (annual degradation rate of c-Si is around 0.5-1% rel./year, for halide perovskites in the best cases ~3% rel./year) can be closed in the upcoming years.

III-V SINGLE-JUNCTION AND MULTI-JUNCTION SOLAR CELLS

Most III-V compound semiconductor materials, *e.g.* gallium arsenide (GaAs), are direct-bandgap semiconductors. III-V solar cells are typically realized by metal organic vapor phase epitaxy (MOVPE), molecular beam epitaxy (MBE), or hydride vapor phase epitaxy (HVPE), while MOVPE is the industrial standard today.

With an efficiency of 29.1% for a single-junction GaAs solar cell, III-V semiconductors have demonstrated the overall highest efficiency among single-junction solar cells. Due to their high radiative efficiency, the utilization of photon recycling is crucial and excellent rear side mirrors are required. In addition, III-V semiconductors offer the potential to realise multi-junction configurations. Adjusting the composition of ternary, *e.g.*, AlGaAs and InGaP, and quaternary compounds, such as GaInAsP, allows for tuning the bandgap of III-V semiconductor from < 0.7 eV to >2 eV by changing the composition.

III-V solar cells can either be used as stand-alone multi-junction solar cell or as top cells for *e.g.* silicon bottom solar cells. In silicon-based tandem solar cells, III-V solar cells are suited for both 2-terminal and 4-terminal operation. However, champion efficiencies of 2-terminal III-V-on-Silicon (record 36.1%) currently are higher than their 4-terminal counterparts.

All-III-V multijunction solar cells are used in space mainly, but can also be interesting in terrestrial applications such as unmanned aerial vehicles (drones), vehicle integrated PV, etc. One standard product has been a triple-junction GaInP/Ga(In)As/Ge solar cell on Ge substrate, however also a 4 junction is available for space. They often feature a distributed Bragg reflector below the Ga(In)As to allow for a thinner subcell. This is beneficial, as this cell suffers from degradation due to particle bombardment in space, and thus the lifetime of minority charge carriers decreases. A thinner subcell decreases the effect of this degradation and allows for a higher end-of-life-performance, which is the key measure for space solar cell efficiency. An alternative approach are so-called inverted metamorphic cells on a metal foil. Special about this cell concept is that the cells are grown invertedly, and the rear side of the device is directly accessible. In this way a rear side mirror can directly be implemented. Here, very high efficiency is possible, but the • • •

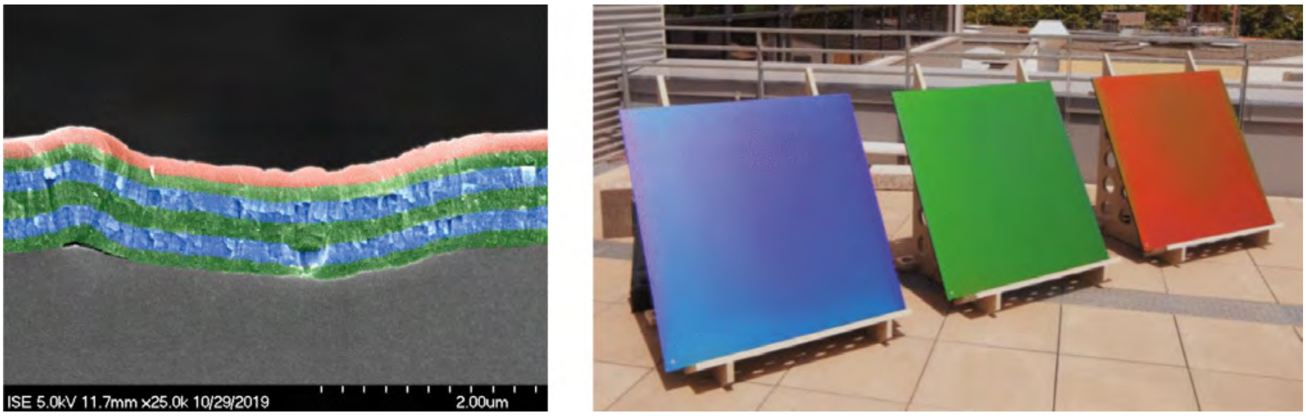

Figure 6. Coloured modules. (a) SEM cross section of the layer stack deposited on a textured glass surface to act as a narrow Bragg reflection filter with low angular dependence. The stack is made of SiN (green), TiO_2 (blue) and SiO_2 (coral). (b) The 1 m^2 modules exhibit with vivid colours, with power loss induced by reflected light of less than 6%. Credit: Fraunhofer ISE, reference [7].

required substrate lift-off is currently difficult and thus expensive.

For applications on earth, where high efficiencies or superior power-to-mass ratios are required, a two-junction GaInP/GaAs – also often grown invertedly – with rear side mirror is an interesting option. In these devices the mirror enhances absorption in the bottom cell, but even more importantly it severely improves photon recycling and thus the voltage of the device. The currently best device has an efficiency as high as 32.8% under the AM1.5g spectrum. A triple junction solar cell even allows for 37.9% and the overall highest efficiency under one sun was realized with a 6-junction solar cell and an efficiency of 39.2%.

While those multi-junction devices for one sun on earth are still a small niche, 4-6 junction solar cells are state of the art in concentrator photovoltaics (CPV). CPV are systems made of large lenses or mirrors to focus direct sunlight into tiny solar cells, with typical concentration factors up to x1000. Highest efficiency overall was reached with a wafer-bonded 4 junction solar cell with an efficiency of 47.6% under the AM1.5d spectrum (x665). The highest efficiency for a 6-junction solar cell currently is 47.1% (x143). While these cells are lab cells, 5-junction III-V solar cells based on Ge are industrially available for CPV. They are optimized for elevated (realistic) operating temperatures, and to account for the water absorption bands in the AM1.5d spectrum that are not present in the AM0 reference spectrum for space applications.

To further extend the use of III-V solar cells to terrestrial applications, the cost (typically of the order of 100 €/W for space applications) needs to be significantly reduced. Deposition rates beyond 100 µm/h have been demonstrated and are the subject of industrial pilots. To decrease material consumption and ultimately reduce costs, ultrathin solar cells utilizing multi-resonant photonic structures receive increasing attention. Using only 205 nm of active III-V absorber, efficiencies of 19.9% have been demonstrated with a single-junction GaAs solar cell (see the section on photon management).

POLYCRYSTALLINE CDTE AND CIGS THIN-FILMS

Thin-film solar cells made of polycrystalline inorganic semiconductors have been investigated for decades and have recently reached lab cell efficiencies over 23% [4]. They have been commercialized on a large scale, and offer a number of advantages: thin-film modules have a low levelized cost of energy, they can be produced over large surfaces with a high throughput, and they exhibit long-term stability and recyclability.

Thin-films are made of direct bandgap semiconductors with typical absorber thickness of about 3 µm. The two main representatives of this chalcogenide family are CdTe, a II-VI alloy which can incorporate Se, and $Cu(In,Ga)(S,Se)_2$ (CIGS), a I-III-VI_2 compound. Both are p-type semiconductors typically combined with n-type layers called “buffer” or “window” to form a p-n heterojunction, and transparent conducting oxide (TCO) layers as front or backside contacts (see Figure 3). CdTe and CIGS thin films are deposited on glass substrates at moderate temperatures between 450 and 600°C, resulting in polycrystalline, highly defective thin films.

The efficiency is hampered by the presence of defects in grain interiors and at grain boundaries. They originate from the crystal structure (stacking faults, vacancies), or the presence of extrinsic elements such as dopants. Several strategies have been developed over the years to passivate these defects and have led to significant efficiency improvements.

CdTe has a bandgap close to 1.5 eV. CdTe solar cells are fabricated in a superstrate configuration. The glass substrate is covered by a TCO layer (fluorine-doped tin oxide, a few hundreds of nanometres) and an n-type buffer layer made of MgZnO or CdS (a few tens of nanometres). CdTe or CdSeTe is commonly deposited by close space sublimation or vapor transport deposition. After deposition, annealing at temperatures ranging from 350 to 500°C in $CdCl_2$ contribute to recrystallisation and passivation of grain interiors and grain boundaries. Cu doping has recently been replaced by group-V elements as As. The industry of CdTe PV is still growing and was able to keep costs competitive with Si modules. It is mainly located in the United-States and dedicated to utility-scale PV systems.

CIGS is fabricated in the substrate configuration. The CIGS thin film is usually deposited on a Molybdenum back contact using the so-called sequential process, sputtering, or the multi-stage co-evaporation method. The bandgap of CIGS can be tuned over a large range; record CIGS solar cells have an effective bandgap close to 1.15 eV. A composition gradient between the front and back contacts is typically used to increase the Ga content and the bandgap towards the back contact and repel electrons from the surface. An heterojunction is formed with an n-type CdS buffer layer (chemical bath deposition) or a high-bandgap Zn(S,O) layer a few tens of nanometres thick. Subsequently, an intrinsic ZnO layer and a TCO window layers are deposited. The incorporation of alkali elements (Na, K, Rb) has played a crucial role in the continuous increase in efficiency over the last decade, and the partial substitution of Cu by Ag has led to the record efficiency of 23.6% [5].

The CIGS PV industry has been historically active in Europe and Japan, but has struggled to keep up with the falling cost of silicon in recent years. There are hopes that the aesthetic appearance of thin-film modules and the potential use of lightweight flexible substrates such as polymer or metal foils for CIGS will make them attractive for building-integrated photovoltaics (BIPV) and new markets such as agri-PV or remote power applications such as electric vehicles and aircrafts.

Future research directions of both CdTe and CIGS are related to new applications and functionalities, such as bifacial cells. It is noteworthy that the realization of transparent back contacts and the reduction of absorber thickness to decrease the usage of Te in CdTe and In in CIGS are two important issues for both technologies. For tandem applications, wide-bandgap (>1.6 eV) CIGS solar cells still need substantial improvements, with current efficiencies around 16%. Research on CIGS is particularly active in Europe, with several ongoing projects involving most European groups in the field, on CIGS/Si tandem solar cells (SITA project) and ultrathin and bifacial CIGS thin-films (Hi-BITS project).

There are other potential candidates for large-scale, low-cost PV made of inorganic polycrystalline thin films with abundant and non-toxic elements. $Sb_2(S,Se)_3$ and kesterite $Cu_2ZnSn(S,Se)_4$ (CZTSSe) solar cells still have limited conversion efficiencies (<14.5%) but have demonstrated continuous progress in recent years and are still active research areas.

PHOTON MANAGEMENT

Sunlight absorption is the very first stage in the conversion process of solar energy into electricity. Among the wide range of semiconductor optical devices, one specificity of optics in solar cells lies in their very broad spectral range. A conventional silicon solar cell must absorb and convert photon energy between 1.1 eV and 4.1 eV, *i.e.* encompassing the entire visible spectrum and the near infrared. In conventional solar cells, most optical losses are found at short and long wavelengths. For example, high-energy photons are partially absorbed in the a-Si:H top contact layer of SHJ solar cells, triggering research in alternative materials such as MoO_x or TiO_x, and in the CdS buffer layer of CIGS solar cells, which can be replaced by the high-bandgap Zn(S,O).

At long wavelengths, highly reflective back mirrors and efficient light trapping are necessary to compensate for the steep drop in absorption coefficient near the bandgap and to allow for a reduction in the absorber thickness. As seen in the previous sections, the development of ultrathin solar cells is an active field of research, with potential benefits for carrier collection, material savings, and • • •

cost reduction [6]. Beyond the usual Lambertian scattering strategy, novel concepts for efficient light trapping combined with affordable fabrication processes are being investigated (see Insert 1).

OPTICS FOR TANDEM SOLAR CELLS

Emerging tandem solar cells raise new challenges. For instance, the textured surface of conventional silicon is poorly compatible with the low-cost, scalable deposition techniques currently being developed for perovskite solar cells. On the other hand, the deposition of perovskite on a flat silicon surface requires additional attention to achieve broadband

LIGHT-TRAPPING IN SOLAR CELLS

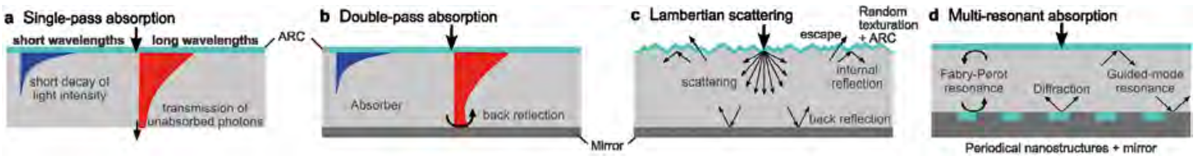

Figure 4. Main strategies and basic mechanisms to trap light in solar cells.

The presence of coatings, back mirror, roughness, textured or patterned surfaces can modify the way light enters the cell, propagates, scatters and is trapped in the absorber (see Figure 4). The optical path enhancement factor *F* is used as a figure-of-merit for light trapping, and absorption can be expressed by the generalized Beer-Lambert law: $A = 1-e^{-F\alpha d}$, where α is the absorption coefficient and *d* the thickness. F=1 for single-pass absorption with a perfect ARC, and F=2 with an additional perfect back reflector (double-pass absorption).
The first requirement to optimize sunlight absorption is the suppression of reflection at the front interface, about 30% for bare silicon or III-V materials. This is commonly achieved by a double-layer anti-reflection coating (ARC). Textured or rough surfaces also help suppress optical reflection by creating a graded effective refractive index.
To compensate for the drop of α near the bandgap, light-trapping is used to increase the optical path. The most common scheme is based on textured silicon surfaces obtained by chemical etching. The resulting randomly-positioned pyramids approximate Lambertian scatterers, whose upper limit is given by the Lambertian scattering model derived by E. Yablonovitch: $A=\alpha d/(\alpha d+1/F)$ and $F=4n^2\approx50$ (n: refractive index of the absorber).
Actually, the Lambertian model is not a fundamental limit, and it could be exceeded by new light-trapping strategies (see Figure 5). Correlated disorder such as hyperuniform structures have emerged recently in the photonics community and offer new degrees of freedom to investigate the full range of possibilities between fully disordered structures such as currently used in silicon, and fully ordered patterns. Periodical patterning has already been successfully used in III-V/Si tandem solar cells and in ultrathin GaAs solar cells to achieve absorption enhancement via multiple resonances.
Low-cost fabrication processes are favoured in the search for new light-trapping solutions. They should enable the development of ultrathin solar cells with thickness 10 times lower than conventional solar cells without performance degradation, enabling material savings and cost reduction.

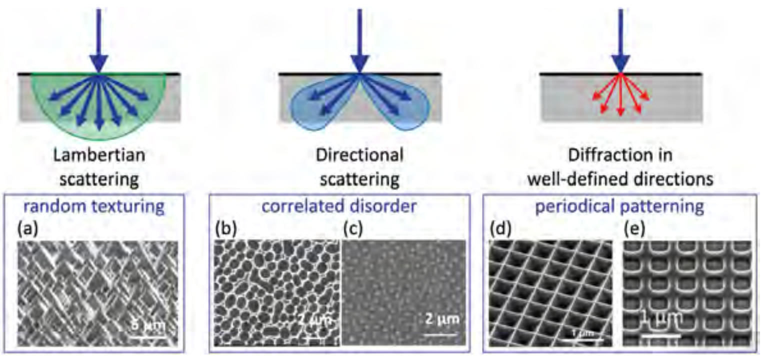

Figure 5. Scattering and diffraction effects and structures used to trap light in solar cells. (a) Chemical etching of silicon by KOH leads to randomly-positioned pyramids with well-defined angles, acting as a good approximation of Lambertian scatterers. (b,c) Recent advances in the physics of correlated disorder open new routes to achieve directional scattering using low-cost nanopatterning techniques such as polymer-blend (b) and colloidal (c) lithography. (d,e) Perfectly ordered structures fabricated by nanoimprint lithography result in diffraction in well-defined directions and absorption enhancement by multi-resonant effects: (d) inverted pyramids chemically etched in silicon, and (e) nanogrid made from sol-gel-based material. Credit: Images from CNRS.

suppression of optical reflection. Additionally, the entire stack of the top cell must be transparent to long-wavelength photons. This rules out the use of narrow bandgap semiconductors or highly-doped TCO, which would exhibit parasitic absorption of free carriers in the near infrared. In the 4T configuration, the additional TCO and the shading induced by the front and backside grids of the top cell impose additional design and material constraints. Finally, the luminescent coupling between the different cells has already been evidenced with III-V materials and should be taken into account in high-efficiency tandems, and the introduction of innovative light trapping structures to reduce the thickness of tandem solar cells has been little explored.

COLOURED MODULES

Coloured PV is an attractive option for building integrated PV applications (BIPV). However, it is obvious that optimal absorption of sunlight would results in black PV modules, and the performance cost of introducing colour is expected to be high. A solution inspired by the vivid structural colours of the Morpho butterfly was developed recently at the Fraunhofer ISE, achieving highly saturated, angularly stable colours with a remarkable performance loss of only 6% [7]. A narrow-band reflection filter is obtained through interference effects in a multilayer stack deposited on a textured glass substrate, and the central wavelength can be easily tuned to provide the desired aesthetic appearance (see Figure 6). Since the structural colour is created in the cover glass of the PV module, it is compatible with all PV technologies.

CONCLUSION

Silicon will remain the dominant technology for the next few years, with a continuing shift towards TOPCon and heterojunction technologies. Many research groups and a few industries are actively working on the next generation of solar cells, which will probably take the form of silicon-based tandem solar cells. Perovskite is considered the most promising candidate for low-cost tandem devices, but it still faces numerous challenges before possible large deployment at low-cost. Thin films technologies and III-V solar cells are mature technologies commercialized in small markets. They are also active fields of research and could contribute to research advances towards low-cost tandem solar cells. Photonics will continue to play a central role in the development of photovoltaics, particularly in the optimization of tandem solar cells, in the reduction of material usage and costs without sacrificing performance, and in the realization of visually appealing modules.

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INERTIAL CONFINEMENT FUSION: A PATH TO CARBON-FREE ENERGY?

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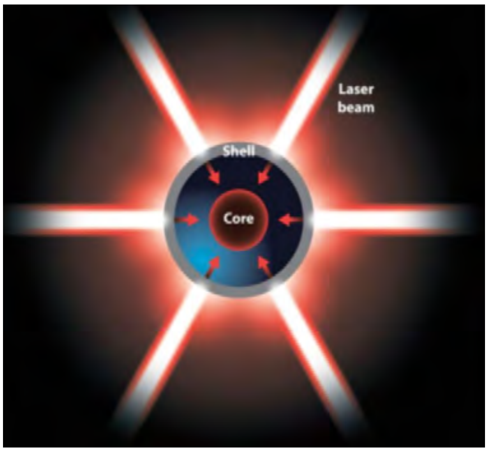

Scientists are trying to harness nuclear fusion reaction since the 1950s. Indeed, fusion of the two isotopes of hydrogen, Deuterium and Tritium ("DT"), generating an alpha particle and a neutron, can produce 337 MJ per mg of fuel, promising abundant, carbon-free energy. The scientific community is pursuing two approaches in this quest: magnetic confinement fusion ("MCF") and inertial confinement fusion ("ICF").

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If MCF has taken the major part of attention and budget in fusion for energy, with the ITER project and other research and private initiatives, ICF has taken a significant step on December 5th, 2022 by being the first to reach the long thought after "ignition point". On this day, the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in California generated 3.15 Megajoule (MJ) of nuclear energy by imploding a capsule filled with Deuterium and Tritium with 2.05 MJ of laser energy.

The principle of ICF (fig 1) is to irradiate a millimetre-scale spherical capsule filled with deuterium and tritium with very high power radiation during a few nanoseconds. The ablation of the outer surface of the capsule leads to compression of the DT fuel, leading to density and temperature (~ 100 millions K) sufficient to trigger fusion reactions. The alpha particles generated are then re-absorbed in the plasma, increasing further its temperature to trigger a large amount of fusion reaction that can consume a large fraction of the DT fuel.

Reaching this state of burning plasma necessitates extremely symmetric irradiation and very tight capsule tolerance. This has made the quest for ignition elusive until the NIF breakthrough, repeated five times since 2022, with energy output reaching 5.2 MJ for 2.2 MJ of invested laser energy, confirming the maturation of the inertial confinement fusion (ICF) science.

Those spectacular results are opening the door for finally making true the precept that fusion has always been "30 years away". Therefore, a number of public and private initiatives are now underway to take on the significant technological and engineering challenges that stay in the road between ignition at NIF and viable carbon-free ICF based power plant.

FROM IGNITION TO A FUSION POWER PLANT?

In an extremely simplistic way, a fusion power plant will follow the basic principle highlighted by the schematic of Fig 2. A capsule filled with about one mg of deuterium and Tritium is injected in a reaction chamber where it will be irradiated by multiple laser beams of megajoule energy. The implosion of the capsule can lead to

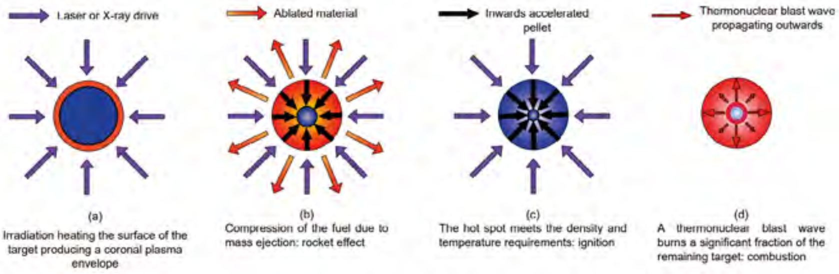


Figure 1. Principles of inertial confinement fusion (taken from Ref 3).

the combustion of up to 30% of the DT, leading to the release of more than 100 MJ. Repeating the process multiple times per second will result in Gigawatt average power generated mostly in the form of fast neutrons (14.3 MeV).

A lithium-based compound will absorb neutrons, providing two functions: convert the energy to heat and regenerate Tritium (whose supply is extremely scarce on earth). The conversion of heat to water vapour and electricity will then be very similar to a traditional power plant.

THE PATH TO LARGE GAIN

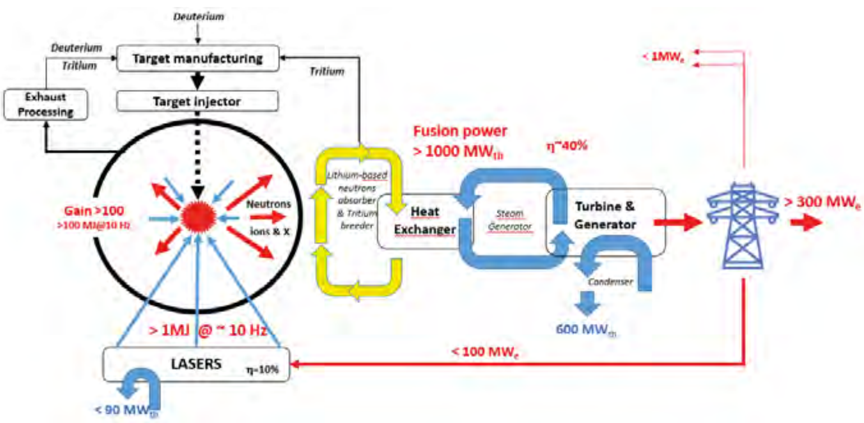
The gain of the reaction (ratio of fusion energy divided by laser energy) has to be large enough to compensate the energy required for the lasers and other sub-systems in the power plant. This is not the case in NIF where a gain of ~ 2.5 does not come close to compensate the laser efficiency far below 1%.

The experiments at NIF and its French equivalent the Laser Mega Joule ("LMJ") use the so-called indirect drive irradiation. In this case, X-ray radiation, generated by interaction of the main laser beams with the inner wall of a cylindrical cavity ("Holrhaum"), implodes the deuterium-tritium capsule. It benefits from the X-ray very short wavelength but has a poor efficiency, only a small fraction of the laser energy being coupled to the capsule.

Even if NIF expects gains of around 15 with indirect drive in a near future, direct drive, where the laser beams directly irradiate the capsule seems more promising to reach gains of 100 or more.

All potential ICF "recipes" face a major challenge: controlling the instabilities at work during the implosion. Hydrodynamic instabilities occur at the interface between two fluids moving in opposite direction (in case of ICF, the light and hot ablated matter against the heavier and cold capsule) or at different speeds (see Fig. 3). They will grow from any even minor non-uniformity in laser irradiation ("laser imprint") or capsule structure, stopping the compression from converging towards ignition conditions. • • •

Figure 2. Simplified principle of an ICF power plant.



Laser-plasma instabilities ("LPI") exacerbate those non-uniformities and reduce efficient coupling of the lasers into the plasma. LPI include several non-linear processes occurring when a high-intensity laser interacts with a plasma: stimulated Brillouin scattering ("SBS"), stimulated Raman scattering ("SRS"), two-plasmon decay ("TPD"), cross beam energy transfer ("CBET"). Each one depends on specific laser parameters (intensity, wavelength, spectral bandwidth...) and plasma characteristics.

ADVANCED DIRECT DRIVE SCHEMES

To control instabilities, complex trade-offs are necessary but some schemes can offer realistic paths to high gain by decoupling the compression and ignition function. In shock ignition (Fig. 4), a first irradiation ramp over ~ 10 nanoseconds provides a more modest compression, followed by an ignition spark provided by a faster (~ 1 ns) laser pulse that creates a corresponding shock at the end of the compression. In **fast proton ignition**, a proton beam generated by a short laser pulse (<ps) laser provides the spark.

PROTON-BORON: ALTERNATE FUEL

The reaction of fusion of a proton with a nucleus of boron, yielding 3 alpha particles is an alternate path that poses the additional challenge of requiring much larger energies to initiate than the deuterium tritium reaction.

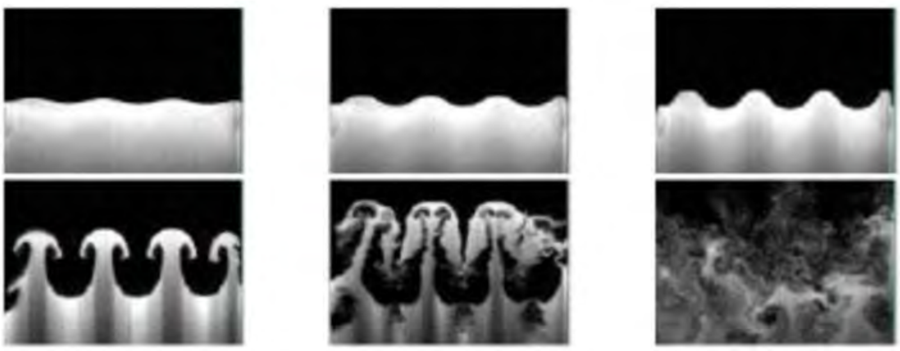
Marvel Fusion (Germany) proposes to use the interaction of ultra-fast and ultra-intense lasers (< 100 femtosecond pulse duration & Petawatt peak power) with nanostructures, creating extreme electric and magnetic fields to reach the necessary conditions for fusion without the need for compression.

THE LASERS

NIF and LMJ lasers represent logically the blueprint for fusion lasers but choosing and developing the right lasers for energy generation is a game of trade-off between the need of ICF physics and robust and economically viable solutions. Meeting the stringent requirements described in the previous paragraph requires several key decisions:

- **The choice of wavelength and spectral bandwidth:** the scaling of LPI instabilities and the ablation efficiency favour short wavelength like the third harmonic of Neodymium-glass laser ("3ω") at 351 nm selected for ICF facilities: NIF, LMJ and OMEGA (LLE, Rochester). On the other end, visible lasers (like second harmonic of Nd:glass at 527 nm) offer better efficiency and reduced risk of optical damage. Larger spectral bandwidth is preferred because it increases the threshold for LPI instabilities and reduces temporal coherence-induced non-uniformities but a compromise with efficiency is necessary. Excimer lasers that have the advantage of naturally emitting in deep Ultra-violet (248 nm or 193 nm) are another option but require complex technologies to scale up to very high energy.
- **Multi-beams irradiation and beam "smoothing":** reaching ignition requires a near-perfect spherical irradiation with typically 50 to 100 "meta beams" attacking the capsule at different incident angles. To minimize laser imprint, techniques like phase plates reduce coherence-induced speckle. Choosing the right "energy quantum" is a matter of providing the best uniformity but also finding an economic and reliability optimum. Consensus within the industry is to choose a reduced energy compared to NIF and LMJ for individual laser beams (10 kJ beamlet combined in 4 "quads") but will mean manipulate and control a very larger number of individual laser beams (probably more than 1000).
- **High repetition rate and high wall plug efficiency:** Flash lamp pumped Neodymium-glass lasers (NIF, LMJ, Rochester) are limited to shots every few hours with efficiencies well under 1%. Diode pumping is necessary and has shown capability to achieve 10 Hz at high energy with efficiency close to the 10% targeted but reduction in diode cost by one or two orders of magnitude is necessary.
- **Cheap and reliable:** IFE will happen only if it can reach a competitive electricity price (~ 100 € / MWh). This will need aggressive cost target, probably below 1000 € / Joules for laser capital cost and extremely low cost of operation & maintenance.

Figure 3. Hydrodynamic instabilities



FABRICATING CAPSULES

The state of the art capsule structure for ICF, exemplify by the one used for the NIF ignition experiment consists of a hollow shell of solid Deuterium-Tritium at cryogenic temperature (17°K), filled with DT gas. An external envelope serves both as radiation absorber for ablation and as containment for the ice DT. Fabricating those capsules is a gruelling task requiring lengthy injection and layering of the

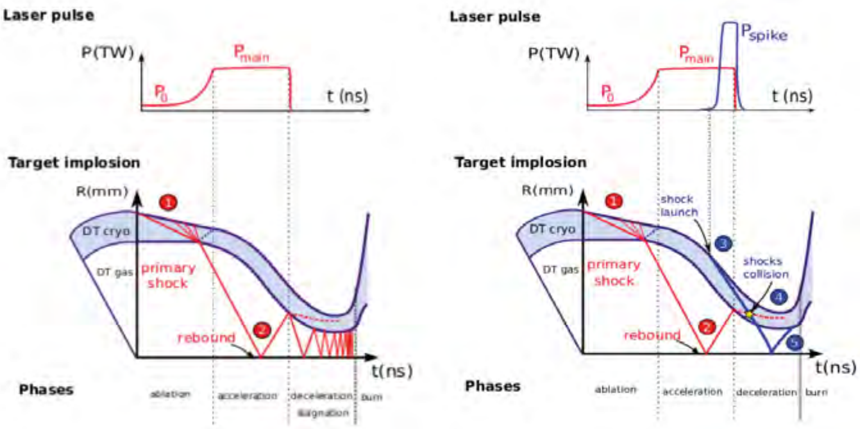


Figure 4. Hot spot ignition (left) and shock ignition (right) – Taken from Ref.[3]

DT ice and tedious dimension control to reach the extreme tolerance required.

Operating at 10 Hz, a fusion power plant will require close to a million capsules a day at a cost well below 1 €, forcing to develop new materials and manufacturing processes is necessary. Amongst the technology candidates, academia and industry consider the use of foams wetted by liquid DT. Work is underway at multiple research laboratories to characterize the interaction between lasers and foams to validate this approach.

If producing cheap ICF compatible capsules is a challenge, so is injecting them multiple times per second in the reaction chamber with synchronisation and position control to meet the laser beams at the right time and the right place.

ABSORBING THE ENERGY AND CLOSING THE TRITIUM CYCLE

Generating Gigawatt level of power is tough, absorbing this power and converting it to heat comes with its own challenges. Inertial confinement shares similar needs with magnetic confinement, creating opportunities for mutualizing the R&D.

In a first architecture, the inner solid wall ("first wall") of the reaction chamber absorbs the ions and charged particles (that can represent 25% of the total power). Tritium breeder modules ("TBM") absorbs the neutrons downstream of the first wall. Magnetic confinement research projects such as ITER consider multiple TBM technologies: Lithium based liquid (LiPb for exemple) or salt absorbing the neutrons and serving as heat carrying fluid or solid lithium based ceramic and in this case, heat exchange is ensured by gas or liquid.

In a second type of architecture, a plasma facing Lithium based liquid wall (for exemple FLiBe or Li-H) absorbs the reaction products inside the reaction chamber. This approach proposed by the project HYLIFE (Fig. 5) for ICF and selected by several companies (such as Xcimer energy in ICF, and Renaissance fusion in MCF) reduces stress on the chamber solid wall but necessitates complex engineering to control the liquid Lithium flow.

Closing efficiently the fuel cycle is critical: Tritium supply is scarce! ICF will be viable only in a self-sustained closed loop operation ensures Tritium self-sufficiency. Tritium breeding must have an efficiency larger than one (meaning that each neutron generates in average more than one Tritium) to account for losses or diffusion, necessitating a neutron multiplying scheme by adding more species for example Pb or Be. Tritium processing including purification and isotopic separation as well as capsules production will need to have a cycle time fast enough to limit the Tritium inventory to the minimum necessary for cost and safety reason (Tritium is radioactive, with a half-life of 12 years).

Intense activities are underway at research institutions for example under the ITER consortium to develop •••

THE NEED FOR DEDICATED DIRECT DRIVE INSTALLATION

ICF progress is limited today by the availability of dedicated laser installations. The NIF and LMJ are the only accessible MegaJoule class facilities and they suffer from two basic limitations:

- **Scarce shot opportunities: they are limited to around 300 shots per year and the majority of their access is dedicated to defence: if the NIF ignition needed 12 years of efforts, less than 200 shots were fired towards the goal over this period.**
- **Their polar irradiation geometry does not support fully symmetric direct drive experiment.**

On the other end, the OMEGA installation at LLE in Rochester is fully equipped for direct drive but laser energy is limited to 30 kJ. A lot of experiments and models are trying to scale results to high gain but uncertainties in the accuracy of this scaling remain.
IFE success will undoubtedly require at least one facility dedicated to R&D that can demonstrate high gain approach at a level that will enable subsequent scaling to power plant levels. This must be a priority and it will require very strong public-private partnerships.

concepts of breeding technologies, while companies and consortium such as Fusion Fuel Cycle Inc., (Canada) are developing Tritium purification capabilities.

A BURGEONING ECOSYSTEM

A large ecosystem of start-ups is emerging, gathering significant funding and forming strong academic partnerships.

Focused Energy (Germany & US) is pursuing direct drive proton fast ignition and is engaging in target and laser development in collaboration with university of Darmstadt. Marvel Fusion (Germany) is developing its concept of proton-Boron fusion based on interaction between ultra-intense lasers and nanostructures, with amongst others, collaboration with Colorado State University. Xcimer Energy (US) has chosen to develop ultra-high energy excimer lasers, beam combination and compression based on non-linear effects in gas, a dual-sided direct drive scheme and FliBe liquid wall for neutron capture and Tritium breeding. Longview fusion (US) is following the indirect drive, NIF-like path. Blue laser fusion (US) is proposing a disruptive approach by which Optical Enhancement Cavities convert the average power of quasi-continuous laser to high peak energy. HB11 (Australia) is also pursuing proton-boron fusion. GenF (Elancourt, France), is collaborating with CEA and CNRS laboratories (LULI & CELIA) with the support from French government and Thales.

Governments are now integrating inertial fusion in their energy policies with significant subsidies. US have launched a "bold decadal vision" with associated DOE funding. Germany has launched joint programs like "PriFusio" gathering startups (Marvel Fusion, Focused Energy), laser and optics companies (Trumpf, Laseroptik, Layertec, Schott) and laboratories (Fraunhofer ILT Achen, Laser Zentrum Hannover...). France selected the project Taranis (led by GenF with Thales, CEA and CNRS laboratories CELIA and LULI) in its H2030 "innovative nuclear reactor" funding program.

Laser manufacturers such as Thales, Amplitude and Trumpf as well as optics suppliers are all part of projects or industry-academic consortium to develop technology solutions towards IFE.

This rich private – public ecosystem is very diverse geographically but also in the broad coverage of all potential technical path: this raise expectations that it will collectively achieve a thorough pathfinding to identify the right combination of technologies to make energy generated by inertial fusion a reality.

CONCLUSION

The NIF results are finally validating the physics of inertial confinement, opening a different phase of the road to energy production. In this phase, the very complex challenge of the ICF physics is broken down into a set of engineering problems, albeit formidable ones but each one with potential solutions that are being worked on by a growing number of private and public actors. Rigorous system engineering is needed in parallel with those technology development efforts to find the optimum trade-offs that could lead to technically and economically viable IFE solutions by the mid-century.

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PASSIVE DAYTIME RADIATIVE COOLING

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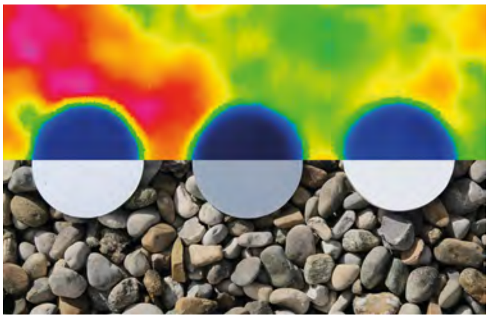

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With average global temperatures constantly increasing, the emerging field of passive daytime radiative cooling holds promise to alleviate our growing cooling needs and protect the environment by providing us with electricity-free cooling power. Here, we briefly revise the principles behind this rapidly expanding field, its main material platforms and implementations, and its outstanding challenges in terms of scalability and durability against weathering agents.

Pointing a thermal infrared camera towards the sky reveals an interesting fact: even during a hot summer day, sub-freezing temperatures can be observed with clear sky conditions. Thermal cameras are sensitive to infrared wavelengths at the peak of the blackbody emission of objects at near-ambient temperature. At these very same wavelengths, our atmosphere happens to be almost transparent, so that pointing the camera at the sky reveals the coldness of outer space. From an opposite perspective, this is what allows thermal satellite imagery of our planet to be acquired from space: a significant part of infrared radiation emitted from the Earth's surface can escape freely through the atmosphere, with a clear sky effectively acting as a radiative heat sink able to dissipate arbitrary amounts of thermal radiation. Morning frost formation on grass or a car windshield despite above-freezing temperatures are common manifestations of this passive radiative cooling effect. In fact, nighttime radiative cooling has been exploited for thousands of years, allowing ancient populations to produce ice also under adverse climates where temperatures would not typically allow it.

The same refrigeration mechanism, in principle, is equally active also during the day, even though in this case its effect is more than offset by the strong irradiance coming from the Sun. Just 10 years ago, however, pushed by the relentless progress in the fabrication of micro- and nano-structured materials, a new milestone was finally demonstrated. By shielding a material from environmental convection and conduction heat gains, and engineering it in such a way to reflect all solar light and emit radiation selectively at the wavelengths in the atmospheric transparency range, spontaneous sub-ambient cooling was demonstrated for the first time under a peak solar irradiance of almost 900 W m^{-2} [1].

Due to its relevance as a renewable and largely untapped source of electricity-free cooling power, interest around passive daytime radiative cooling (PDRC) surged, with several research groups and private companies worldwide working on this topic [2].

FUNDAMENTALS OF PDRC

To achieve passive daytime radiative cooling, the emitter must exhibit a low emittance (i.e., high reflectance) across the whole solar and infrared spectrum, except at wavelengths where the atmosphere is transparent (Figure 1). In order to deliver a net daytime cooling power, however, the full energy balance must be positive:

$$P_{rad} - P_{atm} - P_{solar} - P_{nonrad} > 0$$

where P_{rad} is the power irradiated by the sample, P_{solar} and P_{atm} are the absorbed powers from the sun and the atmosphere, while P_{nonrad} is the total power gain from all non radiative heat transfer processes, such as conduction and convection to the external environment.

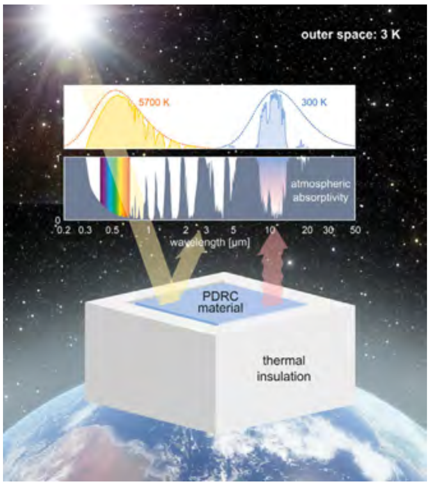
For daytime applications, the power absorbed from the sun $P_{solar} = \int_{0.3\mu m}^{4\mu m} I_{solar}(\lambda)\varepsilon(\theta, \lambda)d\lambda$ must be minimized, with $\varepsilon(\theta, \lambda)$ being the spectral emittance of the sample for incident solar illumination at an angle θ. Considering that global solar radiation can exceed 1000 W m^{-2}, and that an ideal selective emitter can achieve at best about 100-150 W m^{-2} of net cooling power under dry and clear sky conditions, the average solar reflectance must be larger than 0.9 and more likely larger than 0.95 for any material to exhibit a measurable net cooling power under typical atmospheric conditions.

Non-radiative heat transfer contributions are often combined into a single term $P_{nonrad} = h(T_{amb} - T_s)$ where h is the total heat transfer coefficient accounting for both convection and conduction between the sample and the environment, with typical values of a few W m^{-2} K^{-1} for well insulated, low wind conditions. Conversely, the radiative balance is determined by the balance between P_{atm} and P_{rad}.

The power absorbed from the downwelling atmospheric irradiance depends on the coating emittance, atmospheric emittance and the atmospheric (ambient) temperature as

$$P_{atm}(T_{amb}) = \int_0^{\pi/2} \cos\theta \, d\Omega \int_0^{\infty} I_{bb}(\lambda, T_{amb}) \, \varepsilon(\Omega, \lambda)\, \varepsilon_{atm}(\Omega, \lambda)\, d\lambda$$

where $\varepsilon_{atm}(\Omega, \lambda)$ is the atmospheric emittance as a function of direction and wavelength and $\int d\Omega = \int_0^{\pi/2} \int_0^{2\pi} \sin\theta \, d\theta \, d\phi$



The radiative heat balance of a passive radiative cooling emitter results from the interplay between several factors. A first important requirement is to shield the emitter from ambient conditions, insulating it from any non-radiative (*i.e.*, conduction and convection) heat gains coming from the environment, leaving only an open aperture towards the sky. Secondly, to ensure cooling during daytime hours, the emitter must exhibit near-perfect reflectance across all solar wavelengths, and near-perfect absorptivity (and hence, emissivity) between 8 and 13 µm, where molecular gas species in the atmosphere lack significant absorption bands and thermal radiation is free to escape to outer space. Following Kirchhoff's law of thermal radiation, any object at thermodynamic equilibrium with its environment must be characterized by an equal absorptivity and emissivity following a detailed balance principle imposed by reciprocity considerations. At wavelengths in the infrared transparency window, the downwelling irradiance from atmospheric gas species is very low, as well as that from outer space. Hence, the equilibrium condition for a selective perfect absorber/emitter exposed to the clear sky will shift towards sub-ambient temperatures, leading to a net passive radiative cooling effect.

is the angular integral on the upper hemisphere. A small atmospheric emittance (or large transmittance) is found between 8–13 µm, dubbed as the LWIR transparency window (see Insert). The effective transparency in this range depends on several factors including the zenith angle, cloud cover, humidity, aerosol and pollution, with more downwelling irradiance received during cloudy or humid weather.

Similarly, the radiative power of a PDRC coating is a function of its temperature and emittance spectrum

$$P_{\mathrm{rad}}(T_{\mathrm{s}}) = \int_0^{\pi/2} \cos\theta \, \mathrm{d}\Omega \int_0^{\infty} I_{\mathrm{bb}}(\lambda, T_{\mathrm{s}}) \, \varepsilon(\Omega, \lambda) \, \mathrm{d}\lambda$$

where $I_{\mathrm{bb}}(\lambda, T_{\mathrm{s}})$ is the spectral intensity emitted by a standard blackbody at temperature T_{s}. The peak of blackbody emission is located inside the atmospheric LWIR window for typical ambient temperatures, allowing the dissipation of a large fraction of P_{rad} directly to outer space. Considering that T_{s} and T_{amb} are similar, the balance between P_{atm} and P_{rad} is dominated by the radiative power exchange between 8 and 13 µm, where the atmospheric irradiance is lowest (see Fig. 1). When $T_{\mathrm{s}} < T_{\mathrm{amb}}$, a selective emissivity from the sample is key to avoid absorbing the strong P_{atm} outside of the LWIR window. Conversely, when $T_{\mathrm{s}} > T_{\mathrm{amb}}$, broadband emissivity over the whole thermal range leads to an increase of P_{rad} which can be particularly useful in above-ambient cooling scenarios (*e.g.*, cooling of photovoltaic modules, heat-pump condenser units, data centers, etc.). For characterization purposes, the net cooling power is typically calculated by taking $T_{\mathrm{s}} = T_{\mathrm{amb}}$, since under this condition P_{nonrad} vanishes.

SELECTION AND DESIGN OF PDRC MATERIALS

Based on the above power balance relation, any PDRC material must comprise several elements guaranteeing a strong reflectance at solar wavelengths, a high emittance in the LWIR atmospheric window, and ideally some degree of thermal insulation from the environment.

Regarding solar reflectance, two main mechanisms exist involving either a metal-based reflector (typically silver, due to its high solar reflectance), or a diffuse reflector exploiting random and/or hierarchical structures to ensure high reflectance over the broad solar wavelength range (see Figure 2). In the former case, a separate emitter must be added on top of the silver mirror due to the low emissivity of metallic reflectors, as well as a convection shielding membrane. This is a prototypical configuration where each function of a PDRC material is embodied by a dedicated layer. Several examples in the literature belong to this family, with emitters of different types ranging from 1D dielectric stacks, to flat polymer films, photonic metasurfaces or host layers with highly emissive inclusions, to name a few. Conversely, different architectures can emerge when multi-functional layers take on multiple roles. For instance, one can avoid using metal reflectors by delegating solar reflectance to a highly scattering and yet IR-transparent top layer, such as those obtained with porous polyethylene membranes. Alternatively, a single layer can be both highly reflective at solar wavelengths, and highly emissive in the LWIR window. Many examples are known for this class of PDRC materials, ranging from porous polymer mats and aerogels, to paint-like formulations, electrospun membranes, sintered ceramics or delignified wood layers, even though these materials may present very different degrees of thermal resistivity against the substrate where they are applied, and from which they are supposed to drain heat.

Depending on the architecture, an array of materials with specific properties has been explored in the recent literature [4, 5]. For instance, IR-transparent materials used as convection shields are typically made of polyolefins such as polyethylene thanks to their structure containing only saturated aliphatic bonds which do not absorb between 8 and 13 µm. Materials such as ZnS or ZnSe have also been used as infrared windows for de-pressurized chambers used to test PDRC materials in the absence of convection.

Regarding emitting layers, polymers with functional groups such as $-CH_3$, C–O, C–OH, C–O–C all have useful resonances within the atmospheric transparency range, as well as the $-CF_3$ group

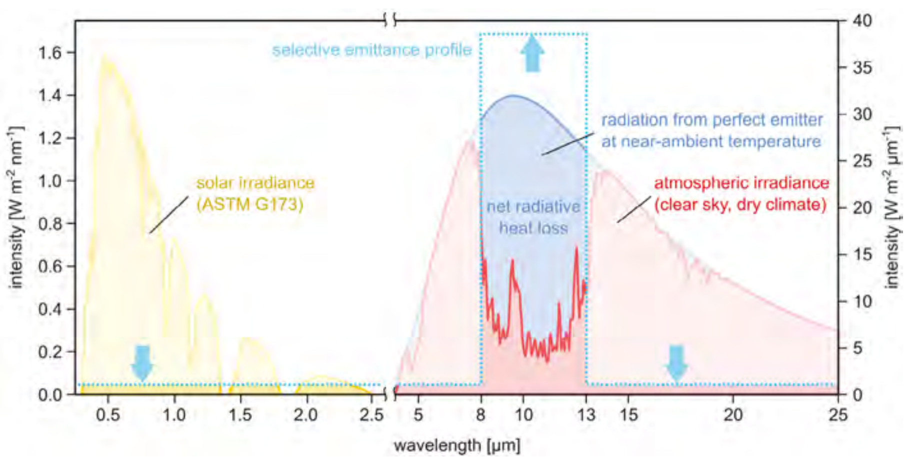


Figure 1. Spectral properties for an ideal passive radiative cooling material, compared to the solar spectral irradiance (yellow) and atmospheric downwelling irradiance (red). By reflecting all radiation outside of the atmospheric LWIR window (8–13 µm), a net radiative heat loss towards the sky sink is obtained considering the blackbody emittance spectrum of a typical object at near-ambient temperature.

present in perfluorinated polymers. The Si–O–Si bond present in silica and polysiloxanes, or the Si–N–Si in polysilazanes are also strongly absorbing in the LWIR window, while bonds such as C=O, C=C, C=N or –CHO should be avoided, as they have resonances outside the atmospheric transparency window and can thus absorb the downwelling atmospheric irradiance.

Several polymers with a desirable mix of such resonances have been identified, such as poly(vinylidene fluoride-co-hexafluoropropene) (P(VdF-HFP)), poly(tetrafluoroethylene) (PTFE) or polyvinyl fluoride (PVF), to name a few. Fluorinated polymers offer high durability against weathering and chemical agents, UV degradation and soiling. However, their extreme persistence raises increasing concerns for health and environmental protection, with a pending EU-wide proposal to ban the use of all per- and poly-fluorinated alkyl substances. Prominent alternatives exist such as polydimethylsiloxane (PDMS), polyethylene terephthalate (PET), polyvinylchloride (PVC), polysilazanes, or poly(4-methylpentene) (TPX) – all the way to biological polymers such as cellulose or chitin, even though their possible degradation with UV light typically requires the use of additives to increase their durability.

In addition to organic polymers, inorganic materials also serve a key role in the development of new PDRC coatings. Endowed with both a higher refractive index than typical polymers and strong absorption resonances at LWIR wavelengths, many of these materials are also chemically inert, non-toxic, and with high mechanical and UV resistance. To minimize solar absorbance in the UV, inorganic compounds with a band gap energy above 4.13 eV (corresponding to a wavelength of 300 nm) are most relevant, such as ZrO_2, Y_2O_3, h-BN, $CaCO_3$, $BaSO_4$, Al_2O_3 or SiO_2. Depending on the envisioned application, some of these materials may be limited by their high density (such as yttrium oxide) and their scarcity as a critical raw material (such as barium), while others can find use in a range of extreme applications despite their moderate or low refractive index (Al_2O_3 or SiO_2), allowing to form fire-resistant porous ceramic materials [6].

APPLICATIONS AND CHALLENGES TOWARDS COMMERCIALIZATION

Developing new fabrication methods and strategies to combine these materials and exploit their complementary optical and thermophysical properties is instrumental to exploring new PDRC applications, as they extend across different areas and may require a diverse range of features. For instance, PDRC coatings can significantly enhance the conversion efficiency and lifetime of photovoltaic modules by lowering their operation temperature. In this case, however, they should not block all solar radiation but only those wavelengths that are not efficiently converted to electricity. Additionally, due to the above-ambient PV cell temperatures during the peak of the day, broadband rather than selective emissivity should be preferred, and convective losses should be favored as an additional cooling mechanism. Thus, depending on the application, different material properties become desirable.

In addition to the straightforward use of PDRC materials for energy savings in the building sector, other prominent applications include cooling clothing and textiles for personal thermal management, as well as cold storage applications combining both daytime and nighttime cooling for the peak-shifting of cooling-related energy needs. Continuous 24h thermoelectric generation enabled by the temperature gradient offered by PDRC materials has been demonstrated, as well as 24h water harvesting by condensation of air moisture. Water desalination by either evaporation or cascaded freezing stages has been shown, and new applications are being considered for ice and food preservation, as well as for more efficient water use in greenhouses, or for the cooling of electronic devices, batteries or power distribution boards.

Meeting the diverse requirements for all these applications remains still challenging to date. Due to the •••

inherent working principle of the sky cooling mechanism, these materials must be able to withstand prolonged outdoor exposure, where even slight contamination of their surface properties can quickly nullify their cooling function. For this reason, considerable efforts are being devoted to developing coatings that are super-hydrophobic and/or amphiphobic, with low roll-off angles allowing their self-clean under rain or water rinsing. Inorganic coatings or additives such as dyes, emitters or radical scavengers are added to mitigate UV aging, with multi-layered structures being developed to trade off part of the spectral performance for a longer durability and resistance to scratches, abrasion or better adherence to the substrate.

Finally, one of the main outstanding challenges towards the widespread adoption of PDRC materials is related to their industrial scalability [7]. Still to date, most of the results in the literature are based on specimens with a lateral size of a few cm, even though rapid progress is being made by adapting already existing fabrication technologies to the materials relevant for PDRC applications. Phase separation and blade coating processes can be scaled up to continuous roll-to-roll fabrication of multi-layered film structures. Multiple inorganic thin layers can similarly be deposited by a continuous PVD process to form selective emitters. Certain PDRC paint formulations can be sprayed directly onto a substrate, even though work is still needed to minimize the use of volatile organic solvents required to reach the high particle volume concentrations typical of these paints. Finally, fiber-spinning techniques have also been proven as a cost-effective and scalable strategy for the production of large-area PDRC materials.

A growing number of startups and larger companies are currently approaching the market with new PDRC materials, which will foster

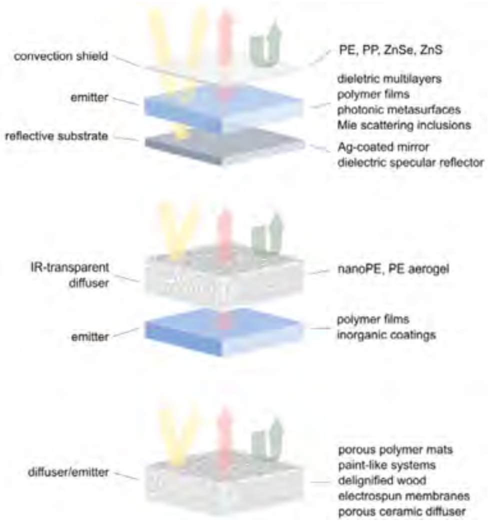


Figure 2. General classification of PDRC material architectures. From top to bottom, different options can exist, based on whether solar reflectance is provided by a metallic mirror, a porous IR-transparent membrane, or a strongly emitting disordered layer.

the development of more stable and scalable solutions, but also raise the question of how to evaluate in a comparable way the cooling performance of this new class of products.

CONCLUSION

In a world with quickly increasing cooling needs, passive daytime radiative cooling stands out as a unique sustainability opportunity enabled by photonics. Compared to all other cooling technologies, it is the only one capable of providing a net refrigeration by directly expelling heat from the planet, rather than discharging it into the environment. Nonetheless, many scientific challenges still require further research efforts, such as finding new ways to mitigate convective heat gains, pollution or dust contamination. Additional limitations of PDRC materials are related to their aesthetics and visual comfort due to their glaring appearance, as well as their static cooling functionality, even though new structurally colored or self-adaptive materials are quickly emerging, which can modulate their spectral properties based on external stimuli. Multidisciplinary approaches are needed for the advanced fabrication and characterization of this new class of materials, driven by the fast progress of photonic structures with selective spectral properties optimized over the broad wavelength ranges encompassing both solar and thermal radiation. ●

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MINIATURIZING GREENHOUSE GAS ANALYSIS WITH FIBER FABRY-PEROT MICROCAVITIES

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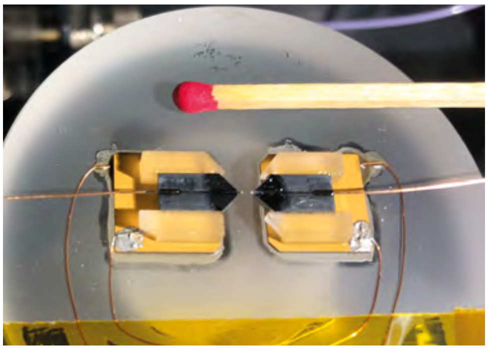

Fiber Fabry-Perot (FFP) cavities with laser-machined mirrors combine exceptional optical properties with a rugged, miniaturized, inherently fiber-coupled design. Originally developed for research on quantum technologies, they have found applications far beyond that field and are now being used to realize miniaturized, mobile greenhouse gas analysers, as this article explains.

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Reducing anthropogenic greenhouse gas (GHG) emissions is a number one requirement for a more sustainable world. Carbon dioxide is responsible for more than two thirds of the global warming, followed by methane, which has a lower concentration in the atmosphere, but has global warming potential more than 80 times that of the same quantity of CO_2. Globally, we know quite well what causes these emissions. For CO_2, fossil fuel combustion is by far the biggest culprit, but also concrete production for example. Methane is released in stages of natural gas extraction, processing and transport (pipeline leaks), but also from agriculture. Under the pressure of evidence, GHG reduction targets are agreed upon, but putting them into practice requires reliable emission measurement. This is why measurement technology has a key role to play here. For example, a recent report [1] of the United Nations Environment Programme puts improved gas leak detection on top of its list of recommended measures to reduce methane by 45 % by 2030. The EU methane regulation which entered into force in August 2024 requires operators in the oil and gas sector to detect leaks and monitor source-level emissions on a regular basis. On the research side, oceanic CO_2 concentration needs to be measured globally with increasing spatial and temporal coverage. In all these measurement situations, small, mobile gas analyzers can provide substantial gains in productivity, coverage and data quality, but this requires instruments which are only starting to exist.

While there is a wide range of technologies for gas analysis in general, very few of them are suitable for precise, quantitative measurement of low concentrations in the ppm (parts per million) range and below, as required for GHG detection and abatement. For example, electrochemical and MOS sensors are cheap and small, which is why they are used in

CO_2 detectors for classrooms or air conditioning systems. But they are prone to cross-sensitivity: their reading may be affected by other gases than the CO_2 they are supposed to measure, such as hydrogen or even water vapor. This makes them unsuitable for more quantitative analysis. The gold standard for quantitative trace gas analysis is laser spectroscopy, mostly by absorption: a laser source is scanned across a specific resonance of the desired molecule; the attenuation of the laser beam is measured as it passes through a sample volume. Resonance frequencies are the fingerprint of a molecule, very specific to each molecular species, making it possible to largely avoid the cross-sensitivity problem. Furthermore, the relationship between the signal (absorption) and the desired quantity (molecular concentration) is governed by simple physical laws, enabling reliable quantitative measurement in real-life conditions, where factors such as gas composition, temperature, pressure and humidity may all vary widely. This is more challenging for methods such as photoacoustic spectroscopy, which has excellent sensitivity, but a detection mechanism relying on acoustic wave conduction between the sampling region and the microphone.

Laser absorption spectroscopy, in its turn, is still a broad term that covers a variety of techniques, ranging from simple, single-pass absorption of a diode laser to powerful and sophisticated methods such as dual-comb spectroscopy. For trace gas analysis, one problem to solve is the extremely weak signal resulting from the low concentration: at the typical ~330pm CO_2 concentration in air, a laser beam which is resonant with one of the relatively strong CO_2 resonances at 2µm wavelength is attenuated by only 0.5 % per meter of path length. In spite of this very weak absorption, today's spectroscopic trace gas analyzers are impressively powerful instruments, easily reaching and even surpassing •••

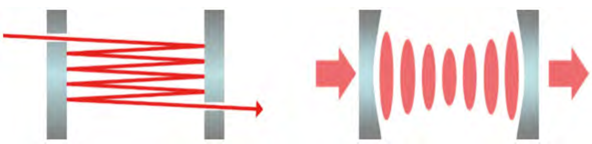


Figure 1. Two ways to increase optical path length for high-sensitivity spectroscopic detection. In a multipass cell (left), the laser beam is reflected multiple times between the mirrors, hitting a different mirror spot at every reflection. Mirrors need to be carefully aligned so that the beam leaves the cell through the exit hole after a high number of passes through the cell. In practice, this limits the number of passes to less than 100 typically. In a Fabry-Perot cavity (right), there is no exit hole. All reflections are exactly superposed and the transmitted beam results from constructive interference of the very weak transmission of each of the partial beams. With high-reflectivity, low-loss mirrors, the effective path length can be more than 100000 times the cavity length.

the sensitivity and uncertainty requirements for greenhouse gas monitoring and abatement in many cases. They reach this performance by using mirrors to multiply the optical path length. This can be done in two ways, using either a multipass cell or an optical cavity (Figure 1). With established technology, however, both cavities and multipass cells are massive, macroscopic objects, requiring sturdy construction to achieve the required stability, measuring tens of centimeters and weighing several kilograms. They also require a dedicated optical system for precisely matching the small spatial mode of the laser diode to the macroscopic cavity mode profile. The end result is a large and heavy instrument, usually weighing tens of kilograms and consuming upwards of 100 W electrical power. Mobile surveys with such instruments typically require trucks or airplanes.

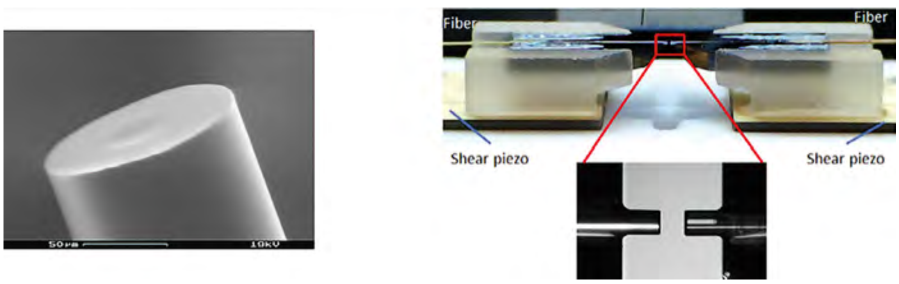
Unsurprisingly, researchers and manufactures are aware of this drawback and are making efforts to reduce the size and weight of their cells and cavities. However, there are limits to what can be done without a radical change in technology. In the case of multipass cells, physics itself imposes limits to miniaturization: here, the last reflected beam should fully pass through the exit hole, while the neighbouring one should still be fully reflected. Due to diffraction, this condition becomes harder to fulfill as the mirror area is shrunk down for miniaturization. The situation is different in cavities, where all passes hit the mirrors at the same spot, so that radical miniaturization is conceivable in principle, while maintaining much higher pass numbers in the hundreds of thousands. However, this requires new approaches to fabricate the miniature, ultralow-loss, concave cavity mirrors. As we will see below, this problem has been recently solved by research advances achieved in a completely different area: this is where gas analysis meets quantum technologies.

FIBER FABRY-PEROT MICROCAVITIES

Quantum technologies have been a main driver for intense development of optical microcavities that has been going on since the early 2000's [2]. This is because qubits – the elementary building blocks of all quantum technologies – often rely on strong and controlled coupling between single photons and single quantum emitters. The latter can be solid-state objects such as quantum dots, defect centers in diamond, or indeed gas-phase atoms and molecules. This research has turned out highly original solutions, many of which have found applications beyond the application they were intended for. Well-known examples are photonic bandgap cavities, silica microspheres, and toroid resonators. However, for most of those microscale technological marvels, the optical field is concentrated with-in the solid, glass or semiconductor structure. As a consequence, gaseous emitters can only couple to it through the evanescent field that is confined to a minuscule layer close to the surface (typically less than 200nm), which leads to unwanted surface interactions and drastically restricts the detection region. For these emitters, free-space cavities such as the Fabry-Perot (cf. Fig. 1) have an obvious advantage, because the photonic field fills the entire free-space area between the mirrors, unperturbed by surface effects. This is true not only for quantum technologies, but also for gas spectroscopy, where the Fabry-Perot's entire mode volume is accessible to gas flow. Yet, traditional technologies do not allow for miniaturization of Fabry-Perot cavities without sacrificing the desired very high finesse (tens to hundreds of thousands). The reason for this is as simple as it is fundamental: high finesse means low loss upon reflection – as low as a few ppm to reach a finesse of 100000. Reaching such an extremely low loss requires correspondingly low surface roughness – below 0.2nm rms for a mirror in the near infrared. When it comes to mirror polishing, the only way to reach this ultralow roughness used to be a technique known as superpolishing, which works well for large radius of curvature of a few centimeters or more, but fails for the small, strongly curved mirrors that would be needed for a submillimeter-scale Fabry-Perot. Things have changed with the advent of fiber Fabry-Perot cavities with CO_2 laser-machined micromirrors [3,4], which turned out to be a game changer.

The idea of laser-machined micromirrors is very simple: focus a high-power laser spot onto a glass surface to obtain laser ablation, and the result will be a concave depression centered at the laser spot. What was less obvious was whether this could be combined with the required ultralow surface roughness. Laser ablation on dielectrics has a

Figure 2. Left: Scanning electron micrograph of a laser-machined, ultralow-roughness mirror shape on an optical fiber. The fiber diameter is 125 µm. Right; Photograph of a complete FFP microcavity. The cavity length in this example is 120 µm; cavities have been realized with lengths ranging from less than 3 µm to more than 1.5 mm.



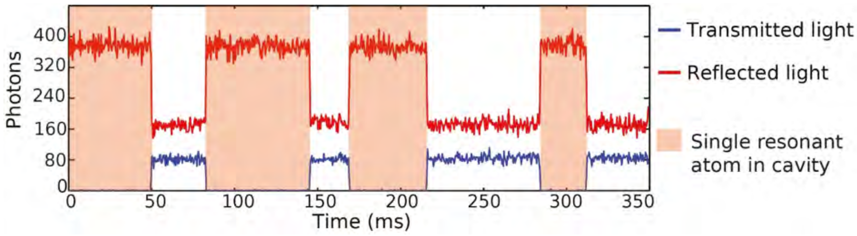


Figure 3. Single-atom detection with a fiber Fabry-Perot cavity. When a single, laser-cooled atom is trapped in the cavity and the cavity and probe laser are tuned to the atomic resonance, the cavity switches from full transmission to full reflection due to the presence of the atom. Figure adapted from [9].coupled average powers.

tendency to create sub-wavelength ripples on the machined surface, limiting the surface quality – our group rediscovered this well-known fact in our first attempts to machine optical fiber surfaces with femtosecond laser pulses. But it turned out that there is an exception: with the right parameters, we found that CO_2 laser pulses can produce ultralow-roughness concave depressions in fused silica – a readily available optical glass. Figure 2 (left) shows a scanning electron micrograph of a concave mirror shape machined in this way. Radii of curvature as low as 10 µm have been reached with this technique, with a surface roughness that consistently reaches 0.2 µm rms. These remarkable features are the consequence of two physical processes occurring simultaneously: ablation is one, and is responsible for evaporating material to create the overall concave structure. At the same time, melting occurs in a thin surface layer, allowing surface tension to dress the liquid surface into a low-roughness state. The fact that these two processes can occur simultaneously is a lucky consequence of fused silica's material parameters in the regime of CO_2 laser wavelengths. The original publications [3,4] use 10.6 µm lasers, 9.3 µm lasers were later shown to work as well [5]. Machining mirror surfaces in this way solved the micromirror problem: once the substrate has been machined, it can be coated with high-reflectivity dielectric coatings using existing, commercially available coating processes, yielding mirrors with absorption and scatter losses as low as a few ppm, approaching the values achieved with traditional superpolishing.

Good luck did not stop there. Fused silica happens to be the glass from which most optical fibers are made. Cleaved optical fiber • • •

Figure 4. Left: The Fiber Fabry-Perot tunable cavity available from Mirega.com. Right: With its 100 m optical path length in a mm-scale form factor and <100g weight, this device enables a drone-mounted trace gas analyzer (artist's view).

tips thus provide an ideal substrate on which to realize the newly discovered low-roughness micromirrors. This gives rise to a microcavity with exceptional properties: finesse values above 200000 have been achieved, while at the same time, coupling light into the cavity is as easy as plugging together optical fiber connectors. Indeed, the problem of aligning the incoming beam with the cavity mode is now solved at fabrication time, rather than on the user's optical bench. By appropriately matching the mirror parameters, fiber type and cavity length, excellent mode matching can be accomplished without additional optical elements, and cavity transmission losses below 1.5 dB have been reached. In cases where cavity parameters cannot be chosen in that regime, permanent low-loss mode matching can still be achieved by integrating a stretch of gradient-index fiber, as shown in [6].

Recently, laser-machined micromirrors have been further improved [7] by going beyond the single-shot process that was used in the original version. With a single laser shot, the resulting depression has a Gaussian shape, rather than the desired spherical one. Close to the center, the Gaussian can be approximated by a sphere, and this is why these mirrors still give good results if the beam diameter is small enough. However, the Gaussian shape limits the usable cavity length and gives rise to nonstandard higher-order modes. In the improved version, mirrors are machined by applying dozens of laser pulses to the same surface in a carefully optimized pattern. The result is a close approximation of the desired spherical shape over a much larger area. This is what has enabled millimeter-long fiber Fabry-Perots [7], and we now routinely apply this process to produce our fiber mirrors. It is a key factor in the application to gas detection, as we will see below.

SINGLE-ATOM DETECTION AND MOLECULAR SPECTROSCOPY WITH FFPS

Fiber Fabry-Perot microcavities excel in ultrasensitive detection of atoms down to the single-particle level [8]. Figure 3 shows how cavity transmission changes from full transmission to full reflection due to the presence of a single resonant atom trapped in the cavity mode [9]. Experiments like this brought FFP microcavities to the attention of many researchers. Today, FFPs are employed in research applications ranging from single-photon sources and quantum network nodes to optomechanics and biomolecule detection, and they are considered a promising technology for future atom-based quantum simulations. A novel FFP-based scanning microscopy technique has been demonstrated [10] and is now commercially available from the startup Qlibri. Interestingly, different applications exploit very different elements of the FFP's rich feature set: strong coupling to quantum particles, extremely large free spectral range and narrow resonances making them a remarkable optical filter, built-in fiber coupling, miniature size and robustness making them suitable for field applications. A review article [11] describes many of those features and applications as of 2021, but the field is moving rapidly and the list of applications continues to grow.

Some experiments have already demonstrated different forms of gas spectroscopy with FFP cavities. Early on, a beautiful series of experiments focused on Raman spectroscopy [12]. The FFP was used in a doubly resonant configuration, where both the pump beam and the Raman emission were resonant with the cavity. CO_2 in air was measured in this way, resulting in a cavity-enhanced emission signal that was enhanced by an impressive factor of 10^7 with respect to what would have been observed without a cavity under comparable conditions. More recently, absorption spectroscopy of oxygen has also been demonstrated [13]. However, these were laboratory experiments not intended to leave the well-controlled conditions of a research lab.

MINIATURIZING TRACE GAS ANALYSIS WITH FFPS

Empowered by the FFP microcavity, the vision of a compact and robust, drone-mountable cavity-enhanced greenhouse gas analyzer is now getting fulfilled. The challenge has been taken up by the newly founded startup Mirega SAS in collaboration with Laboratoire Kastler Brossel in Paris, with support from SATT Lutech and an ERC Proof-of-Concept grant of the EU. The first, crucial step was to develop the FFP cavity itself from its laboratory implementation into a high-TRL product. As a stand-alone product, it acts as a tunable optical filter with extremely narrow bandwidth and an exceptionally large stopband. It is available as a standard product in the telecom C-band wavelength range. Other wavelengths and filter parameters will follow next year.

Most importantly however, this device has removed the main miniaturization roadblock for mobile, cavity-enhanced trace gas analysis. Based on the FFP technology, constructing an MVP-level portable CO_2 analyzer became a straightforward task, requiring a very small number of external components. We have built two of these devices which now routinely detect CO_2 in our lab. Characterization of their detection properties (sensitivity, drift etc) is under way. The optical circuit is entirely fiber-coupled with no need for free-space components. The project received another boost when this analyzer was selected for support by the Nova incubator by GRTgaz, a major European operator in pressurized gas transport. As part of this program, a methane version of our analyzer will be tested in GRTgaz's test and calibration laboratory in November. In parallel with this work, we are also pushing forward the software development that will turn the analyzer into a turnkey product.

Beyond its primary advantage, the FFP analyzer comes with additional benefits. Power efficiency is one of them, because the microscopic cavity and gas volume can be temperature stabilized with very low heating power, and because a micropower MEMS pump is enough to ensure a stable gas flow. Another advantage is the extremely small cavity volume, which is on the order of a nanoliter. This enables even the smallest gas samples to be analyzed, as required for dissolved gas analysis, for example. Moreover, it significantly increases the analyzer's response time, because the gas exchange rate is very fast. Last not least, the microscopic, monolithic construction drastically reduces sensitivity to vibrations and shock. With all these features under its tiny hood, the FFP analyzer has a lot to offer to the gas analysis market. Greenhouse gas abatement requires a multitude of new technologies; we hope this one can make its miniature contribution.

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MOLECULAR STRONG COUPLING

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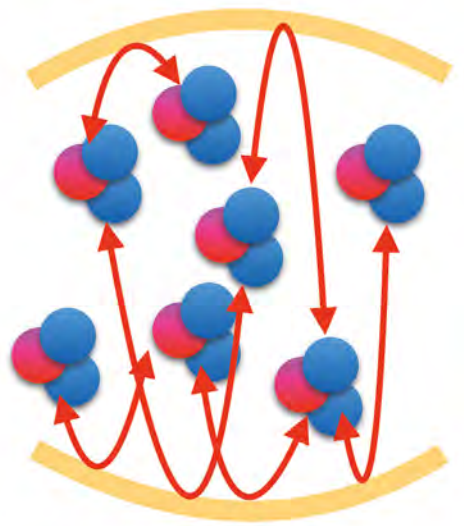

Strong coupling between an ensemble of molecules and an optical cavity mode offers exciting prospects in photonics, materials science and chemistry. We look at the conceptual background of strong coupling by making direct connection with cavity-QED. We then look at two topical areas in which researchers seek to exploit strong coupling, energy transport and chemical reactivity. We conclude with a summary and a look to the future.

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Think of an excited atom inside an optical cavity Figure 1a, the cavity is tuned to be in resonance with the atomic transition by adjusting the path length between the mirrors. If the atom can exchange its energy with the cavity mode at a rate g that is faster than any dissipation rate – *e.g.* the rate of photon leakage from the cavity κ, and the decay rate of the atom γ – then the atomic transition and the cavity mode have time to interact with each other and form two new hybrid states, the excitations of these hybrid states are called polaritons. Polaritons inherit both light and matter character and are at frequencies different from the uncoupled atomic and cavity resonances, see Insert 1. The frequency gap that opens up between the new modes is known as the Rabi splitting of the system. Figure 1a shows such an atom cavity system from the 1990s, when such systems were explored as part of a wider endeavour to better understand and exploit quantum mechanics, a field known as cavity quantum electrodynamics (c-QED) [1].

The extent of the Rabi-splitting in c-QED is sub meV, much too small to have an effect on the properties of a single molecule. However, experiments with several atoms in the cavity at one time showed that the energy level (Rabi) splitting scales with the square root of the number of atoms involved, see Insert 1. This scaling is exploited in molecular strong coupling such that systems involving millions/billions of molecules, Figure 1b, may show a Rabi splitting of a significant fraction of an electron volt. The hybrid nature of the newly formed states can have several useful consequences; giving photonic modes mass (a matter characteristic) in this way has led to the creation of Bose-Einstein condensation, whilst giving material excitations (e.g. excitons) photonic properties leads them to have significant spatial coherence, enabling polariton lasing.

The large number of degrees of freedom associated with an ensemble of molecules in a cavity inevitably means that the picture we have just described is a very idealised one. In practice many other important phenomena are involved. Of particular interest are the dark states, collective states that do not emit or interact with far-field photons as they lack the electric dipole moment of the bright (polariton) states. Recent work suggests that the presence of disorder (inevitable in most experimental situations) can enable the dark states to contribute with the collective response of the system in a useful way, see Insert 1 [2]. It has also become clear that all of the modes supported by a cavity need to be considered, not just the mode in resonance with the molecular transition.

What may be accomplished by harnessing strong coupling? Here we focus on two topics by way of example: intermolecular energy transfer and chemical reactivity.

ENERGY TRANSFER

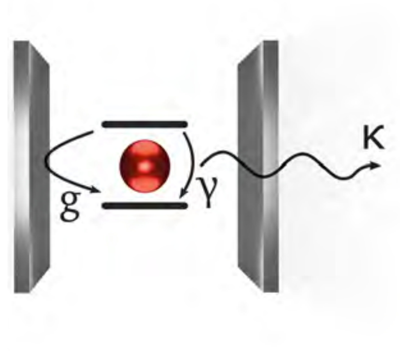
The transfer of energy from donor to acceptor molecular species is a key part of nanophotonics, and harnessed very effectively by nature in photosynthesis. By strongly coupling either donor and/or acceptor molecules to a cavity mode, new energy transfer opportunities are opened up. Particularly appealing is the idea of extending the usual nanometre (nm) range of the transfer process by harnessing the delocalised yet coherent nature of polaritons, thereby bypassing the usual dependence on spatial separation. Energy from the donor may be coupled to a polariton state, from where it may in turn couple to the acceptor, a process known as polariton-assisted energy transfer. Several demonstrations of polariton-assisted molecular energy transfer have been reported in the past few years [3,4].

Figure 2, panel a, shows the arrangement used in both of these demonstrations. A planar microcavity is formed containing a layer of donor molecules (blue) separated from a layer of acceptor molecules (red) by a spacer layer (grey). The spacer is thick enough (>10 nm) to prevent the usual Förster energy transfer process. With appropriate tuning of the cavity resonance with respect to the molecular energy levels, clear evidence of polariton-assisted energy transfer is obtained, panel b. When the molecular system is pumped by a UV light source, and the cavity is ill-tuned, donor emission dominates (blue circle data points). When the tuning is correct then the emission is dominated by acceptor emission (red diamond data points) despite the acceptor molecules being located on the other side of the spacer layer; the 'bare' donor and acceptor spectra are shown for comparison.

These initial results now need to be translated into working opto-electronic devices, perhaps focussed on improving power conversion efficiencies in organic photovoltaics. Looking ahead one can envisage spatially manipulating the photonic landscape and in so doing provide a means to provide funnelled (directed) polariton-assisted energy transport.

CHEMICAL REACTIONS

The modified spectra that arise as a result of strong coupling naturally lead to the question of whether the formation of hybrid polariton states might also result in changes to chemical reactions. It is not obvious that this will be the case, since typically ground state reactions proceed through the cumulative effect of a large number of individual collision events, whilst strong coupling involves the collective response of the molecular ensemble. Electron transfer • • •



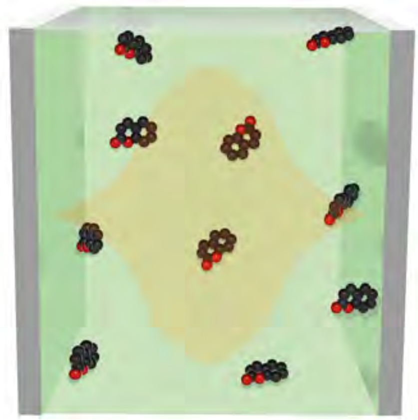


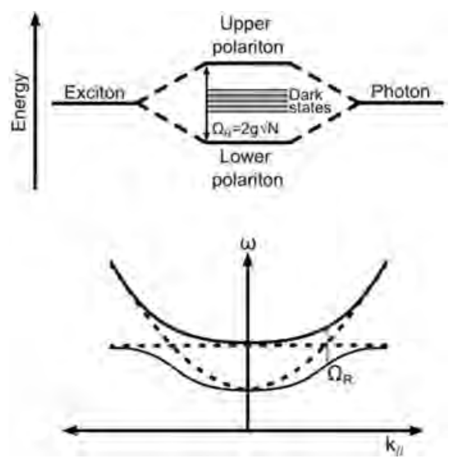
Figure 1. (a) Schematic of single atom c-QED cavity system, (b) Schematic of molecular strong coupling cavity, showing optical field profile for first order cavity mode. For clarity only a few molecules are shown.

reactions, such as those involved in photosynthesis, are different in the sense that the reactive event does not involve two-particle collisions, rather an excited electron undergoes a tunnelling transition from a donor to an acceptor state within a molecular complex. Interestingly, it was shown in 2016 that when donor excited states are coupled to a cavity field to form a donor-polariton state, the excited electron is delocalized over N molecules, and this increases the probability of tunnelling to a local acceptor state, increasing the electron transfer rate [5]. In contrast, if the acceptor states are coupled to the cavity, forming an acceptor-polariton, an excited electron localized in a donor state is now less likely to be transferred because the acceptor wavefunction is diluted over N molecules, decreasing the donor-acceptor charge density overlap. We can encapsulate this information in a 'rule of thumb': molecular transitions that are collective-to-single (N→1) can be enhanced by strong coupling, whilst single-to-collective transitions (1→N) are suppressed.

Should this simple rule of thumb also hold for thermodynamic reactions inside cavities? This question is the subject of ongoing theoretical debate about the microscopic mechanism behind observations of modified reaction rate constants for several chemical reactions in infrared cavities [6]. Since reactive collisions are local and strong coupling is collective, the 1→N scaling argument should naively hold, so that no rate modifications are expected. However, thermodynamic chemical reactions do not proceed *via* ultrafast tunnelling transitions such as electron transfer, so this simple argument breaks down. The rate constant is a macroscopic observable that encodes an average over a very large number of individual reactive collisions occurring over timescales much slower than the time it takes for strong coupling to be established in a cavity.

One suggested origin of the observed rate modifications is a change in the reaction energetics due to collective strong coupling. However, the cavity field ideally couples and modifies the energies of only a pair of collective molecular states that are bright. An overwhelming majority of dark molecular states, see Insert 1 (top), keep the same energy as in free space and effectively do not see a difference in the reaction energy landscape.

If spectral changes (polariton splitting) due to strong coupling do not have an influence on the reaction rate, another possibility is that somehow the strong light-matter interaction modifies the way in which reacting molecular ensembles thermalize. This is a macroscopic effect that affects all molecules and could modify the probability of overcoming the reaction barrier that separates reactants from products. Under what conditions this mechanism might be possible is the subject of intense debate, since our usual understanding of reaction rate



TOP. In molecular strong coupling the molecular and cavity modes interact to form upper (UP) and lower (LP) polariton states. This is similar to the interaction between atomic states to form bonding and antibonding orbitals. For N interacting molecules the difference in energy between the UP and LP is $2g\sqrt{N}$. In addition to the two bright collective states (UP and LP) there are N-1 dark states centred around the original molecular frequency. BOTTOM. The simple energy level picture in the upper half of the figure is better indicated by a dispersion diagram, where the variation of the energy of the UP and LP states with momentum in the plane of the cavity, $k_{//}$, is shown. The dashed lines indicate the uncoupled photon and molecular states, the full lines the coupled modes (for clarity dark states are omitted).

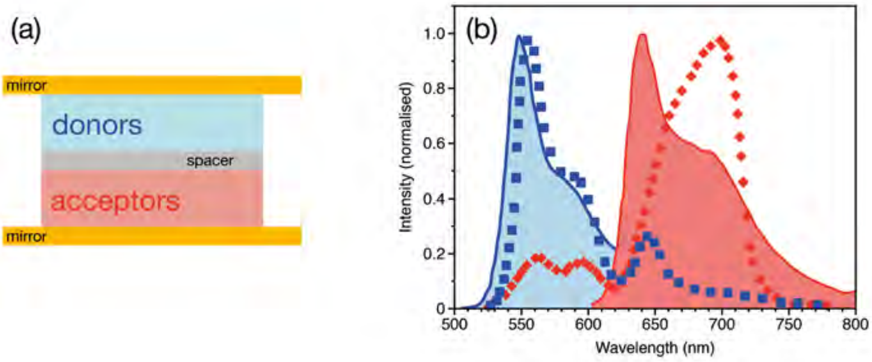


Figure 2. Polariton assisted energy transfer. (a): the cavity contains a layer of donor molecules (blue) and a layer of acceptor molecules (red) separated by a spacer layer (grey) that is thick enough to prevent Förster transfer. (b) Emission spectra of bare donors and bare acceptors are shown as blue- and red-filled spectra. When the donors in the donor and acceptor filled cavity are pumped by a UV light source the emission depends on the cavity tuning. For poor tuning there is very little energy transfer and donor emission dominates (blue squares). For correct tuning the emission is dominated by acceptor emission, despite the donors and acceptors being separated by more than the Förster distance. All spectra have been normalized, and are adapted from [4].

theory rests on canonical ideas of thermal equilibrium that, in principle, should also hold under strong coupling. All of these theoretical ideas need to be tested in carefully controlled experiments.

SUMMARY

Molecular strong coupling has caused much excitement as a result of the dramatic prospects on offer by using nanostructured optical environments to modify material behaviour, particularly the tantalising prospect of controlling chemical reactions. The field is currently at a cross-road because an underpinning theoretical and conceptual framework capable of explaining all strong coupling phenomena has yet to be developed [7], and because some questions concerning reproducibility of experiments remain. In particular, the scope of what can be achieved with strong coupling, and what cannot, has still to be fully defined, *e.g.* what type of chemical reaction is amenable to control via strong coupling? Research on both experimental and theoretical fronts is intense. On the theoretical side a key challenge is to capture all of the relevant physics and chemistry in one model, on the experimental side a major challenge is to exploit non-optical ways to monitor cavity-based chemical reactions in real time. Many research groups are making good progress, but it is likely to be several years before we have a complete picture.

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ULTRASTABLE LASERS FOR OPTICAL CLOCKS

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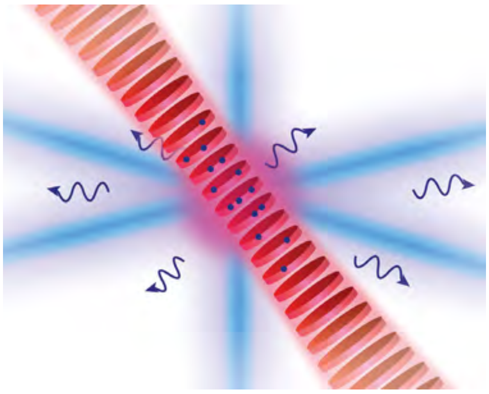

In quantum science and technology applications such as optical clocks, ultrastable laser sources can address extremely narrow atomic transitions without introducing noise to the system. The required level of stability and precision has historically only been achieved under controlled laboratory conditions. Novel commercial solutions combined with new approaches are now meeting the high demands for field applications of emergent quantum technologies.

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Since its first experimental demonstration in 1960, the laser has evolved from being "a solution in search of a problem," to a ubiquitous tool in our everyday lives. Spectroscopy is one such "problem" that lasers have revolutionized, bringing high-precision spectroscopy to prominence in real-world commercial applications. The ability to address ultra-narrow linewidth transitions in matter has led to an explosion of research in the fields of optical clocks, metrology, and generally in quantum science and technology [1,2].

Precise measurement of time intervals relies on a stable, high-frequency oscillator, whose performance is rated in terms of the fractional frequency stability. Cesium atomic clocks, based on the transition between hyperfine states of cesium-133, oscillate in the microwave region at 9 192 631 770 Hz and can reach accuracies of around 10^{-16}. They have formed the basis of Universal Coordinated Time since 1967 [3], but to reach the next level of timing accuracy, a higher frequency oscillator is required. Moving from microwave to optical frequencies, realizing an optical atomic clock, results in several orders of magnitude increased oscillations and can offer better performance, but such frequencies are harder to measure.

An optical clock involves the spectroscopy of atoms or ions using laser light for higher-energy transitions on the order of hundreds of THz, as opposed to 9 GHz atomic transitions in Cs. These so-called clock transitions typically have narrow linewidths, requiring an ultrastable laser with linewidths of less than 1 Hz, and can result in an optical clock with an accuracy of 10^{-18}. But historically, the laser sources required for this were large, complex systems requiring optical tables and controlled laboratory environments. Here we discuss compact technological solutions that can enable the newest generation of optical atomic clocks.

ULTRASTABLE LASERS

The typical linewidth of a stable free-running laser is on the order of a few hundred kilohertz, so to reach the criteria for the high-precision spectroscopy in an optical clock, some kind of method of frequency stabilization is required.

One method of achieving this involves the comparison of the laser output frequency with an ultrastable reference, and then converting the resulting offset between the two into an electrical signal. This electric signal can then be fed back to the laser control parameters to realize active frequency stabilization. The frequency comparison can be performed between the laser output frequency and a chosen resonance frequency of an ultrastable reference cavity. Modulation of the laser frequency across the resonance results in peaks (dips) in the transmission (reflection) signal on a photodiode. The resulting error signal slope, with zero crossing at the resonance frequency, serves as the locking point for the laser control parameters. This approach is known as the Pound-Drever-Hall (PDH) technique [4].

Put simply, a cavity-based ultrastable reference laser system typically comprises a single-mode laser source, an optical reference cavity, as well as the necessary optics and electronics for feedback control. A Fabry-Pérot cavity can be used as the optical reference, and is the heart of the entire system. It is formed of two mirrors with highly-reflective coatings, optically-contacted to a spacer that defines the cavity length. The challenge is keeping the distance of the mirrors stable at the 10^{-16} level on the timescale of a second, despite the impact of environmental perturbations. Ultralow expansion (ULE®) glass can be used for the spacer and the mirror substrates, to minimize thermal effects on the cavity length. ULE glass boasts the property of vanishing thermal expansion at the so-called "zero-crossing temperature." In the specific case where the zero-crossing temperature is room temperature, the need for bulky and complex thermal management is reduced. ULE compensation rings enable the use of alternative substrate materials for the mirrors, for example fused silica, to achieve a lower thermal noise floor.

Figure 1 shows examples of resonator cavities with two different spacer geometries; a 5 cm cubic cavity and a 12.1 cm cylindrical cavity. The shape can help optimize the mechanical stability and decoupling from environmental perturbations like vibrations, but one of the critical parameters determining the overall performance of a high-finesse Fabry-Pérot cavity is the linewidth of its resonant transmission frequencies. This is given by the ratio of its free-spectral range (*FSR*, the frequency spacing of the resonator modes) and the finesse (*F*, a measure of how sharp the resonances are):

$$\Delta\nu_{FWHM} = \frac{FSR}{F}$$

A longer cavity length, L, reduces the FSR of the cavity and thus also the cavity linewidth (c is the vacuum speed of light):

$$FSR = \frac{c}{2L}$$

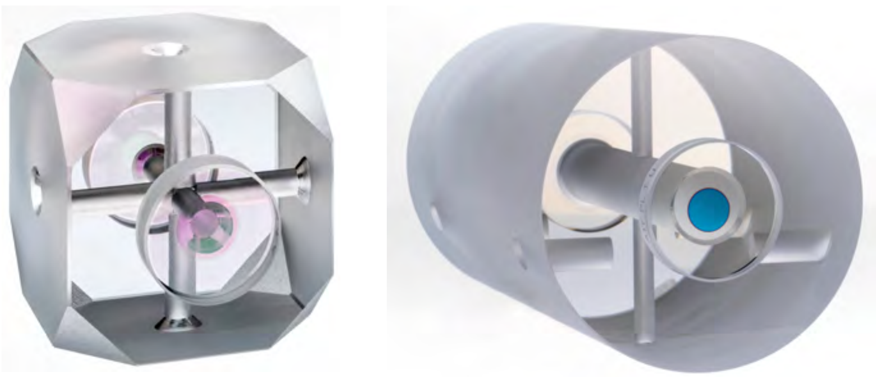
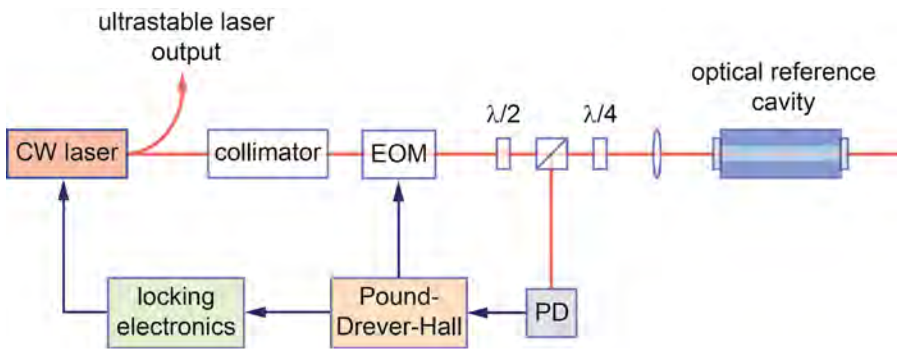


Figure 1: A 5 cm cubic Fabry-Pérot cavity developed by the National Physical Laboratory (left), and a 12.1 cm cylindrical cavity designed by the Physikalisch-Technische Bundesanstalt (right), each comprising an ultra-low expansion (ULE) glass spacer with optically contacted highly reflective mirrors (external faces anti-reflection coated).



The finesse related to the reflectivity, *R*, of the cavity end mirrors via:

$$F = \frac{\pi\sqrt{R}}{1-R}$$

The higher the reflectivity of the cavity mirror coatings, the higher the finesse, and the lower the cavity linewidth. A typical reflectivity on the order of 99.999% yields a finesse value of >300,000.

The PDH technique is a powerful scheme used for the active stabilization of a laser frequency to an ultrastable optical reference. Figure 2 depicts the principle of PDH stabilization of a continuous-wave (CW) laser. An electro-optic modulator (EOM) adds sidebands to the laser light in the frequency domain to modulate the phase of the laser light. A photodetector (PD) detects the fraction of light reflected from the cavity, delivering a signal that is dependent on the EOM modulation frequency. Subsequent down-mixing with the modulation frequency results in an error signal, which contains information on how far off the carrier is from the cavity resonance. This error signal can thus be used for the active stabilization of the laser to the cavity resonance by serving as a feedback mechanism to the laser controls.

Figure 2: Principle of the Pound-Drever-Hall locking scheme: A small fraction of the single mode laser light is inserted into the reference cavity after frequency modulation. The reflection off the cavity end mirror is measured by a photodiode (PD) providing an electrical signal, which is converted into an error signal serving as laser feedback.

Fluctuations of the cavity length can impact the performance of the cavity-locked laser. It is thus important to ensure the cavity is isolated from ambient conditions like temperature, pressure, acoustic noise, and mechanical vibrations. This can be achieved via operation of the cavity in a vacuum, active temperature stabilization, acoustic shielding, and vibration isolation. Examples of commercial, 19-inch rack-mounted ultrastable reference systems, complete with CW laser, ultrastable reference cavity, PDH locking electronics, vacuum system, and environmental shielding, are shown in Figure 3. The system on the left-hand side includes a vibration isolation

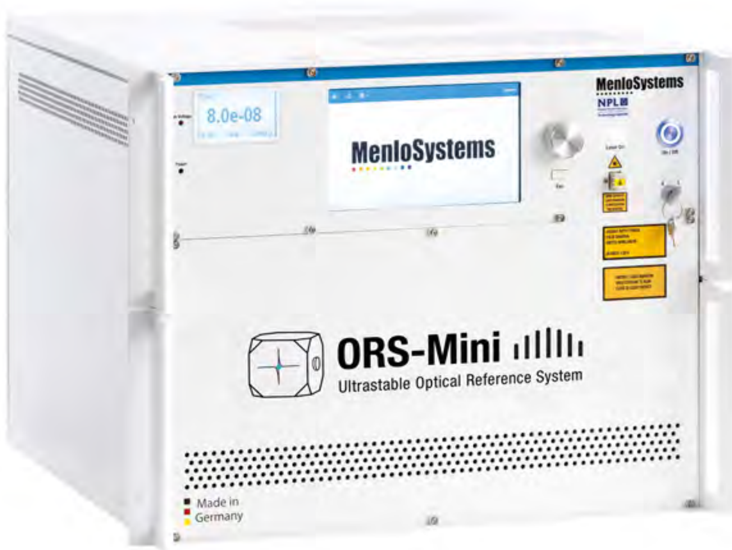


Figure 3: An example of a complete rack mounted compact ultrastable reference system providing sub-Hertz laser linewidth (left), and an example of a compact version providing < 2 Hz laser linewidth (right).

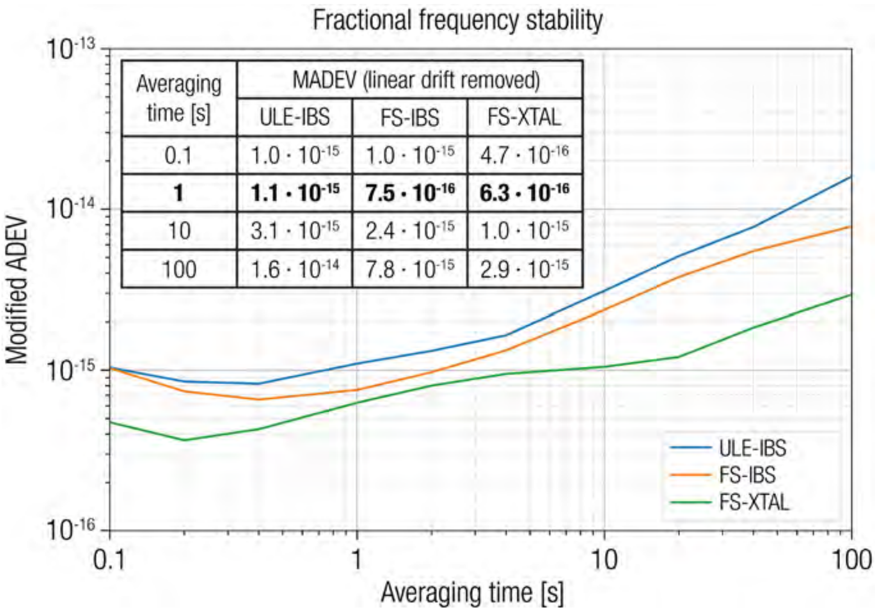


Figure 4: Comparison of the fractional frequency stability of a commercial ultrastable laser using different substrates and coatings of the cavity end mirrors.

platform and is 1.6 m tall. The system on the right-hand side does not include the vibration isolation platform, but is only 8 height units. This shows substantial development from the historical systems that occupied large areas in research laboratories, to a rack-mounted system that can be turnkey operated.

The performance of an ultrastable reference is given by the fractional frequency stability. For the system shown in Figure 3 on the left-hand side, the fractional frequency stability, measured by the modified Allan deviation (modified ADEV), is shown in Figure 4, where comparisons of performance using different cavity mirror substrates and coating technologies are presented: ULE-IBS (ultralow expansion glass-ion beam sputtering), FS-IBS (fused silica-ion beam sputtering), and FS-XTAL (fused silica-crystalline coatings). A slow linear frequency drift, arising due to continuous length shrinking of the ULE substrates due to aging, has been removed by data post processing. Such an ultrastable reference can provide CW laser light with < 1 Hz linewidth measured over several seconds, and fractional frequency stability better than 7×10^{-16} at 1 s sampling time. This level of stability is comparable to many complex setups from research laboratories, albeit in a smaller footprint, and can enable some of the most demanding applications where high precision is required. By way of comparison, the system on the right-hand side of Figure 3 can demonstrate sub-2-Hertz linewidth and fractional frequency stability of $< 5\times10^{-15}$.

OPTICAL ATOMIC CLOCK

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Optical clocks have the potential to dramatically improve the accuracy of precision timing and measurements, but their operation and the ability to measure their frequencies is challenging.

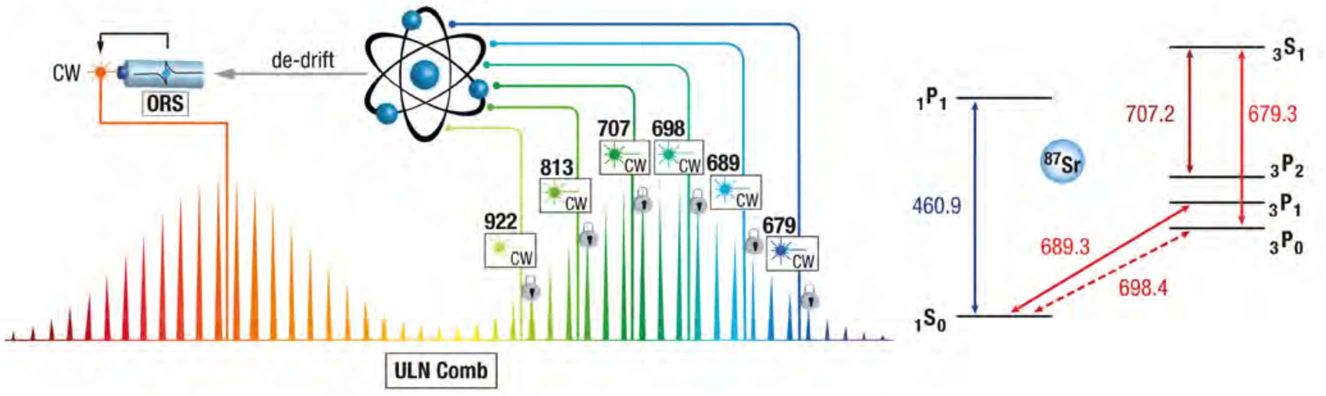

Figure 5: Schematic of a strontium-87 optical lattice clock (left), starting with an ultrastable reference (ORS), which is used to stabilize an ultralow noise frequency comb (ULN Comb), which is then frequency shifted to reach all wavelengths required to realize the clock. Simplified energy level transitions in strontium-87 atoms (right).

and measurements, but their operation and the ability to measure their frequencies is challenging. Optical clocks make use of ultranarrow transitions in the visible part of the spectrum to exploit long coherence times for high-precision measurements. In order to access this high precision, we rely on lasers tuned precisely to the transition frequency. Not only this, but optical clocks require some way of counting the oscillations of the transition – some kind of optical clockwork that "converts" the optical oscillations into oscillations of a lower frequency that can be measured by standard electronics [5]. This can be achieved by combining an ultrastable reference laser with an optical frequency comb.

Figure 5 shows the principle of doing exactly this to realize a type of optical clock known as an optical lattice clock [1], using strontium-87 atoms. In an optical lattice clock, the atoms are confined within an interference pattern of several laser beams to minimize the effect of atomic motion on clock performance. Each atomic species has a so-called "magic" wavelength, where the trapping light does not perturb the resonant frequency of the clock transition. For strontium-87, the magic wavelength is 813 nm. The clock transition in strontium-87 is around 429 THz with sub-Hertz linewidth, so a sub-Hertz ultrastable laser is required at 698 nm for a strontium optical clock. In addition to these two wavelengths, laser light is required to trap and cool the strontium atoms; these wavelengths are 461 nm, 689 nm, 679 nm, and 707 nm.

To realize the strontium-87 optical lattice clock, the scheme in Figure 5 starts with an ultrastable reference laser around 1542 nm. This is then used to stabilize all comb lines of an optical frequency comb, the output of which is then shifted to reach the wavelengths needed for the clock. This process transfers the frequency stability of the ultrastable reference to all wavelengths. The stabilized comb light is then sent to the strontium physics package to result in an optical lattice clock. Finally, to measure the optical clock frequencies the frequency comb is used to convert the optical oscillations into microwave oscillations, which can be counted by electronics. This can be achieved by measuring either the carrier-envelope-offset frequency or the pulse repetition rate of the frequency comb. When these parameters are known, all frequencies of the comb can be determined.

Commercial ultrastable laser systems have become partners in the race to develop the most accurate optical clocks, and are paving the way to portable systems that can be used in the field. By alleviating the need to build such systems in the lab, more resources can be focused on the application itself and outcomes can be accelerated. This is the case not only for optical atomic clocks, but for the burgeoning quantum technology market as a whole, where a high-level of integration ensures turn-key operation for some of the world's most challenging applications.

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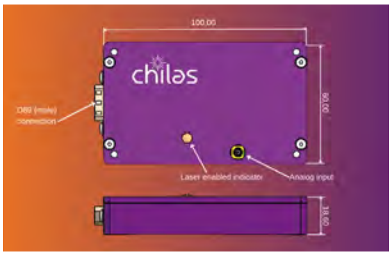
Compact narrow-linewidth swept source laser for the C-Band



This laser developed by Chilas is based on a hybrid-integration External Cavity Laser technology. It is suited for a large range of sensing applications like structural health monitoring using Fiber Bragg gratings, molecular detection using ring resonators, and LiDAR remote sensing.
https://chilasbv.com/chilas-swept-source-laser/?preview=true&_thumbnail_id=1312

HERMETIC FIBER-OPTIC FEEDTHROUGH

SEDI.ATI released the KTRAV-M10, a reconfigurable hermetic fiber-optic feedthrough. This component is suitable for vacuum and pressure applications up to 600 bars. It ensures a high level of hermeticity better than 10^{-10} mbar.l/s.
https://www.sedi-ati.com/hermetic-fiber-optic-feedthroughs/m10-thread-fiber-optic-feedthrough-for-vacuum-and-pressure-up-to-600-bar/

Full HD resolution SWIR camera

New Imaging Technologies (NIT) developped a full HD resolution SWIR camera designed to meet various industries' rigorous demands and to offer imaging quality and precision developped. This camera features ultra-low-noise performance at 25e-.
https://new-imaging-technologies.com/news/full-hd-resolution-sens-1920-a-new-jewel-in-our-swir-camera-portfolio/

NANOLITHOGRAPHY SYSTEM

Heidelberg Instruments launched its new NanoFrazor nanolithography system designed for high resolution, flexibility, throughput, and modularity. Combining Thermal Scanning Probe Lithography, Direct Laser Sublimation and enhanced automation, the NanoFrazor supports research in quantum devices, 1D/2D materials, and nanoscale electronics, as well as applications in nanophotonics, meta-optics, and nanofluidics.
https://heidelberg-instruments.com/heidelberg-instruments-launches-new-modular-and-10x-faster-nanofrazor-nanolithography-tool/

Compact fluorescence detection module with excitation source and detector

Optics module C16028-01 from Hamamatsu is an integratable optical module specialized for fluorescence detection applications such as PCR equipment. It includes high-stability LEDs for exciting fluorescent reagents, high-sensitivity Si photodiodes for detecting fluorescence, and optical systems and circuits optimized for fluorescence detection.
https://www.hamamatsu.com/eu/en/product/optical-sensors/photodiodes/optics-module/C16028-01.html