Photoniques

N°137

LIGHT AND APPLICATIONS | EOS & SFO JOINT ISSUE

INTERVIEWS
Aldas Juronis,
Goëry Genty

ZOOM
Laserlab-Europe
AISBL

EXPERIMENT
Coherent emission
of light

PRODUCTS
Supercontinuum
Lasers

FOCUS ON

MANUFACTURING WITH SHORT PULSE LASERS

- Femtosecond laser structuring of glasses
- Micromachining with ultra-short laser pulses in burst-mode
- Laser-induced nanostructuring
- Advanced manufacturing by ultrashort pulse lasers

\+

- LISA – a giant laser interferometer in space for gravitational waves detection
- Extreme Light Infrastructures (ELI)

European Optical Society

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Editorial

NICOLAS BONOD
Editor-in-Chief

Light as the ultimate tool

Since the first tools shaped by human hands, technological progress has been driven by an ever-increasing ability to control matter. From forging to precision manufacturing, each step has extended our mastery of matter. This continuous refinement has also enabled the emergence of increasingly sophisticated technologies, and among them, lasers, which in turn have deeply transformed this trajectory. By enabling matter to be shaped, modified and probed with light, lasers introduce a new paradigm: light itself becomes a tool. From deep-ultraviolet photolithography to laser-based processes, both at the heart of intense research and major industrial challenges, light is no longer only used to observe the world, but also to shape and transform it with finesse and precision.

With ultrashort and intense laser pulses, light–matter interactions enter highly nonlinear regimes and are governed by complex physical processes. Etching, structuring, or even creating new states of matter relies on mastering these regimes. Advanced optical manufacturing with ultrashort laser pulses is extending beyond the laboratory into industry. Laser processing has become a key technology, driven by its precision, versatility, and its inherently clean, contactless, and chemical-free nature.

At the same time, lasers are at the core of some of the most ambitious large-scale scientific projects. The Extreme Light Infrastructure (ELI) pushes laser intensities to unprecedented levels, opening access to extreme regimes of light–matter interaction and enabling entirely new fields of exploration. In parallel, initiatives such as Laserlab-Europe play a key role in structuring the European laser community, providing access to cutting-edge facilities and fostering collaboration across disciplines. Together, they illustrate how laser science now operates across all scales, from industrial applications to fundamental physics, and both are featured in this international issue.

Light has accompanied every major step in our technological progress, from early experimentation to the most advanced scientific developments. Today, it enables us to shape and probe matter with a level of precision and control unmatched by any other approach. As new frontiers continue to emerge, light increasingly defines how we interact with matter, emerging as the ultimate tool.

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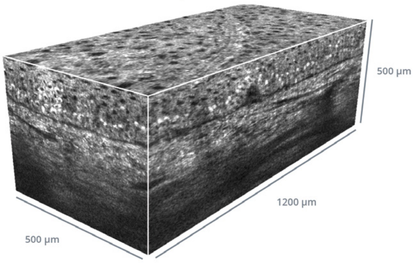

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SFO/EOS forewords

ANTOINE GODARD
President of the French Optical Society

Education: the Cornerstone of Excellence in Photonics

The dissemination of knowledge and the promotion of excellence in the fields of optics and photonics are among SFO's core missions. A key driver for addressing these priorities is education and training.

At the European level, the most visible of our initiatives is undoubtedly the thematic schools aimed at PhD students and early-career researchers. These are, in particular, residential schools organised in partnership with the renowned École de Physique des Houches. Each year, an international thematic school is held there, focusing on a fascinating cutting-edge topic, where participants have the privilege of attending lectures delivered by leading scientific figures. SFO is also delighted to have been associated with the 360 CARLA Career Symposium & Training in Photonics, organised by EOS in Grenoble last March.

SFO is actively involved at many other levels thanks to the significant work carried out by the Education Commission whose mission is to encourage, support and promote all types of initiatives aimed at advancing the teaching of optics in France. The LightBox kit is one of its flagship initiatives, in close partnership with AtoutSciences Association. This educational kit is made available to teachers at all levels, trainers, facilitators, associations and student societies.

Last but not least, the starting five-year LUMIFORM national programme, funded by France 2030 plan (Compétences et Métiers d'Avenir), aims to support and assist teachers for photonics education at operator and technician level, as well as to develop initiatives designed to make the photonics sector more attractive to students. This project is built around a rich and diverse consortium, fully illustrating the complementary roles of academic, voluntary and industrial stakeholders.

Through all these initiatives, SFO has set itself the mission of helping to attract the brightest, most innovative and most visionary talents in order to ensure academic, scientific and technological excellence in the fields of optics and photonics in France and Europe.

François Salin, Antoine Godard, Philippe Grangier
Presidents of SFO

EMILIANO DESCROVI
President of the European Optical Society

Expanding Global networking & Youth Engagement

In a time marked by global uncertainty, EOS is placing greater emphasis on the education of young people and on strengthening collaborations beyond the EU.

In March, the 360 CARLA Symposium and Training, organized by Patricia Segonds (EOS Past President), David Ferrand, Nathalie Destouches and a highly dedicated team at the Institut Néel in Grenoble, brought together more than 150 participants. The atmosphere was informal yet focused, with young researchers moving between scientific discussions and conversations about career paths and opportunities in industry. A highlight was the talk by Anne L'Huillier, which stood out not only for its scientific value but also for the enthusiasm and inspiration she conveyed to the young audience. The effort was carried out in collaboration with the French Physical Society and SFO.

Looking ahead, the next major milestone will be the EOS Annual Meeting 2026 in Tampere this August, chaired by Goëry Genty, Juha Toivonen, Jyrki Saarinen, and Ignacio Moreno, with the support of Photonics Finland, Tampere University, and the PREIN Flagship. The program is broad, with 8 topical meetings, 5 focused sessions and several tutorials, alongside a strong line-up of plenary speakers including Hui Cao, Daniele Faccio, Fedor Jelezko, Donghyun Kim, and Polina Bayvel. Worth recalling the participation of Anne L'Huillier as an invited guest of excellence. A plenary session will be dedicated to education pathways in EU, from Erasmus and Marie Skłodowska-Curie schemes to newer initiatives such as Phortify. EOSAM will also feature a joint session co-organized with the Optical Society of Korea.

This June, EOS is co-organizing a session on light-responsive polymers at the Light Conference in Changchun, China, supporting the Light Publishing Group and the Chinese Optical Society.

Stay updated with EOS activities through our website and social media, where news, events, and opportunities from across the optics and photonics community are regularly shared.

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

AGENDA

■ **From Single Photons to Continuous Variables: 40 Years of Quantum Optics**

Institut d'Optique, Palaiseau

June 4, 2026 — 8:30 AM–6:30 PM

A one-day event honoring **Philippe Grangier**, CNRS Research Director Emeritus, and his major contributions to quantum optics—from squeezed light and quantum non-demolition measurements to quantum communications and simulations.

Free registration (mandatory)

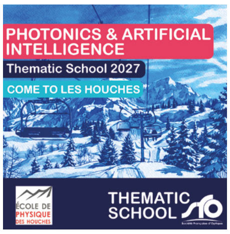
■ **OPTIQUE BFC 2026**

Dijon - Palais des congrès

06 - 10 july 2026

+ 670 participants expected

Register now
www.sfoptique.org



■ **Photonics & Artificial Intelligence**

The Houches Physics School, France

04 - 09 April 2027

70 attendees expected

Tour de France of Photonics at OPTIQUE BFC 2026

An initiative of the SFO Early-Career Researchers Club

From Bordeaux to Paris, from Nice to Rouen, and all the way to Dijon, French photonics unfolds as a scientific journey shaped by successive stages. On the occasion of OPTIQUE BFC 2026, the largest congress of the SFO, to be held in Dijon from July 6 to 10, the SFO Early-Career Researchers Club is launching a "Tour de France" initiative to highlight the diversity of actors, themes, and dynamics structuring the field today.

Through this initiative, the Club offers an original perspective on French photonics, structured around three complementary dimensions: territories, themes, and career paths.

Based on a series of interviews conducted during the congress, the project gives voice to researchers, academics, engineers, and industry representatives. Each contribution becomes a "stage," illustrating a field of expertise or a local ecosystem and contributing to a broader vision of the photonics landscape. The initiative will culminate in a round-table discussion bringing together leading women researchers, offering a cross-cutting and dynamic perspective spanning fundamental science to industrial applications.

Held in Dijon in collaboration with ICB and Institut FEMTO-ST, the congress represents the point of convergence of this initiative, bringing together the different actors of the field in a shared space for exchange.

Through this "Tour de France," the SFO Early-Career Researchers Club aims to enhance the visibility of photonics and foster dialogue across generations, disciplines, and territories, and local innovation and research ecosystems. With our warmest thanks to the commitment of early-career researchers leading this initiative with creativity and strong community roots, led by Mathis Fauchart (IMASOLIA), Julien Guise (IES, University of Montpellier, CNRS), Rémi Kieber (Institut FEMTO-ST, Besançon), and Arnaud Rogemont (Institut Carnot de Bourgogne, Dijon).

Register now to take part in OPTIQUE BFC 2026 and join this collective journey across French photonics.

www.sfoptique.org

Training through Experimentation:

LumiForm and the Challenge MP

Through the 2026 Challenge in Physical Measurements (Challenge MP), the LumiForm programme highlights the already central, yet often implicit, role of photonics within Physical Measurements curricula. Here, these approaches are brought to the forefront as structuring elements, contributing to the recognition of photonics as a field in its own right.

Within this framework, as part of the LumiForm programme, the French Optical Society is developing a national initiative to strengthen and structure photonics training in France by connecting existing efforts and fostering new synergies between academia, research and industry.

Under the theme "Like a Taste of Summer", 15 student teams from across France and Québec gathered on March 20–21, 2026, at IUT Montpellier-Sète. The event illustrates a hands-on approach to learning, where students design and implement their own measurement systems.

Drawing on four key optical techniques, transmittance for syrup classification, refractometry for honey moisture, spectrophotometry for olive oil acidity, and light-beam interruption for counting objects, the projects illustrate both the diversity and the tangible nature of optical approaches to physical measurement.

To address these challenges, students relied on a broad set of photonic tools, lasers, LEDs, photodiodes and prisms, combining experimental approaches depending on the problem.

More than a competition, the Challenge acts as a revealer: it highlights pedagogical practices that are already widely implemented, while contributing to the structuring of photonics as a discipline in its own right. In this dynamic, the next edition of the Challenge MP will take place in 2027 at IUT de Schiltigheim, continuing to build momentum across the national network.

LUMIFORM is a national programme supported by the France 2030 plan (Skills and Occupations of the Future).

CONGRESS OF THE **SFO**

French optical society

July 06/10, 2026

OPTIQUE

BOURGOGNE FRANCHE COMTÉ

WELCOME TO DIJON, FRANCE

2026

www.sfoptique.org

Finland:
Optics & Photonics Days, OPD

Jyväskylä, 26-28 May 2026

Germany:
127th Annual Meeting of the DGaO

Hamburg, 26-30 May 2026

Italy:
Italian Conference on Optics and Photonics, ICOP

L'Aquila, 15-17 June 2026

France :
OPTIQUE BFC 2026

Dijon, 6-10 July 2026

Portugal:
7th International Conference on Application of Optics and Photonics, AOP

Lisbon, 7-10 July 2026

United Kingdom:
Photon 2026

Newcastle-upon-Tyne,
31 August –
3 September 2026

Sweden:
Optics & Photonics in Sweden 2026

Norrköping, 6-8 October 2026

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Join us at EOSAM 2026 in Tampere

EOSAM is attended by around 500 attendees each year, including top researchers, key leaders, students, and industry experts from over 30 countries all over the world.
Join and explore the latest topics and emerging trends featured at EOSAM. Register with an Early Bird Fee by 15 June 2026! We look forward to seeing you in Tampere, Finland, 24-28 August 2026!
EOSAM 2026 is organized by The European Optical Society, EOS, in close collaboration with Photonics Finland, Tampere University, and PREIN Flagship. More details available through the QR code.

A successful 360 CARLA Career Symposium & Training in Photonics in Grenoble!

Over two inspiring days, we brought together more than 150 participants, both online and on site, including students, researchers, and industry professionals, to explore careers, research, and the future of photonics. A highlight was the inspiring talk by Anne L'Huillier, Nobel Prize Laureate in Physics 2023.
Thank you to all speakers, participants, partners, and organizers for making this event a success. If you missed it, you can rewatch the symposium and tutorials on the @europeanopticalsociety YouTube channel.

EOS BOARD ELECTIONS 2026 ARE NOW OPEN!

All members of the European Optical Society are invited to take part in shaping the future of our community by voting in this year's Board of Directors elections. **Voting period: 20 April – 20 May 2026**

JEOS-RP
Journal of the EOS
European Optical Society

See the Latest
Flipbook
July–December 2025

Building bridges between students and industry

On Wednesday, April 1, 2026, six partner companies — HGH, Thales, Pasqal, Exail, STMicroelectronics, and CEA DAM — joined students at the Institut d'Optique as part of the « Partenariat École », a partnership program between Institut d'Optique and key photonics companies.

The event opened with a conference in the auditorium, where each company introduced its environment, activities, and current projects, giving students valuable insight into the world of photonics, optics, and quantum technologies. The event continued with a networking village of booths set up in the lobby. Over a savory buffet and in a relaxed atmosphere, students had the chance to connect directly with company representatives, ask questions, and explore internship opportunities, projects, and potential career paths. These informal conversations created a real bridge between students and the professional world, helping them planning their future.
This event reflects the broader ambition of the « Partenariat École » program: to build stronger, more direct connections between Institut d'Optique engineering students and leading companies in photonics and quantum industries. By encouraging regular exchanges throughout the year, the program helps students better understand the diversity of careers available while giving companies the opportunity to meet and engage with future talent.

A PRESTIGIOUS CONFERENCE HONOURING PHILIPPE GRANGIER: REGISTRATIONS ARE OPEN !

After a career of more than forty years that has profoundly shaped quantum optics and technologies, Philippe Grangier, CNRS Research Director at Laboratoire Charles Fabry (Institut d'Optique, CNRS, Université Paris-Saclay) will be honored with a scientific event highlighting his career and major contributions.

This one-day conference, co-organized by Quantum-Saclay and Institut d'Optique, is entitled **"From Single Photons to Continuous Variables: 40 Years of Advances in Quantum Optics"** and will take place on **June 4th, 2026** at the Institut d'Optique (Paris-Saclay).
From his fundamental research on squeezed states of light and quantum non-demolition measurements to his groundbreaking innovations in quantum communication and quantum simulation, the conference will feature how Philippe Grangier's ideas continue to shape the future of the field.
Highlights of the program include an introductory lecture from Alain Aspect, an exploration of the connections between AI and scientific practices, and a session on the foundations of quantum mechanics.
The conference will also be live broadcasted all around the world on Institut d'Optique Youtube channel.
More information and free registration at: **grangier26.sciencesconf.org**

100%

participants in our training courses of Continuing Education are satisfied with the training content and would recommend it to their colleagues, 99% of them appreciate the teaching methods used and 96% are satisfied with the good balance between theoretical principles and practical application (exercises, experimental demonstrations). These excellent results encourage us to continue our efforts to offer high-quality professional training in the field of photonics.

AGENDA

- **Understand laser sources**
  June 01-05
- **Optomechanics**
  June 02-05
- **Introduction to quantum technologies: challenges and applications**
  June 03-05
- **Optical fibers and applications**
  June 08-12
- **Optical design with Zemax®-OpticStudio - Advanced**
  June 09-11
- **Optical design of IR imaging systems with Zemax®-OpticStudio - Advanced**
  June 09-11
- **Optoelectronics imaging systems**
  June 23-25

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News

- NANO-PHOT people have taken part in the CNRS Summer School of the Nano-or GDR (https://ecole2026.sciencesconf.org/?lang=fr) and the EMP26 international conference dedicated to Energy, Materials and Photonics - https://evenium.events/emp26-paris-saclay/emp26-KBX6C NANO-PHOT sponsored EMP26

- Two important recently published articles presenting achievements of NANO-PHOT's students:
  ACS Nano: M. Chen *et al.* *« Beyond Geometrical Symmetry: Revealing Near-Field Optical Chirality on Achiral Gold Nanoparticles under Linear Polarization Excitation"* https://pubs.acs.org/doi/abs/10.1021/acsnano.5c22237
  Nano Letters: M. Dewynter *et al.* *"Broadening the Plasmonic Spectral Range of Metallic Metasurfaces Using Dual-Material Arrays"* https://pubs.acs.org/doi/abs/10.1021/acs.nanolett.5c05943

- Prof. Alexander Govorov from Ohio University visits UTT for 4 months during this academic year as part of the Fulbright program. He is hosted by NANO-PHOT

AGENDA

- **META 26, the 16th International Conference on Metamaterials, Photonic Crystals and Plasmonics**
  Dublin, Ireland,
  14 - 17 July 2026
- **NFO18, the 18th International Conference on Near-Field Optics, Nanophotonics, and Related Techniques.**
  Brno, 31 August-
  3 September 2026
  (https://nfo18.org/)

CONTACT

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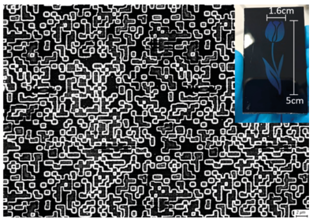
nanophot@utt.fr

European Research Institute

During the week of the 16th March 2026 took place the EUT+ Week at Troyes. The EUT+ is the European University of Technology which is an alliance formed of 9 european universities: the Hochschule Darmstadt, University of Applied Sciences (Germany), Rīgas Tehniskā universitāte (Latvia), Technological University of Dublin (Ireland), Technical University of Sofia (Bulgaria), Cyprus University of Technology (Cyprus), Universidad Politécnica de Cartagena (Spain), Universitatea Tehnică din Cluj-Napoca (Roumania), Università degli studi di Cassino e del Lazio Meridionale (Italy) and the Université de technologie de Troyes (France) which is the coordinating university of this alliance. The EUT+ is getting structured to become a unique, single university with 9 different sites and within this structuration, research also needs to be structured. The alliance thus created a new 'tool' for doing research at the EU level via a European Research Institute or ERI. More specifically, the ERI EUTINN, for the EUT+ Institute of Nanomaterials & Nanotechnologies, has been officially recognised by the EUT+ in 2025. This new model for a future European research is based on 6 Research Streams: Nanomaterials, Nanotechnologies and sensors, Nanotechnologies for communication and information technologies, Nanotechnologies for energy applications, Nanomedicine & nanobiology, Nanomaterials & nanotechnologies: toxicology, pollution, food and agriculture. The NANO-PHOT graduate school is fully involved. More info here: **https://www.univ-tech.eu/eutinn**

MICROGRAPH AWARD 2026



Currently third-year PhD student within the NANOPHOT graduate school, Antoine Dussard is carrying out his CIFRE thesis between the Université de Technologie de Troyes at the laboratory L2n (Light, nanomaterials, nanotechnologies - UTT) and the company SURYS (IN GROUPE) within the framework of the joint laboratory In-Fine (Innovation center for industrial nanostructured foils), which focuses on the fabrication of large-scale nanostructures. Antoine had the opportunity to participate and win one of the prizes of the "Micrograph Award 2026" organized each year by the company Raith, a world leader in maskless nanofabrication systems. Antoine's thesis focuses on the development of large-scale 2.5D electron beam lithography, consisting in the fabrication of hierarchical structures over several square centimeters by electron beam lithography for the production of structural colors. Structural colors are generated by different physical mechanisms such as diffraction, resonance phenomena, cavities, waveguides, etc. Hierarchical structures (nanostructures on microstructures) make it possible to create colored animations, where the microstructures can selectively redirect the incident light which is colored thanks to the nanostructures. These effects can be observed in specular reflection, diffuse reflection or transmission.

The awarded design consists of a Tulip pattern, 5 cm high and 1.6 cm wide, fabricated using a Raith eLINE electron beam lithography system. This tulip is composed of structures producing structural colors, without the use of pigments. These patterns make it possible to obtain a first color in diffuse reflection, as well as a second one in specular reflection.

The elementary structure consists of a Fabry–Perot cavity, in which a fine control of the depth and the refractive index makes it possible to modify the optical path difference between the different interfaces, and consequently the interferometric conditions and the resulting colors.

Green Mantis: a European project to decarbonise industry

The ALPHA-RLH cluster has been selected as a laureate of the European Green Mantis project, dedicated to the energy transition and the decarbonisation of industry, within the framework of the second Euroclusters call for projects. This ambitious project brings together six European clusters (ALPHA-RLH, ITECAM, PRODUTECH, Confindustria Emilia Area Centro, SOLARTYS, Inteligentna Energija) to cover the entire value chain of the industrial manufacturing and energy sectors.

Green Mantis is developing a comprehensive innovation support scheme designed to help industrial and energy companies design and adopt new net-zero carbon technologies. Through cascade funding, the project will offer financial support for the development of innovative projects, fostering the emergence of green, scalable and replicable industrial solutions.

Photonics players will play a key role in this dynamic, contributing through breakthrough technologies to the control, optimisation and energy efficiency of industrial processes, thereby directly contributing to the decarbonisation of industry. With Green Mantis, ALPHA-RLH, acting as coordinator, reaffirms its leading role in sustainable industrial innovation in Europe.

Green Mantis has officially launched its 1st Open Call for SMEs, that will select 10 projects for EU manufacturing decarbonisation.

PLI CONFERENCES 2026

The PLI Conferences will take place on July 1–2, 2026 in Limoges, France. Organized by the Club Laser & Procédés (CLP), in partnership with ALPhANOV and with the support of ALPHA-RLH and the European Ceramic Center, the event will bring together key players in industrial laser processes.

Recognized as a reference meeting point for the international laser community, PLI Conferences offers a high-level program of expert talks showcasing the latest technological advances and industrial applications.

The 2026 edition will highlight key topics such as laser micromachining, laser welding, additive manufacturing, and process control, as well as laser safety, machine learning, and artificial intelligence.

In addition to the conference program, attendees will benefit from an exhibition area, networking sessions, a thematic panel discussion, a convivial evening event, company visits, and a poster session dedicated to PhD students.

PLI Conferences 2026 offers a unique opportunity to explore the latest innovations, exchange with industry leaders, and foster new collaborations.

Information and registration:
https://www.clp-laser.fr/fr/evenement/pli-conferences-2026

Learning Expedition to China

From March 17 to 26, 2026, ALPHA-RLH led a delegation of French companies to China. The mission began at the Laser World of Photonics China trade show in Shanghai, where several member companies showcased their innovations at the cluster's shared exhibition space.

Following the trade show, the delegation participated in a program of industrial visits and institutional meetings in various economic development zones: Suzhou, Shanghai, Mianyang and Chengdu, where a Franco-Chinese business park is located. These immersive experiences allowed the companies to explore local ecosystems and value chains. Participants also took part in several matchmaking sessions, during which they were able to showcase their expertise, establish qualified contacts, and identify opportunities for technological or commercial collaboration in the medium term.

This mission fully illustrates ALPHA-RLH's role in supporting the international expansion of microbusinesses and Nouvelle-Aquitaine' SMEs: bringing stakeholders together, facilitating access to strategic markets, and fostering partnerships and business opportunities.

UPCOMING INTERNATIONAL EVENTS

- **3rd Photonics Talent International Summer School**
  June 15-19 in Bordeaux (France)
- **PLI Conferences**
  July 1-2 in Limoges (France)
- **EUROPHOTON**
  September 21-25 in Arcachon (France)

All events on www.alpha-rlh.com

NEW MEMBERS

Welcome to our new members!

Yotta has two goals: first, to create industrial jobs through economic development, and second, to reduce the carbon emissions of the industrial SMEs we support.

Heddenhain, develops and manufactures linear and angular measurement systems, rotary encoders, and CNC controls for all demanding positioning tasks. It also offers practical software solutions that enable end users to fully digitize their production ecosystem.

EPSA is a European leader specializing in performance. Recognized for its technical expertise and diverse range of business specialties, the EPSA Group helps its clients optimize their financial, operational, and sustainable results.

Latecoere supports the world's leading aircraft manufacturers and airlines from design through to production. As a century-old aerospace group, Latecoere invests in R&T and new technologies to ensure it can offer increasingly customized innovative solutions.

AGENDA

- **Photonics for visual health**
  May 29 2026 – Créteil
- **Photonics Tour**
  June 4 2026 – Paris
- **Webinar: Meeting with new members**
  June 2026 (tbc) – online
- **French Photonics Days**
  November 9-10 2026 – Grenoble

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www.photonics-france.org

Photonics France annual meeting

Photonics France held its Annual Meeting on April 3 at Bpifrance headquarters, followed by a public conference about major photonics projects.

The members of Photonics France met on April 3 for their annual meeting at Bpifrance headquarters in Paris. Bpifrance is France's public investment bank.

The Annual General Meeting is an important event for Photonics France, enabling members to validate the actions taken by the national board.

Photonics France has elected its new board of directors for a two-year term. Welcome to the new team: ALPhANOV (Benoît Appert-Collin), Bertin Technologies (Luc Renouil), ENSSAT (Thierry Chartier), EssilorLuxottica (Laurent Gatté), Exosens (Claire Valentin), Fiber Optics Group (Jean-François Vinchant), Lumibird (Sebastien Ranc), ONERA (Thierry Fusco), Oxxius (Thierry Georges), Safran (Thierry Dupoux), Thales (Franck Leibreich), Alpha-RLH (Yvan Martin), Club Laser et Procédés (John Lopez), Photonics Bretagne (Patrice Le Boudet), SFO (Francois Salin).

During the afternoon, conferences presented investment in photonics, featuring presentations by Bpifrance, Aster, Bloom Laser, Stifel, Yotta Capital, and Exosens.

PHOTONICS FOR VISUAL HEALTH

WITH ESSILORLUXOTTICA AND THE INSTITUT OF VISION

Photonics France, EssilorLuxottica and the Institut of vision are hosting a Business Meeting on May 29, 2026 on photonics for visual health at EssilorLuxottica's Research and Development Center in Créteil.

Photonics France, EssilorLuxottica and the Institute of vision are organising a business meeting focusing on photonics for visual health, with the support of the Photonics 4 Visual Health.

EssilorLuxottica is the world leader in the design, manufacture and distribution of ophthalmic lenses, frames and sunglasses, whilst pay particular attention on research and development.

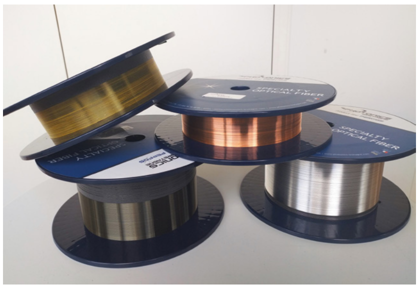
The Institute of vision, one of the world leaders in research into eye diseases, works on major public health challenges in ophthalmology and rare diseases, with the aim of bringing hope to all those affected by visual impairment. It brings together researchers, doctors, patients and partners under one roof.

Come and discover the needs of EssilorLuxottica and the Institute of vision in terms of photonics for visual health, and present your innovative solutions.

JTECH Photonics & Plants:
An Event Dedicated to Synergies Between Sectors

On 2nd April, Photonics Bretagne co-organised the JTECH Photonics & Plants with VEGEPOLYS VALLEY and CEVA at the Roullier World Innovation Centre (CMI) in Saint-Malo. Around forty participants attended this day dedicated to synergies between photonics, plants and algae. The event featured conferences, pitches, B2B meetings and tours of the Roullier CMI's greenhouse and laboratories, fostering discussion and the development of collaborations. It was a fruitful and highly appreciated event, illustrating the key role of photonics in innovation serving the life sciences sector.

Conclusion of the 3F2E Project:
French-Made Optical Fibres for Extreme Environments



Conducted and funded by "France Relance" between 2022 and 2025, the 3F2E project – French Fibre for Extreme Environments – aimed to develop specialised optical fibres with metallic coatings for extreme nuclear environments. The project successfully addressed several challenges: Photonics Bretagne mastered the microstructure of the coatings (particularly aluminium) in line with the requirements of EDF and TechniAtome, whilst SEDI-ATI made progress on assembly and connectorisation. Four manufacturing processes were developed (aluminium, copper, carbon, polyimide), achieving a high level of industrial maturity. Already, 10 aluminium-coated fibre products are being marketed by Exail, featuring a germanium-doped core or a pure silica core optimised for radiation resistance. These results pave the way for a 100% Made in France supply chain, strengthening national autonomy and sovereignty over this strategic technology.

UCAIR:
A EUROPEAN INITIATIVE TO TRANSFORM CANCER DIAGNOSIS

uCAIR
Ultra-Fast Chemical Analysis Imaging With Raman

Led by the University of Limerick, the Horizon Europe uCAIR project – Ultra-fast Chemical Analysis Imaging with Raman – aims to develop a photonic technology for the early diagnosis of cancer. The aim is to provide an ultra-fast, real-time chemical imaging solution based on coherent Raman spectroscopy, enabling the identification of unlabelled biomarkers in biofluids and tissues, both ex vivo and in vivo. At their half-yearly meeting, the consortium partners were able to view an initial working prototype, as well as the first experimental results. Building on these results, the project is entering its second phase. Photonics Bretagne, in collaboration with FEMTO-ST (CNRS), will develop and manufacture a new all-solid-state optical fibre, intended for integration into the uCAIR device to accelerate analysis with a view to a future system suitable for medical use.

Global Industry:
The First Photonics Village Promotes Our Sector

This initiative by Photonics France brought together several key players from the photonics ecosystem, including booth shared by Photonics Bretagne, Oxxius and Arlumen, and alongside ALPhANOV, PYLA, OptoPartner and Photonics France. Combined with a series of conferences, the Photonics Village demonstrated the value of sharing spaces to enhance the sector's visibility and profile, thereby raising awareness of the industrial applications of technologies that are still too often overlooked by end-user sectors.

AGENDA

- **Photonics & Plants Workshop**
  26 May, online
- **Mobility & Photonics Meetup**
  28 May, Rennes
- **Annual General Meeting**
  26 June, Lannion
- **Photon2Startup Days**
  26-27-28 October, Lannion

Doctoral students (French and foreign) are invited to this unique 3-day, English-speaking event to present your research work and take part in an entrepreneurship workshop! The program also includes 1-to-1 meetings with CEOs and visits to companies and labs... All this in a friendly atmosphere overlooking the sea in Brittany! Info and registration: **photonics-bretagne.com/en/agenda/photonics-phd-days-2026/**

A Physicist Among the Immortals
Alain Aspect's Reception at the Académie française

Thursday, April 23. The grand hall beneath the Dome is filled. Drums roll. The Republican Guard, sabres raised, welcomes the Immortals in full ceremonial dress. At precisely three o'clock, the formal session of the Académie française begins: the reception of its newest member, who will take Seat 22. In the audience, glances meet, and knowing smiles pass from one face to another—signs of shared understanding, of quiet satisfaction. Yet the moment is solemn. How could it be otherwise? Seat 22 is to be occupied by a physicist, the first since Louis Leprince-Ringuet was elected to Seat 35 in 1966. Since the Academy's founding, physicists admitted to its ranks have been so few they can be counted on two hands. And those few names point us to giants: Louis de Broglie (1944), Maurice de Broglie (1934), Henri Poincaré (1908), Jean-Baptiste Biot (1856), Joseph Fourier (1826), Pierre-Simon Laplace (1816)... and, going further back, Jean-Jacques Dortous de Mairan, elected in 1743.

Founded in 1635, the Académie française serves as a forum for intellectual debate devoted to "advancing the influence of letters," most notably through the publication of its authoritative dictionary of the French language. It is therefore no surprise that, among its forty members, representatives of the natural sciences have been few, and physicists rarer still.

The future holder of Seat 22 rises, places his notes on the lectern, and in keeping with tradition, begins by paying tribute to his predecessor. Much of the audience is already familiar with his eloquence. Even so, this is unfamiliar ground. His predecessor, René de Obaldia, was neither a quantum physicist nor a scientist of any kind nor, for that matter, an oenologist, a magician, or an expert in Southwestern cuisine, but a playwright, poet, and novelist. The setting is formal, the task delicate. In those opening moments, those who know Alain Aspect sense an unusual restraint, even a hint of emotion. But as the forty minutes unfold, his eloquence returns in full force, along with his presence, and even reveals a new dimension: that of a conjurer of words, where the sleight of hand lies not in cards, but in phrasing. Yet his speech is far more than an 'exercise' in style. He returns repeatedly to what matters most to him: the formative role of his public-school teachers, the importance of science, and the need to recognize it as an integral part of culture without qualification. He touches, in passing, on scientific ideas such as wave–particle duality, and promises to answer any questions the members of this distinguished assembly might wish to pose, even those left unasked. The result is a speech that is at once brilliant, thoughtful, moving, and humorous. One detail, however, stands out: Alain Aspect, whose reputation is closely tied to a paradox, pointedly refrains from commenting on René de Obaldia's remark: "A paradox is an opinion that thrives on its charms at the expense of truth."

Alain Aspect surrounded by some members of the SFO. From left to right: Ariel Levenson (former President), Philippe Grangier (incoming President), Pierre Chavel (first Elected Secretary), Françoise Chavel (first General Secretary) and Benoît Boulanger (former President).

The ceremony then proceeds in keeping with tradition. The audience, captivated, witnesses a first touch of "magic" from the newly received academician. The honor of formally welcoming him and presenting his achievements falls to Academician Jules Hoffmann. In a rich and carefully crafted address, Hoffmann retraces the major milestones in the development of modern physics: the rise of quantum mechanics, the epistemological debate between Einstein and Bohr, the unresolved tension of the Einstein–Podolsky–Rosen paradox, and the breakthrough provided by Bell's inequalities. He goes on to underscore Alain Aspect's vision and perseverance, as well as the experiments that earned him the 2022 Nobel Prize, shared with John Clauser and Anton Zeilinger. Moments earlier, Alain Aspect had vowed never to miss an opportunity to speak about quantum physics and optics. The promise is already fulfilled: Jules Hoffmann, a biologist, rises to the occasion with remarkable brilliance.

But let us not confuse science with magic, Alain Aspect would surely object. It is worth recalling that the first physicist (and, in a sense, optician) elected to the Academy, Jean-Jacques Dortous de Mairan, advocated a rigorous and systematic approach to experimental observations, precisely to dispel the fanciful interpretations often attached to rare or "marvelous" phenomena such as the aurora borealis, phenomena that even Halley still partly explained in fantastical terms. Let us give him the last word:

"And thus the pious, the moral, the fabulous, the romantic, even the political have, in all times and places, become intertwined with the physical nature of our phenomenon. Yet all the examples I have just cited show that the physical ultimately prevails: it shines through the chimeras it generates or transforms, depending on the objects it presents to the observer's eye, objects themselves shaped and altered by the point of view and latitude from which they are perceived."

There is little doubt that Alain Aspect, a worthy heir to Jean-Jacques Dortous de Mairan and to his other distinguished predecessors, will bring both clarity and wonder to the sessions of the Academy, dispelling mystification while illuminating the beauty of optics and quantum physics. Congratulations, Alain!

Ariel Levenson


Key to Markets
Messe Stuttgart

INTERVIEW

Interview with Aldas Juronis

CEO of EKSPLA, a Lithuanian company developing and commercializing femtosecond, picosecond and nanosecond lasers.

https://doi.org/10.1051/photon/202613714

Can you tell us about your background?
My background is in electronics. I graduated in that field many years ago and spent most of my career in business development and sales management across very different industries, none of them related to photonics. Ekspla is actually my first experience in this sector.

How did you come to lead Ekspla?
I joined the company about seven years ago as OEM Program Manager. After a few years, I became Head of Production, and later I was appointed as CEO. This evolution came naturally from my background in business development. When I joined, I quickly realized that Ekspla was a very unique company with truly distinctive products and technologies. The main challenge was to better monetize those innovations, to translate the impressive technical achievements of our engineers into sustainable business growth. Ekspla had already reached a solid level of maturity, but to move forward we needed to prepare for the next strategic step.

How did Ekspla begin?
The company was founded in 1992 by eleven engineers, just a couple of years after Lithuania regained its independence. Before 1990, there were no private companies in the country, since everything was state-owned. Those engineers realized that they had something very special: deep expertise in picosecond laser technology.

At that time, picosecond lasers were still cutting-edge, and very few groups worldwide could design reliable systems. These engineers were already building such lasers for research institutions. When Lithuania's economy opened, they decided to stay together and create a company, even though they had no business training at all. It was a difficult time. They knew how to build lasers, trusted in themselves, technology and most importantly – each other. I am sure that was the main reason that helped Ekspla to overcome tough economical environment conditions – focusing on cutting edge technologies and strong innovation culture.

What are the reasons why Lithuania managed to develop such strong laser expertise so early on?
Laser technology turned out to be one of the rare advanced fields where Lithuania could excel. The roots of this expertise go even deeper. The first laser in Lithuania was built in 1966, just six years after the invention of the laser itself, by scientists at Vilnius University. They were working on semiconductors and realized that a laser would be the perfect tool for characterizing materials. As importing lasers was impossible under Soviet rule, they built one themselves. Later, young researchers went to Moscow to study photonics and brought their knowledge back home, laying the foundations for a strong scientific community.

How would you describe Lithuania's photonics landscape today?
Today, Lithuania is widely recognized as a photonics country. Whenever I travel abroad, whether to the United States, Japan, Korea or elsewhere, people in our field immediately associate Lithuania with photonics. For a nation of fewer than three million people, we have more than sixty companies active in this area.

It is not just laser manufacturers. There are optics producers, coating specialists, machine builders and system integrators. We even like to joke that Lithuania has the world's highest density of coating machines per capita. There is now a complete ecosystem, an entire infrastructure for photonics, from design to production and applications.

What we lack, on the other hand, are local end-users. Only a few universities or industries in Lithuania use ultrashort-pulse lasers or advanced photonic systems. But this limitation has also made us more open and flexible. It pushed us to collaborate internationally and to build partnerships with research institutes and industrial customers all around the world. This global mindset is one of our strongest competitive advantages today.

Can you describe the early days of Ekspla?
The beginning was really tough. At that time, the founders had no money to purchase advanced equipment, not even basic metrology tools. They had to improvise everything. For example, they built their first optical tables using empty coffee cans as supports. We still have some unique photographs showing those early setups. Buying a proper optical table was simply unaffordable in Lithuania at that time.

Interestingly, the very first market for Ekspla was not local but Japan. Even before the company was formally established, during the Laser World of Photonics exhibition in Munich, the founders met a Japanese businessman who believed their technology was truly unique and could be of interest to Japanese researchers. As a result, the first laser produced by Ekspla was shipped to Japan.

The first sale took place in 1993, when they sold a single picosecond laser. The income from that single sale was enough to sustain all eleven founders for six months and to reinvest in the company's production. It gives you an idea of how modest the living conditions were in Lithuania at that time. One laser sale was enough to pay salaries and finance further innovation.

From there, the company gradually expanded into other markets—first in Germany and across Europe, then later in the United States and other regions. Today, Ekspla operates worldwide wherever ultrashort-pulse lasers are needed. Technologically, we remain focused on pulsed and ultrashort-pulse lasers, from nanosecond down to femtosecond systems. Over the years, the product portfolio has grown steadily.

The company that started with eleven founders now counts more than 150 employees. Interestingly, five of those original founders are still working with us today, in various roles, not necessarily in management. They are excellent specialists who remain passionate about what they do.

It must have taken a lot of determination to keep the team together.

Yes, those were hard times, and it is really exceptional that the founders managed to stay united. Even when there are only two founders, it is common to see them split after a few years because of different visions on how to use profits or develop the company. But these eleven engineers stayed together and grew the company. What united them then, and still unites all of us today, is the passion for innovation. Innovation is what drives Ekspla forward and keeps the company evolving.

How do you maintain that pioneering spirit?

From the very beginning, the company has been built around the idea of constant innovation. When Ekspla started, picosecond and mode-locked laser technologies were already remarkable, but our founders never stopped looking for new ways to improve and differentiate. We have always sought to adapt existing technologies and to bring new ones to market with a distinctive edge.

The best proof of this commitment to innovation lies in the international recognition our products have received. Two of them have won the "Photonics Oscar" - PRISM Award, which is quite rare. The first was in 2010 for a DPSS-pumped OPO system integrated into a single housing. At that time, this was a real breakthrough. Traditionally, researchers had a separate pumping laser and an OPO system in another box. DPSS technology itself was still quite new, as most OPOs were pumped by flashlamp systems. Our engineers decided to take the next step: to use a diode-pumped laser source and integrate it directly with the OPO, in one compact and robust enclosure. This made the system far more user-friendly and earned Ekspla the PRISM Award in the Scientific Laser category.

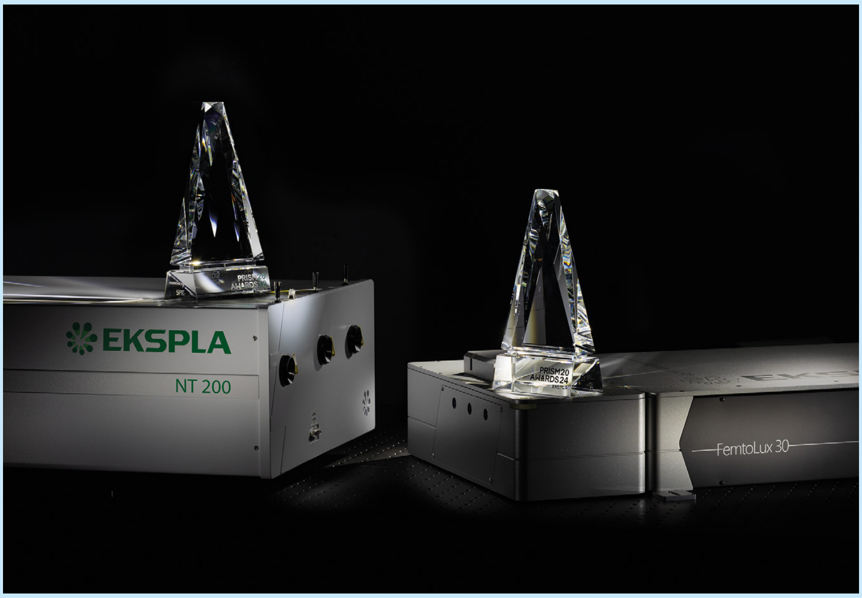
We received our second PRISM Award in 2024 for our industrial femtosecond laser *FemtoLux*. Of course, we were not the first company to develop an industrial femtosecond laser but we knew that launching just another system would not be enough. The key innovation was dry cooling. For moderate and high-power lasers, efficient cooling is always a challenge. Traditional water chillers require frequent maintenance and are often the weakest point of a laser system. We decided to rethink this entirely by adapting a cooling technology from the defense sector. Instead of circulating water, we use a refrigerant that flows directly through cooling plates. This makes the laser maintenance-free, eliminates leakage risks and ensures robust, reliable operation. In addition, it enables a smaller footprint, ~50% greater energy efficiency compared with water-cooled systems. In comparative tests, direct refrigerant systems consumed half the power of liquid chillers under identical conditions. Compressor lifetime typically exceeds that of a pump by a factor of three to five. And, with a mean time between failures of >90,000 h, the system can operate continuously for more than a decade without downtime.

What are your most recent innovations?

I would say the gigahertz burst operation, offering the most flexible regime available: from two up to nearly a thousand pulses per burst, with adjustable pulse duration from the same laser source. Our patented active fiber loop design enables the same laser to operate in femtosecond, picosecond or nanosecond regimes while keeping the same optical path and pointing stability.

How does Ekspla stand out in such a competitive market?

Competition is global and intense. Our strength lies in deep scientific expertise, flexibility and reliability. We are small enough to listen closely to our ●●●



customers and to customize. Our innovations, such as the integrated tunable wavelength lasers, active fiber loop or the new direct refrigerant cooling system, are not just about better specifications but about stable and predictable performance in real-world conditions.

What markets do your products address?

We serve two main markets. The first, and historically most important, is the scientific community. Thirty years ago, ultrashort-pulse lasers were mainly research tools, often built by scientists themselves. Our mission was to provide reliable picosecond and later nanosecond lasers for research institutions. Today, eighty out of the world's top one hundred universities use Ekspla lasers.

As ultrashort-pulse technology matured, we moved into industrial markets, first with picosecond systems, and now mainly with femtosecond ones, such as the FemtoLux. Our portfolio expanded naturally thanks to close interaction with academic users, who constantly need new capabilities. In industry, the goal is different: to optimize parameters and scale up for production. Our main target markets are consumer electronics, display manufacturing, semiconductors and medical technologies, including stent cutting and precision marking.

This combination of scientific roots and industrial ambition makes Ekspla unique. We understand the physics deeply and know how to turn it into reliable, manufacturable systems.

How is your R&D structured to support innovation?

Innovation is deeply rooted in our organization. Out of more than 150 employees, about 25 percent work in R&D. Beyond photonics, we maintain strong in-house expertise in mechanics, electronics and software. We design and build much of our hardware ourselves, including mechanical components like lens and mirror mounts. Our teams continuously improve fixation methods, model environmental stability and refine control electronics, which enhances robustness and reliability.

Being located in Vilnius is a real advantage: most of Lithuania's photonics companies are nearby, allowing very fast iteration with local partners for optical components or coatings. We also collaborate with universities and research institutes, both in Lithuania and abroad.

Each R&D team follows its own roadmap to improve existing products and explore new concepts across femtosecond, picosecond and nanosecond technologies. Maintaining excellence across all these domains requires sustained investment, but it is the foundation of our success.

Do you also develop high-intensity laser systems?

Yes, we have a dedicated team working on high-intensity laser technologies, primarily for large research centers using terawatt and petawatt-class systems. We have delivered several systems for the ELI facilities in Hungary and the Czech Republic, in collaboration with our partners , and we supply similar systems to customers worldwide.

So you collaborate regularly with other companies?

Absolutely. Collaboration is essential. We work closely with Lithuanian and international partners, depending on the project. In science, such cooperation is natural ; you can only innovate effectively by combining complementary expertise. Sometimes we even collaborate with competitors if together we can create something new and meaningful.

Could you tell us more about Ekspla's structure and global reach?

Our headquarters are in Vilnius, where we have R&D, production and administration. As the company grows, we are looking for additional space to expand. Beyond Lithuania, we have subsidiaries in the United States, the United Kingdom and South Korea, which handle sales and customer support. We also rely on a network of more than twenty-five distributors who sell our lasers and provide local service and maintenance. A dedicated service team travels globally to support our customers.

From your perspective, what are Europe's strengths and weaknesses in developing photonics?

Europe is an excellent place for photonics, with strong traditions in Germany, France, the United Kingdom and, of course, Lithuania. The weakness lies in inconsistent governmental support. The European Union recognizes the importance of photonics but often acts too slowly, and funding levels remain far below those in the United States or China.

Photonics is now a strategic technology, essential for quantum science and artificial intelligence. Chips, data transmission and even data processing increasingly rely on photonic components.

Europe has the expertise, infrastructure and academic excellence to lead, but without stronger public support and faster decision-making, it risks becoming a user rather than a developer of next-generation technologies.

Where would you like to take Ekspla in the coming years?

I see tremendous potential in expanding the industrial use of ultrashort-pulse lasers. They are already indispensable for manufacturing next-generation semiconductor devices, and their importance will only grow. Each new chip generation requires more advanced photonic tools, and we intend to play a role in that evolution.

Beyond semiconductors, the consumer electronics and automotive industries will also continue to grow, driven by new technologies and global demographic changes. In parallel, we see promising developments in medical and life-science applications, particularly in photoacoustic imaging, which is now moving from the lab to clinical tools. I believe it is only a matter of time before such technologies become widely accessible in hospitals.

Finally, we will keep working closely with academic partners. Collaboration with universities and research institutes keeps us at the forefront of laser science, helps us understand technological limits, and guides us in developing new products that will serve both research and industry in the years ahead. ●

Interview with Goëry Genty

Professor at the university of Tampere-Finland, specialist of non-linear optics in optical fibers and integrated photonics.

https://doi.org/10.1051/photon/202613717

Could you describe your background and how you discovered science?
I was born in Bordeaux, where I completed all my schooling up to the end of high school, and I was always drawn to scientific subjects, especially mathematics and physics. I knew early on that I wanted to become an engineer, and after graduating, I joined a scientific preparatory class in Toulouse-France at Lycée Fermat, which had an excellent reputation at the time. I sat the competitive entrance exams like everyone else, and although I had no prior interest in optics, my initial preferences were more aligned with advanced marine engineering, but everything changed when I received the school brochures after the exam results. The Ecole Supérieure d'Optique in Paris presented optics and photonics as a dynamic, promising field, and that convinced me. Without that brochure, I might have gone in a completely different direction, but that was the turning point that oriented me toward photonics.

How did your training in optics go?
Rather well. In the second year, the school strongly encouraged summer internships abroad, using contacts from former students. At that time, many aimed for the United States, but I opted for a more strategic approach: fewer applicants meant greater chances. Finland turned out to be such an option, and since students from the previous year spoke highly of their experience there, a friend and I applied. We were both accepted and spent the summer at Helsinki University of Technology (now Aalto University), which turned out to be a decisive experience.

What was your internship topic?
I worked on measuring the linewidth of laser sources using self-homodyne and heterodyne techniques. The internship went well, and I maintained excellent contact with the Finnish laboratory. In my final year, they offered me a PhD position Although I initially hesitated between research and industry, I thought that completing a PhD would allow me to explore research while keeping the option of transitioning to industry later. So I returned to Finland to begin my doctorate.

What was the focus of your PhD?
The project initially focused on advanced measurement techniques such as linewidth characterization, fiber dispersion, ultrafast metrology, but a major shift occurred when I spent three months in Denmark and encountered the first photonic crystal fibers produced by a local spin-off. The Danish group gave me samples because our Finnish lab had suitable dispersion measurement tools, and around the same time I attended CLEO, where supercontinuum generation was being presented for the first time. I was fascinated by the idea of generating broadband light from a narrowband input. Once back in Finland, I initiated experiments using the ultrafast laser of a neighboring group led by Prof. Matti Kaivola and, with the freedom given by my supervisor Dr Hanne Ludvigsen, my PhD evolved into a study of ultrafast nonlinear dynamics and supercontinuum generation. I defended my PhD in early 2004.

What did you do after your PhD?
I continued for two years as a postdoc in the same lab. Two important events occurred: a late-night call from Prof. John Dudley inviting me to co-author a major Reviews of Modern Physics article, which triggered a long-term collaboration that still lasts today; and a call from Prof. Martti Kauranen in Tampere offering a postdoc position in nonlinear optics. After joining Martti's group, I quickly obtained independent funding from the Academy of Finland and was able to build my own research line around nonlinear fiber optics, supercontinuum, and hydrodynamic analogies.

How did you get a permanent position?
Before securing a permanent professorship, I received a five-year Academy of Finland "junior group leader" grant which gave me substantial independence. Shortly before the end of that period, a professorship opened and I was appointed associate professor in 2012, then full professor in 2014. Looking back, my trajectory owes much to timing and opportunity: internships, research stays, and unexpected phone calls all played a decisive role.

What are the main scientific themes that structure your research?
My work is structured in several blocks. First, between 2009 and 2015/2016, we focused heavily on studying extreme nonlinear dynamics in fibers, special propagation solutions, and the influence of noise and instabilities. In parallel, we launched a second line of research on ghost imaging, translating the concept from spatial to temporal and spectral domains, enabling ultrafast pulse reconstruction, ghost spectroscopy and ghost OCT. A third direction emerged from applying machine learning to nonlinear optics, initially to predict extreme wave events from spectral measurements and later to systematically control nonlinear propagation and supercontinuum generation via feedback optimization. To gain more degrees of freedom, we moved into multimode fibers, exploring active (spatial/spectral modulation) and passive (nonlinear self-organization) control of structured light. We also developed advanced real-time measurement •••

techniques, sub-30 fs temporal resolution and pulse-by-pulse spatial/phase characterization. Most recently, we began using fibers themselves as physical analog computing elements for classification tasks, a direction we are now extending to multimode fibers for higher dimensionality.

You also work on integrated waveguides. What is the objective there?

We are now in the process of transferring part of what we learned in fibers to integrated platforms such as thin-film lithium niobate or tantalate. These systems offer strong nonlinear and electro-optic effects over very short distances, enabling compact devices with lower power requirements. Our goal is to determine whether key nonlinear fiber phenomena can be replicated, or re-engineered, on-chip for future integrated photonic applications.

Which emerging topics do you find particularly promising?

Two lines of inquiry stand out. The first is optical computing using nonlinear media, whether in fibers or integrated waveguides, to act as analog processors. This is attractive, although I remain cautious: it is beautiful physics, but it may not replace GPU-based computation. The second is nonlinear self-organization in multimode systems, enabling passive shaping of spatial and spectral profiles simply by tuning input power and conditions. Overall, the unifying theme is structured light across temporal, spectral and spatial dimensions using nonlinear control.

What about modelling and numerical complexity?

In single-mode systems, well-established models accurately describe nonlinear propagation. In multimode systems, however, simulation becomes dramatically more complex: one moves from one-dimensional fields to three-dimensional spatiotemporal data cubes. Simulating long propagation distances with high resolution becomes computationally prohibitive, especially when scanning parameters. This is one reason why we increasingly combine experiments and machine learning instead of relying solely on brute-force numerical modelling.

What are your main collaborations?

Locally, I collaborate with several groups at our university. Internationally, my longest-running collaboration is with Prof. John Dudley in the Louis and Marie Pasteur University in France. I also collaborate with groups in Sapienza University in Italy, the Institute for Photonics Technologies in Germany and a group in Chengdu University in China.

Are you using photonics to support machine learning or machine learning to support your investigations in photonics?

Both directions are now active. Initially, machine learning served photonics by helping to analyse and control nonlinear dynamics. More recently, we have also used photonic systems themselves as hardware for analog computation. Stabilization of experiments is another area where machine learning can be valuable using feedback algorithms to compensate for drifts and maintain alignment during long data acquisitions.

How has the photonics ecosystem developed in Finland, particularly with the national flagship?

Until mid-2000, Finland was not a leading EU country in photonics research despite solid infrastructures in Helsinki, Tampere and Eastern Finland. Three key developments changed the landscape: significant university investments in fabrication technologies; the transformation of the Finnish Optical Society into Photonics Finland integrating industrial stakeholders; and the Academy of Finland's call for eight-year flagship programmes. By unifying the main national academic groups and leveraging industrial momentum, we secured a national photonics flagship in 2019, now involving nearly 500 researchers, with an application for an eight-year extension underway.

What has been the impact of the flagship?

The flagship has increased research quality, strengthened funding, accelerated innovation (more patents and start-ups), expanded training programmes, multiplied scientific and industrial events, and significantly improved international diversity. Finland now hosts more than 300 photonics companies for a population of 5.5 million (which is one of the highest densities in Europe) creating strong demand for highly trained graduates.

What about doctoral education reform?

PhD studies in Finland were considered too long and insufficiently connected to industry. National pilot programmes were launched two years ago to shorten doctoral timelines and increase industry placement. We secured one of these programmes for photonics, and now coordinate a national doctoral network with about 70 PhD students aligned with the flagship and industrial needs.

You also coordinate a national infrastructure network. What does this involve?

Our fabrication and characterization platforms were labelled national infrastructures of strategic importance, meaning they are open to researchers and industry across the country. We provide access, expertise, and support for design and prototyping. This complements the flagship and the doctoral network, forming an integrated ecosystem of research, training and innovation.

How did EOSAM come to be organised in Tampere?

EOSAM is the annual conference of the European Optical Society, whose headquarters are in Finland. I already knew the EOS coordinator, Elina Koistinen, and during discussions I suggested hosting the conference in Finland in Tampere. EOS lacked the manpower to organise it alone, but with the flagship administrative resources, budgetary support and network, we could take on the local organisation. The proposal was submitted and accepted, and EOSAM 2026 will take place in Tampere on August 2026.

What guides your approach to research?

What matters most to me is the articulation between fundamental research, genuinely useful applications, and strong investment in training and mentoring. If this contributes to strengthening photonics in a small country like Finland, then it is a very positive outcome. ●

Laserlab-Europe AISBL: Advancing Laser Science through the Lasers4EU Project

Laserlab-Europe AISBL unites 48 infrastructures across 22 countries to sustain a cohesive European laser landscape. Its core project, Lasers4EU, provides academic and industrial users with coordinated access to 27 top-tier facilities. Supported by a diversified user-friendly access offer and a set of training activities, Lasers4EU empowers scientists, fosters innovation, and strengthens Europe's competitive edge in modern photonics.

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Photonics plays a strategic role in addressing modern societal challenges, ranging from sustainable energy and advanced manufacturing to healthcare and fundamental physics. To meet these demands, Lasers4EU serves as a cornerstone of Europe's photonics ecosystem by bringing together leading laser research infrastructures and offering open access to high-performance systems that individual institutions could not sustain independently. By providing access to these research infrastructures, the project fosters interdisciplinary research and reinforces European leadership in the field.

Lasers4EU: a central platform for accessing European laser research infrastructures

Lasers4EU is a Horizon Europe co-funded project and the latest phase of a long-standing European effort, initiated in 2001, to integrate and coordinate laser research facilities. Building on the achievements of five successive Laserlab-Europe projects, from 2003 to 2025, the strength of the consortium lies in its diversity and in its coordinated activities to keep Europe at the forefront of laser science and technology. The project brings together 29 leading laser research institutions across Europe, 27 Access Providing Infrastructures (APIs) alongside ELI ERIC and the Laserlab-Europe AISBL[1], with all their members participating as associate partners (Fig. 1).

By combining the expertise and resources of its APIs, the project offers a coordinated and highly efficient platform for researchers. Whether scientists are seeking specialised facilities for cutting-edge scientific investigations or applying advanced laser technologies to industrial innovation, Lasers4EU serves as a comprehensive gateway to Europe’s leading laser research infrastructures.

Beyond providing direct access to facilities and services, the project also aims to strengthen and structure the wider European laser research landscape. This is achieved by expanding geographical coverage, promoting science

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[1] Association International Sans But Lucratif (international not-for-profit association)

diplomacy, and fostering closer collaboration and synergies with other European and international networks.

A further core objective of Lasers4EU is the development of the next generation of laser scientists. The project implements comprehensive training activities designed to equip researchers with essential skills, paying particular attention to scientists from emerging research fields and regions with developing scientific communities. In doing so, Lasers4EU supports a more inclusive, connected, and dynamic future for laser science in Europe.

Building a User community: Access, Training, Outreach and cross-facility activities

Now firmly in its operational phase, Lasers4EU has achieved significant milestones by streamlining the way researchers interact with Europe's most advanced laser facilities. Central to this success is a diversified framework comprising three distinct routes for transnational access. The single-instrument route supports curiosity-driven projects requiring a specific laser-based setup, whatever the scientific topics tackled (Fig. 2).

The industry-focused route provides companies and medical centres with the advanced instrumentation and expertise necessary to develop or improve tools and products, while the multi-instrument route, introduced in late 2025, enables parametric studies requiring repeated experiments within a single project or complex experimental campaigns that require the sequential use of multiple instruments through a single proposal. The introduction of this route represented a move towards a more diversified and user-friendly access offer for researchers, these latter being no longer constrained by the technical limits of a given laboratory and benefiting from a reduced administrative burden. This seamless integration of complementary techniques across different European APIs provides a comprehensive understanding of complex physical phenomena, drastically accelerating the pace of discovery in photonics.

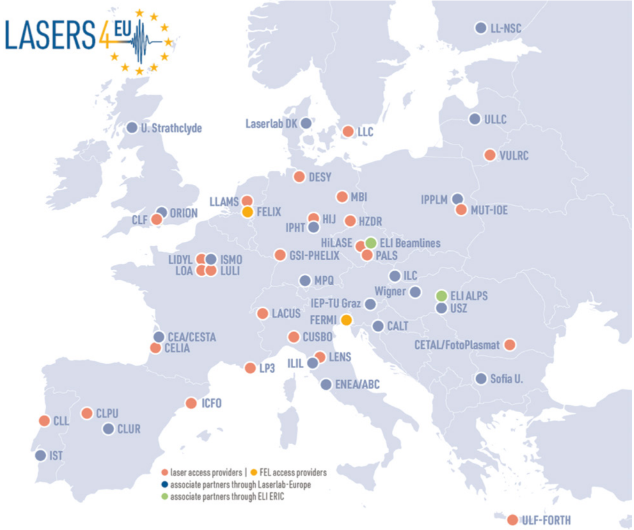
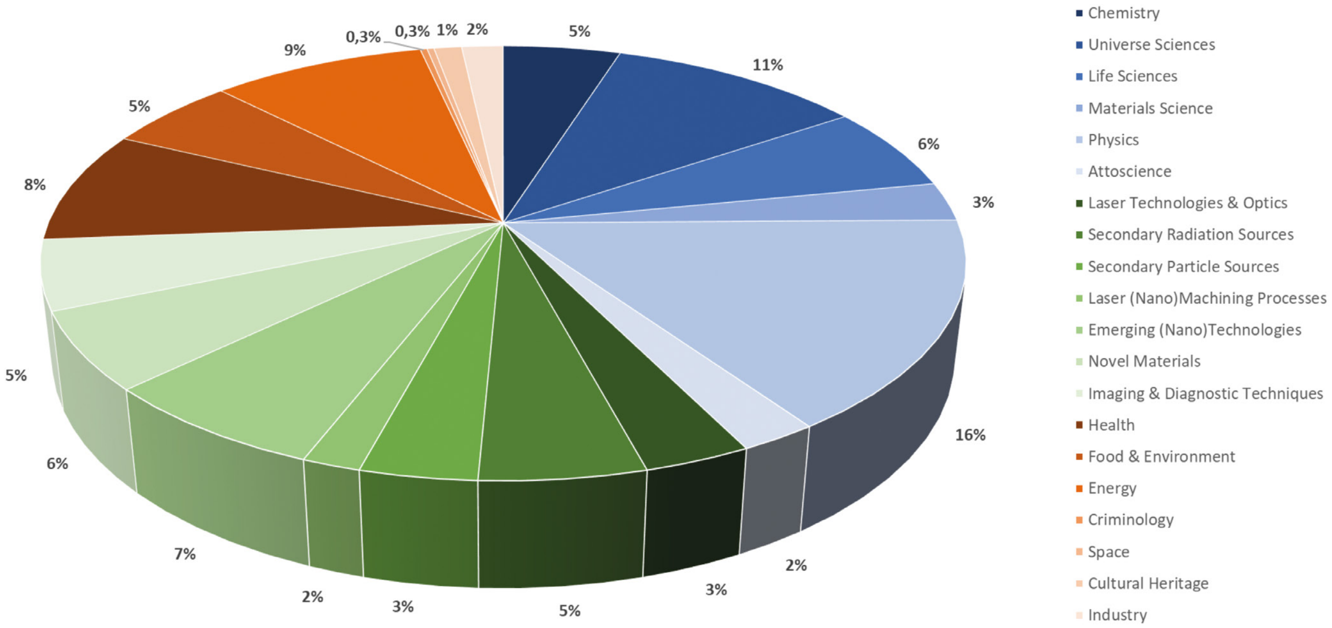


Figure 1: the Lasers4EU network.

To facilitate the access schemes, the project launched the Access Search Tool, a platform that allows users to navigate the consortium's vast resources by matching their scientific interests with detailed laboratory profiles.

Recognising the complexity of operating such equipment, experimental setups, data acquisition systems, and analysis methods, Lasers4EU created a pre-project training scheme. This allows early-career researchers to visit host laboratories for up to one week prior to their official access period to gain ●●●

Figure 2: scientific topics, explored by the Laserlab-Europe access projects for the 2020-2024 period, aiming at deepening fundamental knowledge (blue), developing novel laser-based instruments and exploring societal applications.



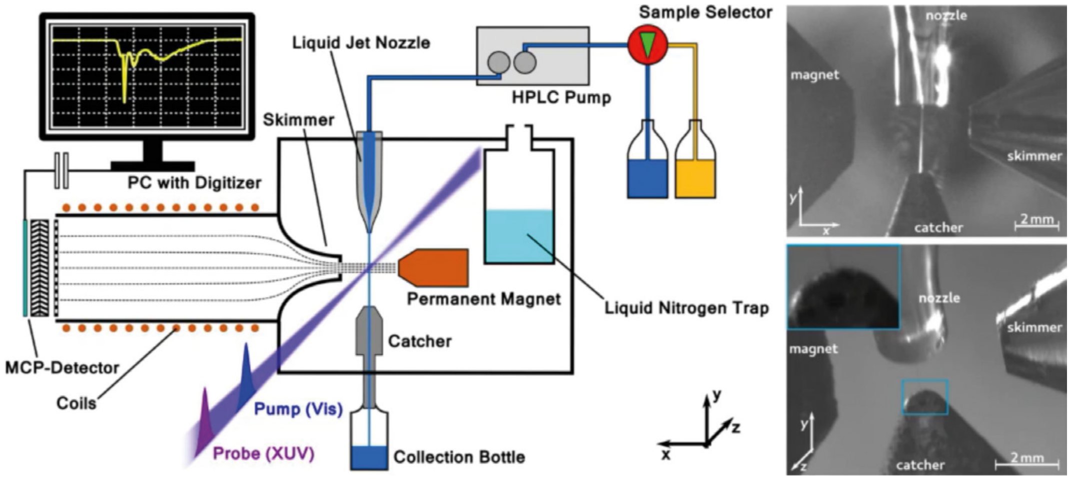


Figure 3: MBI experimental setup [A. Khodko *et al.*, "Ultrafast dynamics of metanil yellow studied by time-resolved transient absorption and XUV photoelectron spectroscopies in solution," Proc. SPIE PC12992, PC129920G (2024); https://doi.org/10.1117/12.3022547].

hands-on experience. This preparation strengthens technical skills, shortens the learning curve, and improves the efficiency of subsequent experimental campaigns.

The training pillar also includes events designed to prepare the next generation of scientists in advanced laser technologies and laser science. These events support non-specialist users from diverse scientific backgrounds in navigating the complexity of the Lasers4EU capabilities, while also helping experienced researchers deepen their knowledge of different laser processing methods. Through hands-on sessions, they give to participants the opportunity to observe laboratory work directly, which enhances understanding beyond what can be gained from reading or lectures alone. Ultimately, they aim to attract new users from emerging fields and regions with developing laser research communities, promoting a more inclusive and multidisciplinary research environment.

ACCESS

A team of scientists from the Center for Collective Use of the Femtosecond Laser Complex at the National Academy of Sciences of Ukraine successfully applied for Lasers4EU access at the Max Born Institute (MBI). The experimental campaign aimed at studying an aminoazobenzene derivated by XUV time-resolved photoelectron spectroscopy in order to understand the role of the environment on the molecular dynamics. Experiments were carried out with two different excitation wavelengths (370 and 490 nm) to investigate the non-hydrated and hydrated forms of the molecule and reveal differences in their dynamics. Apart from its scientific interest, the project was particularly important for the user team, given the challenges posed by the current geopolitical situation.

Lasers4EU organises several thematic "Laserlab-Europe Talks" every year, which present and promote research and applications enabled by laser-based technologies, fostering a better understanding of the links between research and innovation. The project also addresses topics at the intersection of laser science, research infrastructure, innovation, and research services through the Lasers4EU Webinar Series. Furthermore, within the project's framework, the consortium publishes the Laserlab Forum newsletter, highlighting the impact of lasers across diverse areas, from cultural heritage preservation to industrial innovation.

Lasers4EU supports knowledge exchange not only externally and but also internally by promoting initiatives such as staff exchanges and joint experiments, with a strong focus on integrating expertise within the participating institutions. These activities are designed to create lasting impacts that extend beyond the project's duration. Many participants emphasise how valuable these experiences are to grow their expertise in the targeted subject, be this high-energy ultrafast laser systems or advancing expertise in single-molecule and super-resolution microscopy.

Overall, the activities developed by the consortium ensure a coordinated offer for a broad user community. Whether seeking specialised laser facilities for advanced scientific research or aiming to apply cutting-edge laser technologies to industrial innovation, Lasers4EU provides a central point of access to Europe's laser research infrastructures.

Laserlab-Europe AISBL: connecting laser research infrastructures across Europe

The Laserlab-Europe association was founded in 2018 to ensure the continued collaboration of its members in response to evolving European Commission funding priorities. The participating institutions had long valued the scientific opportunities and synergies created through earlier EC-funded projects. To maintain these benefits beyond individual funding cycles, they established a self-funded legal entity that would sustain collaboration, exchange, and strategic coordination even in the absence of major European funding programmes.

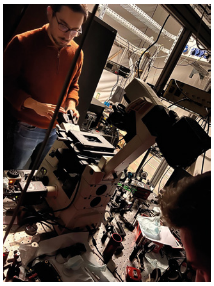
Today, Laserlab-Europe is an association of 48 leading laser research infrastructures in 22 European countries, going far beyond the membership in joint transnational access and technology projects. While Lasers4EU remains a central pillar, the association's reach is amplified through a robust portfolio of EU-funded initiatives. The RIANA project connects 69 facilities to provide cutting-edge nanoscience and nanotechnology tools, while ReMade@ARI focuses on characterising sustainable materials to support the circular economy. In the biological and medical fields, nanoSCAN develops 3D imaging for cancer immunotherapy and fastMOT creates high-efficiency sensing cameras for deep body imaging. The association also prioritises technical innovation through projects like THRILL, which advances high-repetition-rate intense laser technologies.

Finally, Laserlab-Europe maintains a commitment to international solidarity and infrastructure coordination. For instance through the EURIZON project, which specifically supported Ukrainian researchers and institutions. This multifaceted approach ensures that the association remains at the heart of European photonics, driving both scientific discovery and societal impact.

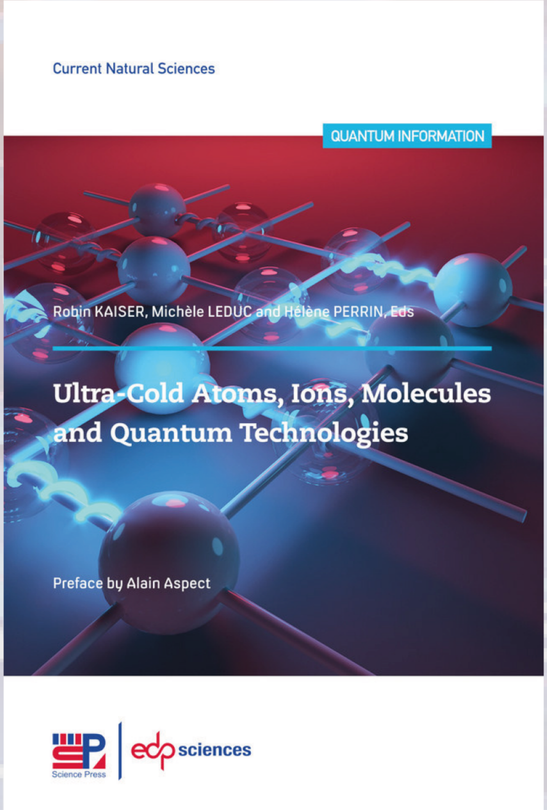
To conclude, Lasers4EU exemplifies the power of European cooperation, providing unparalleled access to advanced tools that drive both scientific and technological discovery. These achievements underscore the value of shared infrastructures in tackling complex global challenges. The project's success is a testament to the strong framework provided by Laserlab-Europe AISBL, which ensures sustained excellence regardless of shifting funding priorities. By integrating emerging technologies and strengthening industrial links, the consortium ensures that Europe maintains its leading role in the global photonics landscape.

More information on https://laserlab-europe.eu/ and https://lasers4.eu/. ●

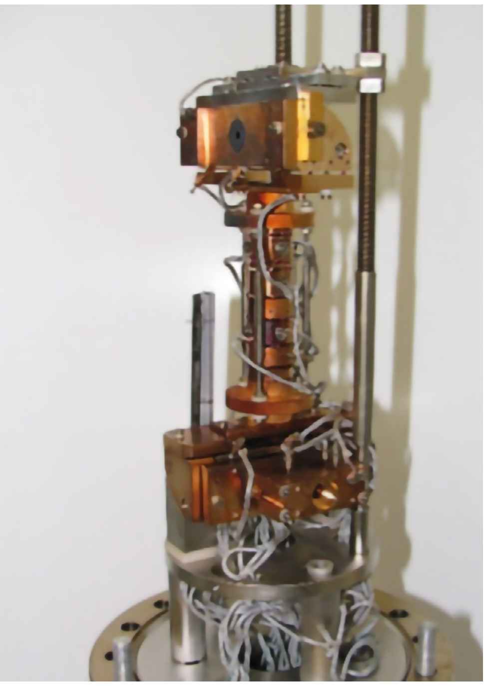
STAFF EXCHANGE



A recent staff exchange supported by the project has for instance strengthened collaboration between the Centre for Ultrafast Science and Biomedical Optics (CUSBO) at Politecnico di Milano and the Institute of Molecular Sciences of Orsay (ISMO). "The exchange confirmed that integrated photonic devices can effectively upgrade conventional microscopy setups into super-resolution instruments. At the same time, it played a key role in establishing shared experimental protocols and defining follow-up activities for the development of integrated optical systems for nanoscopy," says Andrea Bassi, one of the CUSBO participants.



HOW ELECTRON EMISSION UNCOVERED THE LAST MYSTERY OF NITRIDE LEDS



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The remarkable energy efficiency of GaN-based white LEDs has made them the cornerstone of modern lighting. Yet behind this global commercial triumph lay a lingering mystery: why do these LEDs lose efficiency at high currents? That question has finally been answered, thanks to a groundbreaking physics experiment based on electron emission.

https://doi.org/10.1051/photon/202613724

Historical context

Sometimes, technological breakthroughs with major societal impact emerge ahead of our fundamental scientific understanding. The rise of LED lighting is a striking example: high-performance LEDs reached the market even as key aspects of the physics behind GaN, the material at their core, remained poorly understood. In fact, the 2014 Nobel Prize in Physics was awarded to three materials scientists not only for their technical achievement but also for the profound societal impact of their work. While science initially struggled to explain how these imperfect materials could emit light so efficiently, it has now caught up, uncovering why those same LEDs lose efficiency at high currents.

Among the key factors behind the success of nitride LEDs (GaN and its InGaN and AlGaN alloys) were major advances in material science, notably the improvement of GaN crystal quality through a two-step growth process on sapphire substrates, and above all, the achievement of p-type doping via the activation of magnesium acceptor dopant atoms. This activation, first discovered accidentally under electron irradiation and later optimized through thermal annealing, ultimately led to the Nobel Prize together with the discovery of the nucleation layer which leads to materials with high crystalline order. However, the level of p-type doping remained limited compared to n-type doping which might lead to holes injected from the p-side (⑦ in Fig.1) being fewer than electrons injected from the n-side (① in Fig.1). This imbalance might occur in the central region of the LED, composed of InGaN quantum wells, where electron–hole recombination takes place to generate light (② in Fig.1). The non-recombining excess electrons might leak through the active region into the p-doped layer where they recombine non-radiatively, failing to produce photons. This electron leakage from the active quantum wells (shown as ③ in fig.1) translates directly into a loss of luminous efficiency. The solution came in the form of a quantum barrier, an electron blocking layer (EBL), made of the large bandgap AlGaN alloy, inserted between the quantum wells and the p-region to block electron overflow. Thanks to this quantum engineering, nitride LEDs can now reach internal quantum efficiencies of up to 90%, meaning that 90% of the injected electrons are converted into photons. These devices are at the heart of the lighting systems found today in our homes, streets, TVs and cars. The LED emission, that use a transition between two energy levels (conduction band and valence band), is by nature monochromatic, at a wavelength that can be adjusted by the Indium content in the InGaN quantum well. With about 20% In, the LEDs are emitting in the blue. To get white light, one covers the chip with phosphors which absorb part of the blue emission and reemit yellow light, both blue and yellow resulting in white light. The story could have ended there, with a global commercial success and lighting products boasting luminous efficiencies around 150 lm/W, far surpassing competing technologies to the point where competition virtually disappeared. But there was still a small flaw in this triumph: when driven at high current, these LEDs lose efficiency. At high power, their performance can drop by a factor of two or three, a phenomenon known as *efficiency droop*.

In the 2010s, this issue began to stir intense debate within the academic community. Guided by the known challenges of p-type doping and electron leakage, many researchers believed the problem once again lay in these areas: under high injection, the proportion of electrons crossing the active region and even the electron blocking layer (EBL) was thought to increase (③ in Fig.1). To counter this detrimental effect, various structural modifications were attempted, such as adjusting the height of the EBL, changing the number of quantum wells, or altering doping profiles. These studies, often carried out in low

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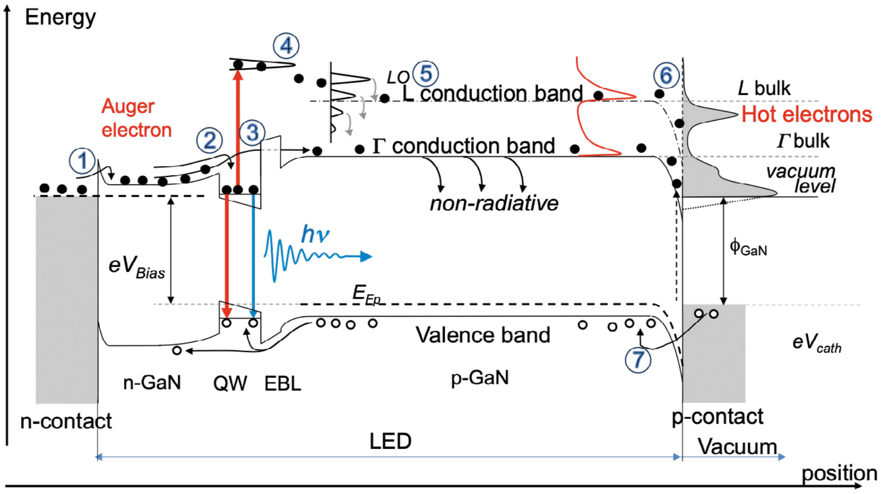
Figure 1. LED band profile and schematic illustrating the Auger effect, which can populate the higher valleys, and electron emission into the vacuum through a cesiated surface. Various mechanisms at work in an LED are illustrated, respectively electron ① and hole ⑦ injection, electron capture in the light-emitting quantum well ②, electron overflow from the active quantum well ③, Auger non-radiative recombination generating hot electrons ④, hot electron energy relaxation into Γ and L bands ⑤, surface energy relaxation generating the electron energy distributions observed outside the semiconductor ⑥.



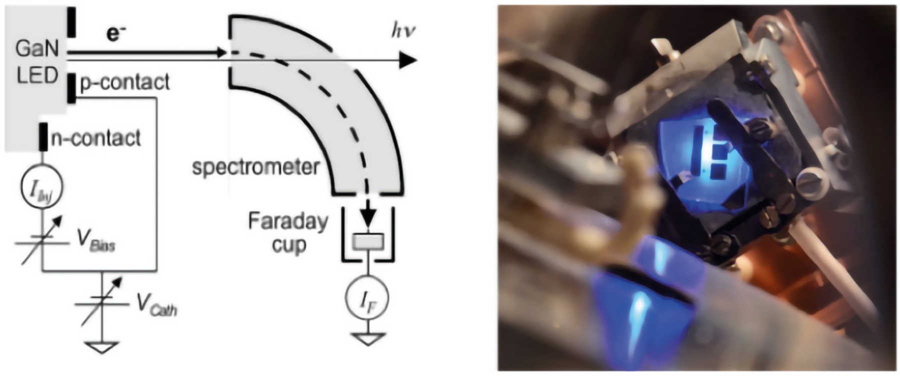


Figure 2. Experimental set up with LED and electron analyzer. Blue LED in operation during measurement, emitting both blue photons and electrons. (photo credit: Ph. Lavialle, École Polytechnique)

efficiency LEDs, met with ambiguous results as they did not improve over state-of-the art LEDs, suggesting that the root cause had likely not been identified. An alternative and not entirely incompatible explanation also existed: the Auger effect (recently renamed the Auger–Meitner effect). During the recombination of an electron with a hole in an InGaN quantum well, the released energy can, instead of generating a photon, be transferred to another electron (or hole), giving it a large kinetic energy within its band (④ in fig.1). This excess energy is then dissipated as heat (phonons) (⑤ in fig.1). This process directly reduces luminous efficiency as an electron hole pair has disappeared in the process and becomes significant when carrier densities are high (its probability scales roughly with the cube of the charge density n^3) and thus under high current injection. This led to the emergence of the so-called *ABC models*, which describe LED efficiency as a function of current, incorporating contributions from defect-related recombination ($A\cdot n$), radiative recombination ($B\cdot n^2$), and Auger recombination ($C\cdot n^3$). These models provided remarkably good fits to experimental data. However, the somewhat arbitrary choice of the A, B, and C coefficients (and later refinements to the model [1]) meant that the argument was not yet watertight. Moreover, proponents of the electron leakage theory claimed that leakage could itself be modeled with an n^3 dependence.

Well known in small–bandgap materials, the Auger process was long considered negligible in wide bandgap materials like nitrides, where energy and momentum conservation make such interactions unlikely. For this reason, the hypothesis initially seemed implausible. In 2007, a precise analysis of the change in carrier lifetime in photoluminescence concluded that an n^3 mechanism, seen as a signature of an Auger effect, explained the data. Then, around 2011, Auger processes were revisited theoretically [2], taking into account various *indirect* mechanisms. Specifically, the involvement of phonons or changes in wavefunction extension caused by defects, alloy disorder, and other factors can relax momentum conservation, making the process 100 to 1000 times more probable than previously predicted. Doubt began to creep into the nitride LED community, exposed to several alternative explanations: could the droop indeed be linked to the Auger effect? What was missing was a direct, irrefutable experimental proof that could reveal the true origin of the droop. And that proof finally came through a decisive physics experiment were the hot electrons generated by an Auger event could be observed.

The decisive physics experiment

Electron emission is, historically, a technique from surface physics seemingly far removed from the internal physical mechanisms invoked to solve the issues surrounding LEDs. It is at the root of the photoelectric effect. Its basic principle is to observe the energy of electrons emitted from a surface when photoexcited as they retain the energy they had inside. To do this, electrons must first be given enough energy to escape the material. This gives a relation between the photon energy and the maximum energy of the outgoing electron which led Einstein to the photon hypothesis and Millikan to determine the value of the Planck constant by relating the maximum energy of the photoemitted electron from metals to the photon energy. The principle of the experiment carried out in LEDs is to use emitted electrons to measure electron energies *inside* the semiconductor. To study semiconductors, it is beneficial to lower the vacuum level, by coating the surface with a monolayer of cesium, which reduces that level so much that an electron in the semiconductor conduction band has a higher energy than the one in vacuum. Analyzing the energy of electrons emitted then probes the energy distribution of electrons above the conduction band near the surface. This turns out to be crucial for the identification of the Auger processes occurring inside materials. In the Auger effect, an electron initially thermalized at the bottom of the semiconductor conduction band, the so-called Γ conduction band, gains the energy of the electron-hole pair, the bandgap energy, either within that same band or in higher ones ④. The electron relaxes down its energy by returning to the minimum of the Γ valley, so-called Γ point, or by transferring to another higher lying conduction band (L band, ⑤ in Fig.1). In that latter case, an electron in the L valley can relax part of its energy toward the bottom of that valley, the L point, but may also transition back to Γ. These intra- and intervalley relaxations occur through the emission of phonons, primarily longitudinal polar-optical (LO) phonons with an energy of 91 meV in GaN. In all cases, if the initial electron energy is sufficient (that is, higher than the energy separation between the Γ and L valleys plus the 91 meV of the LO phonon), electrons will populate both valleys. If the time required for the Auger-created hot electrons to diffuse to the surface is shorter than the complete relaxation of all electrons from L to Γ, then some electrons with the energy characteristic of the L valley can be emitted into vacuum. In practice, things are a bit more complex: the band profiles near the surface are not flat but bent, so the energy of the Γ and L valleys decreases near the surface, and hot electrons can occupy a range of energies between the valley positions deep in the material and those at the surface (⑥ in Fig. 1). To observe such hot electrons, one simply needs to inject electrons and holes into the quantum wells with concentrations large enough to induce the Auger effect. This is done by forward-biasing an LED. As shown in Figure 1, this forward bias allows electrons to be injected from the n-type region into the quantum wells but it does not give them high kinetic energy: they are injected in GaN and InGaN and relax to the Γ minimum of the main conduction band. If they traverse the active region (through leakage), they will be emitted with the energy corresponding to the Γ valley of the p-side. In contrast, if recombination occurs in the InGaN well through the Auger process, electrons will populate the higher-energy valleys accessible to them.

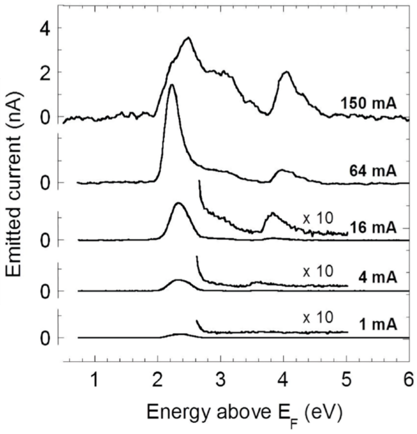


Figure 3. Electron emission spectra for various LED currents showing peaks related to the surface (3), Γ (2) and L (1) valleys.

A collaboration carried out experiments first at the École Polytechnique in Palaiseau, and later at the University of California, Santa Barbara. The LED, engineered with perforations in its upper contact to allow electrons to pass through, was placed facing an electron spectrometer (shown in the photo at the top of the article) in an ultra-high-vacuum chamber. A single atomic layer of cesium was then deposited on ●●●

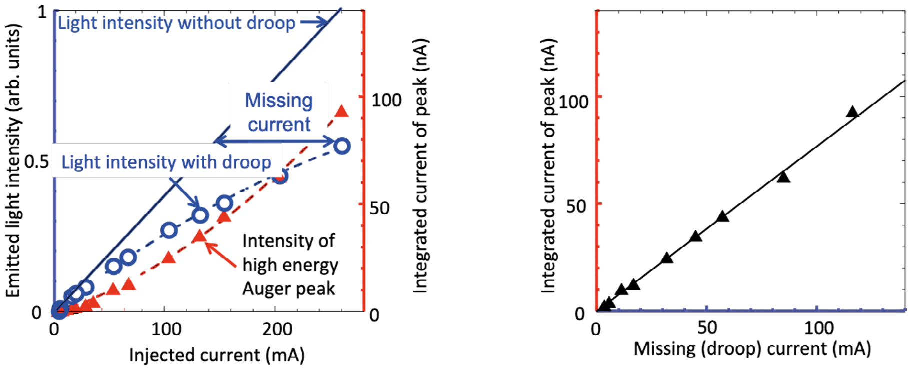


Figure 4. Evolution of the L-valley peak and emitted light intensity as a function of diode current. The extrapolated emission in the absence of droop is shown, defining the "missing current" (left). This missing current is then used to track the intensity of the L-valley peak (right).

the device. After this step, measurements could be performed at room temperature.

Electron energy distribution curves (EDCs) are measured using a cylindrical electron energy analyzer (Figure 2 and top photo). Varying the cathode potential (V_{cath}) allows sweeping the energy. Figure 1 summarizes the energy scale. Note that a hole in the analyser allows taking the electroluminescence emitted by the LED during the electron emission measurement (Figure 2). The electron energy resolution is approximately 50 meV.

The first measurements were carried out on a blue LED composed of eight InGaN quantum wells containing 18% indium [Iveland]. Taking into account both quantum confinement and internal electric fields in the quantum wells, the transition energy in these wells is 2.75 eV (blue light at 450 nm). The device also includes an $Al_{0.15}Ga_{0.85}N$ EBL, and a 200-nanometer-thick p-doped top layer. When the LED is forward-biased and the current is gradually increased, one, then two, and finally three distinct peaks appear (figure 3). The first, at low energy, corresponds to electrons mainly emitted from the metal excited by the blue light generated by the LED. This first peak extends up to about 0.5 eV, which, when added to the vacuum level, gives an energy of 2.8 eV above the Fermi level, consistent with the photon energy of the emitted light. The second peak, separated from the first through spectral analysis, extends up to around 1.45 eV (estimated at 64 mA) and corresponds to the emission of electrons in the Γ valley. It originates from electrons that have crossed the active region and the EBL as well as from electrons initially in the L valley that thermalized into the Γ valley on their way to the surface. Finally, the third peak, extending up to 2.4 eV, corresponds to a higher-energy valley attributed to the L valley. These "hot" electrons are believed to be a signature of Auger processes that excite them into the L valley before they diffuse through the p-type GaN to the surface. Their energy distribution broadens in the final, strongly curved region of the band structure. The energy separation between the Γ and L valleys is about 0.95 eV in this case. As the diode's voltage and current increase, parasitic resistances in the p-contact region cause both the Γ and L valley peaks to shift by roughly the same amount. Tracking these two peaks makes it possible to determine an average separation between the valleys, ultimately estimated at 1 eV. Note that similar electron emission studies were performed on LED structures by optical pumping, *i.e.* photoemission [4]. When the exciting photon energy exceeds 4.2 eV (0.8 eV above the gap), the L-valley signal emerges confirming a value of approximately 1 eV for the Γ–L separation in GaN (and low-indium InGaN).

Studying how the intensity of the peak associated with the L valley varies with diode current also proves highly informative. At the same time, the emitted light intensity is measured (see Figure 4). Initially, the light output increases linearly with current, but then grows more slowly, with a sublinear behavior that reflects the "efficiency droop." By extrapolating the initial linear region, one can estimate the emission that would be obtained if this droop did not occur. Comparing the two curves, with and without the droop, makes it possible to determine the current that did not give emission. This "missing current" corresponds to the portion of the injected current feeding the droop process, *i.e.* Auger recombination. When the intensity of the L-valley peak is plotted as a function of this missing current, a perfect linear relationship appears. In other words, the Auger effect, revealed through the presence of electrons in the L valley, is directly responsible for the loss of quantum efficiency in high-current nitride LEDs.

As further proof of the link between the Auger effect in LEDs and hot electrons, the same measurement was repeated on a simple pn junction without quantum wells where both radiative and Auger recombination are reduced due to the absence of carrier confinement. In that case, only the Γ-valley peak was observed [5].

Thus, roughly a decade of electron emission measurements solved the mystery of the efficiency droop. Have they provided a solution? Partially, yes. Although the problem is intrinsic, it can be mitigated by reducing charge densities. Strategies such as ensuring a more uniform current distribution, increasing the number of quantum wells, or widening them are all feasible approaches and several have already been widely implemented. ●

Acknowledgements

The author aknowledges Prof. Claude Weisbuch (École Polytechnique, France and University of California at Santa Barbara, USA.

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*The research was made on Meltwater Media Monitoring from the year 2000 to 2023.

COHERENT EMISSION OF LIGHT BY THERMAL SOURCES

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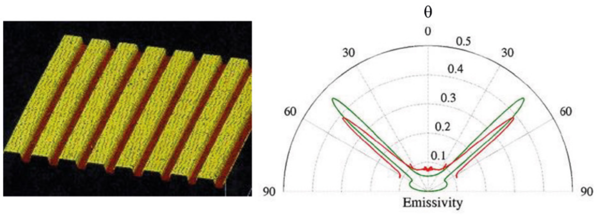

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While the light emitted by an incandescent body is generally quasi-isotropic, it was demonstrated in 2002 that a diffraction grating etched onto a silicon carbide (SiC) surface can exhibit highly directional emission, comparable to that of antennas operating in the radio domain. Directivity is the signature of the existence of spatial coherence of the field in the plane of the source, an unexpected property for a thermal source. This article describes the development of the ideas that led to this experiment and its current implications.

25 years ago "Coherent thermal emission" was an unexpected title as thermal radiation was usually taken as the typical example of incoherent light. In very simple terms, light with a narrow frequency spectrum is said to be temporally coherent and light with a narrow spatial frequency spectrum is said to be spatially coherent so that blackbody radiation has a low coherence whereas laser light is highly coherent. Nonetheless, it is now possible to engineer coherent light emission by tailoring hot bodies. Thermal metasurfaces consisting of hot nanostructured surfaces is today an active field of research and most features of the emission can be controlled including the angular emission pattern (spatial coherence), the emission spectrum (temporal coherence) and the polarization. A tutorial discussion can be found in ref. [1] and a recent rewiew [2] lists more than 500 references. The field was initiated in 1976 by the first experimental observation of a highly directional total absorption of visible light by a metallic grating [3]. Maystre and Hutley demonstrated that by ruling a shallow diffraction grating on a gold surface, a mirror could become totally absorbing for a particular angle and frequency. This highly directional absorption had been predicted theoretically and attributed to the resonant excitation of a surface plasmon. According to Kirchhoff's law derived in 1860 [4], emission is proportional to the absorptivity. Hence, if Kirchhoff law is valid, the thermal emission by a gold grating could be highly directional and behave as a coherent antenna. Hence, one had to conclude that either thermal emission can be coherent or that Kirchhoff's law is not valid, at least for gold gratings. As Kirchhoff's law had been derived in the framework of optical geometry which is not valid for gratings with periods on the order of the wavelength, it seemed reasonable to question Kirchhoff's law validity.

The experiment

The experiment that led to the observation of directional emission was triggered by Michel Olivier at CEA-Grenoble. He envisioned applications and proposed to use a grating ruled on a SiC sample. SiC is a material that supports surface phonon polaritons (SPhPs) which can mimick surface plasmons. When ruling a grating on the surface, an incident plane wave can be totally absorbed in the wavelength range 10-12 µm. Hence, thermal emission could be observed by increasing the temperature by only 100 or 200°C if Kirchhoff's law is applicable. As the angular position of the peak depends on the frequency, directional emission is only observed when detecting at a given frequency. The first design of the grating led to the fabrication of a grating that did not produce the expected directional peaks [5] neither in reflection nor in emission. This was due to the use of a perturbative model to design the surface. Total absorption is a non-perturbative resonant phenomenon that requires an accurate numerical simulation for the design and an accurate nanofabrication of the sample. We designed the surface profile in the team at Ecole Centrale. The team of Yong Chen did the fabrication of the samples at L2M/CNRS using optical lithography and reactive ion-etching. The measurements were made at CESTA/CEA by S. Mainguy in 2002 [6]. The reflectivity measurements displayed the expected total absorption as seen in Fig. 1. The sample was then installed on a heater and emission spectra were taken for different emission angles. As predicted by Kirchhoff's law, we observed highly directional emission by a hot body (see Fig. 1 lower panel). In this first experiment, the angular resolution was limited by the detection system. A second setup was later developed by F. Marquier to study in detail the measured coherence length and to improve the agreement with theory by accounting for the dependence of the refractive index on the temperature [7].

Discussion

At that point, it was clear that Kirchhoff law prediction was confirmed by the experiments. That result raised the question of the origin of the spatial coherence. It also suggested that Kirchhoff law could be derived without making the geometrical optics approximation. We managed to derive Kirchhoff's law beyond the geometrical optics approximation by using a wave equation framework [8]. We also ●●●

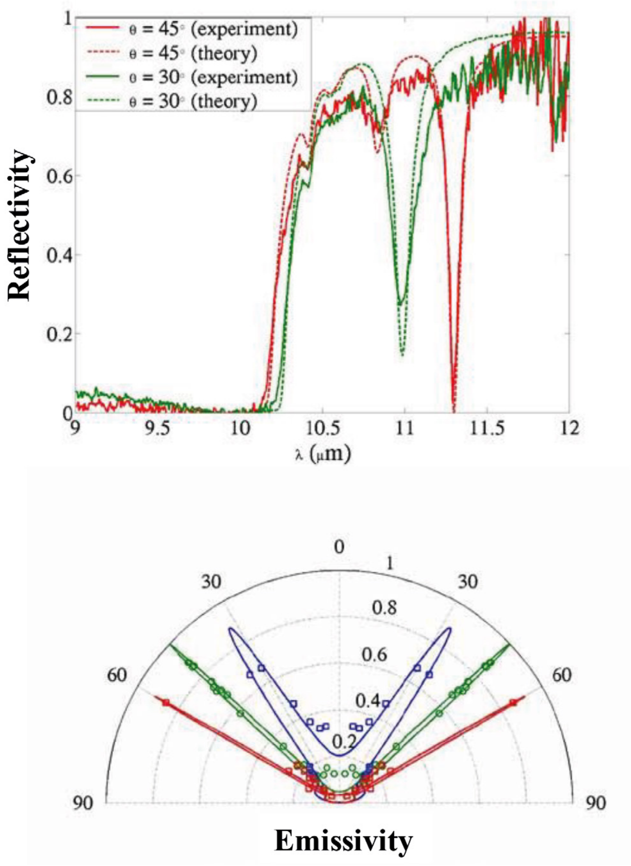

Figure 1. Upper panel: reflectivity of a grating ruled on a SiC sample. A total absorption peak is observed at 11.36 µm for a 45° incidence. Lower panel, emissivity measurement for three different wavelengths (blue: 11.04 µm, green: 11.86 µm, red: 11.36 µm). The experimental data are given by the circles, the theoretical results (solid line) are convoluted to account for the experimental angular resolution. The emissivity is given by the ratio of the emitted power by the power emitted by a blackbody at the same temperature. (reproduced from ref. [6]).

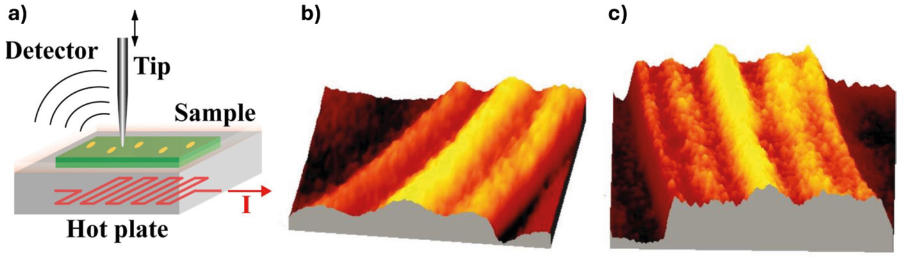

Figure 2. a) Schematic description of the scanning IR microscope. The sample consists of gold stripes deposited on a SiC sample. The sample is not illuminated but heated up to 170°C so that only thermal emission can be detected in the IR. A tip oscillates vertically above the hot sample. It scatters the thermal infrared near-field which is collected by a Cassegrain objective and sent to an IR detector, b) and c) cross section of the IR signal measured through a bandpass filter (centered at 10.9 µm, width of 1 µm) taken for stripe widths: 12 µm (b) and 25 µm (c). The fringe structure reproduces the local density of states. The fringe structure illustrates the spatial coherence of the thermally excited field when only a few modes are available due to the finite width of the stripe which is on the order of the wavelength. Reproduced from ref. [11].

found that another derivation of Kirchhoff law was already available in the framework of fluctuational electrodynamics [9]. This framework is extremely powerful and enables to compute the emitted field in the framework of Maxwell equations and statistical physics. It had been used to analyse Casimir forces and thermal fields in the microwave regime. We applied it to derive the correlation function of the electric field thermally emitted close to an interface separating a material from air. We found that when a surface wave propagates along the interface, a long-range correlation (i.e. spatial coherence) exists [10].

Since spatial coherence results from the excitation of a surface wave, it can only be measured directly in the near field. Near-field optical microscopy had just been introduced and enabled to measure directly the field of surface plasmons. However, the measurement of a correlation of the field measured at two different points was more challenging. To mitigate the experimental difficulty, we briefly attempted to measure the near-field correlation in the microwave regime at the interface between water and air as surface waves may propagate along this interface. K. Joulain did experiments in collaboration with Michel Gross at Ecole Normale but we could not observe the effect. It took some years before Y. de Wilde could directly observe fringes in the structure of a thermally emitted field [11] by a gold stripe with finite width using a near-field microscope as seen in Fig. 2.

The physical mechanism

To grasp the role of spatial coherence, we use a physical picture that emerges from the fluctuational electrodynamics framework. Each volume element of the emitting body contains random currents due the thermal motion of electrons and nuclei. These currents are spatially uncorrelated. If such a volume element is chosen much smaller than a wavelength, it can be described as a random dipole. The field emitted by the dipole can be represented as a sum of plane waves. If we consider that the emitting body is a half-space separating a medium from air, each plane wave emitted in the body may be reabsorbed before reaching the interface. However, if the volume element is close enough to the interface, the radiation may be transmitted (see Fig. 3 a). For a metal or SiC, the transmission factor is low and does not depend much on the angle of incidence so that the emission is low for all directions. A directional thermal source requires an interface whose transmission factor is low for all directions but one.

We now explain why a grating ruled on a SiC surface has this peculiar property. As discussed above, the emitted radiation is the sum of the intensities emitted by each volume element in the hot body. It turns out that a random

Figure 3. Sketch of the mechanism producing spatial coherence and directional emission. a) Thermal emission by a hot body. Each volume element (red disk) contains charges with random thermal motion. The corresponding current density emits light which is transmitted by the interface (red arrows). b) Thermal emission by a hot body sustaining a surface wave. In addition to the transmitted light, a surface wave (thick horizontal line) is excited. The dispersion relation of the surface wave is denoted $k_{sw}(\omega)$. The surface wave propagates along the interface and decays exponentially due to the losses in the material. As a consequence, the field is correlated over a distance limited by the surface wave decay length. c) Coherent thermal emission. When a grating with period d is ruled on the interface, the surface wave is diffracted in a direction θ given by the grating law $\omega/c \sin\theta = k_{sw}(\omega)-2\pi/d$.

dipole close to the interface may also excite a surface wave whose wavevector $k_{sw}(\omega)$ is given by the dispersion relation at each frequency ω (see Fig. 3 b). The surface wave propagates over a typical decay length which is on the order of 100 µm before being absorbed. When ruling a grating on the interface, the different lines of the grating are coherently illuminated by the same surface wave which is thus diffracted in a well-defined direction given by the usual grating law (see Fig. 3 c). This is the mechanism that produces directional emission. In summary, the grating does not generate spatial coherence but reveals the existing spatial coherence of the field due to the excitation of a surface wave.

Applications and further developments

The experiment has proved that a source consisting of incoherent emitters can be turned into a directional source. It led to the understanding that Kirchhoff 's law validity is broader than initially thought so that the tool box of nanophotonics can be used to tailor thermal emission. This idea has been further developed to explore a large variety of thermal sources [2]. More recently, this idea has been applied to analyse and control visible luminescence by semiconductors and quantum dots [12, 13]. The basic mechanism is the same: the incoherent emitters must be coupled to a mode guided by a surface or by a planar guide whose radiative losses can be engineered to control the emission polarization and angular pattern. These features enable the design of light-emitting metasurfaces with a thickness of a few hundred nanometers. This could mark the advent of a new generation of light sources that do not require the use of bulky lenses and polarizers [14]. ●

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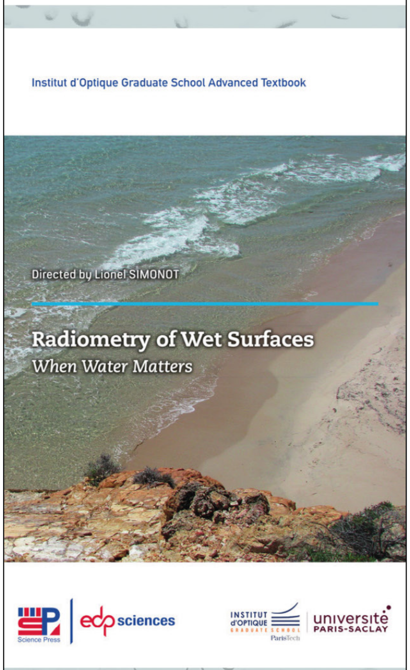

THE ROLE OF PHOTONICS IN FINNISH VOCATIONAL AND HIGHER EDUCATION

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This article reviews the role of photonics in Finnish vocational and higher education, examining how photonics-related topics progress across these pathways. The focus is on university education, particularly the opportunity to study photonics as a primary subject, its integration into broader science and engineering programmes, and its presence in international master's programmes and key educational and research networks. Finally, the article discusses the growing importance of photonics in technology and society, and makes the case for strengthening photonics education through curriculum development, teacher training, and the pedagogical use of artificial intelligence.

In this century, photonics has become a key enabling technology, often seen as the successor to the electronics-driven 20th century. Light-based systems underpin communication, information processing, healthcare and manufacturing: optical fibres enable global connectivity, while lasers drive applications from medical diagnostics to industrial production. As photonics shapes society, basic literacy is needed at all levels, while advanced expertise enables new devices and applications.

Finland stands out through a coordinated national ecosystem, Photonics Finland, linking companies, universities, research institutes and public authorities. The PREIN Flagship[1], Finland's national photonics research and innovation network, unites leading institutions and supports long-term development. Finland's photonics industry grows at almost twice (12%) the global average of 7%, with over 340 companies, more than €2.5 billion in turnover and over 7,500 employees[2]. Strengths include optical sensing, imaging, micro- and nanophotonics, lasers, fibre-optic technologies and extended-reality applications, supported by close academia–industry ties. The National Photonics Roadmap 2025–2030 highlights these assets for future competitiveness.

Finland's strong basic and upper secondary science education provides a foundation for photonics. Building on this, the following section reviews

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[1] The Research Council of Finland's Flagship Programme is an instrument that supports high-quality research and increases the economic and societal impact emerging from the research.

[2] At the end of 2025, Finland's population stood at approximately 5.66 million, and the country hosted about 1,800 companies in the technology industry.

vocational, university of applied science (UAS) and university-level studies, international master's programmes and cooperation networks from a photonics perspective. The discussion addresses skills needs and economic priorities and argues for strengthening photonics education—especially in universities—based on workforce forecasts, national priorities, European trends and the growing role of AI.

VOCATIONAL AND HIGHER EDUCATION

This section overviews photonics education at various levels, starting with vocational and UAS pathways. The focus is on university education, international joint master's programmes and cooperation networks that support advanced learning.

VOCATIONAL EDUCATION

In Finland, vocational education and training (VET) provides practical, competence-based training closely linked to industry, preparing students for employment or further study. Although photonics is mainly taught at universities, VET supports the field by supplying skilled professionals in related technical roles such as electronics, automation, ICT, and precision manufacturing. These competencies enable tasks like assembling optical instruments and maintaining photonics equipment. Targeted initiatives—such as the Joensuu pathway developed with local VET, UAS, and university partners—add photonics basics, laser safety, cleanroom skills, and manufacturing fundamentals, helping meet the sector's growing technical workforce needs.

UNIVERSITY OF APPLIED SCIENCE EDUCATION

UASs provide vocationally oriented higher education aligned with industry needs. While universities offer programmes explicitly titled photonics, UASs complement them by educating application-focused engineers, technicians and opticians. Degree programmes in electronics, electrical engineering, ICT, automation, mechanical and precision engineering equip students for optical instrument assembly, laser and measurement system integration, cleanroom work and precision manufacturing. UASs also offer continuing education in cleanroom practice, machining, instrumentation and quality control, supplying industry-ready talent for photonics-related applications.

UNIVERSITY EDUCATION

At Finnish universities, bachelor's physics includes photonics-related topics such as wave motion, electromagnetism and optics, with an introductory photonics course at University of Eastern Finland (UEF). As no university offers a bachelor's degree specifically in photonics, emphasis is on master's-level studies. Photonics can be studied as a main subject at UEF, Tampere University (TAU) and Aalto University, each offering dedicated or specialised master's options, with PhD studies available at all three. Photonics-related content also appears at several other universities.

University of Eastern Finland

At UEF, photonics focuses on advanced optics and light-based technologies. The National Master's Programme, integrated with the two-year International Master's in Photonics, combines rigorous theory with extensive laboratory training, including micro- and nanofabrication in clean rooms. The curriculum covers light–matter interaction, waves, scattering, quantum and applied photonics, supported by strong experimental work and a thesis. Teaching and research are centred in Joensuu, a long-established photonics hub, and graduates are well prepared for international careers with versatile scientific and technical skills.

Tampere University

At TAU, photonics is part of the Physics Unit in the Faculty of Engineering and Natural Sciences. Research spans communications, lasers, energy, sensing, environmental and health applications. It is offered as a specialisation in the Master's Programme in Science and Engineering, developing expertise in light–matter interaction, materials and optical devices through theory and labs. Facilities include laboratories for optical characterisation, nonlinear optics, fibre lasers and metamaterials.

Aalto University

At Aalto, photonics is embedded across the School of Electrical Engineering. The Department of Electronics and Nanoengineering hosts the Photonics and Nanotechnology specialisation within the Master's Programme ● ● ●

Figure 1. A girl exploring colours through experiments at the Light for Families event. Photo: Anne-Maria Kankaisto, Photonics Finland.

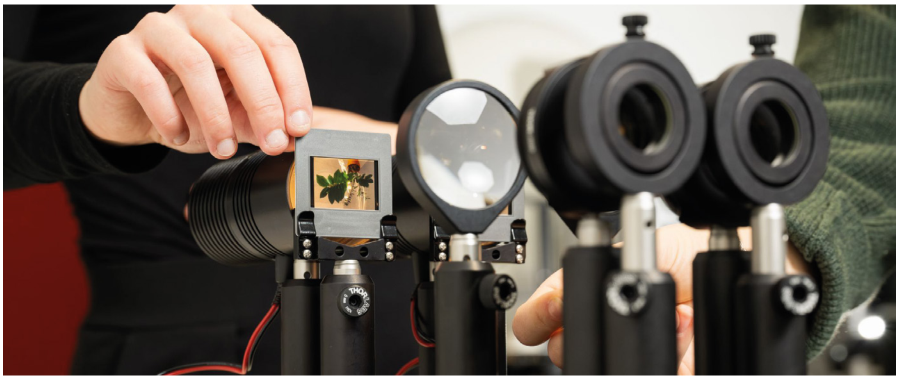

Figure 2. A setup for studying the principle of a 3D movie based on polarisation.
Photo: Niko Jouhkimainen, UEF.

in Electronics and Nanotechnology, covering light–matter interaction, optical systems and device fabrication. Students take courses such as Photonics and Optoelectronics and gain hands-on experience in the cleanroom. Aalto also offers a Photonics and Nanotechnology minor open to all students. Research focuses on integrated photonics, optoelectronics, semiconductor lasers, nanomaterials and advanced optical phenomena.

Other universities

Several universities integrate photonics within broader programmes rather than as a separate major. The University of Jyväskylä includes photonics-related content in its multidisciplinary Master's in Nanoscience. At the University of Oulu, photonics is embedded in electrical engineering, with options in photonics and measurement technology. The University of Helsinki's materials research master's offers a specialisation in optics and photonics. The University of Turku includes photonics within its Master's in physical and chemical sciences, preparing students for R&D roles.

INTERNATIONAL JOINT MASTER'S DEGREE PROGRAMS

International and joint Master's programmes strengthen Finland's talent base and global appeal. By combining expertise from leading universities, they widen access to skilled students, serve industry needs and enhance quality, while helping retain international graduates in Finland's research and innovation ecosystem. UEF participates in three Erasmus Mundus programmes and TAU in one, all two-year degrees with European and global partners, preparing students for high-tech careers and doctoral studies.

iPSRS – Intelligent Photonics for Security, Reliability, Sustainability and Safety

A Master's integrating photonics and AI to address challenges in security, safety, reliability and sustainability. It trains students in intelligent photonics, imaging, sensing and machine learning. Coordinated by Université Jean Monnet (UJM) with UEF, Vilnius University and University Paris-Est Créteil, it includes coursework, projects, seminars and internships.

IMLEX – Imaging and Light in Extended Reality

A multidisciplinary Master's combining imaging, lighting and IT with a focus on extended-reality applications. Coordinated by UEF with UJM, KU Leuven and Toyohashi University of Technology, it blends theory and practice through international mobility for XR-industry roles and applied research.

COSI – Computational Colour and Spectral Imaging

A Master's specialising in computational colour science and spectral imaging, combining photonics, optics, image processing, computer vision and data science for applications from multimedia to biomedical and industrial imaging. Coordinated by NTNU with UJM, the University of Granada and UEF, it features strong industry collaboration, applied research, internships and thesis work.

EuroPhotonics – International Master's Programme in Photonics Engineering, Biomedical Imaging, Quantum Optics, Laser Optics, Optics for Astronomy, Nanophotonics and Biophotonics

A long-running Erasmus Mundus programme offering advanced education from fundamentals to cutting-edge research. Training spans photonics engineering, laser and quantum optics, nanophotonics, biophotonics, biomedical imaging and astronomy optics, combining theory, labs and a research-focused thesis. Coordinated by Aix-Marseille University with TAU, KIT, the University of Barcelona, Vilnius University and other partners, its mobility and joint degree prepare graduates for high-tech industry and research careers.

NATIONAL AND INTERNATIONAL EDUCATIONAL COOPERATION NETWORKS

Educational cooperation networks connect universities, industry and other partners to deliver flexible, high-quality learning. They enable joint courses, shared expertise and coordinated programme development, especially in emerging technologies, and support lifelong learning.

FiTech and LUMA Centre Finland

FiTech unites Finnish universities offering engineering education and provides free courses in AI, machine learning, energy engineering and wood materials. Although multidisciplinary, it currently offers no dedicated photonics courses.

LUMA Centre Finland is a national STEM network of 13 university-based centres. It inspires young people in STEM and supports teacher development from early childhood to higher education. Appointed by the Ministry of Education and Culture for 2025–2028, it promotes equitable, research-based STEM education through study visits, teacher training and pedagogical innovation. Reaching about 400,000 learners and educators annually, LUMA works with schools, universities, industry and international partners. Its StarT initiative is a recognised project-based learning model. In Joensuu, the local LUMA centre runs the Light for Families event with PREIN and UEF.

FysNet and EduQ

FysNet unites university physics educators to develop a joint national study offering with high-quality online and hybrid teaching. It shares best practices across 15 thematic groups, including one on optics and photonics, *e.g.* creating an optical design course.

EduQ, part of Institute Q (the Finnish quantum institute), coordinates master's and PhD-level education in quantum science by combining partner programmes and offers open resources such as QPlayLearn and MOOCs, with planned courses on quantum optics.

Phortify – European photonics network between degree programmes

Phortify, launched in 2025, is a European photonics education initiative linking universities, research organisations and industry. It harmonises training across seven Master's programmes, with UEF among 12 partners. Through shared curricula, short modules, mobility and recognised certification, Phortify provides up-to-date skills across the photonics value chain, including integrated photonics, optical communications and related technologies, helping companies address skill gaps.

DISCUSSION

Photonics plays an increasingly important role in Finnish vocational and higher education, especially at universities. With Finland's technology sector expected to need around 13,000 new experts annually—many in photonics-related roles—the need to strengthen photonics education is clear.

In the EU, photonics underpins major Finnish growth sectors such as digitalisation, manufacturing, healthcare, environmental monitoring and emerging quantum technologies. As reliance on optical solutions increases, so does demand for expertise. Photonics also drives advances in precision sensing and next-generation computing. Expanding photonics education would help address skills shortages, support innovation and maintain competitiveness.

Although light-related topics appear in early science education, photonics remains largely invisible as a coherent field. Clearer links between content, applications and study pathways would raise awareness, increase interest and support university recruitment. Teacher training and curriculum development are critical, as national curricula guide practice even with strong teacher autonomy.

AI is transforming photonics learning through adaptive tools, automated design and data-driven optimisation, but expert knowledge remains indispensable: accurate modelling, meaningful problem-setting and interpreting results still require human judgement, and core skills—experimental intuition, understanding light–matter interactions and making informed design choices—cannot be automated.

Across Europe, education systems and the adoption of AI-enhanced tools vary, so integrating photonics should follow nationally tailored approaches while benefiting from European cooperation. To turn laboratory innovations into scalable applications, education must align research, industry and digital competencies, and emphasise interdisciplinary skills that combine photonics with data science, machine learning and systems engineering, grounded in strong physical understanding.

Within this context, Finland can build on its strengths—flexible curricula, research-based teaching and strong industry links—while integrating computational and AI-assisted tools into studies. By developing strategies tailored to national needs yet aligned with European objectives, Finland and other countries can cultivate experts capable of leading, rather than merely adapting to, future technological change. ●

Figure 3. Two photonics engineering students wearing the distinctive overalls that serve as the student association's informal uniform. Photo: Niko Jouhkimainen, UEF.

FEMTOSECOND LASER STRUCTURING OF GLASSES

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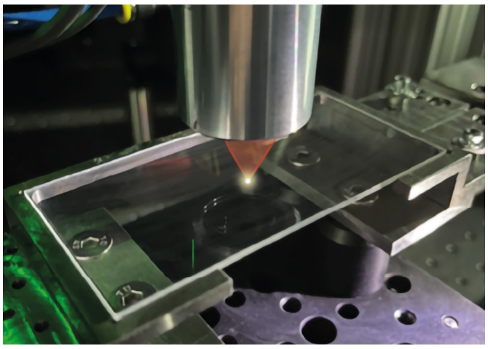

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Femtosecond lasers enable precise 3D nano- and micro-structuring in glasses, transforming photonic devices fabrication. The process relies on highly nonlinear interactions between femtosecond laser pulses and transparent materials, resulting in localized modifications of optical properties. In this article, we explore the fundamental mechanisms of laser-glass interactions, highlight advanced architectures for photonic integrated circuits, and discuss ongoing research aimed at expanding the range of achievable optical functionalities through innovative laser processing techniques and novel glass compositions.

Laser material processing has revolutionized modern manufacturing and materials science, offering precision and versatility across a vast array of applications. From cutting and polishing to surface texturing and bulk structuring, lasers, spanning continuous-wave and pulsed regimes, and wavelengths from ultraviolet to mid-infrared, enable the tailored modification of diverse materials, including metals, crystals, polymers, and glasses. Among these, femtosecond lasers have emerged as a tool of choice, particularly for the three-dimensional (3D) nano- and micro-structuring of glasses. This capability is crucial for photonics, where femtosecond laser writing facilitates the fabrication of advanced photonic integrated circuits (PICs) for quantum optics, ultracompact optical devices, archival data storage solutions with unprecedented longevity and density, and even fiber Bragg gratings (FBGs) when optical fibers are considered.

This article explores the fundamental physicochemical mechanisms underpinning femtosecond laser-induced changes in glasses, with a focus on the 3D-localized controlled modifications of optical properties. We then examine how these fundamental building blocks enable the realization of advanced photonic components and systems, bridging the gap between material science and functional devices. Finally, we highlight ongoing research efforts that aim at developing novel optical functionalities through innovative processing approaches and novel glass compositions.

FROM LASER-GLASS INTERACTION TO OPTICAL PROPERTIES

The interaction of femtosecond laser pulses with transparent materials, such as glasses, is governed by highly nonlinear processes occurring at a (sub)micrometer scale at the vicinity of the focal volume [1], as illustrated in Figure 1. In the single-pulse regime, nonlinear absorption, through quasi-instantaneous (~ fs) multiphoton absorption and tunnel ionization followed by cascade effects like avalanche ionization (~100 fs), generates a dense free electron plasma within the focal volume. Achieving the critical plasma density (~10^{21} cm^{-3}) necessary for optical breakdown typically requires intensities on the order of 10 TW·cm^{-3}, corresponding to a 100 nJ, 100 fs near infrared pulse tightly focused to a micrometer-scale volume. The ultrafast timescale of the laser pulse decouples the initial energy deposition from subsequent lattice heating, as electron-phonon coupling transfers energy to the lattice at the picosecond timescale. As a result, the energy is rapidly confined to a highly localized region, leading to extreme temperature increase (up to several 1000 °C). The relaxation of thermal stress within 0.1–1 ns generates shock waves with pressures ranging from 0.1 to 10 GPa, while thermal diffusion and re-solidification of the molten glass occur on microsecond timescales [2].

In the multiple-pulse regime, the repetition rate plays a critical role in determining the material response. At low repetition rates (typically <100 kHz), where the pulse separation exceeds the thermal diffusion time, each pulse interacts with a cooled modified material, potentially leading to incubation effects that might lower the modification threshold. Conversely, at high repetition rates (> 100 kHz), cumulative heating induces out-of-focus thermal modifications, triggering complex and rich thermodynamical and viscoelastic processes. These include melting, temperature gradient-driven material redistribution, and rapid quenching, which can result in densification, mechanical stresses, the formation of defects and colored centers, elemental migration and local phase transition.

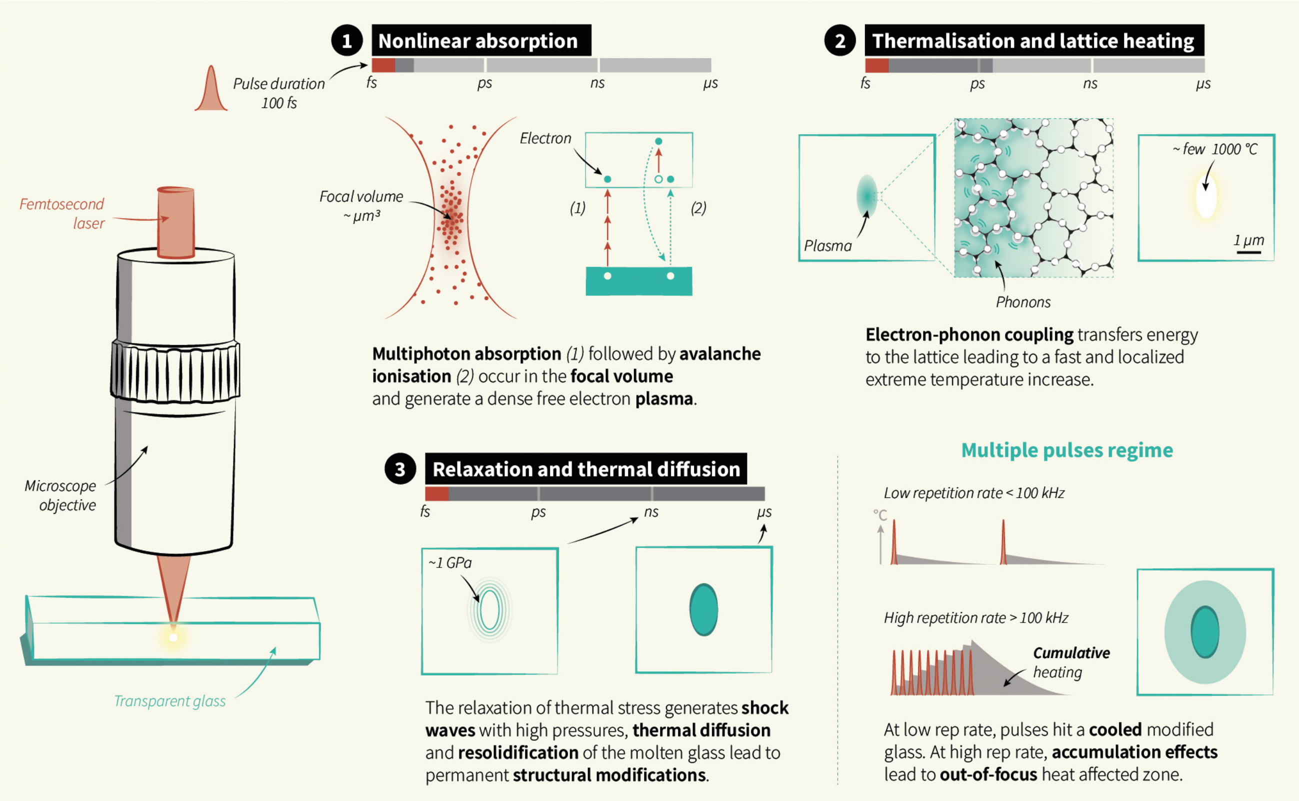
The resulting bulk modifications in glasses span a wide spectrum of 3D-localized microstructural changes leading to a broad variety of optical contrasts, depending on the irradiation conditions and glass compositions. These range from low and smooth refractive index modifications to anisotropic birefringent nanograting structures, and highly scattering micro-voids. Laser-induced formation of new chemical species, space-selective crystallization, nanopores or dielectric/metallic nanoparticles growth further diversify the achievable optical properties that extend beyond linear and passive responses, including, for example, enhanced luminescence, second harmonic generation, magneto-optical responses or giant optical rotation, to cite a few.

ADVANCED PHOTONIC ARCHITECTURES

Glass nano-micro-modifications can be distributed in 3D either by moving the sample or by scanning the beam focus position allowing for the versatile prototyping of embedded multi-scale and multi-properties photonic architectures for innovative bulk optics elements, on-chip photonic integrated circuits (PICs) or fibered components (see Fig. 2).

For example, laser structuring of homogeneous smooth refractive index changes has been widely ●●●

Figure 1. Illustration of the laser-glass interaction mechanisms with typical timescales.



Multiphoton absorption *(1)* followed by **avalanche ionisation** *(2)* occur in the **focal volume** and generate a dense free electron **plasma**.

Electron-phonon coupling transfers energy to the lattice leading to a fast and localized extreme temperature increase.

The relaxation of thermal stress generates **shock waves** with high pressures, **thermal diffusion** and **resolidification** of the molten glass lead to permanent **structural modifications**.

At low rep rate, pulses hit a **cooled** modified glass. At high rep rate, **accumulation effects** lead to **out-of-focus** heat affected zone.

used for the fabrication of low-loss (down to 0.03 dB/cm in commercial borosilicate glass and optical fibers [3]) waveguide-based PICs mainly operating at telecom wavelength with various geometries such as splitters, Y-junctions, cascaded directional couplers for (de-) multiplexing, interferometers and complex arrangement of coupled waveguides. Near-surface waveguides can also be inscribed for evanescent sensing of the environment through absorption, dephasing and/or changes in modal coupling. As illustrated in Fig. 2(c-d), realization of dynamically controllable integrated interferometers embedding active thermal phase shifting now gives access to advanced reprogrammable light management both in the classical and quantum light regime. In the latter context, the great versatility of the direct-laser-written PICs allows for the realization of hybrid multi-material quantum photonic platforms where, for example, the nonlinear generation of entangled photon pairs occurs in a periodically-poled lithium niobate crystal while the advanced complex photonic circuitry takes place in laser-inscribed glass. Complex arrangement of waveguides with tailored couplings also provides a powerful photonic platform to mimic condensed matter configurations and has been pivotal in the topological photonics community. Moreover, advanced waveguide-based architectures are also expected to play a crucial role in astrophotonics, providing ultra-stable and miniaturized devices to be implemented in telescope flux-recombining interferometric systems (see *e.g.* [4] for a review on PICs applications).

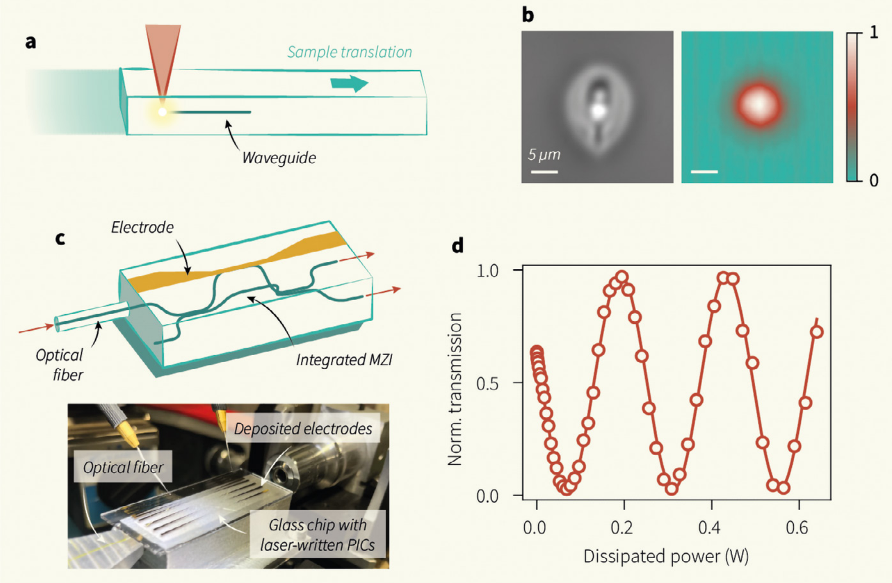
Beyond optical waveguides fabrication, femtosecond laser inscription also allows for the realization of sub-wavelength periodic refractive index modulation for the inscription of Bragg gratings in waveguides (WBGs) [5], see Fig. 3a, or in the core of optical fibers (FBGs). The resulting high spectrally-selective reflectivity can be finely tuned by controlling the grating properties (apodization, linear period chirps or even adapted phase steps). WBGs and FBGs can then be used for filtering and high-precision remote sensing applications as well as for manufacturing optical resonators in passive and active material for bulk and mostly fiber lasers devices. Laser-written periodic media also give access to the management of group velocity and slow light topics with light velocities down to a few tens of km/s.

EXTENDING THE ENGINEER'S TOOLBOX FOR 3D OPTICAL FUNCTIONS IN GLASS

Direct-laser-writing in bulk glass is increasingly used to engineer 3D photonic microstructures that exhibit optical responses extending far beyond simple scalar refractive index modulation and conventional telecom-band applications.

Among the above-mentioned various optical contrasts offered by femtosecond laser structuring, tensorial optical responses (birefringence, fast-axis orientation, polarization-dependent scattering) are gaining strong interest. Such responses typically appear in silica when laser irradiation produces self-organized sub-wavelength structures (so called nanogratings) providing an effective uniaxial medium whose optical axis is linked to the writing laser polarization. In-volume retarders, polarization converters, and multiplexed high-dimensional optical data storage (3D positions, retardance and axis orientation) have been realized, the latter now being close to industrialization [6]. More recently, ultralow-loss birefringent regime has been identified in silica, where birefringence arises from randomly distributed elongated nanopores rather than regular nanogratings [7]. This novel microstructure type is attractive for transmissive devices requiring strong polarization control with reduced scattering, including bulk geometric-phase elements, based on spatially patterned

Figure 2. Waveguide-based photonic integrated circuits (PICs). a) Sketch of the writing setup for PICs fabrication. b) White light microscope image of a single waveguide (left) and the corresponding mode at 1.55 µm. c) Sketch and actual picture of an integrated Mach-Zehnder interferometer (MZI). The dephasing is dynamically controlled with an electrode via thermo-optical effects. The normalized transmission of an MZI is plotted in d) as a function of the power dissipated by the electrode. The markers and solid line correspond to the data and fit respectively (Credits: A. Haykal, L. Bellando, I. Mouely Mouloungui, L. Raju Kalathil, L. Labonté, M. Bellec).



optical-axis orientation, such as lenses, gratings, beam shapers, or multi-plane light converters.

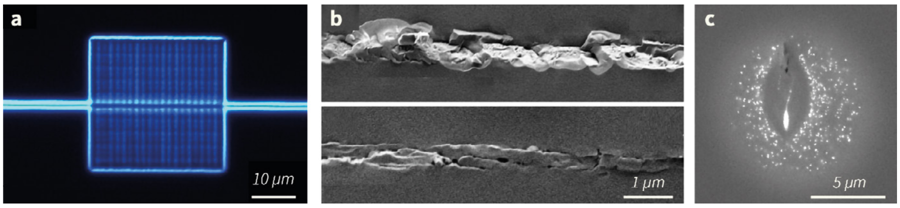


Figure 3. Examples of advanced laser-written nano-microstuctures. a) Waveguide Bragg grating written in a silver doped phosphate glass with 500 nm period [adapted from L. Loi *et al.* Opt. Mat. Exp. 14, 1837 (2024)]. b) Microstructures with chiral optical properties inscribed in silica glass with a polarized Bessel laser beam [adapted from J. Lu *et al.* APL Photonics 8, 060801 (2023)]. c) Laser-induced dissolution of dielectric nanoparticles embedded in the core of a scattering silica optical fiber (Credits: F. Orange, F. Pellerin, W. Blanc, M. Bellec).

A key perspective is to broaden the range of written properties beyond linear birefringence which includes linear and circular dichroism and other circular effects (optical activity, circular birefringence). Advanced anisotropy does not necessarily require explicit laser nano-structuring only and a promising route is to exploit the residual stress field as a design parameter: controlling the spatial distribution of stress can generate and orientate birefringence and more complex circular properties indirectly. Progress along these directions relies on spatio-temporal engineering of the writing laser field. Transversal and longitudinal spatial shaping (elongated foci, Bessel beams, vortex beams [8]) offers additional degrees of freedom by tailoring energy deposition along propagation (Fig. 3b shows an example of such laser-induced microstructures with chiral optical properties). Temporal structuring (laser pulse, pulse trains, and newly coming GHz burst regimes) provides further control over absorption dynamics, heat accumulation, and stress build-up, which collectively determines anisotropy, losses, and repeatability. Looking further ahead, emerging research highlights the potential for achieving sub-wavelength modification limits (few nm to few tens of nm). At this scale, an open question is whether laser-driven processes can be engineered to impose controlled optical anisotropy or chirality through structural rearrangements approaching interatomic-bond length scales, shifting the paradigm from writing shapes to writing material properties at the most fundamental level.

Besides laser writing processes, material science and glass composition engineering are of equal importance. While silica and borosilicate glasses remain the materials of choice for most visible and near-infrared applications, their performance is inherently limited by intrinsic absorption bands, particularly in extended spectral ranges. As the demand for advanced photonic functionalities grows, there is increasing interest in exploring alternative glass compositions, including soft-glass systems such as fluorides, heavy-metal oxides, and chalcogenides. However, their distinct thermomechanical behaviors and photoinduced responses present significant challenges for femtosecond laser structuring. Developing novel processing strategies is essential to achieve high reproducibility, low optical loss, and long-term stability of engineered optical properties.

CONCLUSION

Femtosecond laser processing has revolutionized the fabrication of 3D photonic nano-microstructures in glasses, enabling precise control over various linear, nonlinear, passive or active optical properties for advanced applications in photonics. Laser inscription is evolving to integrate subtractive and additive techniques. By inducing defects and stress, it enables laser-assisted etching for precise 3D microstructures, such as microfluidic channels and optical cavities, which can be infiltrated with active materials to incorporate functionalities in the bulk of robust glass host matrices. Additionally, laser-driven polymerization allows the fabrication of complex 3D architectures, including metamaterials and interconnects, enhancing photonic integration. Within this flourishing context, next generation of photonic platforms embedding sources, light transport, sensing and signal processing will certainly incorporate multiple functionalities obtained by combining various manufacturing abilities. ●

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MICROMACHINING WITH ULTRA-SHORT LASER PULSES IN BURST-MODE

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Modern ultrafast laser systems often allow for so-called burst-mode operation. This means that trains of ultrashort pulses are emitted with intra-burst repetition rates in the MHz- or GHz-range. These operation modes offer new possibilities in micromachining of different materials such as milling, drilling, or cutting. In this article, we give a short overview of recent developments and cite some achievements in micromachining applications of different materials in these new burst-regimes.

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Ultrafast laser processing has become a key technology for high-precision manufacturing in industries such as the automotive, the electronics and the watch industries, the medical technology, and the jewellery. Pulses with durations ranging from femtoseconds to picoseconds are used to process virtually any material with minimal burrs, negligible heat-affected zones, and excellent edge quality. This results in robust and reproducible processes for tasks such as micro drilling of injector nozzles or through holes in glass, stent cutting, trimming of electronic components, laser turning, and functional surface structuring. The high flexibility of beam guidance and scanning systems allows for easy integration into automated production lines and multi-axis platforms. As average power increases towards several 100 W and beam shaping options continue to improve, ultra-fast laser processing is increasingly being used to replace or supplement conventional mechanical and chemical processes in series production. In addition to spatial beam shaping, temporal beam shaping with pulse trains or “bursts” containing several pulses is also possible, paving the way for increased performance.

BURST REGIMES

Due to the increase in average power, strongly focused ultrashort pulse lasers often deliver much more pulse energy than is required for efficient single-pulse ablation of metals. In order to be able to use the high pulse energies more flexibly, they are redistributed into packets of several closely spaced ultrashort sub-pulses, known as bursts, which usually consist of two to several hundred or even thousand pulses. The burst is characterized by the number of pulses, their individual energy, and, in particular, the inter-pulse delay between successive pulses within the burst. Inter-pulse delays of a few tens of nanoseconds are usually referred to as MHz-bursts, while hundreds of picoseconds correspond to so called GHz-bursts (cf. Figure 1).

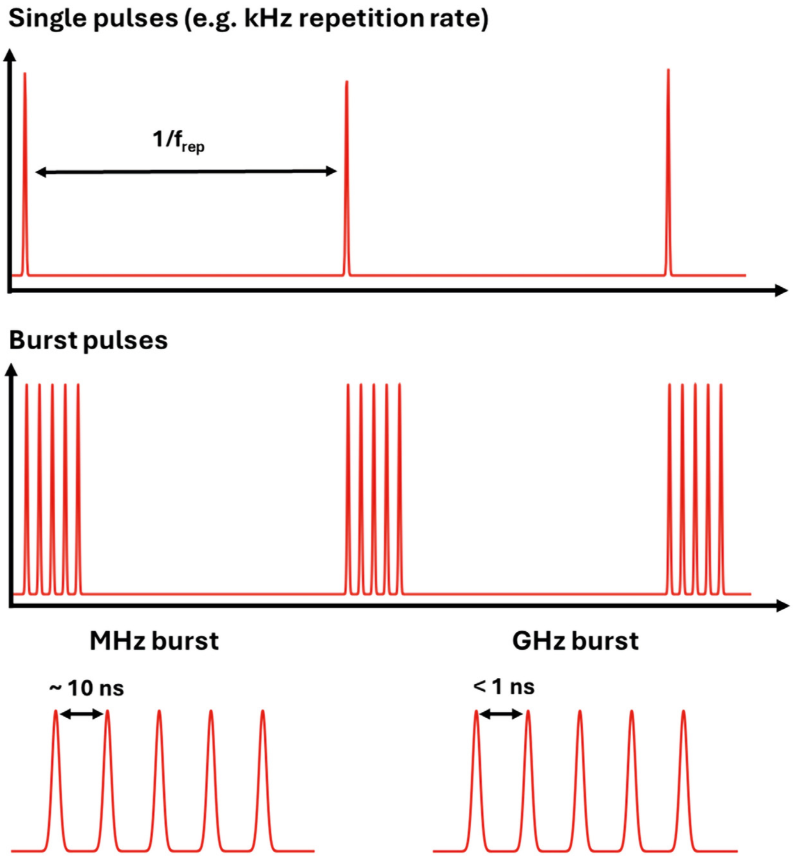

Figure 1. Schematic representation of ultra-short pulse and burst regimes in the time domain, illustrating the redistribution of the energy of an individual pulse into multiple closely spaced sub-pulses and distinguishing between MHz and GHz intra-burst delays. Combinations of both MHz- and GHz-burst pulses are called bi-bursts, which are not shown for the sake of simplicity.

BURST MACHINING OF METALS

When applied to metals, burst processing allows access to interaction regimes that differ fundamentally from those with single pulses. As the sub-pulses within a burst interact with a surface that is already electronically excited, melted, or partially shielded by plasma and vapor, both absorption and energy distribution can change significantly. Depending on the regime used, this can lead to increased ablation efficiency, altered surface morphologies, and improved surface quality at similar or even higher throughput compared to machining with single pulses [1].

Double-pulse experiments show that the second pulse can substantially modify the ablation dynamics by interacting with the transient plume and molten layer, which may either reduce or, for certain delay ranges and materials, partially recover the ablation efficiency compared to single-pulse irradiation. Fine tuning of melted layers can lead to very high surface qualities with Arithmetic Average Roughness of Ra ≈ 100 nm. In practical, in machining strategies such as for scribing and milling, the intra-burst structure determines how energy is distributed across successive phases of excitation, melting, and material removal. Precise polishing strategies can be applied, particularly using longer pulse packets in the GHz range, which consist of dozens or hundreds of sub-pulses and exhibit physical effects comparable to ns laser pulses. This results in smoother topographies and reduced heat-affected zones, but usually at the expense of ablation efficiency. MHz-bursts with intra-burst delays of 10 ns and longer, on the other hand, typically interact with expanded and hence more transparent ablation clouds and melt layers, which can promote high removal rates and efficient material ejection, but can also lead to remelting, resolidified edges, or increased micro-roughness if not carefully tuned. Selecting and switching between these modes and adjusting the number of pulses per burst provides a good way to balance throughput and surface quality for a given metal and target geometry.

Representative micromachining results achieved with metals using burst mode operation include deep grooves, cavities produced with 2.5D milling strategies (projection in a plane of the 3rd dimension), and finely structured surfaces with customized roughness and morphology. In grooves and cavities, burst machining can significantly improve sidewall morphology and the amount of redeposited material with appropriate intra-burst parameters and materials, while maintaining or slightly increasing removal efficiency compared to single-pulse machining. On flat surfaces, burst processing can be used to create deterministic micro- and nanostructures or to control the transition between rough, highly light-absorbing textures and smoother functional surfaces. An example of a geometry after laser milling of copper with MHz-bursts is shown in Figure 2.

BURST MACHINING OF BANDGAP MATERIALS - SEMICONDUCTORS

Materials featuring a bandgap such as semiconductors and dielectrics have longer thermal diffusion times and are thus extremely well-suited for taking advantage of burst-mode processing which is based on beneficial and controlled heat accumulation. For bandgap materials, bursts should typically contain several tens or hundreds of sub-pulses.

The burst-mode constitutes a very interesting and promising approach for in-bulk modifications with femtosecond pulses in semiconductors. These materials are characterized by a very high non-linear index that prevents localized energy deposition at the focal point. Thus, distributing the energy over many sub-pulses constituting a burst is a suitable strategy for overcoming the limitations observed with repetitive ultra-short single pulses. The group of David Grojo in Marseille recently carried out pioneering work based on THz-bursts for semiconductor processing, for example on Gallium Arsenide, where bursts formed by an array of subsequent birefringent crystals of different lengths were used [3]. Figure 3 shows luminescence microscopy images for single pulses and bursts with increasing number of sub-pulses (pulse duration and pulse spacing are 180 fs). Image S corresponds to the longest pulse train containing 64 sub-pulses and shows intense and very localized luminescence confirming successful and localized energy deposition with this approach.

BURST MACHINING OF BANDGAP MATERIALS - DIELECTRICS

For dielectrics, longer inter-pulse delays between the sub-pulses can be very efficient as the heat diffusion time scales are much longer than in semiconductors. MHz-bursts have been investigated for glass processing for more than two decades, in early times since 1999, with

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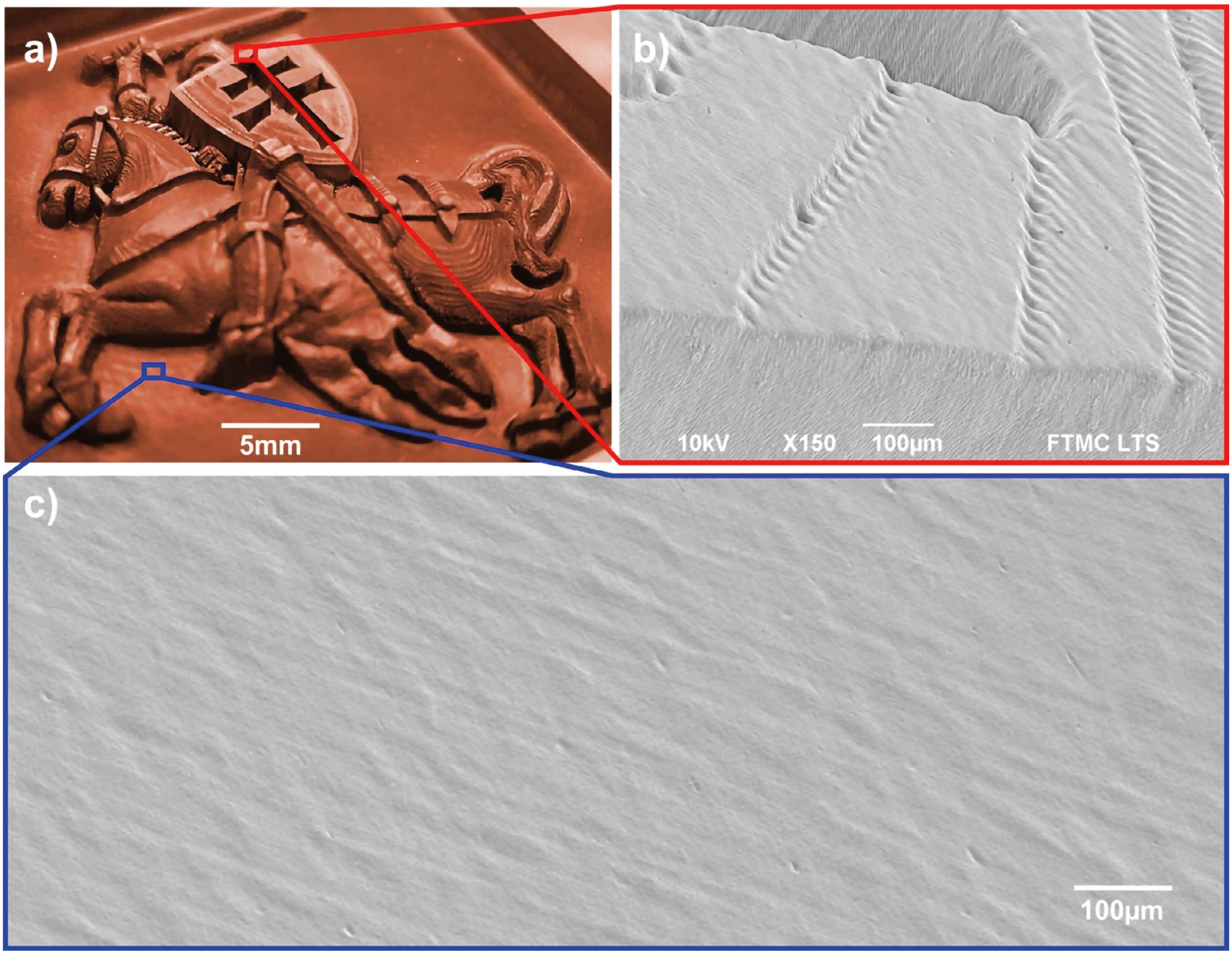


Figure 2. Example of efficient laser milling. (a) Optical image of laser milled coat of arms of Lithuania in a copper plate. (b), (c) SEM images of laser-milled surface illustrating high quality layer-by-layer removal. Reproduced under the terms of a Creative Commons Attribution 4.0 International License, (https://creativecommons.org/licenses/by/4.0/ (accessed on 04 March 2026)) [2]. Copyright 2019, the authors, published by Springer Nature.

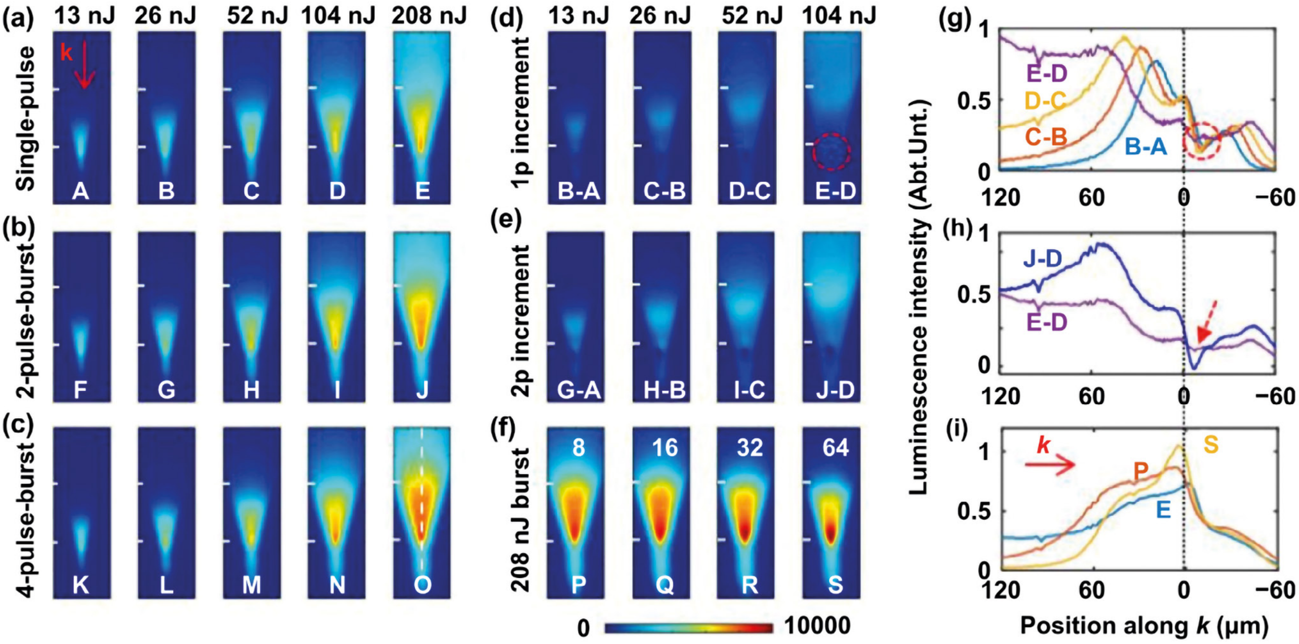


Figure 3. (a)–(c) Luminescence map excited by different pulse energies (written on the top) and different trains of pulses (written left to the images). Each image is represented by a letter written at the bottom of the image. The k vector marks the laser propagation direction. (d) Images obtained after subtraction of lower-energy maps on higher-energy maps according to the letters written at the bottom of the image. (f) Luminescence images obtained from irradiation with a total pulse energy of 208 nJ in a burst with different number of pulses in the burst as indicated on the top of each image. (g)–(i) On-axis luminescence intensity signals (white dashed line in image O) for different images. The black dotted line represents the position of the geometrical focus (z = 0 μm) [3]. Copyright 2022 under Creative Commons BY 4.0 license. https://doi.org/10.1088/2631-7990/ac8fc3.

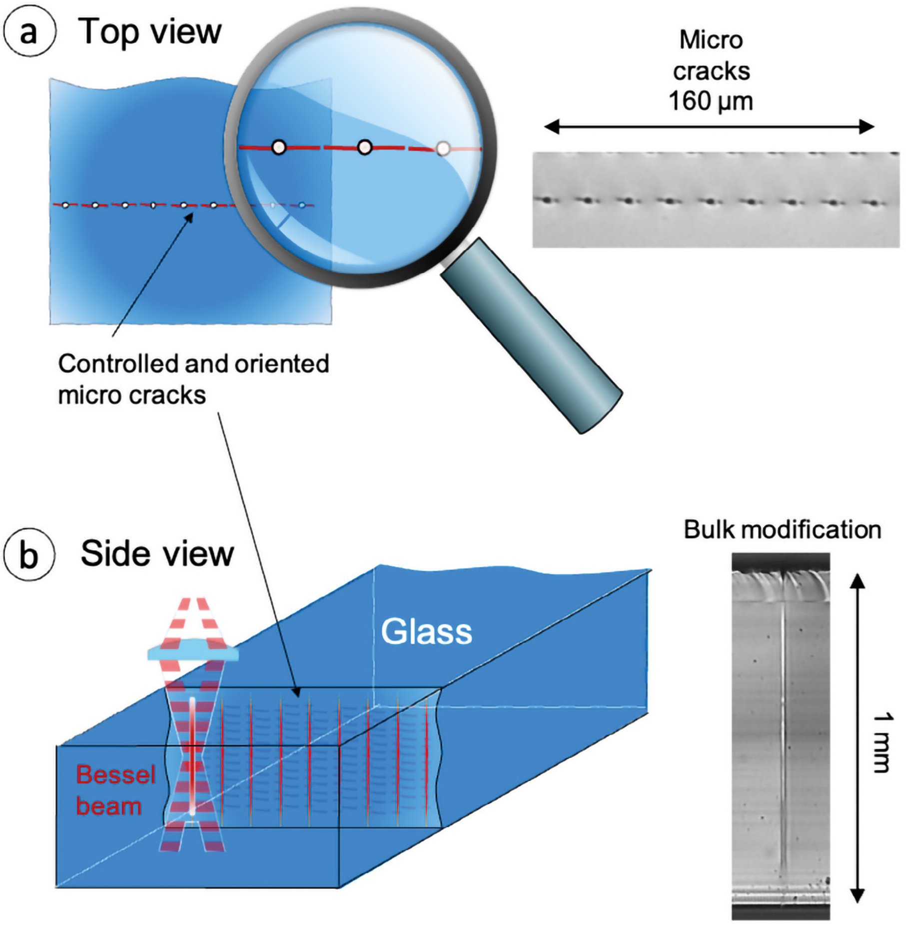
home-made laser systems rendering systematic and comparative studies difficult. However, the benefit of heat accumulation was proven and could be explained by the gentle interaction of the laser with the glass material making it more ductile, and thus, less prone to crack formation.

Nowadays, MHz-bursts are widely used for ablation-free glass cutting with femtosecond lasers for example to cut screens of smartphones and tablets. The time spacing between sub-pulses is typically several tens of ns and the number of pulses within a burst is not necessarily very high, for example 4 to 20, for MHz-bursts of commercially available femtosecond laser sources based on Ytterbium-doped active media emitting at a wavelength of around 1030 nm and meeting industrial requirements.

The ablation-free cutting process [4] is realized in two distinct steps. First, the glass is pre-cut by defined, oriented cracks arising from the interaction with a needle-formed laser beam, a so-called Bessel-Gauss beams. The spatial beam-shaping into such Bessel-Gauss beams is achieved using an axicon and subsequent imaging to adjust the desired size of the Bessel-beam. Second, the parts are mechanically separated. The cutting process is schematically illustrated in Figure 4. The cracks can be oriented along the laser trajectory using a phase mask.

More recently, percussion drilling of different glasses using GHz-bursts was investigated. Here, the time spacing between the sub-pulses is on the order of one nanosecond, and the bursts contain several tens to hundreds of sub-pulses. The energy of the individual pulses is typically much lower than in the case of MHz-bursts.

Figure 4. Schematic illustration of ablation-free glass pre-cutting with a Bessel-beam. (a) Top view of oriented cracks along the glass. (b) Side view of successive shots forming the cutting plane along the laser trajectory. On the right, microscope images.



Modern, commercially available laser systems offer the possibility of switching between operation modes of repetitive single pulses, MHz-bursts, and GHz-bursts. This allows for very accurate studies comparing the three operation regimes as the beam is delivered by the same laser source avoiding fluctuations due to system change or realignment of the beam path.

The GHz-burst approach offers the possibility of drilling holes with a rather different morphology than with standard repetitive single pulses as shown on Figure 5a. The holes produced by GHz-bursts are almost cylindrical and of outstanding quality with smooth and glossy inner walls. Moreover, much deeper drillings are possible compared to machining with repetitive single pulses at near-infrared wavelengths. In fused silica, crack-free holes of very high aspect-ratios of up to 150:1 could be demonstrated. The drilling mechanism has been described as a three-stage process [5]. First, there is surface ablation with free expansion of the plume into the ambient air. Secondly, there is deep ablation and plume confinement due to an interaction of the plume with the inner walls. The confinement induces a saturation of the drilling speed. Finally, termination of the drilling occurs when the fluence within the holes decreases below the ablation threshold due to losses caused by refraction and scattering.

Drilling of through holes (Through Glass Via or TGV) is of increasing interest for the production of glass interposers for applications in microelectronics. Figure 5b shows microscope images of a matrix of through holes in fused silica drilled in GHz-burst operation mode. The holes are very regular and the surrounding material is completely crack-free. The GHz-burst is an interesting and innovative approach for single-step

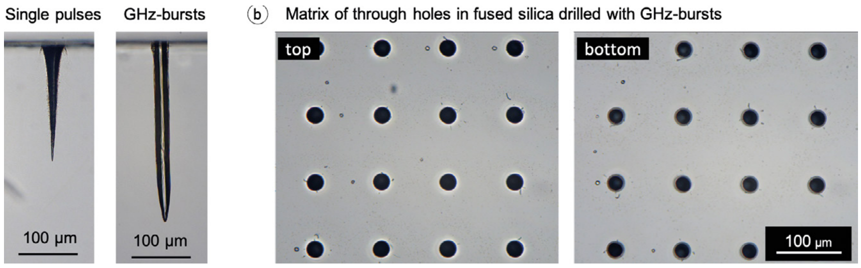


Figure 5 . (a) Microscope images of holes drilled with repetitive single pulses (left) and with GHz-bursts (right) in soda lime glass; note that all other laser parameters are identical (pulse energy, pulse duration, repetition rate, drilling time). (b) Microscope images of a matrix of TGVs in 75 µm thick fused silica seen from the top, inlet (left), and from the bottom, outlet (right).

processing without any use of chemicals and opens the path to a more efficient and more durable production method of TGV with a lower impact on the environment.

CONCLUSION

The GHz-burst mode is still a relatively new technology, and many processes such as milling, surface structuring, and welding of glasses have barely been investigated. Combining the temporal beam shaping by GHz-bursts together with spatial beam shaping into a Bessel-beam has a huge potential not only for cutting, but also for drilling. Very recently, the formation of narrow channel through holes in glass was demonstrated by applying single GHz-bursts. The ability of such a process for chemical-free "on-the-fly" drilling has an enormous potential for industrial applications. For metals, bandgap materials as well as other materials such as ceramics, burst mode processing offers the capability to completely new process regimes and wider process windows. Since surface characteristics as well as energy efficiency and throughput can be tuned independently via the parameters used, multi-step processing with intermediate switching between these different process regimes is becoming more standard in industry. More detailed information about burst processing of metals and bandgap materials can be found in Chapters 16 and 17, respectively, of a recent book [6]. ●

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LASER-INDUCED NANOSTRUCTURING

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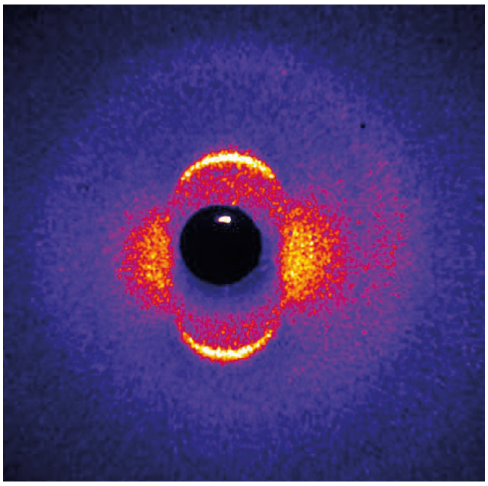

The laser-induced fabrication of nanostructures with feature sizes below the optical diffraction limit is possible for almost any material for arbitrary sample geometries and dimensions by exploiting nonlinear excitations or optical near-field interactions. This overview highlights historical milestones, explains the underlying physical processes and associated challenges, and discusses current and future trends in the field of ultrafast laser nanostructuring.

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Laser-Induced Nanostructuring (LIN) represents one of the thriving industrial demands of the past years [1]. It appears simple and appealing to flexibly functionalize either tiny sample spots or large-area surfaces in a single, contactless, aseptic, and cost-effective processing step that can be even conducted under ambient conditions. This expectation is seeded by the enormous developments in laser technology over the past decades, featuring a Moore-law like scaling through an output power-doubling of *Ultrashort Pulsed Lasers* (UPLs) about every two years. Currently, UPLs emitting in the near-infrared (NIR) or visible spectral range are commercially available at the 10 kW average power level, featuring MHz to GHz pulse repetition rates, while providing µJ to mJ pulse energies. Combined with state-of-the-art scanner technology, this puts areal laser processing rates towards the m^2/s at sight [2].

Unfortunately, the generation of nanoscale structures by simply focussing a laser beam onto a surface or into the volume of a workpiece has to overcome Abbe's fundamental *optical diffraction limit* for far-field applications. This limit defines a minimum achievable focal spot diameter of about half of the radiation wavelength λ. However, ultrashort laser pulses are reaching enormous peak intensities, which helps to enable LIN.

Figure 1 summarizes how UPLs and their interplay with specific physical effects enable LIN with feature sizes below the classical optical diffraction limit. This setting leads to two fundamental approaches. The first is based on *near-field effects*. Optical near-fields typically occur as evanescent fields in the vicinity of interfaces (known from the effect of total reflection). Through their exponential decay, they rapidly vanish on a length scale of typically 10 nm only. Moreover, in the vicinity of sharp topographical features, optical near-fields can exhibit field amplitudes enhanced by several orders of magnitude. Under certain conditions, the enhancement can be further amplified *via* resonant excitation channels, such as *Plasmons*.

The second approach towards LIN is based on *nonlinear absorption*: Several (m) photons are simultaneously absorbed from a laser beam in the sample material, with a transition probability scaling with I^m (I: local intensity). Hence, for a Gaussian laser beam, the profile of nonlinearly excited electrons radially narrows (depending on m) and is confined in the center of the laser beam. Thus, the interaction of high-intensity laser beams with wide bandgap dielectrics can confine the deposited optical energy to the nm-scale.

However, the exploitation of locally confined or enhanced optical absorption for LIN is only successful if the deposited optical energy remains spatially confined until it is transferred to the lattice. This becomes neatly possible for UPLs since their duration is shorter than the typical *electron-phonon relaxation* times that determine how fast a material can be heated. As consequence of this energy confinement during the laser pulse absorption and the subsequent transfer to the lattice, the so-called *heat-affected zone* (HAZ) surrounding the initially irradiated material volume is minimized. For sub-picosecond pulse durations, it extends typically a few tens to hundreds of nanometers into the surrounding.

Finally, UPL-induced damage of irradiated materials is often very deterministic with sharply defined threshold intensities/fluences. If a laser with a Gaussian beam profile is then operated just above the damage threshold, sub-micrometric damage sites can be created in the center of the focussed spot. The need to work very precisely at a peak fluence close to the damage threshold, in turn, imposes rather strict requirements on the pulse-to-pulse stability of the laser. Here, major advances have been made thanks to solid-state laser technologies, which play a key role in the latest generations of UPLs.

In brief, for rendering LIN possible, the ultrashort pulse duration is essential as it translates to high peak intensities and enables energy confinement through nonlinear or near-field effects, along with sharp fluence thresholds for material modifications, and a controlled material response *via* a minimized HAZ.

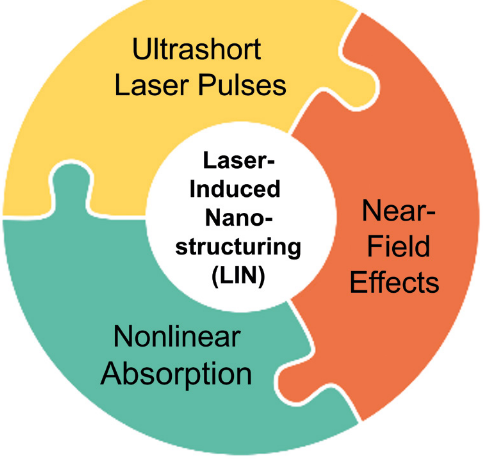
LASER-INDUCED SURFACE AND VOLUME NANOSTRUCTURING

EXPERIMENTAL IMPLEMENTATIONS OF LIN

Since the turn of the millennium, enormous progress has been made by demonstrating LIN through different experimental implementations. At the same time, significant advances have been achieved in the scientific understanding and control of the physical and chemical effects, as well as in the improvement of engineering aspects. Figure 2 provides a collage highlighting some selected LIN results. The experimental methods can be categorized in surface processing (left panels) and volume processing (right panels). Within each of those methods, LIN can be realized either through direct focussing (top panels) allowing a punctual nanoscale material modification or sculpturing, or it can be realized through matter self-ordering effects (bottom panels). The latter are enabled via coherent optical scattering and matter redistribution in the spatially extended focal regions upon loose focussing often realized along with laser beam scanning.

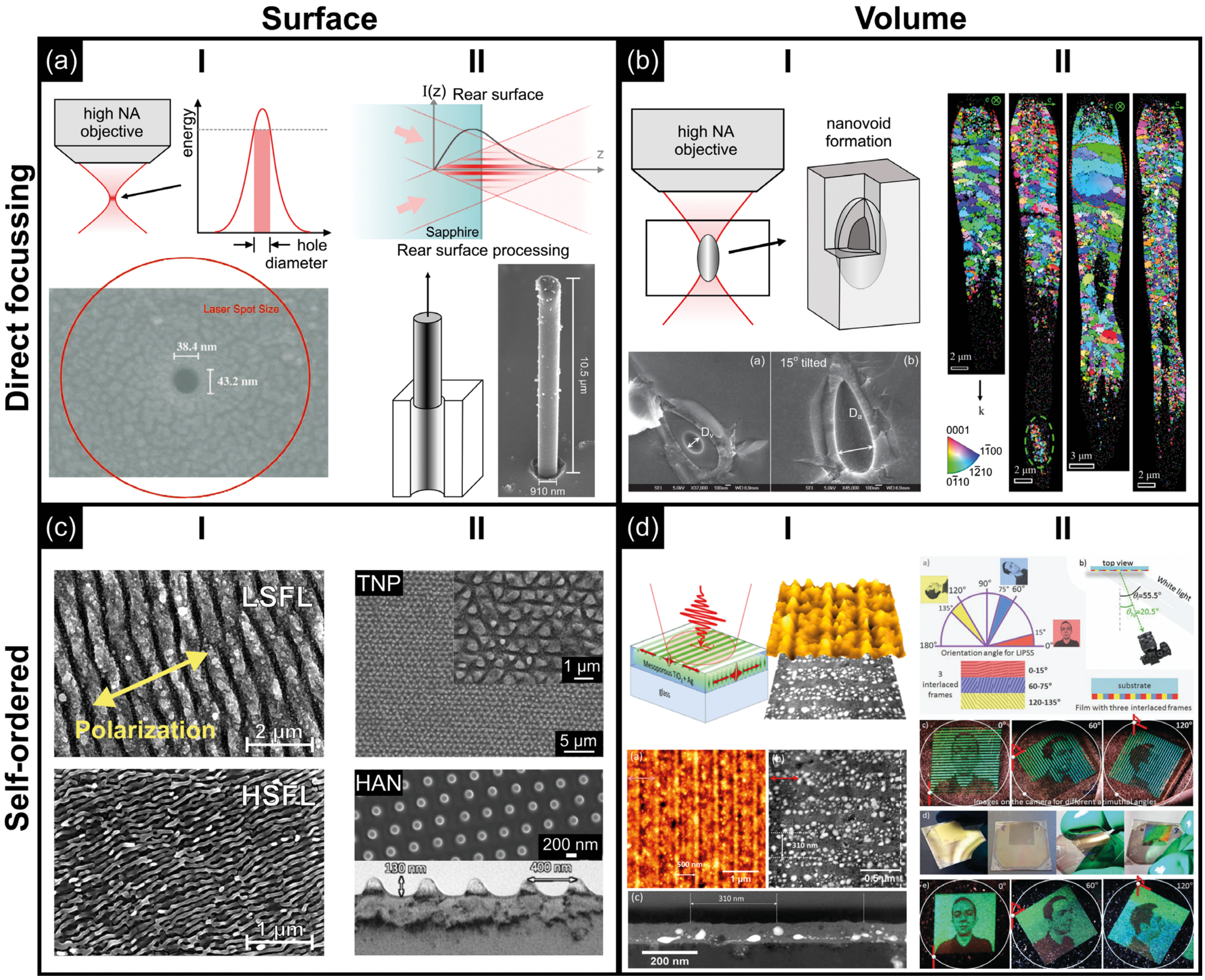
Joglekar *et al.* [3] demonstrated the concept of combining direct focussing of a NIR fs-laser beam with a high numerical aperture (NA) microscope objective onto the surface with nonlinear absorption effects in a glass sample (Fig. 2(a.I)). With a Gaussian focal spot diameter of $2w_0 = 0.41$ µm they obtained surface crater diameters of a few tens of nanometers only. Belloni *et al.* [4] also used direct focussing but employed a beam-shaping spatial light modulator and interference for creating a doughnut-shaped first-order Bessel beam at the rear-surface of a sapphire crystal. Utilizing a single Ti:sapphire fs-laser pulse, they were able to eject a nano-pillar-like, still crystalline sapphire rod of less than 1 µm in diameter with a length of ≈10 µm (Fig. (2a.II)). Juodkazis *et al.* [5] focussed single Ti:sapphire fs-laser pulses tightly into the volume of the sapphire for generating bulk-confined micro-explosions (Fig. 2(b.I)). Cross-sectional inspection by scanning electron microscopy (SEM) revealed the formation of a tear-drop-shaped nano-void with a diameter of a few hundred nm, surrounded by a sub-µm shell of amorphous material embedded in a locally defective crystal. When reducing the pulse energy and increasing the number of laser pulses applied per tightly focussed laser spot, void-less local material modifications can be generated in the volume of the laser-irradiated material. This can be used, *e.g.*, for writing optical waveguides in glasses, or for 3D additive manufacturing on the nanoscale by using two-photon-polymerization in suitable organic liquids. Cao *et al.* [6] used this sub-ablative NIR fs-laser bulk scan processing strategy at high pulse repetition rates (500 kHz) to locally crystallize a lithium niobate-silicate multi-component glass, visualized in Fig. 2(b.II) in cross-section by SEM and electron backscatter diffraction for different laser processing conditions. Loose focussing with low NA optics also provides the possibility of LIN at the surface and in the volume of solids. At first glance, this appears counterintuitive since • • •

Figure 1. Physical effects and technologies for jointly enabling LIN.



the focussed laser beam spot sizes exceed the desired size of the laser-induced nanostructures by orders of magnitude. However, here intra-pulse coherent scattering and near-field interference effects emerging in the laser-irradiated area/volume can seed periodic nanoscale patterns of the absorbed optical energy. The latter are subsequently transferred to the lattice of the solid and eventually imprinted as a corrugated surface topography or in sub-ablative periodic volume modifications. These two scenarios of LIN are demonstrated in the lower part of Figure 2. The left panel (Fig. 2(c)) collects SEM images of several different types of so-called *Laser-Induced Periodic Surface Structures* (LIPSS). They are classified as *Low Spatial Frequency LIPSS* (LSFL), *Triangular Nano-Pillars* (TNP), or *Hexagonally-Arranged Nanostructures* (HAN) – all with spatial periods close to λ, or as *High Spatial Frequency LIPSS* (HSFL) having periods down to the tens to hundreds of nm range, *i.e.*, far below the optical diffraction limit [1,7]. HSFL are solely formed upon irradiation with UPLs. The right panel (Fig. 2(d)) assembles results from

Figure 2. Selected LIN results and their methodic categorization into surface and volume processing (columns), while using direct focussing or selfordering effects (rows). Figure 2(a)I (bottom) reprinted from [3] Copyright (2004) National Academy of Sciences, U.S.A.; Figure 2(a)II (top and bottom right) reprinted from [4] Copyright 2023 under Creative Commons BY-NC-ND 4.0 license, and with permission from the authors of that article (F. Courvoisier.); Figure 2(b)I (bottom) reprinted with permission from [S. Juodkazis *et al.*, Phys. Rev. Lett., 96, 166101, 2006] Copyright (2006) by the American Physical Society.; Figure 2(b) II reprinted with permission from [6]. Copyright 2019 American Chemical Society; Figure 2(c)I reprinted from [S.V. Kirner, *et al.*, J. Appl. Phys. **122**, 104901 (2017), with the permission of AIP Publishing; Figure 2(c)II (top) reprinted from [S. van der Poel, *et al.*, Lubricants 7, 70 (2019)] Copyright 2019 under Creative Commons BY 4.0 license; Figure 2(c)II (bottom) adapted from [L. Porta-Velilla, *et al.*, Nanomaterials **12**, 2380 (2022)] Copyright 2022 under Creative Commons BY 4.0 license; Figure 2(d)I reprinted with permission from [8]. Copyright 2017 American Chemical Society; Figure 2(d)II used with permission of Royal Society of Chemistry from [Mater. Horiz., N. Sharma *et al.*, 6, 978-983, 2019]; permission conveyed through Copyright Clearance Center, Inc.



fs-laser processed metal-ion doped titania films that were subjected to scan-processing [8]. Here, the coherent scattering and interference leads to a 3D spatially patterned deposition of the laser pulse energy that, in turn, promotes the local precipitation and formation of plasmonic metallic nanoparticles (NP), see Fig. 2(d.I). These NP, being periodically spaced and arranged in different layers, allow the generation of macroscopically visible structural color effects and can serve to encode view-point dependent images as security tags (Fig. 2(d.II)) [9].

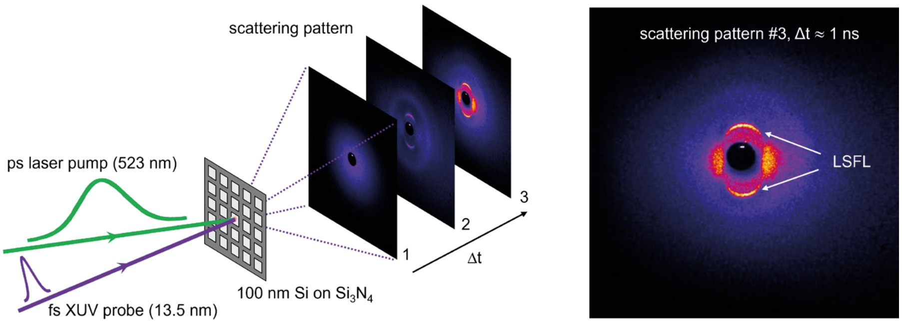


Figure 3. Time-resolved scattering experiment performed at the FEL FLASH in Hamburg [1,10]. The scattering patterns are recorded by a CCD camera that is synchronized with the fs-XUV probe pulses. (Adapted from [10], © 2024 under Creative Commons BY 4.0 license. Retrieved from https://doi.org/10.1002/lpor.202300912).

ADVANCED CHARACTERISATION OF NANOSTRUCTURES

A problem that immediately emerges with the successful realization of LIN is that conventional optical far-field characterization methods – such as optical microscopy – are no longer applicable for *in-situ* evaluation of the LIN results. Hence, either slow scanning probe or near-field optical characterization techniques, or far-field spectral ensemble measurements are required. The latter refer, *e.g.*, to optical scattering from NP, where the scattered light is spectrally resolved and analysed in the far-field. Alternatively, shorter wavelength electromagnetic radiation may be applied, pushing the required photon energies into the XUV- or X-ray spectral range.

In this direction, the development of short wavelength *Free Electron Lasers* (XFELs) has opened up exciting new possibilities since these sources combine an extremely high tuneable photon flux with spatial coherence and pulse durations in the fs- or even as-range. The potential of such short wavelength and ultrashort-pulsed radiation sources for studying the multi-scale processes transiently manifesting in laser processing was recently reviewed in [10]. XFELs allow, for example, the *in-situ* investigation of laser-driven structure formation at extreme scales in space and time *via* fs-pump-probe *small-angle X-ray scattering* (fs-SAXS) or even *grazing-incidence small-angle X-ray scattering* (fs-GISAXS). This covers the entire spatial range from atomic scales, over the nano- and meso- towards the micro-scale, while simultaneously covering temporal observation ranges up to ms, probed with sub-ps temporal resolution. Apart from clarifying the dynamics of ultrafast phase transitions or the formation mechanisms of the HSFL [7] featuring ≈100 nm spatial period only, also the disintegration of a laser-molten surface layer into voids and NP during fs laser ablation can be successfully revealed [11].

Figure 3 exemplifies a time-resolved single-pulse scattering pump-probe experiment (ps optical pump with λ = 523 nm / fs XUV probe with λ = 13.5 nm) performed in transmission geometry on a 100 nm thin silicon film at the FLASH FEL at DESY (Hamburg, Germany) [1,10]. A sequence of pump-probe far-field scattering patterns acquired at different delay times Δ*t* allow to record in a stroboscopic fashion the spatial frequency distributions of the laser-induced nanostructures. For example, the characteristic double-arc feature arranged symmetrically in the vertical direction on pattern #3 (Δ*t* ≈ 1 ns) represents the transient signature of classical LSFL ("wavelength ripples") formed on laser-molten silicon and featuring spatial periods of ≈ 300 nm, here.

PROCESSING OF LIPSS AND THE CONTROL OF REGULARITY

In the following, we will focus on LIPSS as an example of LIN with a tremendous technological and industrial potential, having surface functionalization applications in the fields of optics, tribology, and medicine. Figure 4 visualizes LSFL and HSFL created on the surface of titanium by LIN in a laser beam scanning approach with an industrial laser system (1030 nm, 860fs, 10 kHz). For both types of LIPSS, the left panel shows an SEM image with the same magnification, while the right panel displays a two-dimensional *Fast Fourier Transform*, representing the spatial frequency distributions of the corresponding spatial domain. LSFL are formed perpendicular to the linear laser beam polarisation indicated by the double-arrows, while the HSFL are rotated by 90°.

The LSFL have a most frequent period of $\hat{\Lambda} = 773$ nm, with standard deviation of $\Delta\hat{\Lambda} = \pm 44$ nm. For the much smaller HSFL, values of $\hat{\Lambda} \pm \Delta\hat{\Lambda}$ = (87 ± 12) nm can be deduced, *i.e.*, < λ/10. Comparing the 2D-FFTs of both types of LIPSS, it becomes clear that their signatures differ remarkably: While the LSFL are represented by a pair of sickle-shaped, radially asymmetric arcs, the HSFL appear as a pair of broad, radially symmetric "clouds". The ratio of the spread of the periods to the most frequent spatial ●●●

period value reveals that the LSFL have better regularity (smaller ratio $R = \Delta\hat{\Lambda}/\hat{\Lambda}$) than the HSFL. Generally, the regularity of LIPSS is better, as sharper their peaks in the Fourier domain are, *i.e.* as smaller *R*.

The technological potential of LIPSS for functional surface engineering critically depends on how regular and homogeneous these self-organized patterns are. Although many studies have shown how laser parameters, material properties, and optical effects influence LIPSS formation, assessing the quality of the resulting structures has remained a major challenge. The main reason is that suitable routines and software programs for automated evaluation were not available. Instead, evaluations were often performed purely visually or based on partly automated Fourier-based methods. Thus, the subjective influence of the person performing the analysis is a central problem, as the evaluation criteria are defined manually and the complex surface morphologies are usually reduced to a single indicator. This significantly limits the comparability between assessments and slows down systematic process optimisation.

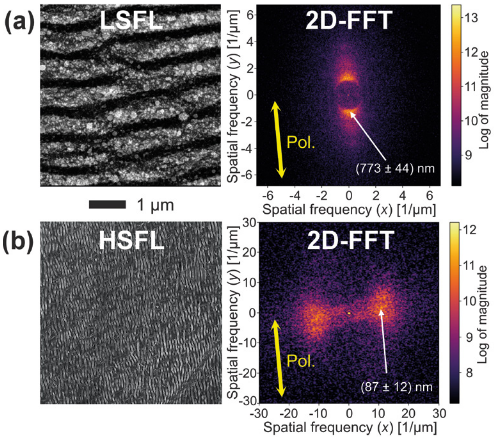


Figure 4. LIN of two types of LIPSS (LSFL and HSFL) on titanium featuring different spatial periods, orientations, and regularities. SEM images (left) and two-dimensional Fast Fourier Transforms (2D-FFT, right). The double-arrows indicate the direction of the linear laser beam polarisation.

With the introduction of *ReguΛarity* [12], a free, fully automated software tool developed specifically to quantify the regularity of LIPSS from microscope images, the transition from subjective, case-specific assessments to a standardised and reproducible description of LIPSS quality has been achieved. Instead of relying on a single metric, several complementary descriptors form a multi-parameter regularity tuple that is used to evaluate LIPSS. This approach considers that LIPSS regularity is multifaceted: highly functional surfaces require not only a precisely defined average period, but also low local period fluctuations, uniform alignment, spatial homogeneity and continuous phase development.

By enabling fast, objective and high-throughput regularity analysis, new perspectives are opening up for LIPSS research and applications. *ReguΛarity* supports the data-driven optimisation of laser processes, facilitates comparisons between different materials and laboratories, and lays the foundation for machine learning-assisted design of functional laser-structured surfaces. In this sense, the software represents an important step in transforming LIPSS from a complex physical phenomenon into a reliably machinable surface technology.

CURRENT AND FUTURE TRENDS

Currently, several trends are emerging in the field of LIN. One direction concerns the transfer of specific surface functionalities demonstrated in the laboratory into robust industrial and everyday applications. This includes the development of antibacterial surfaces in medical or public settings, or the development of bioactive surfaces that can improve the differentiation or enhanced/reduced growth of certain cells on medical implants. Beyond, nanostructures allow precise control over reflection, transmission, and structural coloration. Such capabilities are relevant for advanced display technologies, improved photovoltaic devices, and high-density optical data storage. The intrinsic irregularity of LIPSS, arising from self-organization processes, further enables the fabrication of non-cloneable security features for product authentication. In tribological systems, LIN can reduce friction and wear under sliding contact, lowering energy consumption and extending the operational lifetime of mechanical components.

A second trend focusses on deepening the fundamental understanding of the underlying processes. Ultrafast laser-matter interactions involve highly non-equilibrium dynamics starting already on fs to ps timescales, where nonlinear optical effects, transient electronic excitation, and rapid phase transitions interplay. Time-resolved experimental techniques are, therefore, increasingly employed to resolve ultrafast carrier dynamics, energy transfer pathways, and the onset of structure formation. In parallel, multi-scale modeling approaches are advancing, combining electrodynamics with molecular dynamics, hydrodynamic and thermomechanical descriptions to capture the coupled evolution of electromagnetic fields, electron-phonon interactions, structural changes, melt flows, pressure waves, and resolidification.

A third trend addresses scaling and manufacturing strategies required for industrial implementation [2]. Modern UPLs operating at repetition rates of several hundred kHz to several MHz along with fast beam deflection systems, such as high-speed polygon scanners, in combination with adaptive optical elements, enable large-area processing at high throughput. Optical parallelization concepts – employing diffractive optical elements or spatial light modulators – allow the simultaneous generation of multiple structured spots, significantly enhancing productivity. Automated quality assurance through *in-situ* monitoring and feedback control is becoming increasingly important to ensure process stability and reproducibility under industrial conditions. In this context, the integration of artificial intelligence and machine learning represents a transformative development. Data-driven predictive modeling can link process parameters to resulting nanostructures and their functionalities, enabling accelerated optimization, adaptive process control, and the identification of previously unexplored parameter regimes. At the same time, such predictive approaches can save energy and material resources, further developing laser processing towards a green laser technology. Overall, scaling of LIN is less about overcoming a single physical limit than about intelligently combining self-organization, optical parallelization, fast beam delivery, and advanced laser sources.

CONCLUSION

This review presented a brief summary of important milestones in the field of LIN of solids with surface- or volume-related features sizes below the diffraction limit. Features smaller than one-tenth of the laser wavelength can be realized. This is made possible by the minimal HAZ achieved by the ultrashort pulse durations and high intensities, which effectively drive nonlinear excitation processes and enable coherently excited collective near-field optical effects. Such tiny structures then require advanced characterization techniques as they are provided through XFELs, to investigate even *in-situ* the formation mechanisms at extreme scales in space (nm to µm) and time (fs to ms). A special focus was on LIPSS that are often manifesting in laser processing. Recent developments and trends in their generation, characterisation, and scaling were outlined, and the potential for further promoting their use in industrial applications was highlighted. ●

ACKNOWLEDGEMENTS

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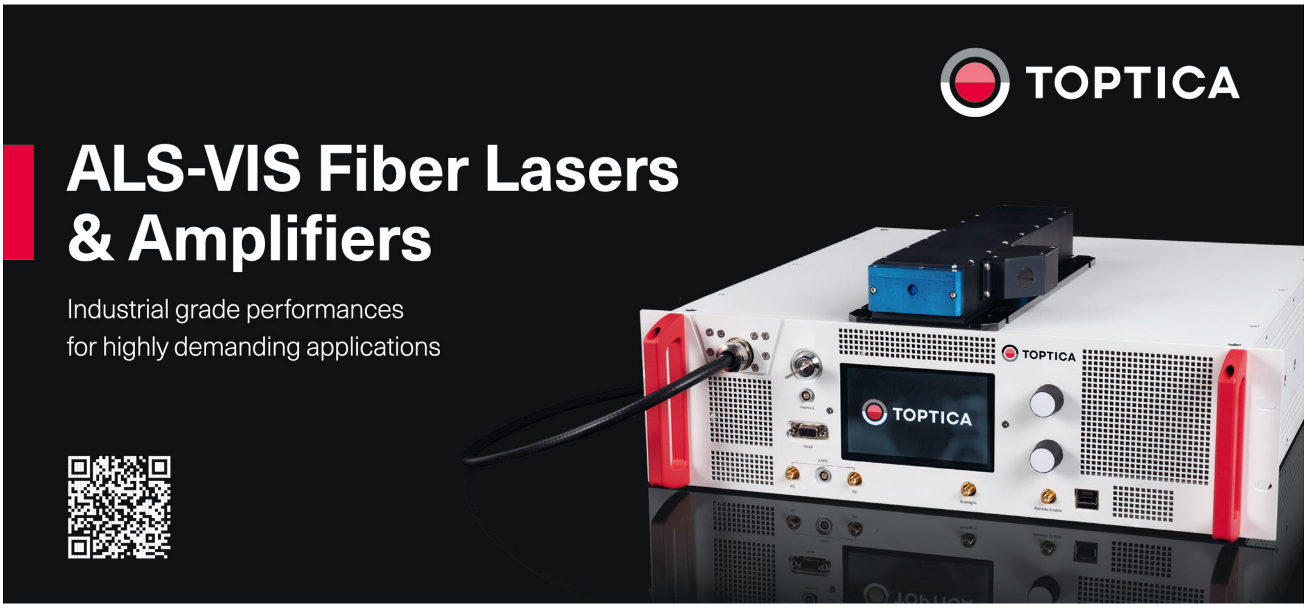

ADVANCED MANUFACTURING BY ULTRASHORT PULSE LASERS

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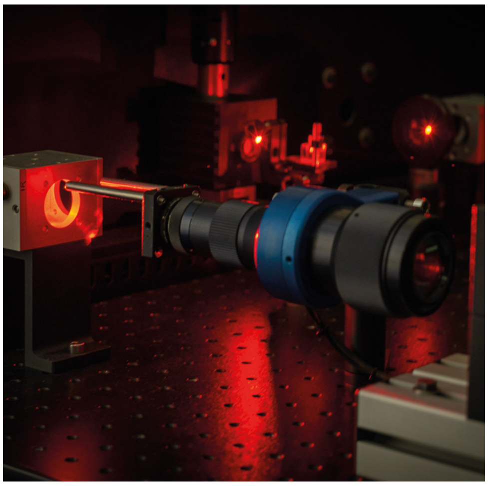

By achieving extremely high peak power with remarkably low energy, ultrashort pulse (USP) lasers have unlocked innovative and original approaches for material structuring and micromachining. After explaining the fundamental principles of how these ultrashort pulses interact with matter, this discussion will present their primary applications and the associated challenges.

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Lasers have long been used in manufacturing for cutting, drilling, welding, and thermal annealing of a wide range of materials, from polymers to metals. However, with Continuous Wave (CW) and nanosecond pulse lasers, the absorption rate is highly material-dependent. Additionally, a thermally affected zone inevitably forms around the processed area. Ultrashort pulse lasers where pulse durations range from 10 femtoseconds (10^{-15} s) to 100 picoseconds (100^{-12} s) exhibit fundamentally different behavior. Due to non-linear absorption mechanisms (such as multiphoton absorption, avalanche ionization, or tunneling), the laser pulse can be absorbed by virtually any material once a specific fluence threshold is reached. This versatility makes USP lasers "universal tools."

Another key advantage is that USP laser processing is often considered non-thermal. While it is commonly stated that the ablation process is "faster" than thermal processes, this is not entirely accurate. To understand why, it is essential to recognize that the material's response primarily depends on the peak power density (W/cm^2). With USP lasers, exceptionally high peak power Ppeak (W) can be achieved with relatively low pulse energy (E [J]) due to the ultrashort pulse duration (Δτ): $P_{peak} = E/\Delta\tau$ (see Figure 1). For example, 1 joule is the energy emitted by a basic LED in less than a second, an almost negligible amount. When this 1 joule is concentrated into 1 picosecond (10^{-12} s), it results in a peak power of 10^{12} W, or 1 terawatt (TW). This immense peak power is further spatially concentrated using an f-theta lens or microscope objective, focusing it onto an area of just a few square micrometers. This enables the achievement of extraordinarily high peak power densities (W/m^2). In the example above, concentrating the energy onto a 10 µm^2 surface yields a peak power density of 10^{18} W/cm^2 (10,000 petawatts/cm^2). In practice, with a pulse duration of 300 femtoseconds, only a few microjoules from a 1030 nm Ytterbium laser are sufficient to ablate metals or transparent glass. Since each pulse involves only a few microjoules, the thermally affected volume remains minimal. The extraordinarily high peak power density allows for the modification, fusion, or ablation of any material, but only within a highly confined volume due to the low energy involved.

THERMAL EFFECTS AND MATERIAL PROCESSING WITH USP LASERS

In reality, the extent of the thermal effect depends on both the repetition rate (the number of pulses per second) and the thermal response of the material. The local temperature increase after a single pulse is minimal. If the interval between two consecutive pulses exceeds the material's thermal diffusion time, the thermal effect is negligible. However, at high repetition rates—where the time between successive pulses is shorter than the thermal diffusion time—thermal accumulation occurs (see figure 2). USP lasers can thus be considered remarkable tools for controlling temperature fields with exceptional spatial and temporal precision, even at microscopic scales.

As demonstrated, high-power USP lasers can modify any material—whether on the surface or within the volume (if transparent)—at the micrometer scale while precisely managing thermal effects. This technology enables applications as diverse as engraving your name on ultra-hard materials like diamonds or performing delicate procedures such as correcting corneal curvature in LASIK eye surgery. USP lasers are therefore invaluable tools for advanced manufacturing.

INDUSTRIAL ROBUSTNESS AND LASER TECHNOLOGIES

USP lasers have been robustly integrated into industrial applications for years, including glass cutting and drilling for smartphone screen manufacturing. The two most widely used high-power USP laser technologies are:

- **Ti-Sapphire (Ti:Al_2O_3) lasers** (λ = 800 nm): These lasers achieve higher peak power with shorter pulses (>10 fs) but operate at lower repetition rates (kHz range).
- **Ytterbium fiber lasers** (λ = 1030 nm): These lasers offer higher repetition rates (up to 10 MHz or more) with pulse durations exceeding 100 fs. Their fiber-based design enhances robustness, making them ideal for industrial use.

For example, commercial 300 W (average optical power) femtosecond Ytterbium lasers can generate 1 million pulses per second, each delivering 300 µJ of energy in 300 fs. The first kilowatt-level average-power USP lasers are now also available. Other high-power USP laser technologies have emerged at different wavelengths, such as Erbium-doped fiber lasers (1550 nm), Holmium femtosecond lasers (2100 nm), etc.

Most of these lasers can be frequency-doubled or -tripled using nonlinear crystals to produce wavelengths like 515 nm or 343 nm, though this process reduces the output power.

Unlike conventional lasers, the advantage of exploring new wavelengths with USP lasers is not to enhance absorption but to exploit the material's transparency windows. This enables volumetric processing rather than surface-only modification. For instance, glass is transparent at 1030 nm, while silicon wafers are transparent at 1550 nm.

SURFACE FUNCTIONALIZATION

One of the most studied applications of USP lasers is **surface functionalization**—the modification of a material's physical properties through micro-structuring. Micrometer-scale structuring can be achieved by etching the material • • •

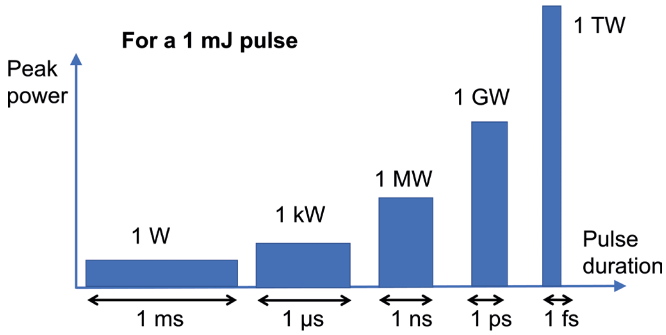

Figure 1. Peak power of a 1 mJ pulse depending on its duration, or how high peak power can be reached with low energy.

with a focused USP laser. A galvanometric scanner is typically used to scan the surface and create specific patterns. Alternatively, **Laser-Induced Periodic Surface Structures (LIPSS)** can be formed when the material's surface is melted, leading to self-organized structures smaller than the laser spot (see figure 3). The quasi-periodic structures that form are oriented based on the incident polarization, with periods comparable to or smaller than the laser wavelength.

Surface texturing alters a range of physical properties, including:

- **Wettability:** (Super-)hydrophobic or (super-)hydrophilic surfaces can be created using the lotus effect. Wettability gradients can even be used to manipulate the movement of micro-droplets.
- **Color:** Grating effects produce iridescence, similar to the colors seen on butterfly wings.
- **Non-adhesion properties:** These improve the lifespan of industrial molds.
- **Drag reduction:** Riblet structures on surfaces reduce drag for objects moving through fluids, such as aircraft, boats, submarines, or rockets, enhancing energy efficiency.
- **Biocompatibility:** Certain textures exhibit antibacterial properties, while others promote cell growth.
- **Absorption and emissivity:** Specific textures can trap light, creating ultra-dark surfaces with high thermal emissivity.

These functionalizations can be applied to a wide range of materials, from metals and polymers to ceramics and glasses.

3D MANUFACTURING OF DIELECTRIC MATERIALS

In transparent materials, structuring is not limited to the surface but extends into the volume. Glasses can be etched through **direct ablation** or **laser-induced etching**. In the latter case, wet etching—using hydrofluoric acid, for example—is employed. The wet etching rate is several orders of magnitude higher in regions irradiated by the laser. This enables the fabrication of highly complex shapes through **subtractive manufacturing**, following three-dimensional laser scanning of the material to be removed.

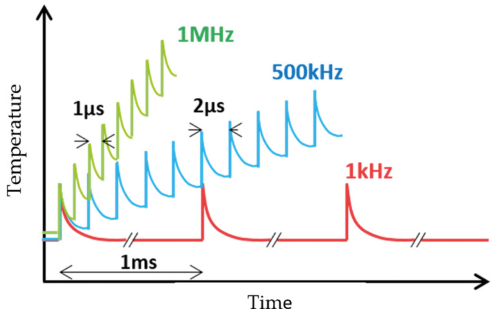

Figure 2. Illustration of thermal accumulation depending on the USP laser repetition rate.

A notable application involves **Through-Glass Vias (TGV)**, which are micrometer-scale holes drilled through glass plates to separate and connect multiple electronic circuits *via* conductive material filling. TGVs can be created through **direct laser ablation** or, more efficiently, *via* **laser-induced etching**. Non-diverging Bessel-like beams allow for the production of long TGVs with high precision.

USP lasers also enable **glass welding**. By focusing the laser beam on the interface between two materials, **multiphoton absorption** occurs, locally melting the glass. This technique can join different types of glass—even those with varying thermal and mechanical properties (e.g., thermal expansion)—as well as glass with metals, semiconductors, and ceramics. Applications include optoelectronic **component packaging, microfluidic systems**, and other scenarios where adhesives are unsuitable due to high temperatures or degassing concerns. While fused silica may develop micro-voids that scatter light, most other glasses achieve excellent transparency after welding.

USP lasers are also used for **precision glass cutting**. The focused beam creates micro-cracks within the material, guiding controlled fracture propagation. Another key application is the **inscription of waveguides** in the volume of the glass by modifying the refractive index. This technique can also produce **Bragg gratings** and other complex optical filters.

FUTURE CHALLENGES

One of the primary challenges is **increasing throughput** to process large mechanical components efficiently (see figure 4). High-power laser sources are already available, and **process parallelization** can be achieved using **multibeam arrays**. As example, it is a requirement for lithium-batterie electrode texturing. These arrays can be generated using static diffractive optical elements, multi-plane light conversion beam shapers or dynamic spatial light modulators (*e.g.*, liquid crystal-based).

High-speed scanning can be accomplished with polygonal mirrors, reaching speeds of up to km/s, while **real-time pulse energy control** is enabled by high-speed triggers. With repetition rates now exceeding **10 MHz** and commercially available **burst modes up to GHz**, process optimization

Figure 3. (left) color effect by surface texturing achieved by (right) Laser Induced Periodic Structures (LIPS) at smaller scale (zoom).

Figure 4. 3D glass manufacturing and micro-drilling in stainless steel plate by IREPA LASER using USP laser.

is within reach. The initial pulses in a burst can preheat the material, enhancing absorption and ablation rates. Methods to monitor the process in real time are also a requirement.

Two additional challenges include: (1) **the developing USP lasers at new wavelengths** to access transparency windows in novel materials and (2) **achieving finer-scale material machining**, such as for **metamaterial fabrication**.

Laser sources that were once unimaginable a few decades ago are now commercially available. They enable **advanced manufacturing** across a spectrum of materials—from the softest to the hardest—and scales—from the smallest features to large surfaces. Their applications span **biotechnology, aerospace, information technology, quantum optics**, and beyond. We are only at the dawn of their potential. These lasers will serve as a **pen to write the future**. ●

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MOIRÉ PHOTONIC CRYSTALS: FROM FABRIC TO MAGIC

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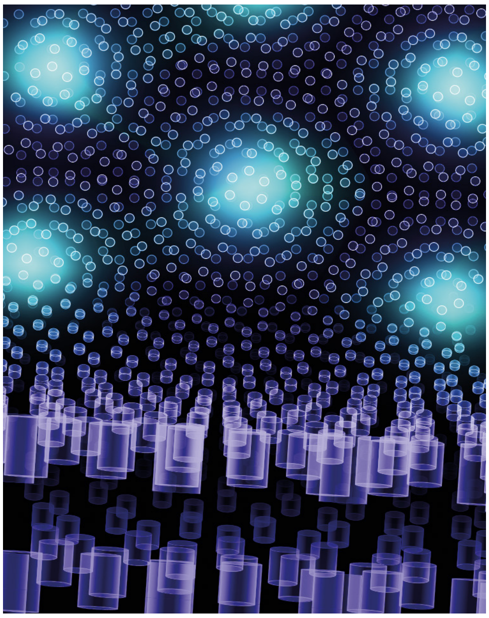

Moiré patterns have recently become a very active field in nanophotonics. Those structures exhibit novel photonic properties unattainable with traditional photonic crystals. Especially, moiré magic configurations have been shown to allow intriguing slow light modes with zero group velocity. Starting from macroscopic moiré patterns in the everyday life, we will then shift to the subwavelength scale of moiré photonic crystals and detail some of their unusual properties.

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Have you ever noticed those weird wavy and flowing shapes magically appearing on your laptop screen when you try to take a picture of it with your smartphone? This is a moiré pattern. Originally, moiré [*mwaʁe*] was an adjective describing fabrics with wavy effects, obtained by strongly pressing the fabrics to flatten the fibres and modify light reflection. This technique was brought from Bagdad to England by the explorers from the 14th century, and reinvented during the 1740s by John Bagder who designed a machine named calender consisting of a heavy rectangular piece of rock used to press the fabrics. This invention gave the monopole of moiré fabrics in Europe to England. In 1753, the French government, worried by the French dependence on England's moiré fabrics, invited John Bagder to settle in France, in Lyon, and transmit his knowledge to French weavers. Later, the calender underwent many developments and improvements, and Lyon became the French capital of moiré fabrics.

Moiré fabrics are not the only support to host moiré patterns. Similar wavy or beating shapes can be seen in curtains, on a bridge with grid barriers, or even if you take a picture of your computer's screen with your smartphone (Figure 1). In each case, the effect results from the superposition of two frames or lattices: two fabrics' lattices, two grid barriers, the computer's screen resolution and the picture resolution. Hence, moiré patterns extended to name every large-scale pattern formed by the superposition of two smaller-scale patterns.

Today, moiré patterns are well-known in art and industry, sometimes desired and sometimes hated. Indeed, moiré effects can destroy the visual rendering of colour printing if the frames from the different colours have a particular alignment, or the display of pictures on LED screens due to the mismatch between the screen and the picture resolutions. On the other hand, the hypnotic aspect of their shapes has attracted artists' attention, and took part in new artistic movements in the 1960s such as the so-called "optical art" or phase music. Moiré patterns also found applications in precise measurement: just as beating allows to tune two music instruments, moiré patterns can be used to align precisely two objects, or to measure their misalignment. Following this idea, they were applied to deformation and stress measurement, and to topography and 3D imaging with the technique called "projection fringes". The level of precision that can be achieved is so high that similar methods are even used for precise alignment in nanofabrication processes such as some lithography techniques. Finally, moiré patterns were found to be useful for measuring thread density in fabrics using a type of striped ruler called lunometer, an invention that closed the loop with the textile industry.

All the moiré patterns that have been mentioned so far are macroscopic. The underlying geometry is much larger than the wavelength of light in the visible range, and the ray optics framework applies. However, when the size is reduced down to the subwavelength scale, completely different and fascinating phenomena occur. This scale reduction was first introduced in a completely different field of physics. In 2018, it was discovered that, when two graphene sheets are stacked with a slight angular misalignment between their crystal lattices, bilayer graphene electronic properties could be tuned by varying the twist angle. More importantly, for some small and very precise angles ($\lesssim 1°$) known as "magic angles", twisted bilayer graphene becomes superconductive [1]. This discovery gave rise to twistronics, a new research field dedicated to twisted 2D materials. Since electrons in condensed matter crystals exhibit a wave-like character and behave similarly to photons in photonic crystals, parallels with photonics were quickly drawn, and research on moiré photonic crystals was launched.

PART 1: MAGIC MOIRÉ PHOTONIC CRYSTALS

The exploration of moiré patterns in photonics started by emulating twisted bilayer graphene. Following this idea, each graphene sheet was modelled by a slab photonic crystal with a honeycomb lattice, consisting of a thin dielectric membrane that provides in-plane light confinement, and contains a subwavelength periodic modulation of the refractive index within the plane. When the two layers are stacked with a small angular offset, a new large-scale hexagonal pattern appears: this corresponds to the moiré pattern (Figure 2.a).

What happens geometrically can be viewed as a kind of spatial beating phenomenon. Beating in acoustics occurs when two sine waves of slightly different frequencies $\omega_0 \pm \delta\omega$ are superposed. It results in an average sine wave at frequency ω_0 slowly modulated at frequency $\delta\omega$. Similarly, in moiré photonic crystals, the temporal frequency offset is replaced by a spatial offset arising from the twist angle between layers. This offset generates a long-range modulation that forms the moiré superlattice, whose period increases as the twist angle decreases. Just as with acoustic beats, the smaller the offset, the slower the modulation. This new periodicity is reflected in reciprocal space where a new Brillouin zone corresponding to the superlattice can be defined. It is smaller than the monolayers' Brillouin zones, and shrinks as the twist angle is reduced (Figure 2.b). However, it is important to notice that it is not always correct to talk about a "perfect" periodicity for the moiré pattern. In the general case, a moiré pattern is only quasi-periodic. This can be illustrated by the example of two square lattices twisted by 45°, for which no translational invariance exists due to $\sqrt{2}$ being irrational. Moiré patterns are strictly periodic only at specific discrete twist angles known as commensurate angles. At these angles, the perfect superposition of two lattice nodes at one point implies the existence of other perfectly aligned nodes elsewhere in the lattice. In such cases, the smallest distance between two points of perfect superposition defines the true lattice parameter of the superlattice. Nevertheless, it is always possible to refer to the moiré lattice corresponding to the pseudo-periodicity of the beating pattern.

Figure 1. Macroscopic moiré patterns. (a) Moiré fabrics. (b) Moiré patterns in curtains. (c) Resolution mismatch moiré pattern. (d) Stripped moiré pattern resulting from the superposition of the bridge barriers. (e) Moiré pattern on the back of a chair.

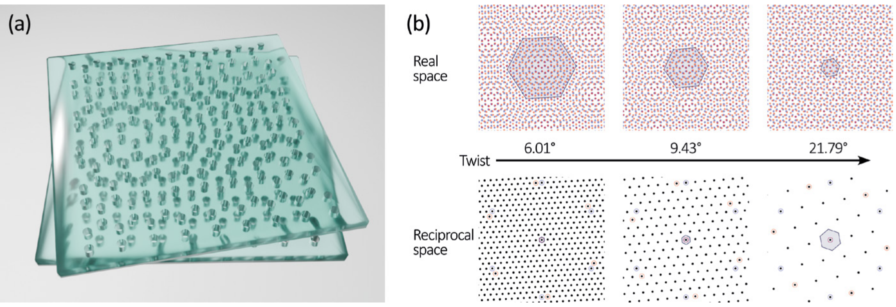
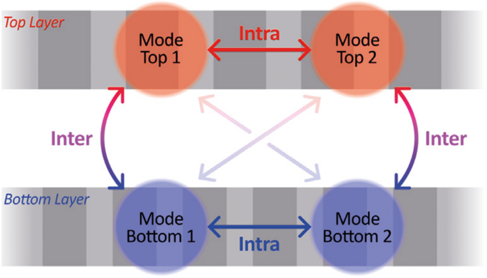


Figure 2. Graphene-like moiré photonic crystal. (a) Bilayer geometry. (b) Moiré lattice and reciprocal lattice depending on the twist angle.

How does light respond to these multiple periodicities? It depends on the distance separating the two layers. Qualitatively, if the interlayer spacing is larger than the operating wavelength, light will propagate through the two slab photonic crystals successively without noticing the moiré pattern. The observed effects are simply the combined influences of both layers individually, just as two successive gratings on an optical bench diffract light in two directions to form a 2D lattice of points in the far field. However, when the two layers are placed in near-field proximity, such that the interlayer distance is smaller than the wavelength, new behaviours emerge. In this configuration, light within the bilayer system not only perceives the periodicities of individual monolayers, but also experiences the moiré potential landscape, resulting in new photonic modes. In other words, the modes localized in each layer will interact with the (tilted) ones from the opposing layer. If the interlayer coupling between modes in different layers is of the same order of magnitude as the intralayer coupling within a single layer, the modes from each layer will strongly hybridize to form new bilayer modes (see Figure 3 for intra and interlayer couplings). These "moiré modes" inherit the characteristics of the moiré pattern, displaying a spatial profile that reflects the moiré (pseudo-)periodicity and are highly sensitive to the twist angle.

What has attracted attention on moiré photonic crystals is that, for a few very specific twist angles, some moiré modes see their field being strongly localized to small spots in the bilayer superlattice. This behaviour is unusual because the geometry does not contain any heterostructure that could confine the modes so tightly. Instead, this effect is related to the moiré modulated interaction between the two layers. More specifically, it results from the interplay between the intra and interlayer coupling strengths, which determine the spatial profile of the bilayer moiré modes. The sharply localized modes are easy to identify in the band diagram of the bilayer photonic crystal: they are characterized by the emergence of a flat band, $\forall \vec{k}$, $\omega(\vec{k}) = \omega_0$, that signifies zero group velocity across all wavevectors. This is why people refer to "slow light" in the context of moiré photonic systems. The twist angle plays a crucial role in the emergence of these slow modes. Changing the twist angle effectively shifts both lattices relative to each other, hence modifying the way two modes located in different layers interact together. Consequently, a slight change in the twist angle has a pronounced impact on the interlayer coupling, giving rise to "magic angles" that correspond to a particular balance between intra and interlayer coupling strengths. While looking at the formation process of the flat band as a function of the twist angle, it can be seen that it originates from the interaction between the slightly shifted dispersions of the two layers in k-space. Analogous to electrons in graphene, photonic dispersion in a honeycomb photonic crystal exhibits Dirac cones, a characteristic feature marked by a linear dispersion close to the K points, where the conduction and valence bands touch. At "magic angles", the Dirac cones from the two layers strongly hybridize and merge into a quasi-flat band dispersion (Figure 4).

Figure 3. Intra and interlayer couplings in a bilayer photonic crystal. The modes can be guided modes living in each layer for example.



PART 2: NEW MOIRÉ GEOMETRIES

The first studies on moiré photonic crystals with honeycomb lattices were very similar to those on 2D materials. While retaining the concept of the moiré patterns, photonic crystals physics allows much more freedom in the geometry and shape of the moiré patterns than condensed matter physics, which is constrained by the availability and stability of existing materials. Consequently, the bilayer photonic crystal platform opens the door to a wide variety of moiré patterns, as there is no reason to restrict our imagination to bilayer graphene-like geometries at small twist angles [2].

The first deviation from bilayer graphene geometry lies in the order of magnitude of the twist angle. In photonics, magic angles are not always small, but can be as large as 22° for example [3]. This difference might be related to the interlayer coupling being stronger between slab photonic crystals than between 2D materials, because photonic modes have a longer evanescent tail than electronic orbitals. This coupling can be tuned by adjusting the interlayer distance: the closer the two layers, the stronger the interlayer coupling. However, contrary to what one might think, the strongest interlayer coupling is not necessarily optimal as it must be balanced with the intralayer coupling.

Working with photonic crystals, completely different moiré geometries can also be explored. The lattices are not restricted to honeycomb structures, they can also be square, triangular, or even one-dimensional (1D). The mismatch parameter that generates the moiré pattern can arise either from a rotation or from a slight difference in lattice parameters. Figure 5 presents different types of moiré patterns. In particular, the moiré pattern made of two 1D photonic crystals with slightly different periods has been studied as a simplified system to explore the mechanism of flat bands formation. It has been shown to exhibit flat bands as well as the graphene-like geometry for specific "magic configurations" [4]. This 1D moiré pattern is strictly periodic with period Λ if the two periods a_1 and a_2 satisfy $\Lambda = (N+p)\,a_1 = N\,a_2$, where N and p are positive integers. For simplicity, p is generally chosen to be equal to 1. The moiré number N is the mismatch parameter that plays a role analogous to that of the twist angle. With this geometry, the balance between intra and interlayer couplings can be easily tuned, by adjusting the relative width of the rods and grooves and the interlayer distance respectively. This flexibility makes it easier to reach a "magic configuration", regardless the value of the mismatch parameter N.

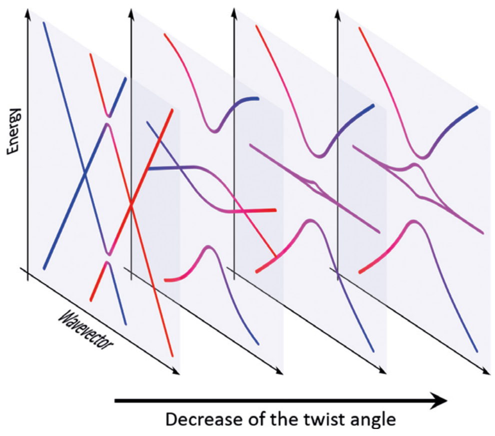


Figure 4. Flat band formation within graphene-like geometry.

PART 3: PROPERTIES

Initially, the main interest of photonic crystals was their capacity to control emission or absorption rates. An emitter emits photons at a rate proportional to the ability of the surrounding medium to support photonic modes, *i.e.* proportional to the photonic density of states. In free space, a photon with frequency ω_0 must have a wavevector with $k = \frac{\omega_0}{c}$, which limits the number of available states. In a moiré photonic crystal with a ●●●

flat band at ω_0, the same photon can be associated with a wide range of wavevectors, providing many more possible states. If the band is perfectly flat, the density of states even tends to infinity. Consequently, an emitter at ω_0 embedded in this moiré photonic crystal can experience a strongly enhanced emission rate. This effect is opposite to the bandgap phenomenon that would prevent any emission of photon. This property makes moiré photonic crystals excellent candidates for compact devices requiring strong light-matter interactions such as laser sources.

Even in the absence of a flat band mode, the tunability of moiré photonic crystals' resonances and their sensitivity to slight geometrical changes make them very attractive. Moiré resonances are related to the moiré pattern, which can be strongly modified by adjusting the mismatch parameter and interlayer distance. These parameters represent additional degrees of freedom that, when carefully controlled, provide powerful means to tune the resonant wavelength or wavevector, making moiré photonic crystals promising platforms for the design of tunable and reconfigurable optical devices.

Finally, due to their bilayer structure and the symmetry breaking induced by the twist angle, most of moiré photonic crystals are chiral. Consequently, right- and left-circularly polarized light do not generally behave identically within this structure. Therefore, moiré photonic crystals are able to support resonances that are selective to the polarization handedness. This property is highly relevant for applications such as detection and separation of enantiomers, or more generally for polarization dependent light applications and enhanced chiral light-matter interactions.

To date, the vast majority of results on moiré photonic crystals come from theory and simulation. They are therefore largely restricted to commensurate configurations, since strictly periodic systems are easier to handle and to simulate numerically using standard simulation methods for photonic crystals. On the experimental side, achieving the structural precision required to observe flat bands and magic configurations remains challenging. The interlayer spacing and the mismatch parameter must be precisely controlled to observe a flat band. Then, to confirm that there is indeed a magic configuration, the spectral width of the band must be shown to pass through a minimum of almost zero when varying the mismatch parameter. One way to relax the fabrication constraints is to merge the two lattices into a single layer, *i.e.* to etch both photonic crystals in the same slab. However, this approach loses control over the interlayer coupling and removes key bilayer properties. Finally, although quasi-flat bands have already been reported, direct experimental demonstrations of true magic configurations are still lacking and their observation remains an active area of ongoing research.

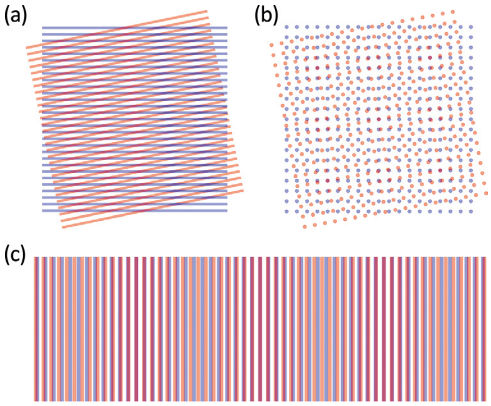


Figure 5. Various moiré geometries. (a) Twisted 1D gratings. (b) Twisted square lattices. (c) 1D gratings with lattice mismatch.

Despite these challenges, the field is rapidly evolving. Recent advances with moiré photonic crystals have demonstrated tunable optical sensors exploiting the additional degrees of freedom [5], as well as quantum well lasing [6] or polariton lasing in perovskites [7] benefiting from moiré flat bands, high density of states and sharp field localization. With the development of nanofabrication techniques and continued progress in experimental precision, direct observation of true magic configurations is becoming increasingly feasible. As experimental hurdles are overcome, moiré photonic crystals are poised to unlock new regimes of light-matter interaction, paving the way for novel quantum devices, enhanced optical sensors, and reconfigurable photonic platforms.

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LISA – A GIANT LASER INTERFEROMETER IN SPACE FOR GRAVITATIONAL WAVES DETECTION

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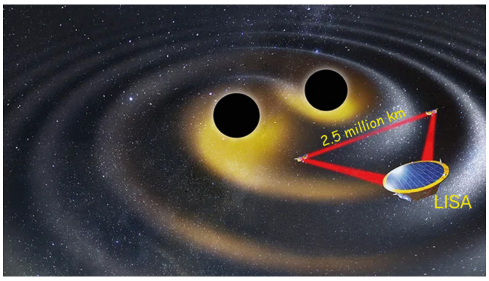

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LISA will be a space-based gravitational-waves observatory to be launched mid-2030, targeting the mHz band, inaccessible from Earth. Using a 2.5 million-km laser interferometer, it measures pm-scale distance variations between free-falling test masses. This article introduces LISA's most critical technologies such as ultra-stable lasers, precision interferometry, ultra-stable optical benches, telescopes, gravitational reference sensors, drag-free control with micro thrusters, Time Delay Interferometry, and stringent stray light control.

Introduction to LISA mission

Gravitational waves (GWs) are perturbations of space-time generated by the accelerated motion of massive systems, such as compact binaries. Propagating at the speed of light, they slightly stretch and compress distances between free-falling objects in orthogonal directions. These effects are extremely small: for astrophysical sources detected so far, relative distance variations are typically ~10^{-21}.

Predicted by Einstein in 1916–1918 [1], GWs remained undetected for a century. Their observation became possible thanks to modern technologies used by ground-based detectors (LVK Collaboration): narrow-linewidth lasers stabilized to ultra-stable optical cavities, large-area mirrors with extremely low losses, free falling test masses and low-noise photoreceivers. Since 2015, these instruments have detected more than four hundred GWs sources, opening a new era of astronomy [2].

While ground-based detectors can only observe sources in the audio-frequency band above 20 Hz, low-frequency sources from μHz up to 1 Hz can be detected only from space, where the quieter environment avoids terrestrial disturbances such as seismic noise. The concept of a laser-interferometric GWs detector in space emerged in the early 1980s [3], with the goal of detecting astrophysical objects inaccessible from ground - such as galactic binaries of white dwarfs, mergers of supermassive black holes,

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or extreme-mass-ratio inspirals - as well as cosmological sources. Furthermore, such an instrument can observe the inspiral of compact binaries that will eventually be detected on Earth, but much earlier in time - from a few hours to up to a year - well before they enter the audio-frequency band of ground-based detectors.

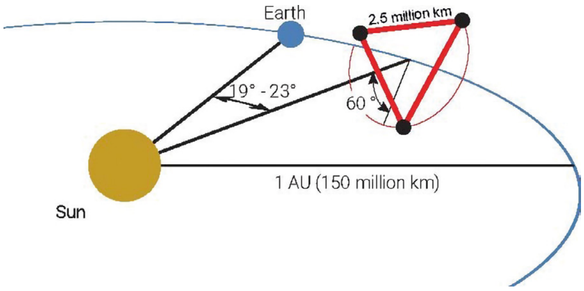


Figure 1. LISA mission orbit (not to scale): three S/C in an equilateral triangle of 2.5 million km arm, trailing on heliocentric orbit, behind the Earth at ~ 50 million km.

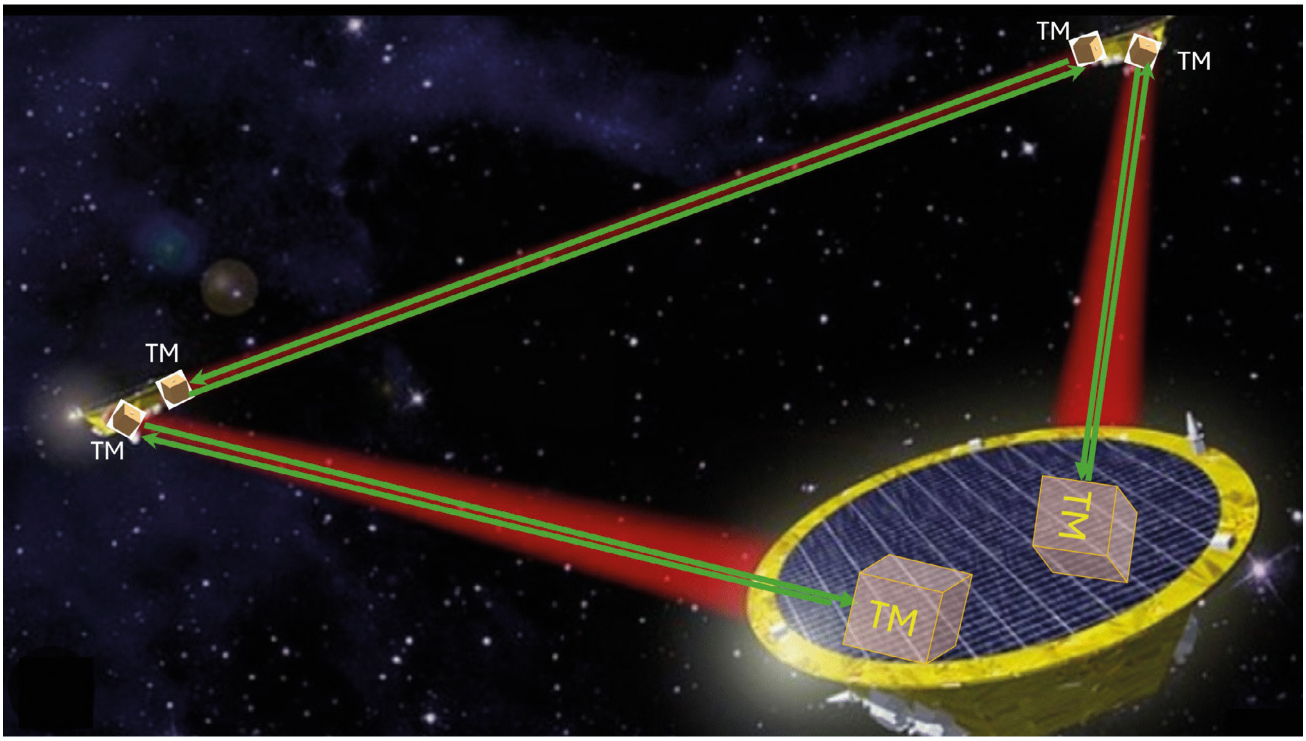
After decades of development and the successful demonstration of free-falling test-mass technology with ESA's LISA Pathfinder mission [4], the Laser Interferometer Space Antenna (LISA) was selected in 2017 [5] as the L3 mission of ESA's Cosmic Vision program and formally adopted in 2024. Launch is planned in the mid-2030s [6].

LISA consists of three spacecraft (S/C) forming an equilateral triangle with 2.5-million-km sides in a heliocentric orbit (Fig. 1). Together they act as a giant space-based Michelson interferometer, with a third arm providing independent measurements of the two GWs polarizations and system redundancy. The formation is centered in the ecliptic plane, 1 AU from the Sun and about 20° behind Earth. Its plane is inclined by 60°, and the S/C orbits are designed to preserve the triangular configuration throughout the year, making the formation appear to rotate once per year around its center.

Each S/C houses two free-falling test masses (TM), one at the end of each arm (Fig. 2). A drag-free control system adjusts the S/C position to follow the TMs, ensuring they remain in near-perfect free fall and serve as inertial references. Along every arm, two laser beams are continuously exchanged between S/C. By comparing the phase of the received light with that of the local laser, LISA measures tiny distance variations projected along the arms—variations that directly reveal the passage of GWs through the three-satellite constellation.

The three S/C will be launched from the Guiana Space Centre in Kourou, aboard an Ariane 6.4. The scientific payload is composed of subsystems developed by sixteen European partners - space agencies, laboratories and industry – together with NASA, under ESA leadership. OHB System AG serves as Industrial Prime Contractor, leading a consortium in which Thales Alenia Space Italy is a core team member responsible, among others, of avionics and telecommunications.

Figure 2. LISA measures pm distance variations between free-falling test masses situated at the end of each arm, using laser beams exchanged between the satellites.



LISA payload critical technologies

The LISA mission relies on several tightly integrated, high-performance technologies that enable the detection of GWs in the mHz frequency band, with a required noise floor below 10 pm/√Hz. The main technologies - shown in Fig. 3 and described below - push the limits of current space optics and engineering, and must operate with exceptional stability and reliability throughout the extended mission lifetime of ten years.

A core technology of LISA is the realization of near-perfect free-fall TMs, which serve as inertial references and act as a mirror for the laser beam. Each S/C houses at the end of the arm a cubic gold–platinum TM (≈2 kg, 46 mm side length), selected for its extremely low magnetic susceptibility and thermal sensitivity. Non-gravitational forces must be reduced so that residual acceleration noise stays below $\sim 3 \times 10^{-15}$ m·s^{-2}/√Hz above 0.1 mHz. This requires tight control of electrostatic forces (few fN/√Hz), magnetic and thermal fluctuations (few nT/√Hz and <10 µK/√Hz), and of TM charge ($< \sim 10^{7}$ e-). The surrounding Gravitational Reference Sensor (GRS) provides capacitive sensing and electrostatic actuation with < ~1 nm/√Hz, displacement noise in ultra-high vacuum ($<10^{-5}$ Pa), enabling near-ideal free fall as demonstrated by LISA Pathfinder.

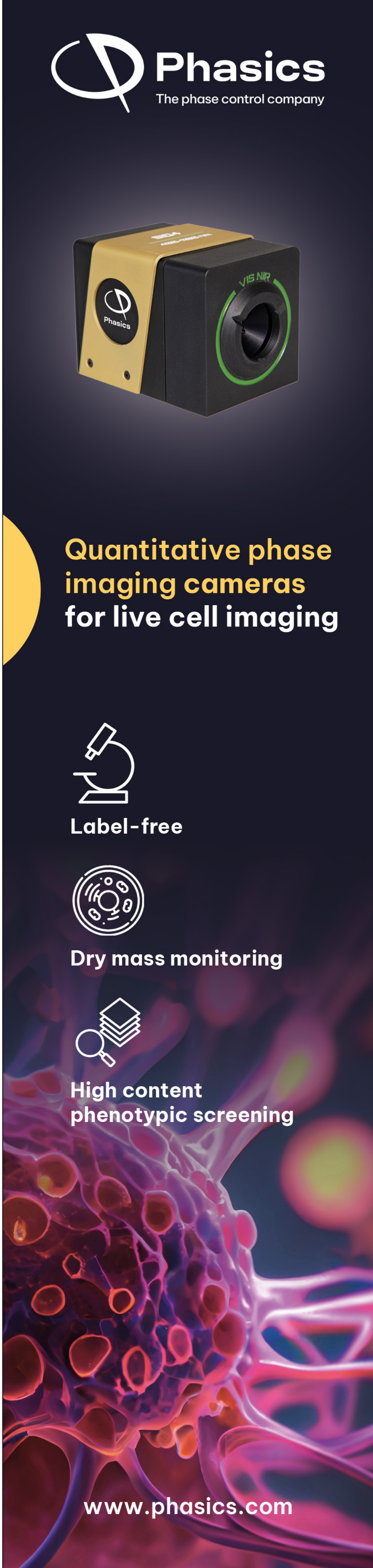
Ultra-high-precision laser interferometry is at the heart of LISA's measurement system. The mission uses single-frequency, continuous-wave Nd:YAG lasers at 1064.5 nm delivering ~2 W, and MHz-beat-note heterodyne interferometry achieves phase readout noise below ~10 µrad/√Hz, corresponding to ~1–2 pm displacement resolution. Despite pre-stabilization to an ultra-stable cavity (~30 Hz/√Hz in the mHz band), laser frequency noise still dominates because of the ~8 s light-travel time over the 2.5 million km arms. Time Delay Interferometry (TDI) suppresses this noise by 8–9 orders of magnitude by combining time-shifted phase measurements from the three spacecraft to synthesize virtual equal-arm interferometers, pushing laser noise well below TM acceleration noise and shot noise across the LISA band.

The optical bench is a central, performance-critical element of the interferometric system, providing a mechanically and thermally ultra-stable platform for measurement. Built as a quasi-monolithic structure from ultra-low-expansion glass-ceramic with optics bonded by hydroxide-catalysis, it offers sub-nanometer long-term stability. Optical pathlength noise must remain below a few pm/√Hz, requiring strict control of thermal gradients, mechanical stress, and alignment.

LISA telescopes are key optical subsystems that transmit and receive the laser beams between S/C while preserving wavefront quality and pointing stability. Each telescope has an aperture of 30 cm and must deliver diffraction-limited performance with extremely low wavefront distortion. Pointing jitter and pathlength fluctuations must remain of ~ few nrad/√Hz and ~1 pm/√Hz to avoid degrading the interferometric phase measurement.

Maintaining the TM in free fall requires drag-free control of the spacecraft, implemented using ultra-low-noise micro propulsion systems. Microthrusters provide continuous thrust at the level of a few µN to counteract non-gravitational forces such as solar radiation pressure, while maintaining thrust noise below a few tens of nN/√Hz in the LISA measurement band. This performance is essential to prevent S/C motion without reintroducing acceleration noise onto the TMs.

Control of stray light is another key technology challenge for LISA. Scattered, reflected, or back-coupled light – whether in fibers or free-space – can coherently mix with the main interferometric signals and generate spurious phase noise. Stray-light-induced heterodyne noise must remain at ~1 pm/√Hz in each interferometer. Achieving this requires careful optical design, dedicated baffles and beam dumps, low-scatter optical coatings, tight control of surface roughness, and accurate knowledge of component-level scattering. Complex optical simulation, including imperfections, and dedicated monitoring equipment's are essential to identify, quantify, and mitigate coherent stray light.



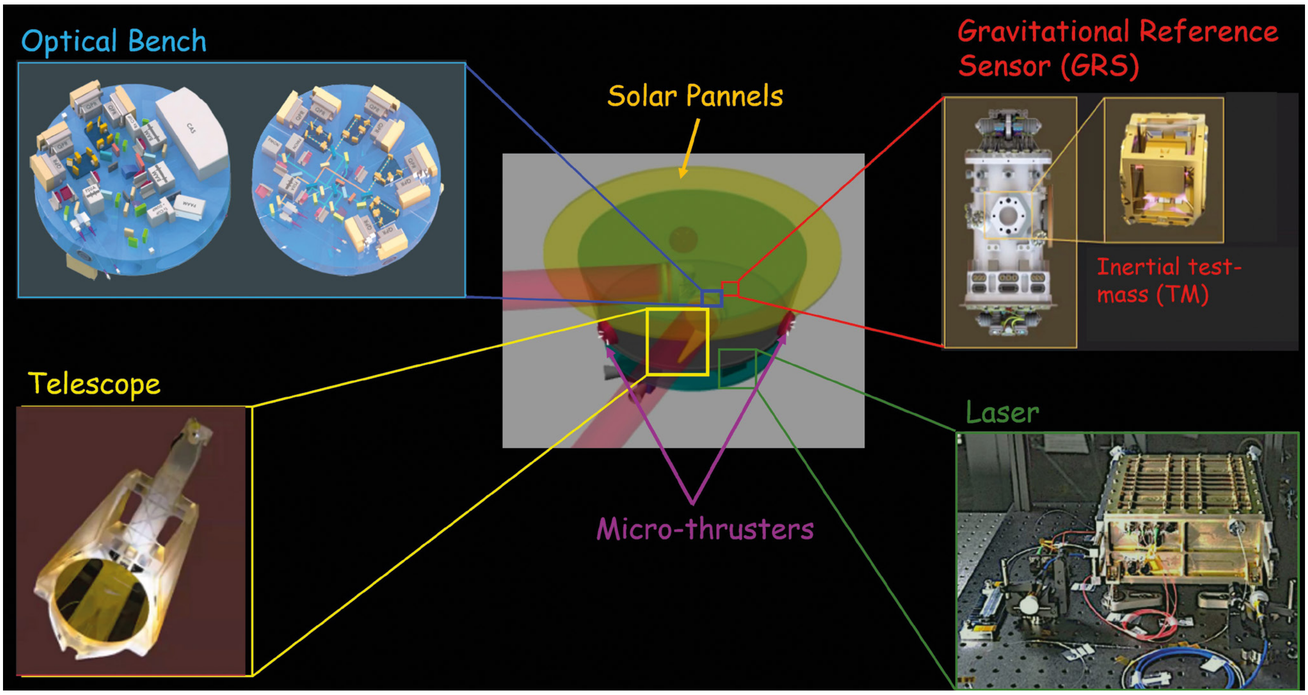


Figure 3. LISA satellite and payload critical technologies.

Finally, low noise photoreceivers and their associated readout electronics are required to detect weak heterodyne signals with high linearity and long-term stability. Shot noise, electronic noise, and parasitic couplings must remain below the allocated displacement noise budget, ensuring that they do not limit the GWs measurement sensitivity.

Dedicated performance tests of the Optical Metrology System (OMS) will support the qualification of LISA's critical interferometric technologies. These tests must confirm that the end-to-end detection noise meets the ~10 pm/√Hz requirement. Using specialized optical, electrical and mechanical ground-support equipment under controlled thermal and mechanical conditions, they will characterize optical pathlength stability, readout noise, stray-light mitigation and the tilt-to-length coupling effects. These activities are crucial for consolidating the OMS noise budget, ensuring compliance with mission requirements, and reducing risk before system-level integration.

Conclusions

LISA brings together an unprecedented combination of ultra-stable interferometry, near-ideal inertial references, drag-free spacecraft control, and advanced signal processing to probe the low-frequency GWs Universe. The mission performance emerges from the coherent integration of these technologies, each operating at the edge of what is achievable in space. By successfully mastering laser stability, precision optics, stray-light control, time-delay interferometry, TM free fall and micro propulsion, LISA opens a new observational window on the Universe, enabling the direct exploration of gravitational phenomena inaccessible by any other means. It is remarkable that this effort, as well as the effort aiming at the processing and interpretation of the future GWs readout data, is indeed pursued by a collaboration of ~10 space agencies, ~40 nations and ~1700 scientists throughout the world. ●

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THE EXTREME LIGHT INFRASTRUCTURE'S HIGH-PERFORMANCE LASER SYSTEMS ACCESSIBLE TO THE WORLD

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The Extreme Light Infrastructure (ELI) operates some of the world's most advanced high-intensity laser systems across three complementary sites. Providing competitive, excellence-based access to international users, ELI enables research in attosecond science, relativistic laser–plasma interaction, nuclear photonics and laser-driven particle acceleration. ELI's integrated User Programme supports frontier science and the development of enabling photonic technologies.

https://doi.org/10.1051/photon/202613767

The Extreme Light Infrastructure ERIC (ELI) is the world's largest laser-based research infrastructure. The international user facility dedicated to multi-disciplinary science and research applications provides access to high-power, high-repetition-rate laser systems. ELI's lasers generate secondary sources from attosecond pulses to high-intensity particle beams, enabling imaging, spectroscopy and studies of relativistic laser–plasma interaction and particle acceleration. These technologies also support the development of high gradient particle accelerators for the next generation of compact photon and neutron sources.

ELI operates as a single multi-site organisation with three facilities specialised in different fields of research with extreme light: the ELI Attosecond Light Pulse Source (Hungary) for high power few cycle lasers with attosecond

●●●

and particle beamlines and ELI Beamlines (Czech Republic) for high-peak and high-average power laser pulses and secondary sources; and the Nuclear Physics (NP) facility (Romania) for combining ultra-intense lasers with brilliant gamma beams.

The complementarity of ELI's facilities support a particularly wide range of science and joint technology development. ELI has also strategically invested in critical building coating facilities for the development of high-damage-threshold optical components required for petawatt-class systems. The ELIAS Coating Laboratory is among the most advanced worldwide, producing large-aperture, high-damage-threshold optical coatings up to 1.2 m in diameter for petawatt-class systems.

ELI's User Programme offers a single access point to ELI's capabilities. Access is competitive, international, free of charge and based on scientific excellence. Since launching the ELI User Programme in mid 2022, ELI has opened two Calls per year. With each Call more instruments and equipment become available to the user community, and the technical capability of the equipment continues to ramp up to full scope. ELI has received a total of 733 proposals from 41 countries, involving over 1,800 individual applicants. Of these, 467 have been awarded beamtime, nearly 70% of experiments have been completed[1].

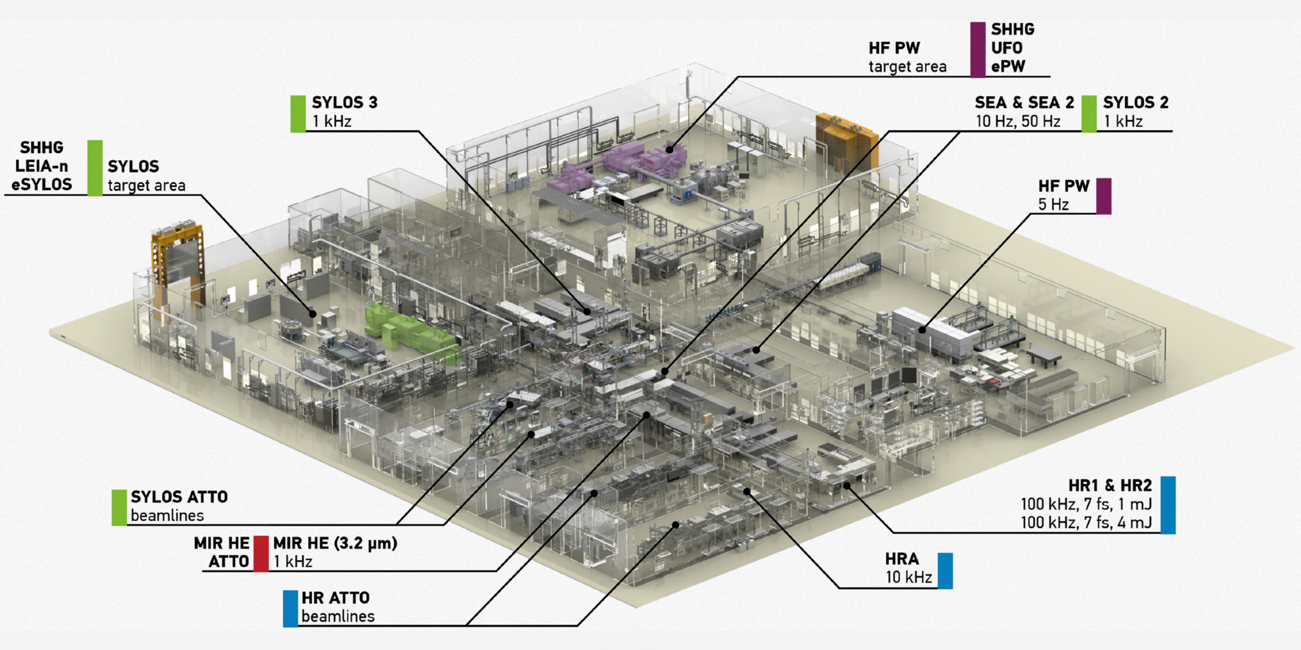
In pursuit of its broader objectives to advance societal progress through cutting-edge research and innovation, ELI has also introduced mission-oriented access calls targeting strategic challenges such as Inertial Fusion Energy (IFE) to support research on IFE concepts and to promote the development of laser-powered IFE technologies. A pilot call attracted 76 institutions from 18 countries. Additional calls are planned.

ELI Attosecond Light Pulse Source (ELI ALPS)

The ELI ALPS Facility showcases a unique combination of state-of-the-art ultrashort pulsed lasers, secondary particle and radiation beamlines and specialised end-stations for studying dynamic processes in atoms, molecules, condensed matter and plasma on the femtosecond and attosecond timescales. Installation of research technology started in 2017, following completion of the specially engineered buildings, including 4,000 m^2 cleanroom facilities with vibration isolation, thermal and humidity control and radiation protection. Following the end of construction and commissioning of the research instrumentation ELI ALPS's instruments were made available to the external user community through ELI's joint open calls for user experiments.

To support a wide variety of laser-based fundamental and applied research in physical, biological, chemical, medical and materials

Figure 1. Layout of the main laboratory building of ELI ALPS with the driver lasers and their target areas.



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[1] ELI User Portal: https://up.eli-laser.eu/

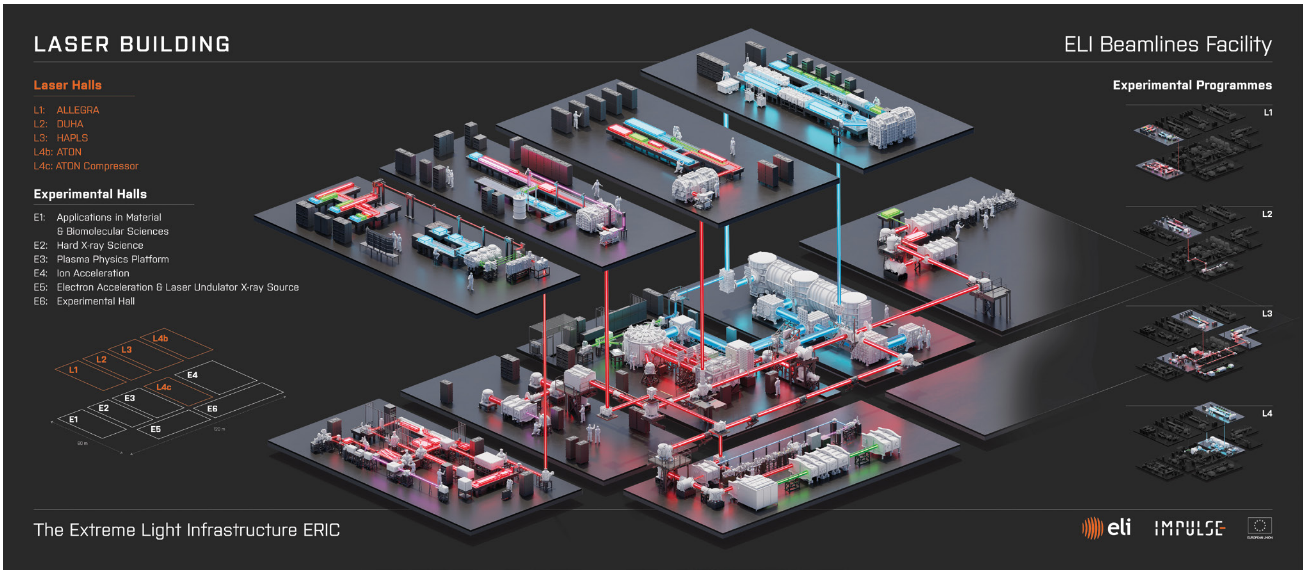
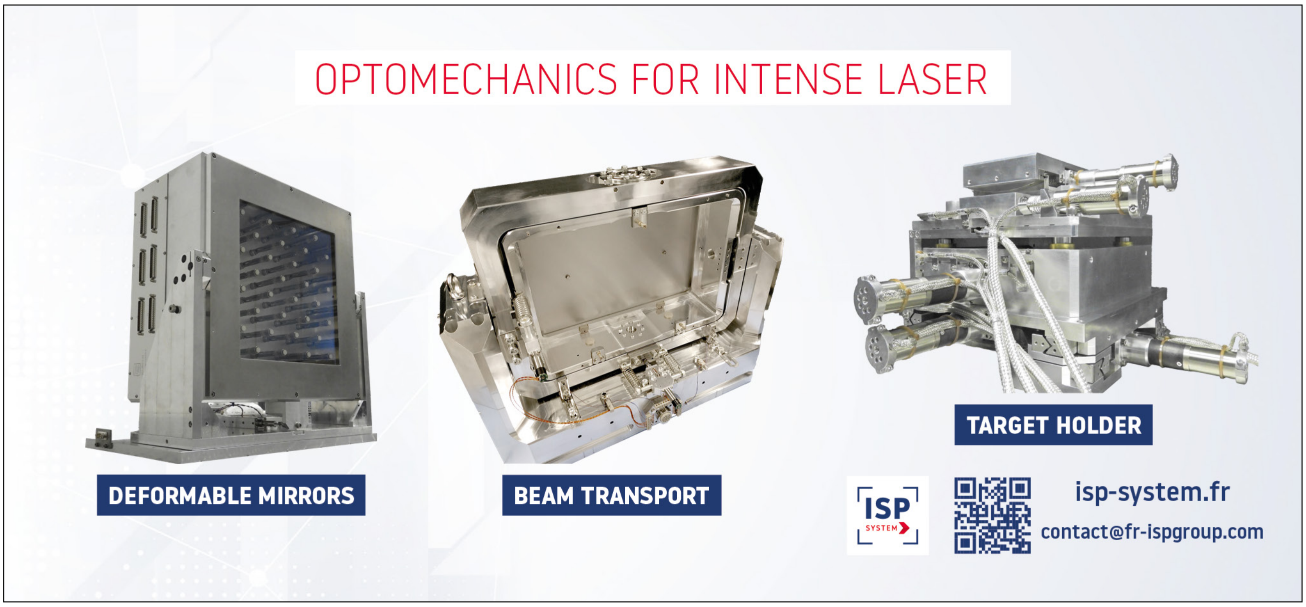


Figure 2. Layout of the ELI Beamlines Laser Systems

sciences, the facility hosts a combination of nine high average power and high peak power primary lasers, operating in the NIR and MIR spectral regions, with repetition rate ranging from 5 Hz to 100 kHz and pulse duration as short as a few optical cycles. These lasers drive nonlinear frequency conversion and particle acceleration processes in twelve different secondary source beamlines equipped with a number of specialised end-stations, such as the “reaction microscope” for studying the full kinematics of molecular photodissociation and the “NanoESCA” to characterise photoelectrons from surfaces in real and k-space, and spin. In addition, high-field physics experiments with the PW laser, particle irradiation of radiobiological samples, photochemical studies or time-resolved nanoscience are enabled in advanced setups.

The world leading expertise in high power laser development by French companies resulted in the development of ALPS’ HF PW laser and the MIR system. Continuous developments of these systems by ELI staff and the developer companies keep these sources at the forefront of laser technology. For example, the MIR laser performance offers opportunities ● ● ●



for novel quantum optics and structured light studies which receive strong interest from French researchers.

The attosecond secondary sources are based on advanced techniques for high-order harmonic generation (HHG). Optically ionised gases serve the production of attosecond pulses in five beamlines, based on concepts and characterisation techniques that were developed by French Nobel Laureates Anne L'Huillier and Pierre Agostini. Attolabs in CEA-LIDYL (Saclay) and CELIA (Bordeaux) have shared research interest with ELI. Oscillating surface plasmas are also exploited for HHG driven by the high intensity SYLOS and HF PW lasers. This field was pioneered by researchers from CEA-LIDYL (Saclay) and LOA (Palaiseau), who helped design and implement dedicated beamlines in collaboration with French photonics companies. ELI ALPS also showcases two laser-plasma electron accelerators driven by SYLOS and HF PW lasers for spectroscopic and structural studies, plasma physics or radiobiology. The technology contained in these beamlines was also pioneered by researchers from LOA (Palaiseau).

ELI Beamlines

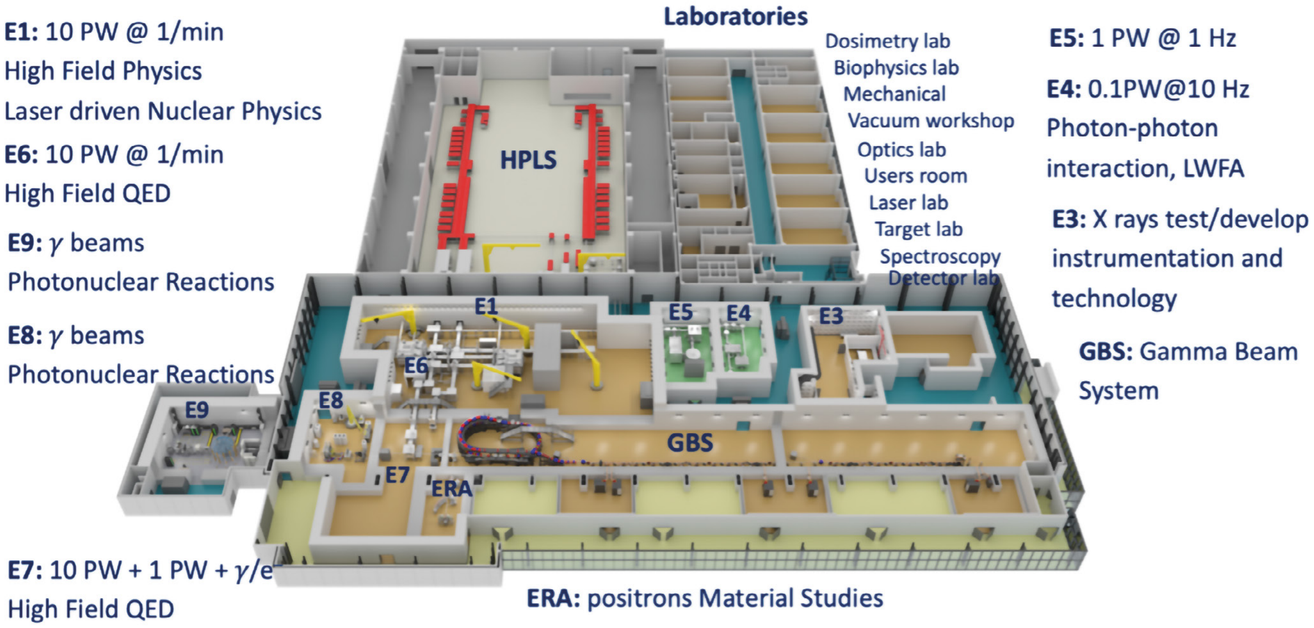
The ELI Beamlines Facility uniquely combines high pulse energy with high repetition rate performance, enabling users to explore light–matter interactions in the relativistic and ultra-relativistic regimes while sustaining unprecedented operational repetition rates. The laser systems are designed to deliver intensities on target as high as 10^{23} W/cm^2 at 1 shot per minute, about 10^{22} W/cm^2 at 10 Hz, and more than 5×10^{18} W/cm^2 at 1 kHz.

These state-of-the-art capabilities support pioneering research in plasma physics, inertial fusion, strong-field physics, and laboratory astrophysics, attracting a diverse international user community. Experiments on nonlinear quantum electrodynamics (QED), positron and muon production, high-brightness gamma-ray beam generation, and planetary science are currently being conducted or are planned.

Laser-driven particle accelerators have gained increasing attention in recent years due to their compactness, versatility, and innovative beam properties. This has driven the development of dedicated beamlines at ELI Beamlines, where users can exploit unique source parameters such as ultrashort bunch duration and ultrahigh dose rates from laser-driven ion and electron beams, as well as broadband radiation sources spanning from XUV to gamma rays. These features open new opportunities across materials science, atomic, molecular and optical (AMO) physics, chemistry, biology, and medicine, as well as pump–probe studies in high-energy-density physics. Ongoing user experiments also include probing ultrafast atomic relaxation dynamics, irradiation studies on cancer cells, simulation of space radiation effects for electronics testing, and non-destructive surface analysis techniques for cultural heritage applications.

Furthermore, the facility offers the combined use of optical, X-ray, and particle beams for advanced studies in inertial confinement fusion and shock physics. This is enabled by a unique kJ-class nanosecond laser operating at an unprecedented repetition rate of approximately 1 shot per minute, featuring temporal pulse shaping capabilities and selectable narrow- or broadband operation, in

Figure 3. ELI-NP: Facility Layout.



combination with secondary sources driven by PW-class lasers for pump-probe user experiments.

To fully exploit these capabilities, ELI Beamlines continuously develops and provides advanced target delivery systems and diagnostics designed to operate under extreme laser–plasma conditions and high repetition rates, ensuring reliable and efficient experimental performance for its user community.

ELI Nuclear Physics

The Extreme Light Infrastructure Nuclear Physics (ELI-NP) facility in Măgurele, Romania, hosts one the most powerful laser systems in the world: the High Power Laser System (HPLS). Together with the Gamma Beam System (GBS), the HPLS is designed to push the frontiers of nuclear physics, particle acceleration, and high-field science.

The HPLS is a dual-arm, 10 PW femtosecond laser system based on chirped pulse amplification (CPA) technology. Each arm is capable of delivering laser pulses with energies of approximately 220 J, compressed to pulse durations of about 22 fs. This performance enables the achievement of peak powers up to 10 PW at a repetition rate of one shot per minute[2]. In addition to the 10 PW capability, each arm provides auxiliary output beams operating at lower power but higher repetition rates, namely 100 TW at 10 Hz and 1 PW at 1 Hz, offering a broad range of experimental operating regimes.

The HPLS features an exceptional temporal contrast exceeding 10^{12}, ensuring that the main pulse is overwhelmingly dominant with respect to pre-pulses and amplified spontaneous emission (ASE). This high contrast is essential for experiments involving relativistic laser-matter interactions, as it preserves target integrity prior to the arrival of the main pulse. Furthermore, the excellent spatial beam quality enables focusing to ultra-high intensities approaching 10^{23} W/cm^2, thereby providing access to extreme regimes of light-matter interaction relevant for advanced particle acceleration, laboratory astrophysics, and strong-field quantum electrodynamics.

Conclusion

The ELI Facilities stand at the frontier of high-field science, offering an unprecedented platform to explore matter under extreme electromagnetic fields and to push the limits of laser–matter interaction. As the capabilities of ultra-intense and ultra-short pulse lasers continue to advance, ELI provides the perfect environment where fundamental discoveries can translate into transformative technologies. ELI is positioned to address some of the most pressing scientific and technological challenges of our time—ranging from clean energy and nuclear photonics to space science, enabling breakthroughs in health through novel imaging and radiotherapy approaches. By combining cutting-edge infrastructure, international collaboration, and interdisciplinary research, ELI will shape the future of high-field science and its societal applications. ●

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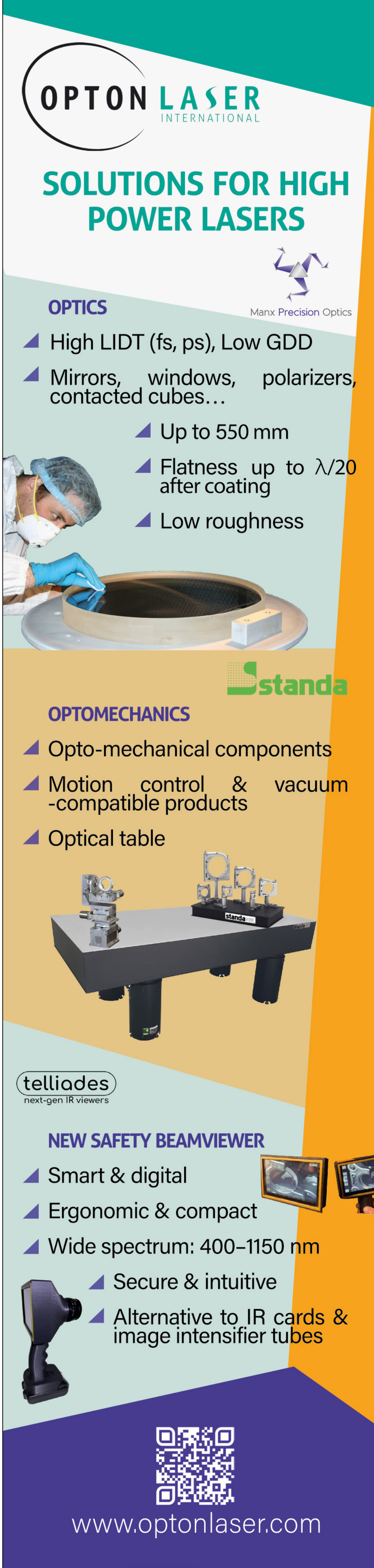
[2] https://www.eli-np.ro



SUPERCONTINUUM LASERS — PRINCIPLES, PERFORMANCE, AND KEY SUPPLIERS

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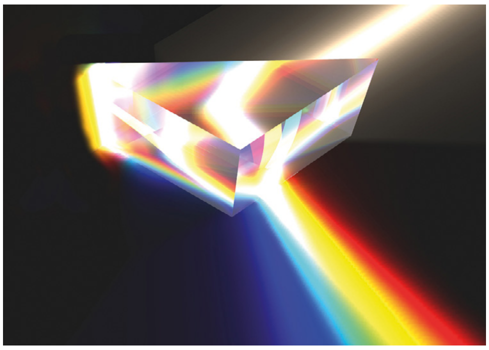
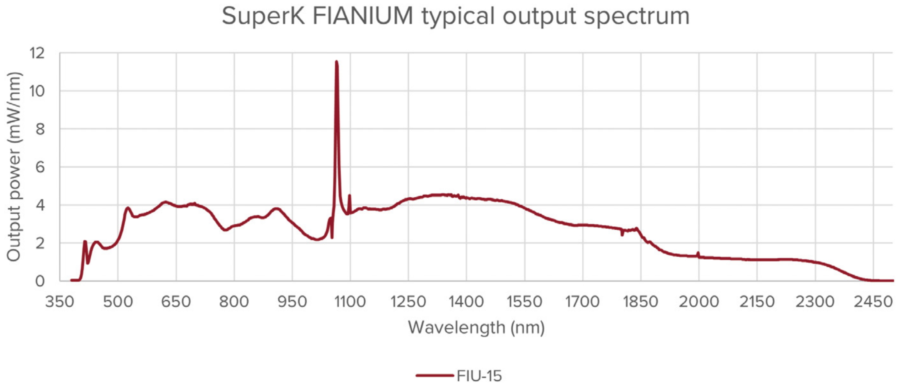


https://doi.org/10.1051/photon/202613772

Since the first demonstration in optical fibers, supercontinuum sources have evolved quickly, driven by advances in ultrafast fiber lasers and nonlinear fiber design. Today, supercontinuum sources are available as robust, turnkey systems suitable for both laboratory and industrial environments. This buyer's guide provides an overview of the physical principles behind supercontinuum generation, highlights the key performance parameters, and presents the main suppliers in this rapidly evolving market.

Broadband light sources play a central role in modern photonics, supporting applications that range from spectroscopy and imaging to metrology and industrial inspection. Traditionally, users have had to choose between incoherent sources, such as lamps offering wide spectral coverage but low brightness, and lasers providing high spatial coherence but limited spectral bandwidth. Supercontinuum lasers bridge this gap by combining both properties in a single source, delivering diffraction-limited beams over extremely broad spectral ranges.

Figure 1. Typical spectral power density of a commercial 78 MHz supercontinuum light source pumped at 1064 nm. (SuperK FIU-15 – NKT Photonics).



PRINCIPLES OF SUPERCONTINUUM GENERATION

Supercontinuum (SC) lasers are versatile light sources, delivering bright, broad-spectrum light from the visible to the infrared. Often referred to as "white lasers," they combine the high spatial coherence of lasers with the wide spectral coverage of thermal sources. This unique combination has driven their rapid adoption in fields ranging from spectroscopy to biomedical imaging and industrial inspection. Supercontinuum generation is a nonlinear optical process in which a narrowband input pulse is transformed into a broad and continuous

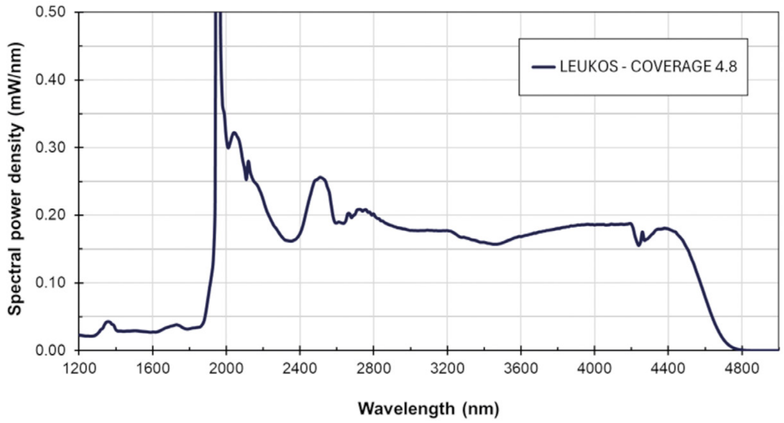


Figure 2. Typical spectral power density of a commercial mid-IR supercontinuum light source. (Coverage – LEUKOS)

spectrum. This transformation occurs when intense optical pulses propagate through a nonlinear medium, most commonly a dispersion-engineered optical fiber. The resulting spectral broadening arises from a complex interplay of nonlinear effects. Self-phase modulation induces spectral broadening through intensity-dependent phase shifts, while four-wave mixing redistributes energy between spectral components. Stimulated Raman scattering shifts energy toward longer wavelengths, contributing to infrared extension. In the ultrafast regime, soliton dynamics—particularly soliton fission—play a central role, whereas dispersive wave generation enables extension toward shorter wavelengths.

In practical implementations, the nonlinear medium is typically a photonic crystal fiber or a highly nonlinear fiber designed to tailor dispersion and enhance light confinement. The pump source is generally a pulsed fiber laser operating in the picosecond or femtosecond regime, often around 1 µm. Femtosecond pumping tends to produce smoother and more coherent spectra, while picosecond or nanosecond pumping offers higher average power, broad spectrum and improved robustness, at the expense of spectral coherence.

KEY PERFORMANCE PARAMETERS

The selection of a supercontinuum laser requires careful consideration of several interdependent parameters. The spectral range is a primary criterion, with most commercial systems covering wavelengths from approximately 400 nm to beyond 2.5 µm, depending on the fiber design and pumping conditions. However, the practical value of this range is set by the spectral power density, which determines how much power is delivered at each wavelength.

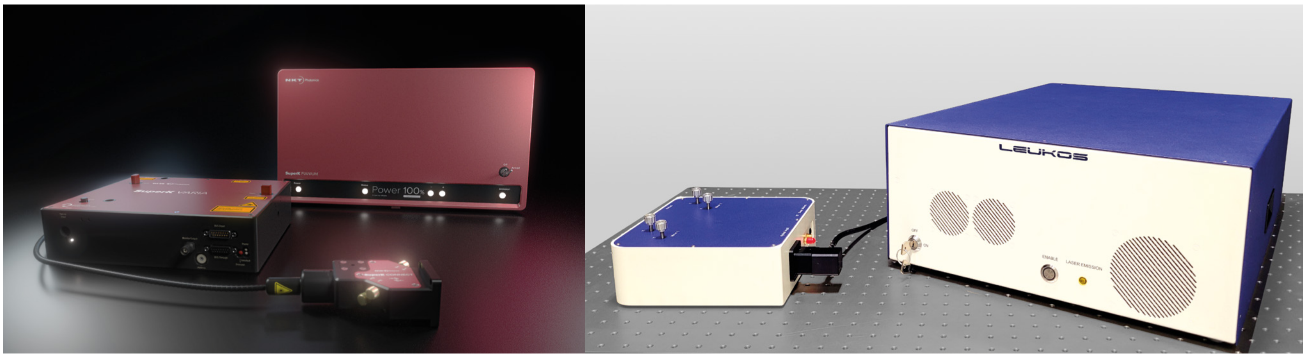
Temporal characteristics are equally critical. Pulse duration, repetition rate, and peak power directly influence the efficiency of nonlinear processes and the structure of the generated spectrum. Short pulses generally favor broader and more coherent spectrum, whereas longer pulses enable higher pulse energy and average powers. These trade-offs must be matched to the requirements of the application.

Fiber guidance keeps the beam close to the diffraction limit, ensuring high spatial coherence.

In contrast, spectral coherence depends strongly on the pumping regime and may limit performance in interferometric or phase-sensitive applications. Relative intensity noise (RIN) is another important parameter, particularly for imaging and sensing applications, where fluctuations can degrade signal quality. Modern systems often integrate active stabilization schemes to improve noise performance.

Finally, wavelength selection is a key practical advantage. Supercontinuum sources are frequently combined with tunable filtering devices, such as acousto-optic tunable filters, enabling rapid and flexible wavelength selection across the emission spectrum.

Figure 3. Supercontinuum light source with tunable wavelength filter and fiber delivery solution.



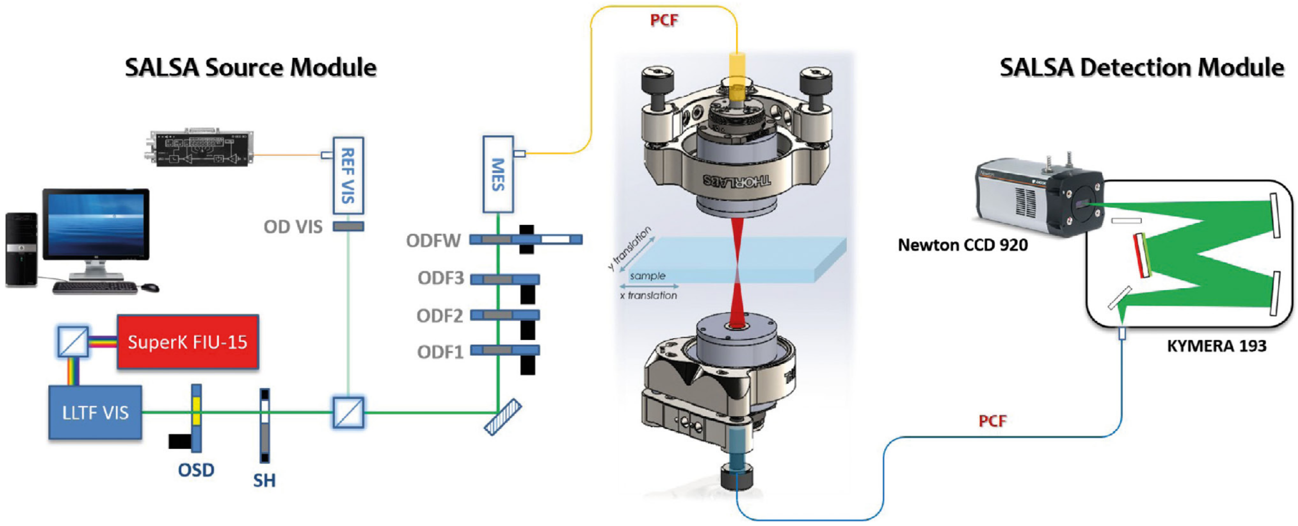


Figure 4. Schematic representation of the local spectral transmittance measurement apparatus (SuperK FIU-15, supercontinuum laser source; LLTF VIS, tunable volume hologram filter; OSD, order sorting device; SH, shutter; ODF1, ODF2, ODF3, ODFW, and OD VIS, optical densities; REF VIS, MES, reflective collimators for the reference and measurement channels, respectively; PCF, photonic crystal fiber; KYMERA 193, Czerny–Turner monochromator; and Newton CCD 920, low-noise scientific-grade CCD camera). (Courtesy of Aix Marseille Univ, CNRS, Centrale Med, Institut Fresnel, Marseille, France).

APPLICATIONS

The combination of broadband emission and high brightness makes supercontinuum lasers highly attractive for a wide range of applications. Their use in Raman, fluorescence and absorption spectroscopy is now well established. In spectroscopy, they enable measurements at multiple wavelengths simultaneously, significantly reducing acquisition times and enabling comprehensive material characterization (see below Figure 4 and 5 illustrating a compact opto-mechanical setup developed for the precise characterization of optical filters with spatially varying spectral responses).

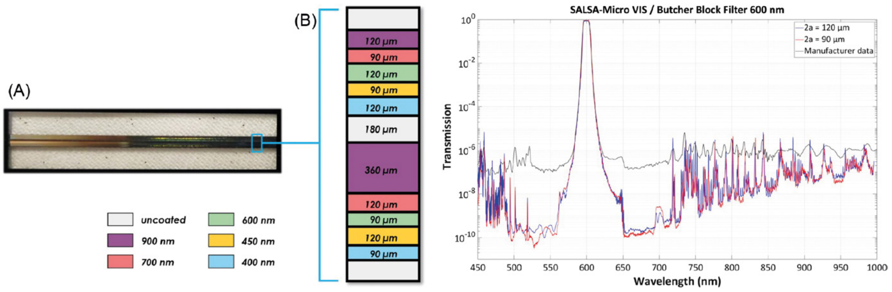
In biomedical imaging, particularly in optical coherence tomography, the large spectral bandwidth of supercontinuum sources translates into high axial resolution, which is essential for detailed tissue imaging. In fluorescence microscopy, a single supercontinuum source can replace multiple discrete lasers when combined with tunable filters, simplifying experimental setups while expanding excitation capabilities.

In metrology, femtosecond generated supercontinuum light is used to create optical frequency combs, which enable extremely precise measurements of time and frequency. Industrial applications are also expanding rapidly and include machine vision, semiconductor metrology and inspection, and hyperspectral imaging, where broadband illumination improves contrast and defect detection. Environmental sensing represents another key domain, as SC sources allow simultaneous detection of multiple gas species across wide spectral bands.

INTEGRATION AND PRACTICAL CONSIDERATIONS

The integration of supercontinuum lasers into experimental or industrial systems requires careful attention to engineering constraints. Fiber-coupled outputs are generally preferred due to stability and ease of alignment, although free-space configurations remain relevant for certain high-power or specialized applications. Thermal management and system footprints are ●●●

Figure 5. Right : Butcher block filter description: (A) Image of the filter and (B) scale representation of the stripes showing their respective widths and central wavelengths (color code). Left : Transmission spectra of the bandpass filter centered at 600 nm [measurement performed with Micro-SALSA on 120 µm stripe (blue curve), 90 µm stripe (red curve), and measurement performed on the deposition wafer by the manufacturer (black curve)]. Courtesy of Aix Marseille Univ, CNRS, Centrale Med, Institut Fresnel, Marseille, France).

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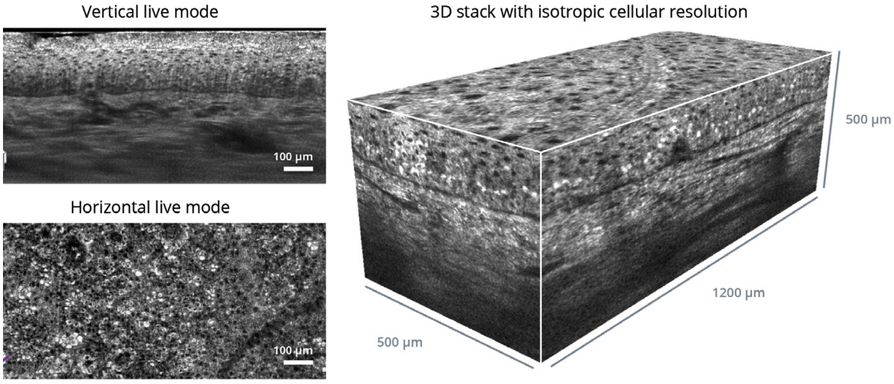
important considerations, particularly for embedded systems.

Control and interfacing capabilities are also important. Many modern sources provide advanced software environments and application programming interfaces that facilitate automation and synchronization with other instruments. Safety is essential, as the broad high-intensity emission requires proper protective measures. Turnkey systems are widely available and optimized for ease of use, whereas OEM modules offer greater flexibility for integration into custom platforms. The choice between these options depends on the level of customization required and the expertise of the user.



LC-OCT vertical (top left), horizontal (bottom left) images and 3D stack (right) of healthy human skin in vivo

iedical Optics Express (2020): «Dual-mode line-field confocal optical coherence tomography for ultrahigh-resolution vertical and horizontal section imaging of human skin in vivo» (DOI: 10.1364/BOE.385303)

Figure 6: LC-OCT vertical (top left), horizontal (bottom left) images and 3D stack (right) of healthy human skin in vivo (courtesy of DAMAE Medical)

MAIN SUPPLIERS

The supercontinuum laser market has matured significantly, with several established players offering a range of solutions:

NKT PHOTONICS (A HAMAMATSU COMPANY)

A pioneer in commercial supercontinuum lasers, offering widely used platforms such as the SuperK series. The company is known for reliability, modular architecture, and very broad spectral coverage extending from the visible to the infrared.

nktphotonics.com

LEUKOS (AN EXAIL COMPANY)

Leukos develops supercontinuum lasers for over 20 years and offers one of the broadest product ranges on the market, covering wavelengths from the UV 350 nm to the mid-IR beyond 5 µm.

leukos-laser.com

FYLA

FYLA develops fiber-based femtosecond and supercontinuum lasers with an emphasis on robustness and low noise performance. Its systems are primarily targeted at scientific instrumentation, spectroscopy, and quantum technologies.

fyla.com

YSL PHOTONICS

YSL Photonics provides a broad portfolio of fiber lasers, including supercontinuum sources covering roughly 400–2400 nm, with flexible repetition rates and OEM configurations.

ysl-inc.com

OTHER PLAYERS

Additional suppliers include emerging companies and specialized providers focusing on mid-infrared supercontinuum generation, custom nonlinear fiber development, and application-specific light sources.

CONCLUSION

Supercontinuum lasers represent a unique class of light sources, combining broadband spectral coverage with high brightness and spatial coherence. Their versatility has enabled their widespread adoption across scientific and industrial domains. Continuous advances in nonlinear fiber design, noise reduction, and system integration are expected to further expand their capabilities. For users, selecting an appropriate supercontinuum source requires a careful balance between spectral coverage, power, coherence, and stability, as well as consideration of integration constraints. With a growing number of suppliers and increasingly application-specific solutions, supercontinuum lasers are poised to play an even more prominent role in the future of photonics. ●

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Low group delay dispersion quarter wave retarder

Kauai (UFI Innovations) is a quarter-wave retarder operating over a broad spectral range from 650 to 1400 nm, with a reflectivity of up to about 90% and a low group delay dispersion below 3 fs^2. Its compact reflective design preserves the beam direction and facilitates integration into existing optical setups. It is intended for use in high-performance laser systems, including ytterbium-based sources.
www.ultrafast-innovations.com/devices/KAUAI.html

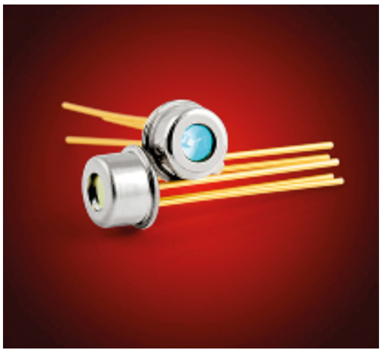
ULTRA-LOW NOISE MICROWAVE SYSTEM

TOPTICA Photonics introduces the X-MMS (X-band Metrological Microwave Solution), a system designed to generate ultra-low-noise microwave signals. Based on a photonic approach, it derives a 9.6 GHz signal from a highly stable optical reference using optical frequency division, enabling high spectral purity and stability.
www.toptica.com

Optical Frequency Discriminator

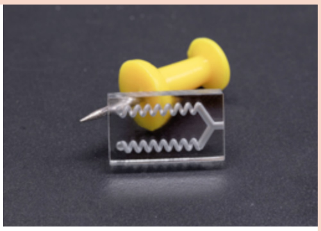
SILENTSYS introduces the OFD-PRO, its next-generation Optical Frequency Discriminator. This system characterizes and stabilizes laser frequency noise, reducing linewidth (FWHM) with enhanced environmental resistance (40x less temperature impact, 10x less vibration sensitivity), plug-and-play servo-control, and 19-inch rack compatibility. It achieves sub-MHz stabilization over long timescales for 200 THz optical carriers.
https://silentsys.com/

SINGLE-MODE VCSEL



Brightlaser's 660 nm single-mode VCSEL excels in precision applications, offering stable linear polarization, high spectral purity, and excellent beam quality. With output power up to 2 mW, a linewidth <100 MHz, SMSR >30 dB, and PER >20 dB, it is ideal for FTIR spectroscopy, medical OCT, and industrial metrology.
www.lasercomponents.com/fr/photonics-portal/actualites/vcsel-monomode-a-660-nm-avec-polarisation-stable/

Transparent photopolymer for 3D printing



Boston Micro Fabrication launches BMF Clear, an optically transparent photopolymer resin for micro-precision 3D printing, offering >90% light transmittance and micron-level accuracy. Ideal for microfluidics, photonics, and biomedical devices, it enables complex, internally structured components previously unachievable with additive manufacturing. Compatible with BMF's 10µm and 25µm systems, it supports scalable production of micro-optical features like lenses, waveguides, and lab-on-a-chip systems.
www.bmf3d.com