N°131

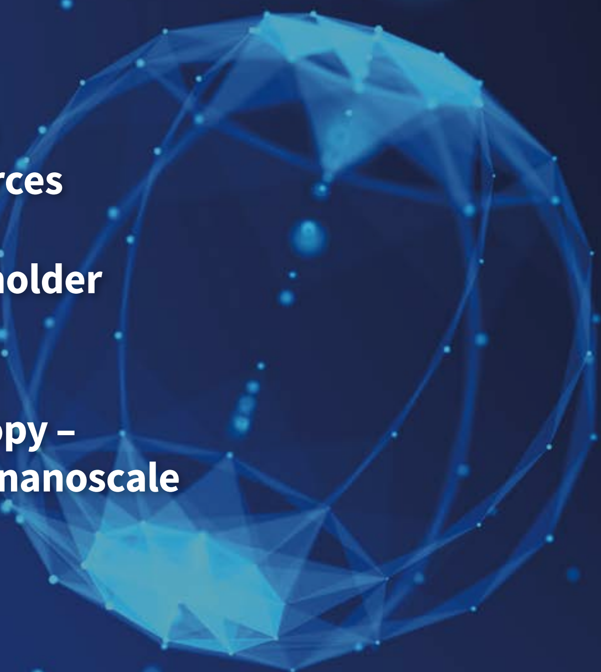
Photoniques

LIGHT AND APPLICATIONS | EOS & SFO JOINT ISSUE

FOCUS ON

QUANTUM SENSING

- Encoding and decoding images in quantum optical correlations
- Light and color: photonic resources for quantum metrology
- Quantum is in the eye of the beholder
- (Quantum) Fisher Information in Localization Microscopy
- Planar scanning probe microscopy – the art of low-level flight at the nanoscale



\+

- Quantum computing: promises, achievements and challenges

SFO Société Française d'Optique | EOS European Optical Society | EPIC European Photonics Industry Consortium

France/EU : 19 € | Rest of the World : 25 €


A HAMAMATSU COMPANY
SOLUTIONS FOR INNOVATORS
Drive innovation further with our lasers and fibers! Innovators across the World use our lasers for quantum experiments, neuroscience, nanomaterial characterization, and space applications. Choose from a wide range of ultrafast lasers, supercontinuum white light lasers, single-frequency fiber lasers, and an extensive variety of specialty fibers.
What's your next innovation?
Contact us!
nktphotonics.com/contact
NKT Photonics

Photoniques is published
by the French Physical Society.
La Société Française de Physique est une association loi 1901 reconnue d'utilité publique par décret du 15 janvier 1881 et déclarée en préfecture de Paris.

https://www.sfpnet.fr/
33 rue Croulebarbe,
75013 Paris, France
Tel.: +33(0)1 44 08 67 10
CPPAP: 0124 W 93286
ISSN : 1629-4475, e-ISSN: 2269-8418

www.photoniques.com

The contents of Photoniques are elaborated under the scientific supervision of the French Optical Society.
2 avenue Augustin Fresnel
91127 Palaiseau Cedex, France
Florence HADDOUCHE
General Secretary of the SFO
florence.haddouche@institutoptique.fr

Publishing Director
Jean-Paul Duraud, General Secretary of the French Physical Society

Editorial Staff
Editor-in-Chief
Nicolas Bonod
nicolas.bonod@edpsciences.org

Journal Manager
Florence Anglézio
florence.anglezio@edpsciences.org

Editorial secretariat and layout
Agence la Chamade
https://agencelachamade.com/

Photoniques is hosted and distributed by
EDP Sciences,
17 avenue du Hoggar,
P.A. de Courtaboeuf,
91944 Les Ulis Cedex A, France
Tel.: +33 (0)1 69 18 75 75
RCS: EVRY B 308 392 687

Subscriptions
subscribers@edpsciences.org

Printer
Imprimerie de Champagne Nouvelle
Rue de l'Étoile de Langres
ZI Les Franchises
52200 Langres
Legal deposit: may 2025
Routing: STAMP (95)

Editorial

NICOLAS BONOD
Editor-in-Chief

Quantum Science in Europe: a legacy of foundations, a future of light

June 1925. A 23-year-old German physicist travels to the small island of Helgoland, in the North Sea, to escape the seasonal allergies that afflict him. In this quiet and isolated setting, Werner Heisenberg works intensively on the foundations of a theory based on observables, one that could explain the emission spectrum of hydrogen and even atoms with multiple electrons. His research is part of the broader momentum in atomic physics building since the start of the 20th century. Heisenberg exchanges intensely with Wolfgang Pauli and Niels Bohr, even sending his manuscript to Bohr for feedback before submitting it for publication at the end of July 1925. That article, Umdeutung ("reinterpretation"), would soon be followed by two more, co-authored with Bohr and Jordan. His work, along with that of other pioneers, marked the beginning of the quantum revolution, a profound intellectual, scientific, and technological upheaval.

2025. The International Year of Quantum Science and Technology, declared by UNESCO, is a unique opportunity to look back on a century of extraordinary progress. Over the past ten decades, one of the most remarkable scientific adventures has unfolded, filled with passionate debates, controversies, and brilliant insights.

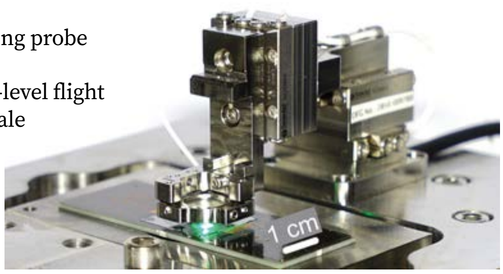
It was in Europe that the foundations of quantum mechanics were laid, and Europe has continued to carry that legacy forward. Thanks to the dedication of leading scientists who have worked closely with policymakers, ambitious programs have emerged to sustain and expand this long-standing tradition of excellence. Today, quantum science and technology are part of many academic programs; they are shaping a wide range of fields, from communications and computing to imaging and sensing. They are driving innovation and enabling the creation of cutting-edge companies poised to transform entire sectors. And they are also reaching a broad audience, sparking curiosity, inspiring new generations, and making science more appealing.

From the intense exchanges among early pioneers and the solitary reflections on a wind-swept island, to today's broad engagement, strong momentum, and groundbreaking technologies, quantum science has linked the rigor of theory with the imagination of society and is now shaping both our present and our future.

This issue is dedicated to all those who helped spark the rise of quantum science and technology, and to all who continue to advance the technologies of light with dedication and vision.

Table of contents

www.photoniques.com N° 131



Advertisers

SFO/EOS forewords

FRANÇOIS SALIN
President of the French Optical Society

More than ever, light and science for everyone!

One of our noblest missions is to promote access to scientific culture and education, but it demands deep commitment, time, and a sense of selflessness. The only reward one can expect is the appreciation reflected in attentive gazes, and the inner satisfaction of knowing that we are doing something worthwhile.
We have already mentioned the adventure of the LightBox Kit, a project launched in partnership between our Education Commission and the Atout Sciences association. Today, let us focus on our Commission Physics/Optics Without Borders, a joint initiative with the French Physical Society. Our primary goal, is to initiate awareness and to develop training actions in photonics, based on frugal technologies, in regions where access to scientific practices may be hindered by the lack of available resources.
Our commission's success stories abound, some come from the recycling of obsolete CD components, while others involve educational microscopes costing just a few dozen euros. There are also light sources made from small photovoltaic cells and recycled plastic bottles filled with water. Many training workshops have been organized as well, such as the International Training in Solar Photovoltaics launched in 2023 within the framework of the International Year of Basic Sciences for Sustainable Development, and still ongoing (Togo, Madagascar, Niger, Côte d'Ivoire, Mauritius, Guinea,...). Additional initiatives are taking place in Peru, Chile, and Mexico.
We take this opportunity to acknowledge the exceptional work and dedication of our colleague François Piuzzi, the outgoing president of the Commission. From our congress to the farthest reaches, he is a tireless advocate for the dissemination of knowledge. We also wish to warmly welcome our colleague Pierre Richard Dahoo, the new president of the commission.
Science knows no border, provided we remain vigilant and actively promote it, especially in these difficult times.

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

EMILIANO DESCROVI
President of the European Optical Society

From the EOSphere

The European Optical Society (EOS) continues to stand at the forefront of the optics community, not only as a premier platform for scientific exchange but also as a driver of scientific collaboration, education and innovation. Along this line, EOS proudly returns to the World of Photonics this June with the Early Stage Researchers Sessions, in collaboration with CLEO®/Europe-EQEC. In parallel, EOS reaffirms its commitment to inclusion through the prestigious Early Career Women in Photonics Award.
In 2024, EOS joined the 360 CARLA European consortium, a forward-looking initiative aimed at equipping students with the skills, mentorship, and practical experience needed to thrive in the photonics industry. As part of this effort, EOS will organize a Career Symposium & Training in Grenoble in March 2026—stay tuned!
The EOS Annual Meeting (EOSAM) is taking place in Delft, The Netherlands next August 24th-28th 2025. Under the leadership of general chairs Stefan Witte and Omar El Gawhary and supported by Elina Koistinen, Ignacio Moreno and myself as program chairs, the event promises a rich scientific experience, with world-class plenary speakers including Pablo Artal, Natalie Picqué, Clara Saraceno, Monika Ritsch-Marte, and Xu Liu and Yoshimasa Kawata as guests from China and Japan. Tutorials will be provided on a wide portfolio of topics, including Photonics for AI (S. Gigan), Colorimetry (J. Muschaweck), Spatial Light Modulators (I. Moreno), Illumination Optics (M. Anthonissen), Scatterometry (H. Cramer), Topological Optics (S. Horsley), Metrology (J. Blakesley) and 2-photon Lithography. The program develops across 10 Topical Meetings and 4 Focused Sessions covering many subfields of optics and photonics. Extended contributions are welcome in the JEOS-RP topical issue EOSAM2025.
As an interesting novelty, a plenary session will be dedicated to present and discuss EU policies and initiatives, with contributions from Photonics21 (R. Ramponi), PhotonHub Europe (H. Thienpont), PHORTIFY (H. Ottevaere), and others to come. Looking forward to seeing you in Delft!

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

AGENDA

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

12 - 23 May 2025

Limited to 70 attendees

■ **LIDAR**
June 15-20, 2025

OHP, Observatoire de Haute Provence, France

Limited to 40 attendees

■ **JNOG Montpellier 2025**
Sète

07 - 10 July 2025

+ 200 participants expected

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

06 - 10 july 2026

+ 670 participants expected

Welcome to the International SFO Thematic School 2026

Ultrafast sources of coherent light: current research and emerging applications

22 / 27 March 2026

The Houches Physics School, Chamonix Mont Blanc Valley France

We are honored to welcome the 2023 Nobel Laureate, as a guest lecturer: Anne L'Huillier is a French-Swedish physicist and a pioneer in the field of ultrafast physics on the attosecond timescale.

PLANNED LECTURES

Sources

- Ultrashort pulse generation and propagation
- Spatio-temporal characterization: **Spencer Jolly** (Université Libre de Bruxelles)
- THz sources: **Clara Saraceno** (Bochum University)
- Ultra-High Intensity sources: **Dimitris Papadopoulos** (LULI, Palaiseau)
- AI in photonics and laser sources: **John Dudley** (FEMTO-ST, Besançon)

Applications

- High harmonic generation and attosecond science: **Anne L'Huillier** (Lund University)
- Nonlinear microscopy: **Emmanuel Beaurepaire** (LOB, Palaiseau)
- Emerging applications of frequency combs: **Nathalie Picqué** (Max Born Institute, Berlin)
- Laser-based particle acceleration: **Jérôme Faure** (LOA, Palaiseau)

The Houches School of Physics, founded in 1951 by physicist Cécile DeWitt-Morette, offers high-quality education in contemporary physics in an idyllic setting designed to foster reflection. Beyond formal classes, informal idea exchanges during meals or mountain hikes have given birth to new avenues of exploration, fruitful collaborations, and significant scientific advancements. Some young students of the School have become illustrious scientists, such as Pierre Gilles DeGennes, Claude Cohen-Tannoudji, and Françoise Combe, passing on their knowledge to the School's students in turn. The SFO, the French Society of Optics, continues this tradition and invites you to participate in the "ULTRAFAST" school. Joining this school offers a unique opportunity to learn, share, and connect with top leaders in the field of Source fundamentals and current developments and applications.

The workshop is devoted to bringing prominent scientists in ultrafast and nonlinear optics together with the goal of, starting from fundamentals, providing overviews of recent research work, covering emerging applications, and devising future directions in the field. It aims at giving to PhD students and post-doctoral researchers a broad coverage, from pulse generation and manipulation to characterization, from the THz domain to the XUV, and describe applications spanning from time-resolved spectroscopy to secondary sources of light and particles. The workshop is motivated by the current blooming of ultrafast sources and applications, triggered by the wide availability of robust and high power femtosecond lasers, and the rapid development of methods to convert them into sources with a wide range of parameters in terms of pulsewidth, central wavelength, or control over the electric field. It will be a unique opportunity to get a unified vision of this research area, and contribute to developing new collaborations and cross-fertilizing the sources and applications communities.

Scientific committee

- **Aurélie Jullien** (CNRS - INPHYNI - Université Côte d'Azur, France)
- **Marc Hanna** (CNRS - IOGS - Université Paris-Saclay, France)

Join these experts and take part in this unmissable SFO thematic school on Ultrafast Sources of Coherent Light.

We expect 70 participants from over 20 countries.

Application (short motivation letter + CV) starts on April 29, 2025.

www.sfoptique.fr

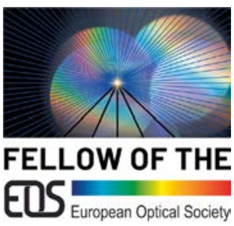
Join Us at EOSAM 2025
Delft, August 24-28

EOSAM is attended by around 500 attendees each year, including top researchers, key leaders, students, and industry experts from over 30 different countries all over the world.
This is the perfect opportunity to connect, catch up, and network alongside the intriguing conference program. Join and explore the latest topics and emerging trends featured at EOSAM. Register with an Early Bird Fee by 12 June 2025! We look forward to seeing you in Delft!
More info: eosam.org

EOS SUPPORTING
EARLY CAREER PROFESSIONALS

Inclusion is essential for innovation and discovery. EOS organizes Early Stage Researcher Sessions at its annual meeting, EOSAM, and also at the World of Photonics (WoP) Congress in June, in collaboration with CLEO®/Europe-EQEC. In these oral sessions, the early-stage researchers have a chance to pitch their research to the conference audience.
EOS celebrates the Early Career Women in Photonics with an award to honor a female scientist who has made outstanding contributions to photonics, acknowledging both her research excellence and dedication to advancing the field. The award consists of a diploma and an honorarium of €2500 and will be presented during a plenary session at the 2025 CLEO®/Europe-EQEC conference in Munich, Germany. In addition to these actions, EOS is part of a mentoring initiative for newcomers to the WoP conference.
More info: europeanoptics.org

Nominate an EOS Fellow by 15 May 2025!



The category of EOS Fellow may be conferred upon distinguished members of the society. It is one of the highest categories of membership of the EOS. Any member of the EOS may nominate a Fellow.
Fellows will be published and honored with a diploma at the Fellow Ceremony during the next international conference of the European Optical Society, EOSAM.
More info: europeanoptics.org

Optics and Photonics Days Finland 2025

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

Photonics Prague 2025

The 9th International Conference on Photonics, Devices and Systems will be held from June 9 to 11, 2025 in Prague, Czech Republic.

DGaO 126th Annual Meeting in Germany

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

LiM 2025
Lasers in Manufacturing Conference

Bi-Annual Meeting of the German Scientific Society for Lasers and Photonics (WLT) – Part of the World of Photonics Congress, June 23–26, Munich, Germany with an industrial exhibition.

PLASMONICA 2025

The 11th edition of the Workshop on Plasmonics, Nano-Optics, and its Applications will be held on June 25- 27, 2025 in Modena, Italy.

EOS has renewed its confidence in EDP Sciences as a publisher for its Journal, JEOS-RP. The median time from submission to online preprint publication is below 70 days. This achievement has been obtained without compromising the reviewing process while keeping very low Article Publication Charges. Discover more: https://jeos.edpsciences.org/.

170

It is the number of enthusiastic, inquisitive high-school girls who took part in the 5th “High School Students and Women Scientists Meetings”. Over an afternoon, they had the opportunity to talk with women researchers, students, engineers, entrepreneurs... and to visit photonics experiments from the Laboratoire Charles Fabry (Institut d’Optique / Université Paris-Saclay / CNRS) and the LEnsE (Laboratory for Experimental Teaching). Let's hope they'll remember the day brightly.

AGENDA

- **Institut d’Optique booth at SPRING Paris-Saclay (Palaiseau)**
  May 20th 2025
- **Institut d’Optique/ Naquidis booth at World of Quantum (Munich)**
  June 23- 27th
- **“Quantum Day in Nouvelle-Aquitaine” at Institut d’Optique d’Aquitaine (Talence)**
  July 4th
- **“French Photonics Days” at 503 (Orsay)**
  November 6-7th
- **“Forum de la Photonique” at 503 (Orsay)**
  November 13th

CONTACT

Clémentine Bouyé,
Head of communication
clementine.bouye @institutoptique.fr

Institut d'Optique launches its "Partenariat École" to bring together training and industry in photonics and quantum technologies

Institut d'Optique Graduate School has officially launched its Partenariat École. The aim of this initiative is to forge closer links between its engineering training programs and key companies in the photonics and quantum sectors.

A bridge between students and industry leaders: a win-win commitment

The aim of the Partenariat École is to create a more direct bridge between Institut d'Optique engineering students and leading photonics and quantum companies. By setting up privileged exchanges, this program aims to provide students with a better vision of the diversity of job opportunities and professions, while enabling companies to better identify the aspirations of future talents in the field.

By joining the Partenariat École, companies gain access to a series of exclusive advantages enabling them to raise their profile with the next generation of engineers:

- Direct meetings with students through site visits or the organization of themed conferences and round tables.
- Targeted distribution of internship, work-study and job offers.
- Participation in the development of training to better meet the needs of the sector.
- Invitations to key events in the curriculum, encouraging concrete exchanges with tomorrow's talent.

Starting with 7 leading partners

The inauguration of the Partenariat Ecole took place on April 10 on the campus of the Institut d'Optique in Palaiseau, in the presence of the first seven members: Exail, Thales, Pasqal, CEA DAM, Imagine Optic, Essilor and STMicroelectronics.

During the morning session, the companies were able to engage in an initial informal dialogue with the students, who turned out in large numbers to meet these key players in photonics and quantum technology.

A call to industry players

Institut d'Optique invites companies in the photonics, optics and quantum technologies sectors to join in this dynamic. By committing to this partnership, they will be actively contributing to the training of highly qualified engineers.

Successful close for the European NewSkin project

Launched in April 2020, the European NewSkin project came to a successful close in December 2024.

Coordinated by ECCS (European Convention for Constructional Steelwork), the project focused on surface and membrane nanotechnologies. NewSkin was an Open Innovation Test Bed (OITB) that provided easy access to physical facilities and services for the development, validation and commercialization of new nanotechnology products.

Its portfolio of services included 10 facilities for surface treatment (laser treatment and texturing, CVD, PVD, Sol-Gel, etc.), 9 facilities for testing treatments under real-life conditions (climatic chamber, off-shore platform, etc.) and services to support the commercialization of nanotechnology products.

As one of 34 partners, ALPHA-RLH oversaw dissemination and communication activities, organization of open calls for projects and management of the NewSkin online platform.

4 calls for projects were successively launched throughout the project to provide free services to companies and laboratories. 68 innovation projects were funded, 10 of them carried out by ALPHA-RLH members.

FRENCH PHOTONICS AT PHOTONICS WEST 2025

French photonics was well represented at Photonics West, the world's premier lasers, biomedical optics, biophotonics technologies and quantum optoelectronics event, which took place in San Francisco from January 28 to 30, 2025.

With the support of the Nouvelle-Aquitaine Region, ALPHA-RLH fosters the internationalization of companies to promote the regional innovations. The cluster was present alongside its members. ALPhANOV, AUREA Technology, BLOOM Lasers, GLOphotonics, Photonics Bretagne and SEDI-ATI Fibres Optiques exhibited in the French Pavilion organized by Business France, and other members on their own booth.

The Naquidis Center, dedicated to quantum technologies, also took part in the exhibition.

Florian Cardinaux, Consul General of France in San Francisco, was able to discover during his visit their expertise and their technologies around photonics, laser, optical fibers, sensors...

Quantum Day #2 in Bordeaux

Following the success of the 2023 edition in the presence of Alain Aspect, Nobel Prize in Physics 2022, "Quantum Day in Nouvelle-Aquitaine" returns for a second edition in Bordeaux on July 4th through the Naquidis Center. This innovation center dedicated to quantum technologies aims to develop research projects, innovative applications and cutting-edge technological solutions around three themes: sensors, communication and supply chain.

Launched in 2021 by the Institut d'Optique Graduate School, the universities of Bordeaux and Limoges, the CNRS, the Nouvelle-Aquitaine Region and the ALPHA-RLH cluster, it brings together internationally renowned scientists.

This event will allow to exchange ideas with leading industrial and academic experts, discover the progress of joint projects between industry and research initiated since 2022 in Limoges and Bordeaux and explore new trends and opportunities in the quantum field.

UPCOMING INTERNATIONAL EVENTS

- **Paris Air Show**
  June 16-22 in Paris-Le Bourget (France)
- **Laser World of Photonics**
  June 27-30 in Munich (Germany)
- **2nd International Photonics Talent Summer School**
  July 15-18 in Bordeaux (France)

>> Find out all events on www.alpha-rlh.com

News in Brief

- **Annual Nanophotonics de NANO-PHOT** with Sasha Govorov (Ohio University), 6 February at UTT. https://nano-phot.utt.fr/news/international-workshop-in-nanophotonics-utt

- **The Institute of Photonics** of which UTT is a member, opened its Website: https://institut-photonique.fr/a-propos/les-fondateurs/

- In January 2025, **UTT has been awarded the Sustainable Development and Social Responsibility** (DD&RS: Développement Durable et Responsabilité Sociétale) national label for a period of four years. https://www.utt.fr/actualites/luniversite-de-technologie-de-troyes-obtient-la-labellisation-developpement-durable-et-responsabilite-societale-ddrs.

AGENDA

- **SPP conference**
  19-23 mai, Tokyo
  https://spp11.tokyo/

- **General conference of the French Physic SFP, three Nobel Prizes will attend !**
  30 June-4 july at Troyes
  https://cgsfp2025.sciencesconf.org/

- **Conference META 2025,**
  22-25 juillet, Malaga
  https://metaconferences.org/META25/index.php/META/index

- **SPIE Optics conference + Photonics Exhibition,**
  5-7 August 2025, San Diego
  https://spie.org/conferences-and-exhibitions/optics-and-photonics/exhibition

CONTACT

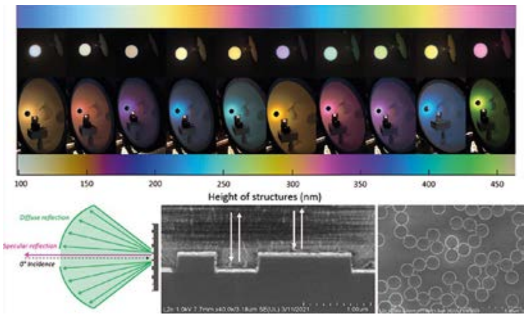
https://nano-phot.utt.fr/
nanophot@utt.fr

FOCUS ONTO A NANO-PHOT INDUSTRIAL CLOSE PARTNER:

In-Fine: 10 years of innovation in structural colours applied to visual security and more

Since 2015, the University of Technology of Troyes, via the Light nanomaterials and nanotechnology laboratory, has worked together with the SURYS company (now IN Groupe) through a joint laboratory called In-Fine. The Innovation Center for Industrial Nanostructured Foils aims at developing innovative optical identification devices by combining two industrial and academic complementary knowhows in large scale structuring (roll-to-roll technology) and nanophotonics. Initially supported by the ANR through the starting and consolidation labcom inititatives, the R&D activity based on an initial 8 years roadmap has been organized in 6 research programs such as PLASMOGRAMTM renamed Metasurfaces, Hybrids renamed Multiscale and as for the diversification aspect a sensing and energy oriented program.

In 10 years more than 15 R&D projects have been conducted. 15 people have been regularly involved (8 FTE). NANO-PHOT students are strongly involved, 5 PhD have been conducted together with more than 16 master internships and 2 postdoctotral studies. 3 technologies have been already implemented. These include the PLASMOGRAMTM Reverso technology, the patented ETMF (enhanced transmissive metallic foils) technology and a recently developed technology aiming for specular and diffuse reflectance control (cf. figure below).



Example of an In-Fine studied technology for diffuse and specular reflectance control and tuning (Y. Billet *et al.* Advanced Optical Materials **12** (15) 2302165 (2024)

The take-home message for this successful industrial academic initiative lies in 4 words, meeting, common interest, precise frame of collaboration and confidence.

As for the coming five years security and diversification remain the main target with a more global industrial and societal scope that includes the creation of a physical platform for pilot production and collaborative R&D activities with UTT and IN Groupe partners without neglecting the sustainability of the developed process and technologies.

THE GRADUATE SCHOOL NANO-PHOT IN FIGURES (PERIOD MAY 2020-MARCH 2025)

- **2** Universities, **6** laboratories
- **4** doctoral schools
- **1200 m²** platform of technology including **700 m²** clean room
- **100 m²** pedagogical clean room
- **140** books in a dedicated library
- **17** courses 100% taught in English
- **3.35 M€** initial budget + **8.62 M€** external funding
- **245 k€** of investment for training
- **29** mobility grants + **12** research grants awarded to master students
- **92%** employment rate after master with an average annual salary of **39.5k€** (UTT's data)
- **21** close academic partners, 9 close industrial partners
- **73** signed agreements with foreign universities
- **104** trained M1 master students + **112** trained M2 master students
- **40** involved faculty members
- **29** "NANO-PHOT-labeled" PhD students, including **16** who are **50%** co-funded by the Graduated School
- **35%** women
- **48%** students from foreign universities
- **82** scientific publications citing NANO-PHOT
- **167** research projects carried out by master students
- **10** PhD student prizes
- **67** completed NANO-PHOT 6-month master internships
- **8** sponsored conferences
- **3** summer schools organized
- **4** "nanophotonics" international workshops organized

NEW MEMBERS

Welcome to our new members:

Institut Photonique brings together over 300 photonics researchers and students committed to promoting technology transfer and attracting new talent.

Institut Photovoltaïque d'Île-de-France (IPFV) is a global collaborative research platform specialized in advanced materials and solar photovoltaic technologies.

NLOptics is an innovator in photonics, specializing in advanced surface analysis solutions for the semiconductor industry and beyond.

SIS Manufacture de Maroquinerie specialized in the development, industrialization and production of leather goods, sheathing and bracelets.

AGENDA

- **Laser World of Photonics**
  June 24-27 – München
- **PLI Conferences**
  Sept. 24-25 – Strasbourg
- **Photonics conquering space**
  October 8-9 - Bordeaux
- **French Photonics Days**
  November 6-7 - Orsay

TO CONTACT
PHOTONICS FRANCE

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

Photonics France annual meeting

Photonics France held its Annual Meeting on April 9 at Bpifrance headquarters, followed by a public conference about major photonics projects.

The members of Photonics France met on April 9 for their annual meeting at Bpifrance headquarters in Paris. The Annual General Meeting is an important event for Photonics France, enabling members to validate the actions taken by the national board.

During the afternoon, conferences presented major photonics projects and the outlook for the French industry. Numerous major projects involving photonics technologies are currently underway, led by major players in the industry and with a great potential for many photonics companies.

The projects presented included quantum photonics (IOGS), laser for fusion (Thales, GenF and Amplitude), future research programs (PHLAM, CNRS) and glasses (EssilorLuxottica).

THIERRY GEORGES
INTERVIEWED AT GLOBAL INDUSTRIE 2025

Thierry Georges, President of Photonics France, attended at the Global Industrie exhibition in Lyon last March 11. He was interviewed to present the French photonics sector.

Global Industrie is a major event for the industry players of today and tomorrow with 45,000 visitors. The 2025 edition took place from March 11 to 14, 2025 at Eurexpo Lyon.

Thierry Georges, President of Photonics France, was on hand on March 11 to meet members exhibiting their technologies.

During a public interview, Thierry Georges presented the advantages of photonics for tomorrow's industry: “Photonics know-how is very strong in France. We have the best laboratories, excellent training, French Nobel Prize in photonics every 2 years, and discoveries rapidly turned into production in industry.”

Watch the full interview on the Photonics France YouTube channel.

Blue Event Sea & Photonics:

Photonic Technologies Applied to the Maritime Sector

Seventy-five professionals gathered in Lannion to explore the potential of photonic technologies in the maritime sector. Co-organised by the Pôle Mer Bretagne Atlantique, Photonics Bretagne and Technopole Anticipa, the Blue Event Sea & Photonics highlighted innovative solutions to the challenges of sovereignty, ecological transition and maritime surveillance. The programme included conferences, round tables and technical presentations by industry experts such as Thales, Safran, Naval Group, Oxxius, Cailabs and many others. Three main themes structured the discussions: Communication, surveillance and navigation. In addition, an exclusive visit to the Exail site gave an insight into the manufacture of optical fibres and inertial units. Rich discussions and networking throughout the day confirmed the key role of photonics in the future of the maritime industry, and opened the way to new collaborations.

PhotonQBoost:

A Lever for the Competitiveness of European SMEs

Late February, Photonics Bretagne took part in the first meeting of the Horizon Europe PhotonQBoost project in Porto. The consortium is made up of 12 organisations from 9 European countries, including 7 photonics clusters: Photonics Bretagne (France), Photonics B.W. (Germany), Photonics Austria, Photonics Finland, TOOLAS (Lithuania), PPTF (Poland) and COC (Czech Republic). For a day and a half, the project partners exchanged ideas to define initial actions and to align on key strategies. Launched in December 2024, PhotonQBoost helps SMEs take advantage of photonic and quantum innovations to improve their sustainability, efficiency and resilience. By facilitating access to these cutting-edge technologies, the project aims to strengthen the competitiveness of European companies on the global market. With €3.6 million earmarked for direct funding of SMEs over four years, PhotonQBoost will launch calls for projects and provide specialised services to develop solutions tailored to current challenges, particularly those linked to the European Green Deal. More information coming soon.

Your contact:

Gwenaëlle LEFEUVRE | Network Coordinator | glefeuvre@photonics-bretagne.com

ENCOURAGING YOUNG GIRLS

TO ENTER SCIENTIFIC CAREERS

Photonics Bretagne took part in the second edition of the Girls & Science Day, an initiative by the CMQe Numérique, Photonique & Cybersécurité, and hosted at the ENSSAT engineering school. Sixty 14-year-old girls explored careers in science—particularly in photonics—through inspiring talks and interactive workshops. Two Photonics Bretagne work-study students shared their experiences, highlighting the diversity of opportunities in the field. In the afternoon, the pupils experimented science in a fun way: laser guitar, holography, light box... Such initiatives help break down stereotypes and encourages young girls to pursue scientific and technical careers. A strong step toward gender equality in STEM!

Photonics PhD Days in Lannion:

Registration is Open!

Co-organised by Photonics Bretagne, Anticipa, ENSSAT, and Foton Institute, the Photonics PhD Days are a unique 3-day, English-speaking event. It aims to bring together French and foreign PhD students, research centres and companies in the field of photonics, to discuss entrepreneurship and careers. The programme is centred around our signature “PhD to Start-Up” workshop, and includes conferences, PhD pitches, posters, one-to-one meetings with company directors, networking, and visits to local companies and research centres.

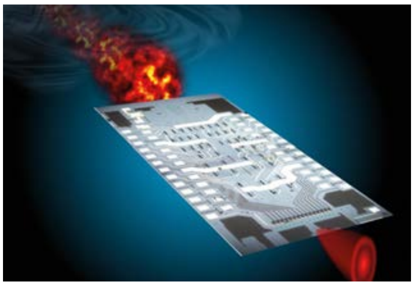
Are you a doctoral student? Come and present your thesis, find out about the latest scientific research in photonics, and take part in the workshop to reveal your entrepreneurial potential (more than eight hours over two days)! All in a friendly atmosphere overlooking the sea (Perros-Guirec, Brittany). Don't miss this event! Registration is now open: https://www.photonics-bretagne.com/en/agenda/photonics-phd-days-2025/

AGENDA

- **Laser World of Photonics**
  24-27 June, Munich (Germany)
- **Photonics Bretagne Annual General Meeting**
  1 July, Lannion (France)
- **ITQW 2025 – Infrared and Terahertz Quantum Workshop**
  1-5 September, Saint-Malo (France)
- **Photonics PhD Days**
  24-26 September, Lannion (France)
- **ECOC**
  28 September – 2 October, Copenhagen (Denmark)

Programmable photonic chip restores chaotic signals degraded by turbulence, enabling robust, secure free-space optical links

The increasing demand for secure, high-capacity, and low-latency wireless communication systems has brought renewed attention to free-space optical (FSO) links, especially for line-of-sight applications.
However, ensuring secure and reliable data transmission over FSO channels remains a major challenge due to their susceptibility to atmospheric turbulence, which induces beam scintillation, wandering, and random fading. In this context, chaos-based optical communication has emerged as a promising physical-layer security technique, leveraging the broadband, aperiodic, and highly sensitive nature of chaotic signals to encode information with high entropy and low predictability.

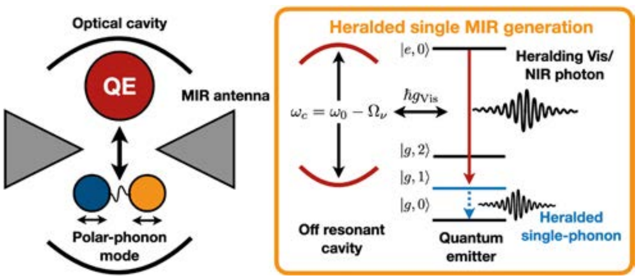


In this work, researchers present the first direct experimental evidence of the degradation of chaotic optical signals caused by atmospheric turbulence, and demonstrate a silicon photonic solution capable of fully recovering their complexity in real time. The turbulent environment is emulated using a spatial light modulator programmed with phase screens derived from the Modified Von Kármán Spectrum. To restore the chaotic signal, they utilize a self-adaptive multi-aperture receiver comprising a two-dimensional array of grating couplers and a programmable optical processor (POP) based on a mesh of Mach–Zehnder interferometers. The POP autonomously compensates for phase distortions by means of real-time local feedback loops, enabling coherent recombination of spatially distorted wavefronts.

REFERENCE
Zaminga, S., Martinez, A., Huang, H. *et al.* Optical chaotic signal recovery in turbulent environments using a programmable optical processor. Light Sci. Appl. **14**, 131 (2025). https://doi.org/10.1038/s41377-025-01784-3

SINGLE PHOTON SOURCE IN THE MID-INFRARED (MIR) RANGE

Single photons are essential for quantum metrology and precision spectroscopy, where they significantly enhance measurement accuracy. While most existing single-photon sources (SPEs) operate in the visible and near-infrared ranges, their efficiency declines significantly in the MIR and terahertz domains. Advancing MIR single-photon sources could enable groundbreaking applications, such as non-invasive biological imaging, pollutant detection in biological fluids, and in-depth studies of molecular vibrations.
In the study, researchers at the Max Planck Institute for the Structure and Dynamics of Matter (MPSD) in collaboration with DTU Electro, the University of Sheffield and the University of Copenhage developed a technique that leverages the coupling between visible-frequency single-photon sources and phonons—vibrational modes of a material's crystal lattice—to generate single MIR photons. The process enhances specific optical transitions, first preparing a phonon mode in a quantum state before converting it into a single MIR photon via a specially designed antenna. This method not only enables on-demand single-photon generation but is also adaptable to a wide range of quantum emitters, including two-dimensional materials, nanocrystals, and molecular systems.
The results pave the way for further exploration of cavity-engineered solid-state materials and the expansion of quantum electrodynamics (QED) in the MIR regime.



REFERENCE
J. Iles-Smith, M. K. Svendsen, A. Rubio, M. Wubs and N. Stenger, On-demand heralded MIR single-photon source using a cascaded quantum system. Science Advances **11**, eadr9239 (2025). https://doi.org/10.1126/sciadv.adr9239


CONGRÈS DE LA SFO
Société Française d'Optique
06/10 juillet 2026
OPTIQUE
SAVE THE DATE
BOURGOGNE / FRANCHE COMTÉ
VENEZ À DIJON
2026
www.sfoptique.org


© Frédérique Plas, CNRS Images

Interview with Eleni Diamanti

CNRS Research Director at LIP6 Paris, the Computer Science Laboratory of Sorbonne University, and specialist of Quantum Optics, QKD and Quantum Networks, co-founder of Welinq.

https://doi.org/10.1051/photon/202513115

What first sparked your interest in science?

I come from a family where discussions about science were common at home, both my parents were physicists, my mother a university professor and my father a high school teacher in physics, chemistry, and astronomy. He had a true passion for all branches of science, and we were surrounded by scientific books. Today, in turn, I try to pass on this enthusiasm for science to my children and to the students I meet.

How did you discover quantum optics?

I pursued my studies in Greece. After high school, I was admitted to the National Technical University of Athens, in the Electrical and Computer Engineering department, with a demanding five-year curriculum. It was a highly engineering-oriented program with a strong scientific approach. It was during my studies in Athens that I became interested in quantum physics and its applications, including in optics, particularly through a course in this field. When I arrived at Stanford in 2000, I was in the Electrical Engineering department but I already knew I wanted to focus on this domain. I chose my PhD thesis accordingly. My PhD advisor, Professor Yoshihisa Yamamoto, had just introduced quantum cryptography to his research group and at that time, it was still an emerging topic. As my first assignment, he gave me a paper on quantum computing with photonic systems, which was far from quantum cryptography. His question was: Is quantum computing with photons feasible? After careful thought and analysis, we concluded that it was not realistic within the scope of a PhD—a conclusion that turned out to be correct, as even 25 years later, despite major advances, photonic quantum computing still faces many challenges. So, we redirected the research topic to quantum cryptography and quantum communication, which were also still in their early stages at that time.

Did you receive any specific training in quantum optics before your PhD?

Not really. I had taken a few lab courses in optics at the university, but looking back, I realize how valuable the trust placed in me was. I was assigned an experimental PhD even though I had not been formally trained in the field in depth. A senior PhD student trained me during my first few months. Comparing this to today's students, I notice they arrive with a much stronger background, which is clearly very helpful for the teams and also for the students. In general, nowadays, young researchers tend to be more experienced than I was at the time.

What was the topic of your PhD thesis?

My PhD focused on the implementation and security analysis of a quantum cryptography protocol, which we were developing in collaboration with Japanese colleagues. I had to design a quantum cryptography system from scratch. I started with an empty optical table, gradually building up the necessary components. Another key part of my thesis was designing single-photon detectors, based on frequency conversion in nonlinear waveguides, which were fabricated by collaborators in another research group at Stanford. The outcome of my work was the development of these up-conversion single-photon detectors, along with the security analysis and the demonstration of secret key generation using a quantum cryptography system. I defended my PhD in 2006.

How did you organize your return to Europe?

In 2006, I returned to Europe, thanks to a double Marie Curie MSCA fellowship. At the time, it was possible to obtain two types of grants simultaneously: a returning European fellowship, allowing a European citizen to return from abroad and work in another European country, and a second grant to finance scientific projects for postdoctoral scholars. This was a perfect fit for my situation since I was Greek and applying to a position in Philippe Grangier's group at the Institut d'Optique (IOGS) in France. The first grant covered my salary, and the second funded my research project. This created ideal conditions for my return to Europe. I didn't even consider other opportunities in the US—it was Europe or nothing.

Can you describe your MSCA research project?

The project was focused on quantum cryptography, but approached through a different type of protocol called continuous-variable quantum key distribution (CV-QKD). This protocol still relies on quantum optics but is conceptually quite different. When I arrived as a postdoc, the main challenge was making these systems deployable in real-world applications. Philippe Grangier was among the leaders in a European project aimed at developing such systems. I contributed to creating CV-QKD prototypes, with the goal of deploying and operating them in real-world settings. This experience allowed me not only to learn new concepts on continuous variables but also to get hands-on experience with practical aspects of quantum communication infrastructures. These are topics I continue working on today, in various contexts. Looking back, I see a clear continuity in my research journey.

How did you manage the transition between your MSCA grant and your permanent position?
I stayed for a little over two years at Institut d'Optique. During my second year, I got a permanent CNRS position. I could have started in the fall of 2008, but I decided to finish my experiments before beginning my new position, which postponed my arrival at CNRS to January 2009.

What did you start your own research activities?
I was recruited to work at the Laboratory for Information Processing and Communication at Télécom Paris (I have now moved; since 2016 I am at the LIP6, the Computer Science Laboratory of Sorbonne University). I spent the first two years securing funding to establish an experimental research activity in this field. Philippe Grangier was incredibly supportive during this phase, notably by lending me equipment to continue my work in CV-QKD. This support allowed me to get started. At the same time, I spent a lot of time applying for additional funding for new projects. This included the successful application for a Franco-Canadian collaboration funded by the French National Research Agency (ANR) I was very happy about.

What were your main research activities during these years?
The most impactful results before 2015 were undoubtedly our demonstration that our continuous-variable QKD system could operate over long distances. At that time, funding was still relatively modest, but this demonstration brought great visibility to our team. That was when I started gaining international recognition for my expertise in QKD, and it also encouraged other teams to enter this field, contributing for example later to building a European Quantum Flagship project around this topic.
At the same time, I began developing a new research direction at the intersection of physics and computer science. I was already interested in this approach back then: taking quantum cryptography protocols beyond QKD, which were mostly theoretical at the time, and demonstrating their practical relevance using photonic systems. These efforts strengthened my collaborations with computer scientists, who appreciated that a physicist was engaging with their work and seeking to experimentally validate the quantum advantage of their protocols. This opened two parallel lines of research for me at that point.

The years 2016–2018 were a turning point for your research funding.
Yes, 2016 was a pivotal year with the launch of the European Quantum Technologies Flagship. I was immediately very involved in this initiative. Then, in 2018, I secured an ERC project, which allowed me to launch new research activities that took several years to come to fruition. The COVID crisis slowed progress, particularly on the experimental side, but now, five or six years later, we are seeing the full results.
Thanks to this funding and the support of talented PhD students, within the stimulating environment of our Quantum Information group at LIP6, we were able to conduct ambitious experiments, particularly on the generation of multipartite entangled states—a topic that had long interested me. This led to major advances in demonstrating quantum advantage, applied to cryptographic protocols and advanced quantum communications.

How did you become involved in the European quantum ecosystem?
Our team's expertise was well recognized, and we were actively sought after to participate in European projects on quantum cryptography. Beyond the scientific results, this also led me to take on a more strategic role in shaping the field in Europe, particularly through participation in the management of large quantum communication projects. I now dedicate a significant part of my time to these collective and strategic activities. I strongly believe in collective intelligence and collaborative dynamics—everything we are building today should benefit the entire scientific and industrial community.

Can you describe your involvement in the European Quantum Flagship?
I was present in 2016 when the Flagship manifesto was officially announced, but my involvement came in a later phase. In 2018, I joined the working groups responsible for setting up the strategic agenda, roadmap, and structuring of the program. The creation of the Flagship was a long process that took place between 2008 and 2015. At that time, I was still in the phase of building my team and developing my own research projects. It was researchers with already well-established teams who had the opportunity to dedicate time to this structuring effort. Today, I find myself playing that role. What these researchers were doing ten years ago, I am doing now—interacting with the European Commission and contributing to strategic decisions, in particular through my role as member of the Strategic Advisory Board of the program. We are currently discussing a future Quantum Act, which is the natural evolution of the Flagship, and I am happy to contribute to these discussions.

Do you manage quantum science at a national level?
Yes, I coordinate the Paris Center for Quantum Technologies (PCQT), which brings together multiple teams from Sorbonne University, PSL University, Université Paris Cité, CNRS, and Inria, along with collaborations with other universities and research institutions in the Paris region. This center has become a major hub for quantum technologies in Paris and beyond. PCQT was initially created to bridge physics and computer science for quantum technologies, but it has since expanded to cover all aspects of the field. Today, we have strong research hubs in Saclay, Paris, and Grenoble, but other cities like Nice, Montpellier, Strasbourg, and Toulouse are also deeply involved in quantum research. The synergy between these different centers is, in my view, •••

one of the keys to the success of the national program. We are also participating in projects like Quantedu France, a national training program in quantum technologies that brings together all major universities in the country. It's truly a collective effort, and I think it's very positive to see the entire French scientific community working together on these strategic issues.

How do you organize your time between your different activities?
Today, my time is split between three major areas:
- Academic research, which remains my primary activity and something I always want to prioritize.
- Entrepreneurship, with the startup I co-founded, which requires significant involvement.
- Participation in European scientific bodies, where I help define research and innovation strategies in the quantum field.

The challenge is finding the right balance between these three aspects of my work, which isn't always easy!

How was Welinq created?
From a scientific perspective, the creation of Welinq was based on a complementary set of expertise with Julien Laurat, who is also a co-founder of the company. His team had been developing highly advanced quantum memory technology for several years, and at some point, these memories reached a level of maturity that made industrialization possible.
That's when Julien and his team approached me to propose a collaboration. My expertise in quantum system engineering and quantum networking protocols perfectly complemented their work on quantum memories. The idea was to combine these skills to bring a real industrial application to life by integrating quantum memories into quantum communication and computing infrastructures. This synergy turned out to be extremely fruitful and led to the creation of Welinq, with the ambition of equipping quantum networks and quantum data centers with real interconnection capabilities, which is fundamental for their scaling.

How did you train yourself in entrepreneurship?
After multiple discussions, we realized that this project required a strong entrepreneurial commitment. It was a completely new adventure for us—neither Julien nor I were experts in entrepreneurship. So, together with our CEO, Tom Darras, who was a former PhD student from Julien's team, who had joined this venture by then, we took training courses, and received precious support from CNRS Innovation, Sorbonne University, and BPI France, among other institutions. We officially launched Welinq in 2022. We secured significant European funding through the EIC Transition and Accelerator grants, as well as support from BPI and other programs. But beyond public funding, we had to convince private investors. We completed our first fundraising round in 2023, and we are preparing for another one soon. Today, Welinq is growing rapidly, with 28 collaborators and fast-developing technology.

Can you describe the technology developed by the company?
Our technology enables quantum processors to interconnect with each other. The quantum memories we develop play a central role in this interconnection. They ensure crucial synchronization between different elements within such a quantum data centre involving multiple quantum processors, increasing the efficiency of the operations involved in quantum communications and computing.
This same technology is also the foundation for quantum repeaters, which are essential for long-distance quantum communication networks. Thus, Welinq positions itself at the intersection of two strategic fields: interconnecting quantum processors in quantum data centers and enabling long-distance quantum networks using quantum memories as key components.

What is your technological roadmap?
We have just launched the commercialization of our first product, which is an industry-grade quantum memory. Our next step is to improve this product, particularly by working on the interfaces between different quantum processor technologies. We have established strategic partnerships with key players in several quantum processor platforms. This will help to further advance in the compatibility in terms, for instance, of bandwidth. Demonstrating multimode capacity for storing multiple qubits simultaneously, but also deploying our technology in long-distance quantum communication links will also be important milestones. The ultimate goal is to enable the emergence of a truly interconnected and operational quantum network.

What are the main objectives of your current research?
My primary objective remains to demonstrate a quantum advantage for real-world applications, particularly in quantum networks. This is becoming increasingly challenging as applied protocols themselves become more sophisticated. This also leads me to more fundamental topics, for example regarding the certification of quantum resources in quantum networks. How do we verify the quantum nature of our resources? To do this, we use concepts from quantum non-locality, a fundamental topic that, while possibly not having immediate applications, fascinates me deeply.
Moreover, through my involvement with Welinq, I am increasingly interested in distributed quantum computing. The goal is to create large-scale quantum networks, not just for long-distance quantum communication but also to build quantum data centers integrating modular quantum processors allowing for their scale up and ultimately revealing their full potential.
This is still a new field, but I find it very stimulating, and I would like to explore this interface between quantum communication and quantum computing. This represents a major scientific and technological challenge, and I hope to make a significant contribution in the coming years.

PHOTONICS – A KEY ENABLING TECHNOLOGY IN THE QUANTUM WORLD

In recent years, quantum technologies have rapidly moved from research labs into industrial applications, supported by increased public funding, venture capital, and patent activity [1].

These technologies harness quantum phenomena like entanglement, tunneling, and superposition to achieve results that surpass classical limitations. Some compelling examples include:

- Quantum computers capable of solving complex problems beyond current supercomputers.
- High-precision time measurement for synchronizing communications.
- Compact sensors that detect minute magnetic fields—replacing room-sized systems.
- Secure communications that resist eavesdropping.

At the core of these innovations is a medium that behaves in a quantized manner. In neutral atom computing, this medium consists of a collection of trapped atoms; in ion computing, it comprises trapped ions; and in certain types of atomic clocks, it is a collection of alkali atoms in vapor phase. Photonics technology plays a crucial role in interacting with and manipulating these delicate quantum media while also exhibiting quantized behavior and acting as a reliable carrier of information for networks of quantum devices. In other instances, such as in photonic quantum computing or quantum communications, individual photons themselves act as the quantized medium. In addition, photons can transfer information over long distances with minimal losses compared to electrons and they are unaffected by electromagnetic fields. Simply put, photonics is foundational to the realization of many quantum technologies.

▼ A small form vapor cell from Hamamatsu

HAMAMATSU PHOTONICS: A TRUSTED PARTNER IN QUANTUM TECHNOLOGIES

Hamamatsu Photonics has long been a trusted partner to the scientific research community, developing some of the most advanced photonic technologies available. Alongside this, the company has deep experience in high-volume production for industrial, medical, and semiconductor applications. This unique combination of precision, scale, and reliability positions Hamamatsu as an ideal photonics partner for quantum technology development.

VAPOR CELL TECHNOLOGY: A FLAGSHIP INNOVATION

One standout contribution is Hamamatsu's vapor cell technology. Known for its expertise in photomultiplier tubes (PMTs), the company has adapted its vacuum technology capabilities to manufacture vapor cells in various shapes and sizes, featuring different coatings and filled with a variety of alkali vapors and buffer gases.

These vapor cells, when integrated with light sources, detectors, optics, and electronics, become the core of quantum sensors. A notable example is Hamamatsu's optically pumped magnetometer (OPM), unveiled at Photonics West 2025 [2]. This compact sensor (under 8.5 cm^3) achieves a magnetic field sensitivity of 20 fT/√Hz, making it well-suited for biomedical functional imaging [3].

▲ OPM detection heads for MEG application

A BROADER QUANTUM PORTFOLIO

Beyond vapor cells, Hamamatsu offers a wide range of products that support quantum research and applications, including:

- Liquid Crystal on Silicon Spatial Light Modulators (LCOS SLMs)[4]
- High-speed, low-noise cameras for qubit readout[5]
- Single-frequency lasers for precise quantum state control[6]

LET'S COLLABORATE

Our engineers welcome one-on-one discussions about quantum innovations and custom solutions. To explore collaboration or learn more, reach out at info@hamamatsu.eu or visit our booth at the Laser World of Photonics this June at Messe Munich.

REFERENCES

[1] McKinsey & Company, The Quantum Technology Monitor 2024s. [Online]. Available: https://www.mckinsey.com

[2] SPIE Photonics West 2025 - Quantum West Business Summit: The Path from Startups to End Users in Commercializing Quantum Sensing Technology, SPIE. [Online]. Available: https://spie.org/photonics-west/event/quantum-west-business-summit-the-path-from-startups-to-end-users-in-commercializing-quantum-sensing-technology/7100481

[3] S. Zuo *et al.*, "Ultrasensitive Magnetoelectric Sensing System for Pico-Tesla MagnetoMyoGraphy," IEEE Transactions on Biomedical Circuits and Systems, vol. 14, no. 5, pp. 971-984, Oct. 2020, doi: 10.1109/TBCAS.2020.2998290

[4] https://lcos-slm.hamamatsu.com/eu/en/application/quantum_technology.html

[5] https://www.hamamatsu.com/eu/en/product/cameras/qcmos-cameras.html

[6] https://www.nktphotonics.com/products/single-frequency-fiber-lasers/

Interview with Carlos Lee,

Director General of EPIC, European Photonics Industry Consortium

https://doi.org/10.1051/photon/202513118

What was your professional background before joining EPIC?

I have worked for 16 years at SEMI, the global association representing semiconductor equipment and material suppliers. SEMI has been around for more than 50 years, that was my first job and where I gained significant experience in the sector working on standardization, advocacy, lobbying, and technology and executive-level events.

When did you join EPIC?

After 16 years at SEMI, I joined EPIC 13 years ago. My departure from SEMI was not due to dissatisfaction but rather an opportunity to bring the experience I had gained in a mature and well-structured industry into an emerging one. Technologically, there is significant overlap between semiconductors and photonics. If you look at a pure semiconductor chip, you need photonics to make it work. However, the key difference is that the semiconductor industry is highly consolidated, well-organized, and supported by market statistics, technology roadmaps, and industry standards—something that the photonics industry lacks. My ambition was to transfer best practices from one industry to another and contribute to the growth of photonics.

What have you learned from your experience at SEMI?

During my 16 years at SEMI, I gained valuable insights into what drives industrial success. One key takeaway is the role of industry in shaping a thriving ecosystem. While universities and research institutions are crucial for innovation, they do not necessarily translate into industrial success on their own. I have seen that having strong academic research does not automatically lead to the creation of a sustainable industry. A compelling example is the semiconductor ecosystem in Dresden. When AMD, the chip manufacturer, established a factory there in 1996, it required suppliers for equipment, materials, gases, and wafers. This led to the development of a full industrial ecosystem around it. Once such an ecosystem exists, it makes sense to have universities, training programs, and internships to support it. In other words, a strong industry attracts talents, research, and further innovation. This is why I strongly believe that industry is the true driver of technological progress. Academia is essential, but for a sector to thrive, it needs a solid industrial foundation. This perspective has shaped my approach at EPIC, where we focus on strengthening the industrial landscape for photonics.

What motivated your transition from semiconductors to photonics?

My main motivation was the frustration of seeing strategic industries disappear from Europe. The photovoltaic industry is a prime example. At one point, Germany led in solar photovoltaic energy, with most of the machines coming from German manufacturers. Europe had leading research institutions, and the market was thriving. Yet, within just a few years, the photovoltaic industry in Europe collapsed between 2010-2015. Today, there are no major solar manufacturers left in Europe. The same happened with the lighting industry—Philips was once a dominant player, but it no longer holds a leading position at a global level. To be provocative, I would even argue that Europe is not a major player in the semiconductor industry. The only reason I believe that Europe is mentioned in global discussions is because of ASML. Without it, I am not sure Europe would be considered a dominant player in semiconductors at a global level. We lost these industries not solely because of competition under fair market rules, but due to other factors. If we do not learn from these past experiences, the same could happen to photonics. That is why I joined EPIC: to help safeguard the European photonics industry before it reaches the same level of importance as those other sectors and risks being lost.

What are the challenges in building a strong photonics industry in Europe?

Both semiconductors and photonics are key enabling pervasive technologies. If the photonics industry continues to grow as we ambition, I am concerned of Europe losing competitiveness in this market unless we take proactive measures. Governments have not effectively protected previous industries in my view. They did not prevent the decline of photovoltaic or lighting, and they are too slow to react and anticipate. Additionally,

If we do not learn from these past experiences, the same could happen to photonics. That is why I joined EPIC: to help safeguard the European photonics industry before it reaches the same level of importance as those other sectors and risks being lost.

decisions made by authorities can be influenced by external political pressures. In general, regretfully, the photonics sector is too small to be *a priori*ty for public authorities. As a result, we cannot solely rely on governments to ensure the competitiveness of our industry. We need to take matters into our own hands and strengthen the industry from within.

How can photonics become more competitive?

A competitive industry operates in a continuous cycle: companies develop products, sell them, generate revenue, reinvest in R&D, improve their products, and keep innovating. This leads to job creation, further investment, and growth. Some companies get acquired, some merge, and new startups emerge, maintaining a dynamic ecosystem. This is the model of a sustainable and competitive industry. Unfortunately, this cycle did not happen in solar, lighting, or even semiconductors in Europe. Since we cannot depend on governments, my vision for a competitive European photonics industry is based on fostering strong collaboration. Europe has around 1,000 photonics companies, and 86% of EPIC members are small businesses, typically with 30 to 50 employees. The legal definition of an SME sets the threshold till 250 employees, but in photonics, a company with over 100 employees can already be considered large.

What is your strategy to increase the competitiveness of the photonics ecosystem?

My strategy is simple: these 1,000 companies need to know each other, understand what each one does, collaborate effectively, and build a strong ecosystem. We work directly with CEOs and CTOs, as they have the best overview of their companies' capabilities. Our goal is to connect these key decision-makers, fostering trust and cooperation, which will ultimately drive innovation and competitiveness in European photonics.

Can you describe some of the key initiatives launched by EPIC?

EPIC has spearheaded several impactful initiatives to support the photonics industry. Among them are:

- The Day of Photonics – an international event to raise awareness about photonics and its applications;
- The Photonics Index – a stock market index dedicated to photonics-related companies;
- The Photonics Sustainability Awards – recognizing efforts toward sustainability in the industry.

As an agile, privately funded organization operating through membership, EPIC has the ability to explore diverse activities and innovate. We experiment—if something works, we pursue it; if not, we move on. The key is always prioritizing what benefits the industry. Some organizations are reluctant to collaborate, preferring to maintain their own "kingdoms," but EPIC believes in fostering openness and innovation. For example, we have built the largest photonics employment website, with over 12,000 job listings, simply because we identified the need and took action.

What are the next steps for EPIC?

One of our primary objectives now is to engage more deeply with end-users. Over the years, EPIC has earned the trust of the photonics community and built a stable, actively engaged membership. Now, we need to extend that engagement to the integrators and end-users of photonics technology. If we want photonics to spread into more applications, we need to listen to end-users—understand their needs, challenges, and aspirations. My goal is to convince them that EPIC provides a trusted environment where they can openly share their requirements, enabling the photonics community to collaborate and develop solutions that enhance their products and manufacturing processes.

Do you make actions at a global scale?
Yes, global engagement is another focus area, particularly in an increasingly complex geopolitical landscape. We are organizing more international events, strengthening our relationships with key markets such as China, Korea, Japan, India, Singapore and broader Asia. While we already have strong ties with the US and Canada—partly due to language and established leading events—our outreach to Asia is about ensuring that European photonics companies understand these markets, their competitive landscape, and potential collaboration opportunities.

Why is it important for EPIC to connect with Asia?
Our engagement with Asia is not about expanding EPIC's membership—it's about supporting European companies that want to operate in those markets. EPIC never dictates what companies should do. Instead, we provide strategic support by building a network of trusted partners to help companies navigate new markets, understand technology trends, and explore partnerships. Whether a company chooses to engage with Asia is up to them, but if they don't, they risk missing revenue opportunities and losing awareness of the competitive landscape. Our role is to ensure they have the necessary connections and insights to make informed decisions.

Would EPIC aim at becoming a global association?
There is sometimes confusion about EPIC's global strategy. Let me be clear: EPIC will always remain a European-oriented organization. Unlike some associations that claim to be global but remain centered in one region, EPIC's primary mission is to serve European industry. In fact, 90% of our members are headquartered in Europe, with only 5% being global corporations and another 5% being non-European entities carefully selected for their added value to our network.

How is EPIC's relationship with academia?
Although EPIC is primarily an industry association, we also count research organizations and universities among our members. It is essential for academia to engage with industry to ensure that research aligns with real-world needs and industrial applications. Collaboration helps research institutions stay connected to market demands rather than working in isolation.

What message would you like to convey to public authorities?
Public authorities must recognize photonics as a key enabling technology and accurately assess its competitive landscape, future opportunities, and challenges. Policymakers often decide which industries to prioritize, but waiting until a sector is struggling before providing support is a mistake in my view. Many industries receive massive funding with questionable impact, while a modest investment in photonics—say, 1 billion euros—could have a transformative effect on Europe's competitiveness.
It is personally frustrating to see decision-makers act too late. Photonics is already strong so my message is "support us now, not when the industry is being challenged". Once a strategic industry is lost, reviving it is much harder, if not impossible. Governments need to act proactively to maintain Europe's leadership in photonics and high-tech manufacturing.

How does EPIC manage to stay so dynamic and innovative?
EPIC has always been inspired by the photonics industry itself, which is highly innovative and entrepreneurial. By spending so much time with the industry, listening to advice and guidance, we're motivated to constantly try new things and come up with new ideas. We've been fortunate to have the support of our members when we try these new ideas. For instance, during COVID, we launched the Photonics+ online platform when in-person meetings were impossible. While the platform didn't succeed, our members were supportive, and I think they appreciate that we're willing to try and sometimes fail. Some of our initiatives have been extremely successful, and others not as much, but that's part of the journey.

What would be EPIC's greatest achievements over the last 13 years?
One of the biggest achievements of EPIC is that it has become a sustainable organization. When EPIC was founded in 2003 by Tom Pearsall, it was a very small organization, with only two employees. When I joined 13 years ago, we had 80 members, and we were still not financially stable. Now, EPIC has grown to over 800 members and has a stable team of technology managers and support staff. I'm proud that we've reached a point where the organization doesn't rely on one individual anymore. If I were to leave, the COO and the 12 member team we have now could keep everything running. We've achieved financial stability, and we're guided by an experienced board of directors. It's been amazing to see the evolution of EPIC from a small startup to a stable organization with a long-term vision. I'm confident that EPIC will continue to thrive for the next 20 years.

When EPIC was founded in 2003 by Tom Pearsall, it was a very small organization, with only two employees. When I joined 13 years ago, we had 80 members, and we were still not financially stable. Now, EPIC has grown to over 800 members and has a stable team of technology managers and support staff. I'm proud that we've reached a point where the organization doesn't rely on one individual anymore.

Interview with Martynas Barkauskas

CEO of Light Conversion, a company specialized in ultrashort pulse lasers and OPAs.

https://doi.org/10.1051/photon/202513121

Can you tell us about the origins of Light Conversion?

Light Conversion traces its origins to the Laser Research Centre at Vilnius University, specifically within the Quantum Electronics Department of the Faculty of Physics. Initially known as the Quantum Electronics Department, it later evolved into the Laser Research Centre. Our company was founded within this academic setting. The formal establishment of Light Conversion was driven by a focus on developing optical parametric amplifiers (OPAs), enabling the tuning of laser wavelengths. Our specialization in femtosecond OPAs became the foundation of our product portfolio and company growth. Prior to this, the university had amassed extensive experience in laser systems, particularly through collaborations with other research institutions. These projects, often centered around spectrometers and precision optical equipment, helped cultivate a strong expertise in the field. Following the dissolution of the Soviet Union, while many sought opportunities abroad, a group of researchers chose to establish a company to retain scientific talent within Lithuania. Their primary motivation was not commercial gain but rather the preservation of expertise. This initiative materialized around 1992–1993. Our work soon attracted the interest of major laser manufacturers. One of our earliest key partners was Quantronix, a company pioneering commercial femtosecond laser systems for research. We supplied OPAs as complementary components to their laser sources, facilitating wavelength conversion. This capability directly inspired our name, Light Conversion—a reflection of our core expertise in modifying light properties.

As our OPAs gained recognition, we became the leading supplier in the field, with only a few exceptions. Today, the vast majority of femtosecond OPAs available on the market originate from us, even when sold under different brand names. By 2000, we made the strategic decision to develop our own laser sources rather than limiting ourselves to auxiliary components. Given our experience with picosecond lasers, this transition was a natural progression. We focused on high-repetition-rate systems, a project that required approximately six years to materialize. By 2005, we introduced our own laser products, and by 2008, they had begun integrating into industrial manufacturing processes. Since then, our business has expanded significantly.

How did Light Conversion expand its product offerings and grow its business after the initial success with OPAs?

While we continue to produce OPAs and custom scientific instruments, the majority of our revenue now stems from laser sources. The scientific market remains integral to our operations, but from a product perspective, laser sources have become our dominant segment. Over the years, we have also diversified into spectrometers, optical parametric chirped-pulse amplifiers (OPCPAs), and large-scale systems for high-repetition-rate terawatt applications. Some of these systems, installed on expansive 8-meter-long optical tables, serve major research institutions worldwide. Currently, our revenue exceeds $130 million, with all our products centered around femtosecond laser technologies. While we are not a billion-dollar enterprise like some of the industry's largest players, we are recognized as a leader in the ultrafast laser sector, specializing in extremely short pulse durations—positioning us in a highly specialized niche.

What have been some of the company's most significant advancements in the past five years?

Rather than a single groundbreaking innovation, our progress has been characterized by continuous refinement and iterative improvements to our products. While these advancements may not always appear revolutionary individually, their cumulative impact has been substantial. Serving the scientific community presents unique challenges. Our customers—typically university professors and research institutions—rarely require standardized systems. Instead, they demand customized solutions, making adaptability a crucial aspect of our business. A key development over the past five years has been our emergence as a major industry player. Despite operating in a specialized market, our reputation for reliability has strengthened considerably. We have grown from a $50 million company to over $100 million in revenue, significantly increasing our global presence. Additionally, we have gradually expanded into the medical sector, complementing our established presence in industrial and scientific markets.

Could you share some insights into your personal background? How did you develop an interest in physics and lasers?

My interest in physics developed early. As a freshman at Vilnius University, I enrolled in the Faculty of Physics and soon took on part-time roles at the Laser Research Centre, working on small-scale research projects. After completing my bachelor's degree, I participated in an Erasmus exchange program at Vrije Universiteit Amsterdam, home to a distinguished laser research group. My master's studies focused on laser physics, particularly high harmonic generation. I then returned to Vilnius University for my PhD, specializing in ultrafast spectroscopy and •••

pump-probe measurements. Science has always been a passion—mathematics and physics came naturally to me. At Vilnius University, laser research was one of the most prominent and successful disciplines, so when the opportunity arose to work in a laser laboratory, I seized it. Following my PhD, I initially intended to pursue a postdoctoral position but struggled to find a suitable opportunity. At that time, Light Conversion was operating within the Laser Research Centre, just across the corridor from my laboratory. I was already familiar with their technology, frequently using their devices and consulting their engineers. The company offered me a position, which I initially saw as temporary—perhaps a year before securing a postdoc role. That was in 2009, and I have remained with the company ever since.

What have been your positions at Light Conversion?

I started as an engineer, focusing on customized systems, before transitioning to the role of the company's sole laser service engineer. Over time, I took on service management responsibilities, then sales management, where I remained for several years. For the past six years, I have been leading the company. During my tenure, Light Conversion has grown from approximately 47 employees to over 650—a remarkable transformation in just 16 years.

Where are your offices located?

Our headquarters, as well as our primary manufacturing and R&D facilities, are in Vilnius, Lithuania. Additionally, we maintain sales and service offices in Bozeman, Montana (USA), Shenzhen (China), and Daejeon (South Korea). In Japan, we collaborate with distributors who also provide technical support. However, the majority of our research and development remains centralized in Vilnius.

How would you describe Light Conversion's market reach?

Given the specialized nature of our industry, we have operated on a global scale since the company's inception. Our market is not defined by geographical boundaries but rather by technical requirements. This is particularly true for the scientific sector. Even within industrial applications, femtosecond laser technology remains a niche compared to continuous-wave or nanosecond lasers. As a result, we naturally evolved into a globally oriented enterprise, serving customers across various regions. Rather than making a conscious decision to target specific markets, our international presence emerged as a necessity driven by demand. Wherever there is a concentration of advanced research institutions or high-precision manufacturing industries, we are present. Our global service centers reflect this reach—while we directly serve customers in Europe, we rely on our regional offices and distribution partners to provide localized support in other parts of the world.

How would you describe your main markets?

I would say that we are in a niche market. From the very beginning of our company, we aimed to serve the global market, whoever needs these types of devices. It's less about being market-specific and more about being specification-specific. Our focus is mainly on scientific applications, but industrial uses are growing. Femtosecond lasers are not as widespread as CW lasers or nanosecond lasers, but the demand is rising. In the industrial sector, applications tend to require high precision or minimal collateral damage, so if something can be done with a less expensive laser, people tend to opt for that. But where precision is key, we see higher adoption of femtosecond lasers. This market is highly diverse—medical applications, OLEDs, consumer electronics, automotive, and luxury products all rely on short-pulse lasers. Some of these markets are smaller, but they offer unique applications that our technology supports well. Overall, it's a broad market, with niche applications where precision and quality are paramount.

Do you sell primarily to academia or industry, or is it a mix of both?

We started with scientific research and academia, but as the company grew, we expanded into the industrial sector. Now it's about half academia and half industry.

What are the main applications of your products?

The applications are very diverse. Femtosecond lasers are more complex and expensive than longer pulse lasers, so industries typically use them where precision, minimal collateral damage, or small modifications are necessary. In medical applications, lasers are used for eye surgery and small-diameter stent cutting. In the display industry, they're used for OLEDs, and in consumer electronics, for cutting brittle materials. Automotive applications involve precision hole drilling, and luxury devices benefit from small-scale laser modifications. So it's a very diverse market, without a dominating application like the metal sheet cutting and welding that's common for CW lasers. Femtosecond lasers are often chosen for specialized applications where precision or flexibility is a significant advantage.

Lithuania has a rich history in optics and photonics. As the CEO of a major company in this field, how do you view the role of Lithuania in the global photonics ecosystem, and how do you continue to foster and support this legacy?

We have a unique ecosystem here in Lithuania. In the capital, Vilnius, photonics and laser research have a strong presence, even though Lithuania has a relatively small population of 2.8 million. Vilnius itself has around 600,000 inhabitants. We have over 2,000 employees working in photonics and laser companies here, which is impressive not only in terms of numbers but also in the variety of expertise. We have precision mechanics for optics, custom coatings, laser components, and applications for both scientific and industrial uses. It's a specialized and broad field, and this diversity is key to our success. The growth potential here is significant because many companies are focusing on niche markets like academia, which is more demanding technologically. There's still room to scale up and serve larger industrial markets.

The success of our laser companies here in Lithuania is self-propelling. Just like how basketball is the dominant sport in Lithuania, despite Europe's strong focus on football, the success of our companies and their ability to produce high-quality products has attracted more young people into the field. Physics students, especially those studying laser physics, make up a large proportion of graduates. This has helped make laser physics a popular field in Lithuania.

What makes Lithuania such a hub for photonics?

It goes back to the early days of laser research. Lithuania has been involved in laser technology since the 1960s. This early start, combined with solid scientific developments, laid the foundation for the laser industry we have today. The success of our laser companies, just like the success of Lithuanian basketball, creates a positive feedback loop—more success attracts more talent, which leads to even more success. So, while Lithuania is small, the laser sector has managed to grow significantly, and we're positioned to continue leading in this specialized field, despite having fewer resources than larger countries.

What are your growth prospects for the company ? How do you see the technologies evolving?

Our growth has been strong, and we're convinced that we've grown faster than the sector itself. Over the last decade and a half, we've increased our market share. We still see opportunities for growth, and we continue to be at the forefront of new developments. We're technology-driven and product-driven, with a strong focus on customer satisfaction. Many of our managers have experience in service, which helps ensure that we maintain strong relationships with our customers and meet their needs effectively. This customer-centric approach allows us to keep growing in a niche market.

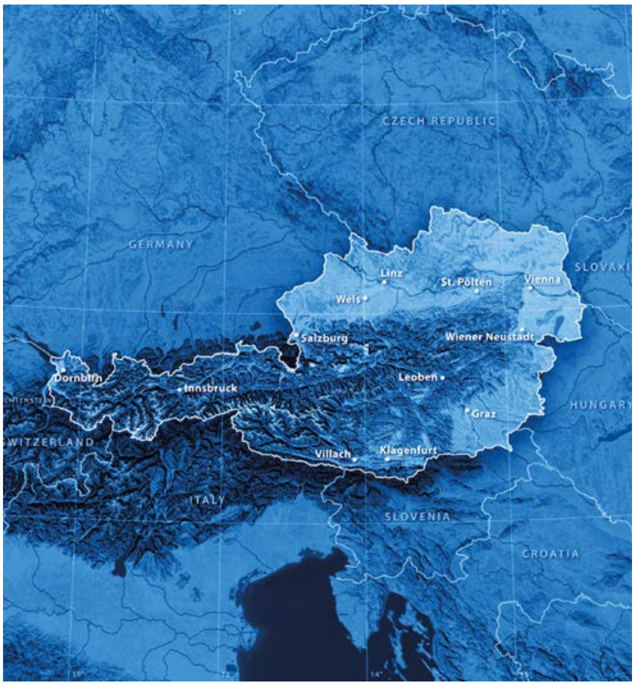
How do you view the global photonics market and its challenges?

The photonics market is huge, but it's not always visible to the public. Photonics is a key enabling technology in many industries, but the value is often captured by the application companies rather than the technology providers. Many times, the full value of photonics is not monetized by the companies that drive the technology. While it's great to enable new applications, it's important for the technology developers to be able to capture more of that value. This also means that photonics, especially in lasers, is a highly innovative and fast-moving field. Unlike industries where a single innovation can sustain a company for 20 or 30 years, here we're constantly adapting and innovating. It's fun to work in this environment, but it can also be tough, especially when technology is overlooked in favor of other aspects like financial investment. ●

Photonics in Austria

Innovation, Research, and European Leadership

Photonics, a key enabling technology, is at the heart of Austria's high-tech industrial and research landscape. From advanced optical sensors, light sources and laser technologies to Photonic integrated circuits and quantum applications, Austria has established itself as a powerhouse in the European Photonics ecosystem.



© iStockPhoto

https://doi.org/10.1051/photon/202513124

Michael WURZINGER*

Heinz Seyringer, Paul Hartmann, Photonics Austria, A-8160 Weiz, Austria

***Michael.Wurzinger@joanneum.at**

The 2024 study of the Austrian Institute of Economic Science identifies Photonics to have the highest revealed technology advantage of all key enabling technologies in Austrian (specialization in the technology based on patent applications). Austria's focus on Quantum Optics – that is underlined by two Physics Nobel prices won for Photonics research done in the country in the last years (Anton Zeilinger, 2022, and Ferenc Krausz, 2023) – can stand representative for the countries blending of cutting-edge research and the strong industrial impact realized in the country.

The History of Photonics in Austria

Austria's contributions to Photonics trace back to its deep scientific tradition in optics and physics, which has played a major role in global advancements. Some of the earliest contributions to the field date to the late 19th and early 20th centuries, when Austrian physicists such as Ernst Mach, Ludwig Boltzmann, Wolfgang Pauli and Erwin Schrödinger laid the groundwork for the understanding of light propagation, energy distribution and quantum physics. Over time, the country's strong foundation in precision optics and engineering led to the emergence of Photonics as a distinct field of research and industry.

A vital sign of the blooming landscape of Photonics was the establishment of Photonics Austria in 2013 as a non-profit association. The national technology platform was created to foster innovation, collaboration, and integration within the European Photonics landscape. It was a direct response to the growing importance of Photonics, facilitated by the Austrian ministry of technology and driven by the local Photonics industry today comprised of around 300 companies that practice Photonics R&D. This variety helped putting Austria on the map internationally: the "Advanced Technology for Industry" dashboard of the European commission placed Austria's Photonics industry on the third rank of all European countries.

Iconic Austrian Companies in the Field of Photonics

Traditionally, Austria has a very strong industry in light sources, with companies like Zumtobel, ZKW, XAL and Lumitech leading the way. Photonics manufacturing technologies are spearheaded by companies like Sony DADC or STIWA. A long tradition in Laser technology is based on established companies like Spectra Physics, TROTEC

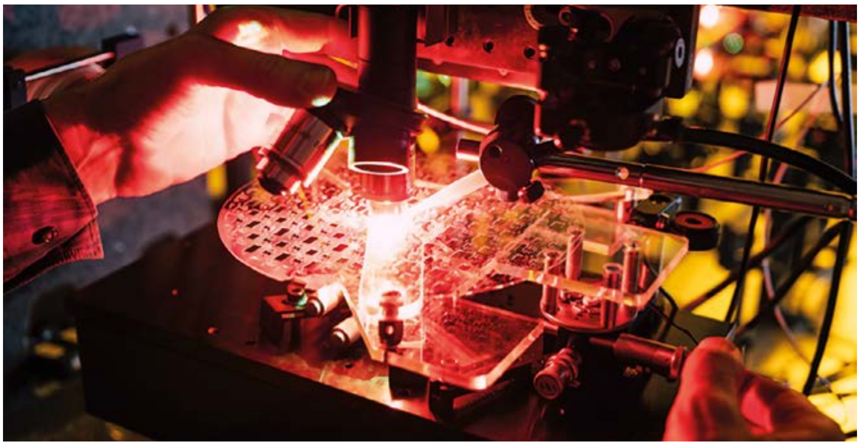


Figure 1. © JOANNEUM RESEARCH/Bergmann

or Trumpf and specialists like Montfort Lasers, nlight Plasmo, upnano or weldmetrix. The Photonics integrated circuit segment is the third pillar of the Photonics industry in Austria with companies like ams-OSRAM and Infineon Technologies at the forefront. System integrators like WILD, Swarovski Optics, In-Vision or the start-up Cerabyte play a leading role in providing optical precision products. And finally, promising start-ups in the Quantum Photonics sector, like qtlabs or Quantum Industries, are developing rapidly in the wake of established stakeholders like Infineon or Astro Systeme Austria in the race for the commercialisation of the technology.

Photonics in Austria's main Universities

Photonics is embedded in Austria's academic curricula and is a key subject in undergraduate and graduate programs in physics and electrical engineering at Austrian universities. Several universities and technical institutions offer specialized programs with a focus on photonics, including: TU Wien (integrated optics, laser physics, and quantum photonics) and TU Graz (optical communication, metrology, and silicon photonics), University of Vienna (Photonic materials science, spectroscopy, and optoelectronic applications), University of Graz, University of Linz, University of Innsbruck (quantum physics, biomedical optics), and University of Salzburg (teacher training programs), as well as Universities of Applied Sciences: FH Vorarlberg, FH Technikum Wien, and FH Burgenland.

Photonics is also integrated as a subject in many other technical degree programs across Austria.

Leading Research and Technology Organizations (RTOs)

Austria is home to several prominent non-university research institutions making significant strides in Photonics. Key players are: the Austrian Institute of Technology (AIT), JOANNEUM RESEARCH, RECENDT, Silicon Austria Labs (SAL), and V-Research.

Austrian Institute of Technology (AIT)

AIT is Austria's largest non-university research institute, known for its cutting-edge research in Photonics. AIT focuses on photonic sensing, data processing, and optical communications. Notable projects include LIDAR technology and neuromorphic hardware architectures for efficient computing and AI applications. AIT's work is crucial for advancing telecommunications, quantum optics, and sensor technology.

JOANNEUM RESEARCH

JOANNEUM RESEARCH emphasizes applied research, with its MATERIALS Institute specializing in sensors, photonics, and production technologies. The institute is involved in green photonics, developing smart, energy-efficient lighting and sensor solutions. Their research includes advanced optical systems and functionalized surfaces, contributing to industrial innovations.

RECENDT

RECENDT is the Research Center for Non-Destructive Testing, based in Linz. The internationally renowned research company develops solutions for industrial sensing and quality inspection, based on cutting edge photonic technologies. Technologies like Laser-Ultrasonics, Optical Coherence Tomography, Terahertz-sensing or various solutions in Infrared- & Raman Spectroscopy serve to solve challenging measurement and NDT-tasks in all industrial branches. The latest field of research is quantum sensing, to be made available for industry soon.

Silicon Austria Labs (SAL)

SAL develops integrated photonic systems and technologies, covering the optical spectrum from UV to mid-IR. Their applications include optical sensors, high-performance laser systems, and intelligent spectroscopic systems. SAL's interdisciplinary work combines optics, physics, and engineering to create solutions for industries like automotive, consumer electronics, and telecommunications.

V-Research

V-Research focuses on energy-efficient lighting, developing next-generation LED systems that save energy and improve functionality through Human Centric Lighting. They collaborate with European lighting manufacturers to create advanced LED drivers and systems that support health, productivity, and sustainability.

Austria's non-university research institutions are making remarkable contributions to Photonics. Through their innovative efforts, AIT, JOANNEUM RESEARCH, SAL, RECENDT and V-Research are driving advancements that have far-reaching implications for various industries, enhancing our •••

understanding of photonics and paving the way for a sustainable future.

Main Programs and Funding in Austria

The Austrian government has recognized the huge potential of the Photonics sector and supports its development through a dedicated funding program within the "Key technologies in the production-related environment". The program is endowed with a yearly budget of around 7-10 Mio. €. This dedicated budget is complemented by open programs managed by the FFG (Austrian Research Promotion Agency). In total the FFG handled a funding budget of 1,8 Bn. € in 2023, a major boost for research, with its main target being applied research including projects in Photonics and Quantum technologies. Furthermore, companies in Austria can benefit from funding by the aws the Austria Wirtschaftsservice Gesellschaft, that focuses on supporting investments that create jobs in Austria, including foreign companies. Austrian stakeholders complement the national funding by being very active and successful in European programs, especially with the focus on Photonics. In the framework program H2020 Austria managed to place fourth in the category funding per capita of photonics21 funded programs. In that respect Photonics Austria supports the European Photonics R&D as an interface between the European stakeholders and potential Austrian partners.

Photonics Research in Austria

Austria's fundamental research is supported by the FWF, the Austrian Science Fund. In Photonics the community covers a wide range of cutting-edge topics, including:

Ultrashort pulse laser, Quantum optics and quantum communication, Optoelectronics, Micro- and nano-photonics, Spectroscopic methods, Photonic measurement concepts, Detectors and sensors, Integrated optics and silicon photonics, Photonic crystals, Laser-based material processing, Optical communication technologies, Lighting and illumination technologies. Research in these areas is conducted

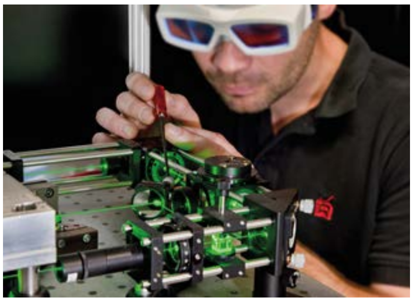


Figure 2. © RECENDT GmbH.

at an internationally competitive level. However, nearly all fields face the challenge of rising costs for experimental and technical infrastructures, which remains a significant concern for Austrian photonics research.

Photonic Austria Roadmap

The Photonics Austria Roadmap 2021-27, available on the Photonics Austria homepage, provides a comprehensive overview of Austria's research areas in Photonics and their future prospects. Austrian Photonics has particularly strong potential and expertise in seven core fields:

Lighting

Intelligent, environmentally friendly lighting "Made in Austria" is used worldwide, whether with a focus on Human-Centric Lighting or horticulture applications. Research into intelligent systems and efficient optical solutions has been *a priori*ty for Austrian companies and research institutes for years.

Mobility and Security

Developments in mobility and security include matrix and laser headlights, cutting-edge 3D camera technologies for autonomous driving and unmanned aerial vehicles (drones), as well as fiber-optic sensors for real-time monitoring and tracking of trains and traffic infrastructure surveillance.

Life Sciences, Health, and Environment

In life sciences, health, and environmental applications, Austria has made significant contributions to optical imaging technologies, such as optical coherence tomography (OCT), which enables non-invasive, high-resolution visualization of tissues. Equally important are advancements in sensors and environmental monitoring methods, including air and water purification and agricultural production technologies.

Sensor, Production, and Quality Assurance Technology

Austrian expertise is also prominent in sensor, production, and quality assurance technology. Photonic methods for non-destructive quality control are highly sought after by industries, and Austrian companies and research institutes are at the forefront of these developments. Lasers are not only essential for high-precision welding but are also the preferred energy source for 3D printing and additive manufacturing.

Information and Communication technologies

Energy efficiency, free-space communication and photonics integrated circuits are the main topics of interest for Austria's ICT research. Compared to electrons, photons in fibre optic cables travel long distances with up to 20 times less signal loss. Photonic technologies are also invaluable for data storage and future computing architectures.

Optical Quantum Technology

Austria is a global leader in optical quantum technology, particularly in the development of optical quantum computers and quantum communication. This leadership is largely due to Austria's high level of education and excellence in fundamental photonics research, which is recognized internationally.

Austria's photonics industry and research institutions continue to drive innovation in these key areas, ensuring the country remains at the forefront of global photonic advancements.

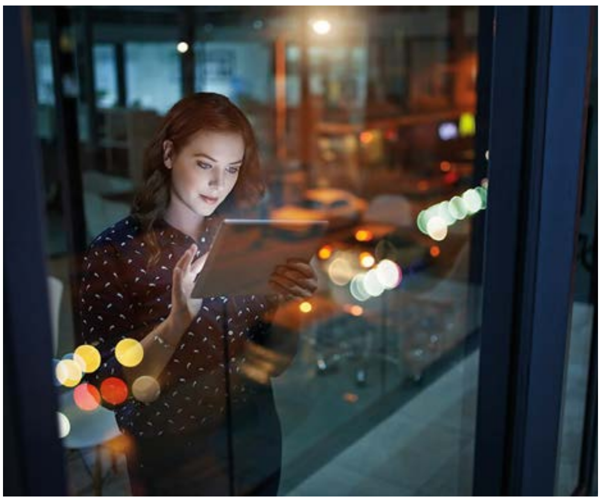
Photonics Austria association

While starting off small in 2013, with less than 20 founding members, today the platform harbours over 60 organisations from industry, research and education.

The platform plays a crucial role in networking and collaboration, connecting experts through meetings, working groups, and innovation workshops while organizing industry events such as the "Photonics4x" series and partnering with other technology clusters like Industry 4.0 and Silicon Alps. It also engages in advocacy and representation, promoting Photonics through public events, publications, and trade fairs like a joint Austria booth at the Laser World of Photonics 2025 while actively lobbying for research funding and policy support. Another key focus is information and support, where Photonics Austria provides insights into funding opportunities, technology trends, and research developments, as well as facilitating expert working groups, such as the Austrian Laser Production Network (ALPIN). By integrating stakeholders from research, industry, and government, Photonics Austria fosters innovation, funding access, and international collaboration, strengthening Austria's role in the global photonics landscape.

Across Europe, Photonics Austria actively connects Austrian and European stakeholders, supporting collaboration and strengthening the photonics ecosystem. By engaging in EU-funded projects, the platform plays a key role in supporting research and innovation while facilitating joint initiatives such as delegation visits and workshops with leading photonics networks like Photonics Finland, Photonics Bretagne, Photonics Baden-Württemberg, Optonet, and Swiss Photonics. These collaborations help Austrian researchers and companies exchange knowledge and explore new opportunities. Additionally, Photonics Austria represents the national community within Photonics21, the European public-private partnership shaping Photonics strategy. It also participates in cascading funding initiatives like PhotonHubEurope and PhotonQBoost, which provide financial support to promising Photonics research and applications. Through these efforts, Photonics Austria helps drive technological progress in Austria and beyond, ensuring that Austrian innovations remain at the forefront of European Photonics development.

Figure 3. © ams OSRAM



Quantum (sensing) leap:
Pushing the technology readiness of Nitrogen-Vacancy sensors in Europe forward

Nitrogen Vacancy centers in diamond interact with local magnetic and electric fields, temperature, strain, and pressure. Their ease of operation and exceptional performance has led to the emergence of a first generation of commercial NV-based quantum sensors, as scanning-probe systems, giving them wide recognition as the quantum technology with the most imminent market potential. In recent years, there is an effort to advance the TRL of those quantum technologies through several European initiatives.

https://doi.org/10.1051/photon/202513128

Paolo TRAINA[1,*], Ivo Pietro DEGIOVANNI[1], Marco GRAMEGNA[1], Xavier VIDAL[2], and Guillermo GIL[2]

[1] INRIM, Istituto Nazionale di Ricerca Metrologica. Strada delle cacce 91, I-10135 Torino (Italy)
[2] TECNALIA, Basque Research and Technology Alliance (BRTA). Parque Científico y Tecnológico de Bizkaia. Astondo Bidea, Edificio 700. E-48160 Derio – Bizkaia (Spain)

***p.traina@inrim.it**

In the 1966 sci-fi movie *Fantastic Voyage* a submarine full of scientists is miniaturized and injected into the body of a critically ill diplomat in a rush to selectively destroy an embolus in his brain before his death. Even if scientists' miniaturization remains science fiction territory, there is great interest to investigate in the micro/nano scale and to probe extremely local properties of small systems such as living cells and/or nanodevices.

Among the most prominent new-generation sub-microscale sensors, the Nitrogen-Vacancy (NV) center in diamond [1] has emerged as extremely promising candidate for measuring very small fields (as in the case of bulk sensors) or for detecting signals with high spatial resolution (e.g. with nanodiamonds).

An NV center is a point defect in a diamond crystal where a nitrogen atom replaces a carbon atom next to a vacancy. These defects exhibit unique quantum properties, including long-lived spin states that can be manipulated and measured with high precision, even at room temperature.

NV centers are particularly valuable for detecting magnetic fields [2], electric fields [3], temperature [4], and even pressure at the nanoscale. Their interaction with external fields, such as magnetic or electric, alters the properties of their electronic spins, which can be measured using techniques like Optically Detected Magnetic Resonance (ODMR). This allows NV centers to act as highly sensitive sensors for magnetic resonance imaging (MRI), magnetic field mapping, and even biosensing.

Some of the most significant advantages of NV centers is their robustness and photostability. These properties make NV centers suitable for applications in quantum computing, materials science, biology, and environmental monitoring. Their potential for precise, non-invasive measurements at the nanoscale positions NV centers as a promising tool in advancing both scientific research and practical technologies.

Thermometry

NV sensors have proven to be versatile and game-changing in advanced applications such as magnetometry, thermometry, imaging, electric field and strain sensing. As an example of the potential of those quantum objects, we will describe here a recent experiment of intracellular thermometry performed at Istituto Nazionale di Ricerca Metrologica (INRIM) in Torino (Italy), in collaboration with the Universtiy of Turin and Charles University in Prague (Czechia) [5].

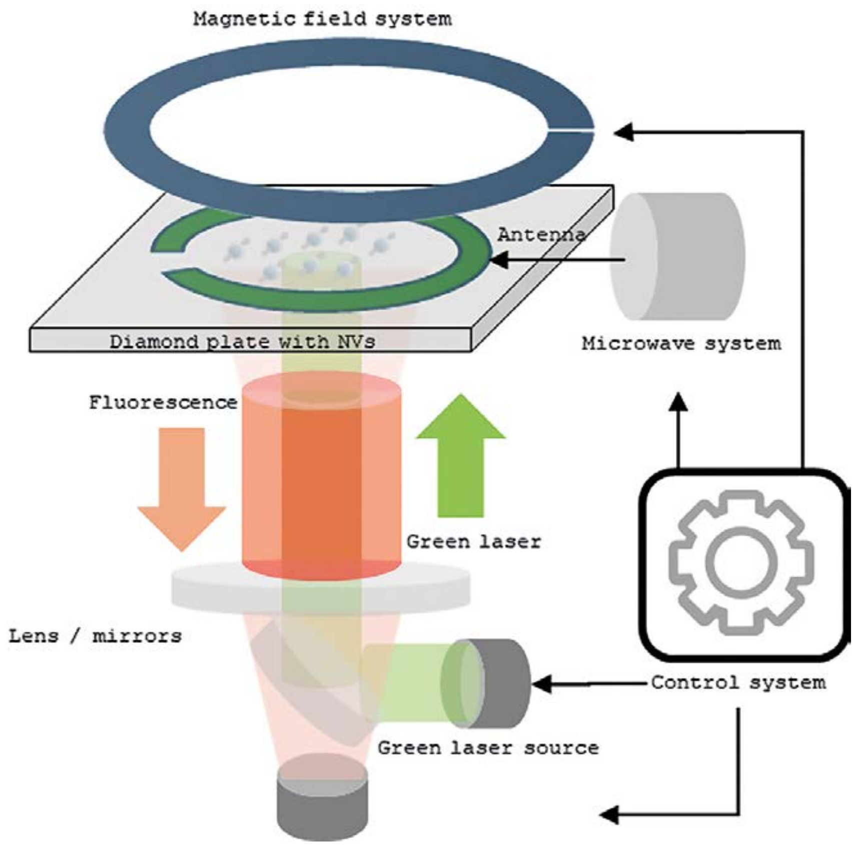


Figure 1. Scheme of the typical setup for the study of color centers in diamond. It includes: diamond sample, detection system, laser excitation, microwave antenna.

Table 1. Overview of NV sensing Companies and SMEs ecosystem.

COMPANY NAME	WEBSITE
QNAMI	https://qnami.ch/
QZABRE	https://www.qzabre.com/
QDTI	https://qdti.com/
QDM.IO	https://qdm.io/
Q.ANT	https://qant.com/
DIASENSE	https://www.diasense.dk/
QUANVIA	https://www.quanvia.com/
QUBIZ.TEAM	https://www.qubiz.team/
QTSENSE	https://www.qtsense.com/
SBQUANTUM	https://sbquantum.com
SQUTEC	http://squtec-tti.com
BOSCH QUANTUM SENSING	https://www.bosch-quantumsensing.com/
SPINFLEX	https://spin-flex.com/
CHINAPROSP QUANTUM	https://en.gshqt.com/
KWAN-TEK	https://www.kwan-tek.com/
DETEQT	https://www.deteqt.com.au/
THALES	https://www.thalesgroup.com/

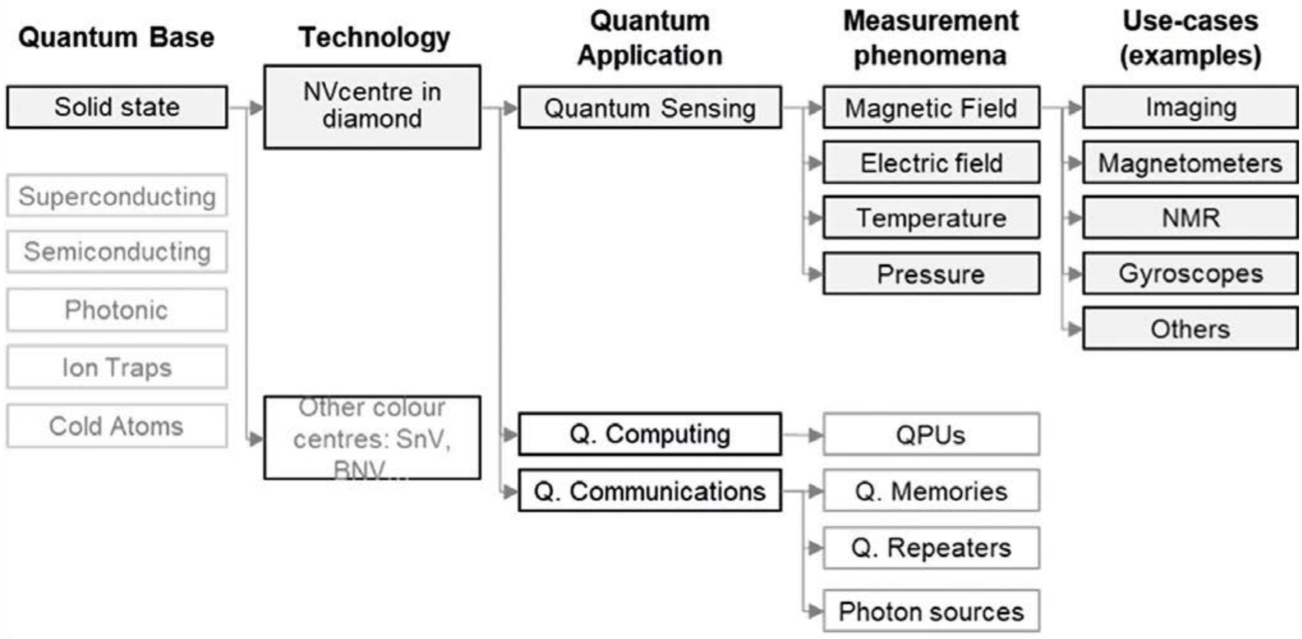


Figure 2. Hierarchy of the quantum-based technologies with particular focus on solid state systems, including NV-based sensors.

Not even the authors of *Fantastic Voyage*, who imagined the above mentioned submarine diving through streams of blood cells and lymphocites, dared conceive a more extreme scenario in which the dimensions of the vessel were reduced to nanometric dimensions to observe the internal mechanism of a single cell. This has been now indirectly realized by probing the temperature variations inside the membrane of a mice neuron by means of a diamond nanosensor, *i.e.* a 100 nm diameter-wide diamond crystal containing the temperature sensitive NV centers. This nanosensor was capable of detecting shifts of the internal temperature of the neuron correlated to different intensity of its signaling activity, stimulated through a protocol consisting of the injection of different doping substances. This multidisciplinary experiment (involving quantum and laser physics, biotechnology, and microwave electronics) not only proves the first ever measurement of a real metabolic process at the single cell scale in mammalians, but also generates further debate as the detected local temperature increase following stimulation is greater than expected, as high as 1°C.

Following the great success in the academic field, it is natural that these NV-based system are nowadays recognized as potential objects of interest also for industrial application and several companies and SMEs have started commercializing products based on this technology (See TAB.1).

For a decisive interest from the industry and a concrete penetration of these devices in the market, two key aspects are expected: the increase of the technology readiness level (TRL) and the development of documentary standards.

Standardization: a global effort

The Development of standards at European level and the harmonization of standards within the European Union are provided by CEN (European Committee for Standardization) and CENELEC (European Committee for Electrotechnical Standardization). The need for standardization of Quantum Technologies was identified as an emerging key requirement for industrial applications by the CEN/CENELEC, which kicked-off a dedicated Focus Group (FGQT) in 2020 [6]. This group of experts developed a roadmap about quantum-technologies and their standardisation needs. This roadmap documents that *there are not standards related to NV-centers based sensors* and *lack of standards for quantum sensor industry is commonly seen as a barrier to market acceptance of new relevant products [...]. The standardisation will help multiple industries in the quantum technologies sector. The existence of a standard that stakeholders can adhere to would therefore significantly de-risk further investments in the market.*

Following the publication of the first release of the Roadmap, the activities of the Focus Group moved in a new entity called Joint Technical Committee 22 "Quantum Technology" (CEN/CLC JTC-22 QT , www.cencenelec.eu/areas-of-work/cen-cenelec-topics/quantum-technologies/), which kicked off in 2022 and is nowadays active.

Similarly, at the International level, ISO (International Organization for Standardization) and IEC (International Electrotechnical Commission) are two key international organizations that develop and publish global standards. ISO focuses on a wide range of standards across various industries, including quality management, safety, environmental, and technological standards. IEC is dedicated to international standards in the electrotechnical and electronic fields, covering areas like electrical engineering, energy, and telecommunications.

Standardization in the field of quantum technologies is developed by the IEC/ISO JTC 3.

Standardization and Metrology: The QADeT and NoQTeS initiatives

Metrology, the science of measurement, is a building block for an industrialised and increasingly globalised and digital society: Reliable measurements are essential for innovation in industry, research, trade and regulation. New societal challenges and emerging technologies increase the need for accurate, precise, and trustworthy measurements and thus for novel measurement capabilities. The European Metrology Partnership aims to support the competitiveness, and economic growth of the European quantum industry.

Among the European metrology projects funded in the field of quantum technologies, INRIM is coordinating the European Metrology Partnership project "Normating colour-center-based quantum sensing technology towards industrial application and standards" (NoQTeS), kicking off in 2024, which is the follow-up of the previous EMPIR project "Quantum Sensors for Metrology based on single-atom-like Device Technology" (QADeT, 2021-2024). Both projects are closely connected to the strategies of the "Quantum Photonics" sector of the "European Metrology Network for Quantum Technologies" (EURAMET EMN-Q), a network that provides an active coordination of metrology research to support the competitiveness of the European industry in the field of quantum technologies.

QADeT project, targeting the development of NV quantum sensors of industrial interest, was notably successful in terms of output and impact, having led to more than 30 peer-reviewed publications, above 90 contributions to international conferences, several connections with stakeholders and Quantum Flagship consortia. Furthermore, experts of QADeT consortium were involved since the starting of FGQT and JTC22.

NoQTeS project is intended to move forward from QADeT and have a lead in the development of standards for color center-based quantum sensors.

The objectives of NoQTeS project are:

- To implement reference methods to produce of NV-based sensors and to develop methods for the standardised characterisation of NV-based sensors.
- To develop and validate reproducible procedures for producing and testing non-NV sensors/single photon emitters (e.g. novel defects in diamond, point defects in Si, SiC, 2D materials (hBN), semiconductor quantum dots (e.g. InAs, etc.).
- To extend current techniques and methods for the production of sensors based on colour centers in diamond, with enhanced performance.

The methods used within the project are controlled ion implantation and advanced photoluminescence microscopy and ODMR, while the sensors to be investigated are Optically active Point defects (NV or otherwise) in diamond, Silicon, quantum dots, etc. The consortium has a strong point of well-established collaboration in color center based quantum sensing (academic & industrial) through previous JRP QADeT and huge availability of ion implanting and characterization facilities.

A TRL sprint: Horizon Europe PROMISE

Several projects funded by the European Commission have focused on developing NV centers as quantum sensors to impact the industrial sector through various prototypes and SMEs. Diadems, funded in 2013 for five years, aimed to advance the NV technology. The consortium of 15 partners grew to 23 in Asteriqs from 2018 and 2022. One relevant outcome of those consortia was the commercialization of a single NV scanning system by two Swiss startups, Qnami and QZabre. Their instrument combines the high spatial resolution of atomic force microscopy with the sensitivity of a single NV center at the apex of a tip connected to a scanning tuning fork.

Horizon Europe in its vision and ambition to facilitate market uptake, has moved quantum sensing to pilot lines where NV-sensing technologies are present in Qu-Test and Qu-Pilot. Also, Innovation Action projects such as AMADEUS, ACDC_Q and PROMISE are three of the examples with the aim to reach high TRL.

Let's take the example of PROMISE (PROtotypes of Magnetic Imaging Systems for Europe); the aim is to develop widefield NV-based magnetometers at TRL7. Currently, this approach is mostly developed in research labs dedicated to NV research, with the only opportunity outside the research lab offered by the US company QDM. Over 44 months, PROMISE will develop a versatile and user-friendly instrument that does not require expertise in quantum sensing or NV technology, but rather an imaging system for magnetic fields. The versatility of the prototypes is addressed from two fronts: research and technology organizations (RTOs) and an SME joining forces to develop the instrument, and from the other front industrial and academic use cases to benchmark and challenge the NV technology. The PROMISE consortium is completed with experts in the standardization of quantum technologies, NV technology in particular, and a business and innovation consultancy for exploitation and dissemination, as well as screening industrial opportunities for the NV widefield approach.

Four use cases will validate the widefield magnetometer prototypes, with implications for the semiconductor industry, materials science, aerospace and biotechnology. The proximity of quantum sensors based on NVs to be integrated into industrial processes and their market potential is evident in PROMISE, where industrial partners are not experts in quantum technologies. The industry, globally, will benefit from a tool that improves its devices, materials, and production processes, deepens understanding of mechanisms at the atomic level, and monitors events and dynamics for more accurate predictions and addressing pressing challenges in various fields. All together PROMISE focuses on technology development supporting industrialization and use case testing.

The NV based widefield magnetometer is an interesting approach where high spatial resolution and high sensitivity need to be combined with dynamic samples. Specifically, the project will show applicability in three fields: Materials engineering, through the analysis of corrosion in alloys; Semiconductor industry, analyzing current flow distribution in electronic chips; and Biotechnology, by monitoring the evolution of tumoral cells. Additionally, the technology will benefit from innovations of the different components of the instrument. The most obvious is the engineering of the NV layer on the diamond surface, requiring a combination of NV layer depth, thickness, and concentration beneficial for the entire NV technology field. An optimized rf controller will be developed to vastly reduce weight, volume, power consumption and cost compared to commercial solutions. This will enhance the user-friendliness of the instrument but mainly pave the way for future commercialization facilitating a reduced final price and commission. Although commercial scientific cameras have different high-performance functions, they are not fast enough to detect single NV spin events. Therefore, a pixel array sensor will be integrated into the instruments for faster and lower signal detection, adapting to various acquisition protocols available for NVs. The exploitation of the results may come not only from a refined prototype that can achieve higher TRLs but also from the exploitation of the individual components relevant in the quantum field.

Machine learning experts will optimize data acquisition and analysis by leveraging their knowledge of the physics of NV centers. Additionally, as mentioned above, standardizing designs and methods will be considered for an easy industrialization.

During the 44 months, PROMISE will operate in two cycles. The second cycle will refine specific details of the prototypes, components, and test with more complex use case samples. The goal is that at some point in the second cycle a potential manufacturer will consider commercialization of the widefield magnetometer in the future. Ideally, the manufacturer will advise the consortium on appropriate testing for future commercialization. However, this is a difficult path, so all partners will protect their designs and methods through patents and IP repositories. They themselves have several commercialization options: licensing the various component designs to instrument manufacturers; creating spin-off companies; using a mixed approach in which the technology is licensed for specific fields and commercialized through spin-off companies for others; and potentially forming a joint venture between the partners. The path chosen will depend on market penetration and certification requirements.

Thus, the NV-based sensing technology has evolved from academic research to actual industrial interest in roughly fifteen years, and it has now already entered in a phase of maturity that reflects in a global effort for standardization of the techniques and in a dash of the technological readiness. A *fantastic voyage* indeed!

Acknowledgement

This article has been prepared in the context of the activities of: the projects 23NRM04 NoQTeS (23NRM04 NoQTeS has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States) and PROMISE project (funded by the European Union, Grant Agreement 101189611).

REFERENCES

[1]L. Rondin, et al. Reports on Progress in Physics **77** (5), 056503 (2014)

[2] J. M. Taylor, et al., Nature Phys. **4** (10), 810 (2008). doi:10.1038/nphys1075

[3] F. Dolde, et al., Nature Phys. **7**, 459 (2011)

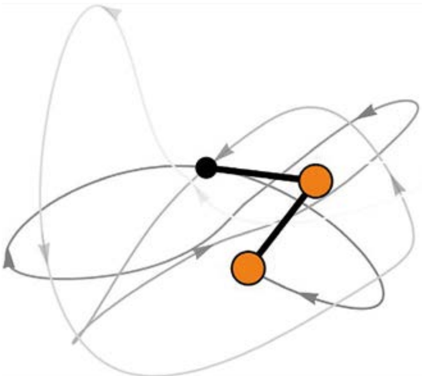
[4]G. Kucsko, et al., Nature **500** (7460), 54 (2013)

[5] G. Petrini, et al., Adv. Sci. **9**, 2202014 (2022)

[6] O. van Deventer, et al., EPJ Quantum Technol. **9**, 33 (2022)

Animating Physics for Science Communication

Jacopo BERTOLOTTI*
Department of Physics and Astronomy, University of Exeter, Exeter, Devon EX4 4QL, UK
***j.bertolotti@exeter.ac.uk**



If a figure is worth a thousand words, how many words is an animation worth? As it is often the case, the answer is a resounding "it depends", but nevertheless animations can be a very powerful tool to convey complex information in a fast and compact form. And, contrary to what you might think, creating an effective animation is not any more difficult than creating an effective figure.

https://doi.org/10.1051/photon/202513133

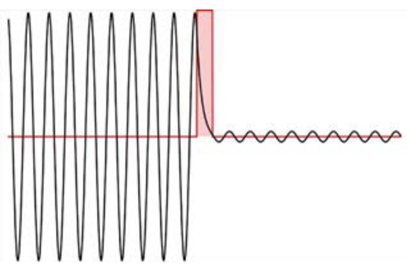
Conveying complex information is a task without a universal solution, and conveying science is no exception. We have a very long history of trying to explain each other counter-intuitive scientific ideas and some approaches stood the test of time better than other. The original explanation of what is now known as Galilean Invariance is roughly half a page of text involving a ship, flying insects, fishes, several buckets of water, and people jumping [1]. Would we explain it in the same way today? Surely my undergraduate classical mechanics textbook didn't, but my professor's explanation in class wasn't all that different from Galileo's one, albeit with far fewer

animals involved. The main difference is that my professor also made a drawing on the blackboard, which helped immensely to visualize what was going on. Even better, as they could draw a piece at the time, what they had was a sort of semi-animation that changed while they were explaining the topic.
Was all that drawing strictly necessary to explain Galilean invariance? Obviously not, as a paragraph of text or one line of equations can easily contain all the necessary information. On the other hand we are very visual creatures and images can help making abstract concepts more real and digestible.

Pictures that move

Figures in scientific papers are ubiquitous for a reason. Often you can get a good idea what a paper is about just by looking at the figures in it and seeing the data neatly plotted is a lot more immediate than having them tabulated. Can an animation do any better? No, but that is not what an animation is for.
Since, by its own nature, an animation doesn't stay still for long, it is not a good fit for anything that requires looking at details. The real power of an animation is to either modify the image (e.g. zooming in on a detail) in synch with a description/explanation, or show how things change with time and/or when changing a parameter. As a practical example we can look at quantum tunnelling, a topic covered in all Physics degrees that is baffling and hard to understand the first time you encounter it. The way it is approached in most textbooks is to consider a particle with a well-defined energy in a constant potential with a rectangular barrier. Then one writes the solution of the time-independent Schrödinger equation both inside and outside the barrier, and the three solutions are then joined smoothly which leads to the transmission coefficient, *i.e.* the probability that the particle will tunnel through the potential barrier. This is accompanied by a figure showing the potential and how the wavefunction looks like in the three regions of space of interest (see figure 1). This works very well, but leaves out all the time dynamic of quantum tunnelling, which is not hard to obtain from the single energy solution, but it is unlikely to be obvious to a student encountering it for the first time. An animation is the perfect tool to show how quantum tunnelling looks like in the time domain (see figure 2), or how it changes as the width of the barrier increases, or as the height of the barrier changes etc.

Figure 1. A typical illustration of quantum tunnelling one might find in a textbook. The solution of the time-independent Schrödinger equation is a wave when the energy is higher than the potential, but an exponential inside the barrier, resulting in a small fraction of the wavefunction to appear beyond the barrier.



Where and when?

An obvious problem with animations is that you can't really show them on paper (flicking through the pages very quickly technically works but it is an impractical solution), which limits their usefulness in scientific papers. You can show animations inside a pdf [2] (you can even run Doom inside a pdf), but to the best of my knowledge there is no tool that makes that easy, and current publishing pipelines are anyway unable to deal with it. Where animations truly shine is on projected slides, *e.g.* in lectures or conference talks, and online, where the technology used is already perfectly suited to showing moving pictures.
That said, an animation for the sake of an animation is not going to be very useful. An animation, just like a figure, should be designed to be easy to parse and to convey useful information. Worse than a figure, the more stuff is moving, the hardest it is going to understand what it is going on. An animation should always be focussed on the information it has to convey, with as few extraneous parts as possible. This doesn't mean one has to always go with a minimalistic style, but any extra complexity should always be there with a precise goal and any animation that is unavoidably complex should always be accompanied by a detailed explanation (see figure 3).
Another thing to think about is length. How long before the animation loops and your audience will have a chance to see again the parts they missed? If you are creating a YouTube video this is not a huge concern, as it is always possible to stop it and go back if you missed something. But if you are showing the animation as part of your presentation at a conference, you have to consider that the audience is likely to be looking at the slides, looking at you, listening at you, taking notes, checking their phone and finishing their own talk, all at the same time. Chances are that they will miss those crucial 2 seconds in the animation, and then have to wait until they show again.

Different kinds of animations

"Scientific animation" is a very wide umbrella term that includes a lot of very different kinds of animations. Making a complete zoology of all possible kinds of animations is well beyond the scope of this article, but it is useful to list at least the most common ones.
Data-based: You have data, but instead of plotting it as a static image you make an animation that shows how things are changing with time. E.g. one might make a video of how a slime mould grows while looking for food, or a map that shows how the borders of France changed in time. This is probably the most common kind of animation.
Formula-based: Formulas have the big advantage of containing a lot of information in a very compact format, and the disadvantage of containing way too much information in a way too compact format. As a result it takes time and work to get familiar enough with the

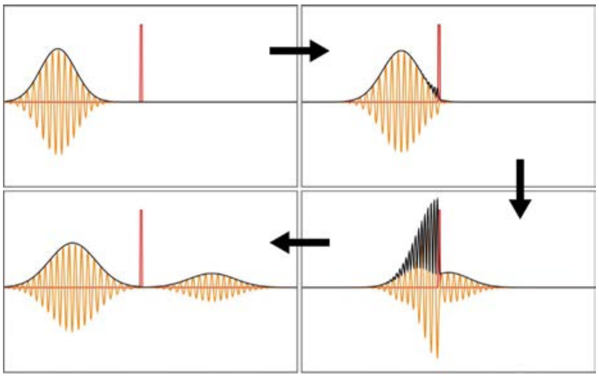


Figure 2 . Four frames of an animation showing a free particle (or better, its wavefunction) hitting a potential barrier. Most of the wavefunction is reflected, interfere with itself, and goes back, while a small fraction passes through the barrier. In this specific case I have chosen to plot also the modulus of the wavefunction (in black) to highlight the fringes due to the incoming wavefunction interfering with the reflected wavefunction.

formulas that we can just see in our mind how they relate to the Physical processes they describe, which makes plots, diagrams, and animations about them invaluable.
Simulation-based: Sometimes it is easier to run a full (albeit often simplified) simulation of the phenomenon you want to show than try to hand-craft an animation about it. This is a particularly attractive proposition if you are already sitting on a lot of suitable code, *e.g.* because you are running those simulations anyway, or might require a significant time investment if you are starting from zero.
Artistic impressions: Accuracy is not always the main goal. You don't want to mislead people or be factually wrong, but sometimes conveying the big idea is more important than the fine details. If you are artistically inclined this might be the easiest way to start making scientific animation. If you (like me) are not artistically inclined at all, it is a non-starter.

How do I make one?

You don't need to be either an artist or any good at coding to make a good animation, but admittedly there is a (largely mental) barrier to entrance. An important first step is to have clear in your mind who the audience is. Are you making an animation to help you with a lecture? For your next presentation at a conference? Are you planning to share it with your friends/colleagues on social media? Do you want to use it for scientific outreach? This will inform you about how complex the things you show in the animation can be before your intended audience loose you completely. Which, to be honest, is not very different from the mental process you have to go through when making a figure.
The second step, and where I feel most people give up, is the choice of the tool you are going to use. The fact •••

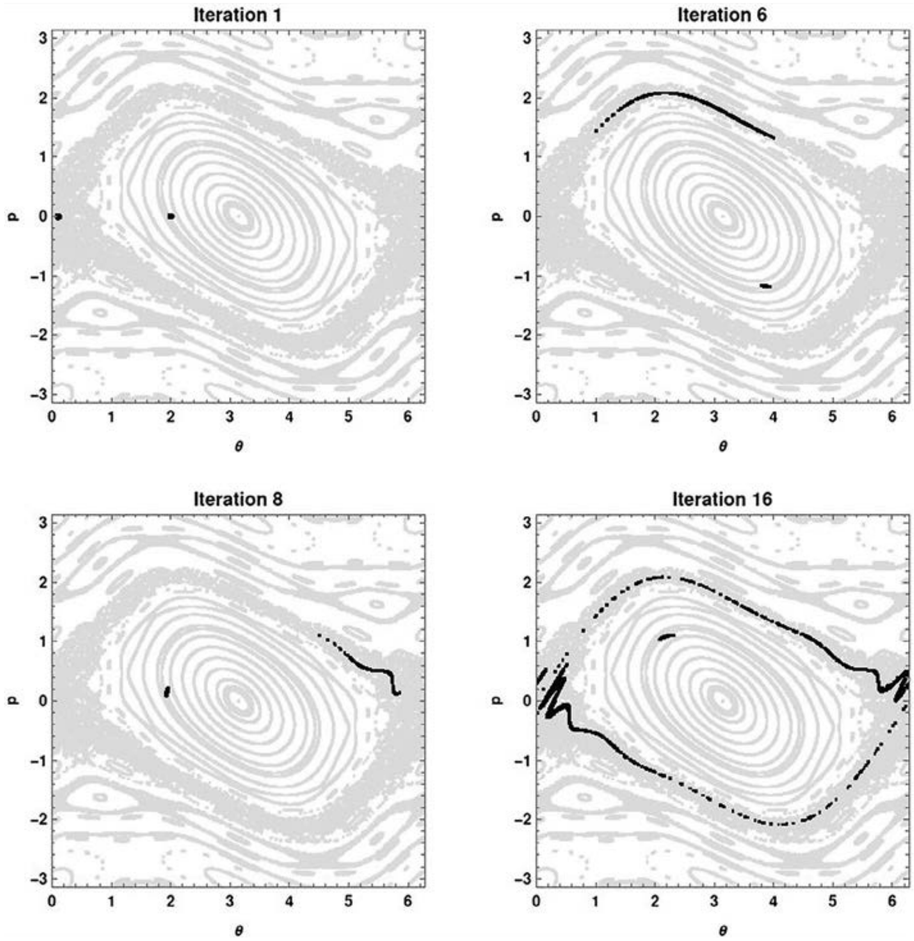


Figure 4. The Poincare section of a kicked rotor is complex, and the difference between the dynamics near an elliptical and a hyperbolic point definitively requires a good amount of explanation. Nothing here is self-explanatory, and wether one prefers to use a set of static images or a short animation, this should always be seen as an aid to the explanation, and not as a self-contained object.

that you don't know how to use professional 3D software is largely irrelevant, as there is a very good chance the tool you commonly use to make your figures and/or analyse your data is perfectly able to create high quality animations. In practice, if you can create a set of figures you can put them together into a .gif file, which will play them one after the other, forming an animation. I have seen people use the most disparate software to create animation, from coding them in Python/Matlab/C, to the use of dedicated graphics software like Illustrator or Blender. It all depends on what you are already familiar with, and/or what you are interested in learning.
The third step is to decide what style you want to use, and this decision will strongly depend on the first two steps. A 10-minutes long video to post on YouTube requires a very different approach than a 5 seconds animate .gif that will loop on your slides. And even within these two extremes there is a lot of scope to find the sweet spot between clarity, aesthetic, complexity, and time needed to actually make the animation that suits you best. I personally like to make short (10-15 seconds) highly stylized animations to use in my lectures/talks, and I found that they work well on social media too if accompanied by enough explanations to make them understandable (I think of my target audience as "PhD students and passionate amateurs").
Finally, it is actually time to make one, which might take anywhere between minutes and days of work, depending on how ambitious your plans are, and how much you can use of your old animations. Not surprisingly, once you have developed a large library of animations things get much easier, so it is advisable to start small, with a simple and manageable one before building up to more complex stuff.

Conclusions

It goes without saying, but there are not many extrinsic motivations to make scientific animations. You are very unlikely to gain fame and riches making them, and while I am sure there are a few people who managed to make it into a job, chances are that it will never go beyond the level of a hobby (albeit a genuinely fun hobby). Making animations is a surprisingly engaging process in and of itself, with the added benefit that in many cases it will put to a test how much you truly understand the science you are trying to animate.
And even if you don't want to make animations, there are plenty out there you can use for your lectures or talks. Just make sure about their copyright status before using them. If you can't find anything, assume that the animation you found online is the intellectual property of its creator. Which doesn't mean you can't use them, but it means you should ask the creator for permission. Most of the time they will be very happy you asked. ●

REFERENCES

[1] G. Galilei Dialogue Concerning the Two Chief World Systems, Ptolemaic and Copernican, 2nd edition (University of California Press, 1967).

[2] https://tug.ctan.org/macros/latex/contrib/animate/animate.pdf

CONTROLLING LIGHTNING WITH LASERS

Aurélien HOUARD
Laboratoire d'Optique Appliquée, ENSTA, École polytechnique, CNRS, Institut Polytechnique de Paris, Palaiseau, France
*aurelien.houard@polytechnique.edu

Lightning is one of nature's most extreme phenomena. As fascinating as it is destructive, it causes billions of euros worth of damage every year. The idea of using lasers to control lightning dates back to the 1970s, but it wasn't until 50 years later, with the European Laser Lightning Rod project, that it was demonstrated for the first time that powerful lasers could guide lightning over long distances.

https://doi.org/10.1051/photon/202513137

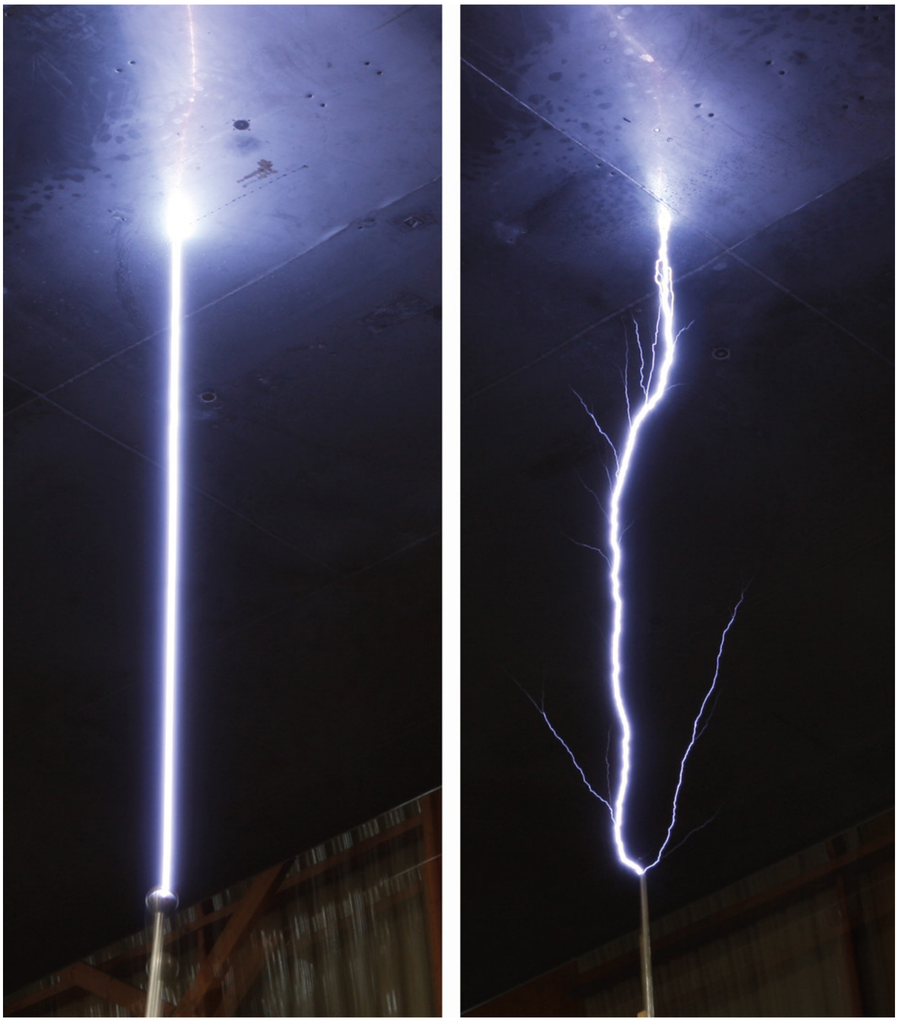
Every year, lightning is responsible for billions of euros in damage and over 20,000 deaths worldwide, triggering forest fires, power surges and disrupting air traffic at airports, since aircraft are highly vulnerable during take-off and landing.

Lightning occurs spontaneously in large cumulonimbus clouds when convection of water particles creates space charges, leading to an accumulation of electrons at the bottom of the cloud. This negative electric charge produces an electric field of the order of 50 kV/m, sufficient to initiate downward discharges towards the ground or, in some cases, even upward discharges from a tall tower or mountaintop. The main existing method of lightning protection is the lightning rod, invented by Benjamin Franklin in 1752. Consisting of a metal rod up to 100 m high, the lightning rod can protect a ground installation up to a radius of 30 m by attracting lightning discharges passing nearby.

To increase the range of action of the classical lightning rod, the idea of using a powerful laser was proposed by Ball *et al.* as early as 1974. Controlling an electrical discharge using light is a not trivial idea, as the speed of photons limits their interaction with the free electrons that form the discharge. To control the lightning flash, the laser has to modify the medium in which it propagates, *i.e.* the atmosphere. It can either ionize the air to make it conductive, simulating the effect of a metal lightning conductor that can attract discharges by bending the field potential, or it can create a preferential path for the discharge by heating the air. Both solutions rely on the laser's ability to ionize the air on its path over very long distances. The first experiments of this type were carried out in USA and Russia in the 1970s, using nanosecond pulsed lasers with an energy of several kilojoules. These high-energy lasers are capable of producing very dense but discontinuous plasmas channels, and the light energy required is very high (of the order of 600 J/m), which limits the length of the plasma column to a few meters. A first lightning guiding experiment was nevertheless carried out using this method in 1997 by •••

Uchida *et al.* in Fukui, Japan. The researchers twice observed a possible laser effect on lightning over a distance of 1 to 2 m, using a combination of several kilojoule nanosecond lasers focused above a tall metallic tower [1].
A major breakthrough came with the development of amplified femtosecond lasers [2]. When these ultrashort pulsed lasers are focused in the air, they generate very long and uniform plasma filaments that can reach hundreds of meters with relatively moderate laser energies. This process known as filamentation is due to a combination of Kerr self-focusing and plasma defocusing that saturate the laser intensity inside the filament. This discovery, at the end of the 90s, quickly triggered the launch of lightning control projects in Quebec with a project piloted by INRS and Hydroquebec, and in Europe with the Franco-German Teramobile project. Numerous laboratory studies were carried out with discharges of several meters produced by Marx generators (see example in Figure 1). In 2005, the first real-life campaign was organized in New Mexico by researchers from the Teramobile project [3]. The experiment consisted in producing plasma filaments at several hundred meters altitude using a TW laser operating at a repetition rate of 10 Hz. In the presence of thunderclouds, the laser was expected to guide or trigger lightning. Unfortunately, very few thunderstorms occurred during the campaign, which nevertheless enabled them to observe the emission of RF signals due to the formation of filament induced corona discharges during the thunderstorms.

Figure 1. Photograph of a 2 m-long electric discharge guided by laser filamentation (left) and without laser filament (right).



The laser lightning Rod project

The Laser Lightning Rod (LLR) project was launched 10 years later, when new laser technologies based on amplification in Yterbium:Yag crystals allowed to increase the laser repetition rate by a factor of 100. These new ultrashort lasers, developed by Trumpf scientific in Germany, were capable of maintaining a permanent hot-air channel by generating plasma filaments at high repetition rate. This greatly increased the chances of intercepting and guiding a lightning bolt. Under the impetus of the Applied Physics group at the University of Geneva and the Laboratory of Applied Optics in Ecole polytechnique (which were already the main players in the Teramobile project) a consortium was then formed with the German company Trumpf scientific, Ariane group, interested as an end user, and lightning experts from EPFL and from the University of Applied Sciences and Arts Western Switzerland. The project officially kicks off in January 2017 with a funding of €4 million from the European commission.
The site chosen for the experiment was the other key to the project's success. Selected by EPFL, it is a 120 m high radio transmission tower on the summit of Mont Saentis (Appenzell, Switzerland, 2502 m), operated by Swisscom. The Saentis tower is one of the most frequently struck by lightning in Europe, but above all, due to the presence of the mountain

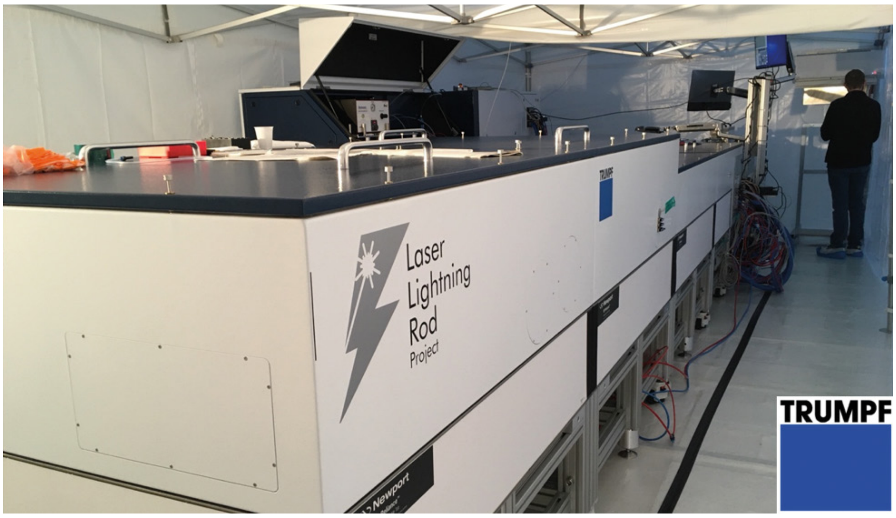


Figure 2. Photography of the laser developed by Trumpf scientific for the LLR project. (Copyright LLR project).

and the tower, the lightning that strikes the tower develops into ascending lightning precursors that start at the top of the tower. Known as upward leader, these discharges are therefore easily intercepted by the laser. This configuration is similar to that used in the pioneering experiment by Uchida *et al.* in the 90s. The first challenge was to build the world's most powerful high-average high-peak power ultrafast laser, with the aim of delivering laser pulses with an energy of 1 Joule, a duration < 1 ps at a repetition rate of 1 kHz. Trumpf's laser prototype is 1.5 meters wide, 8 meters long and weighs over 3 tons (see Figure 2). Its 5-block design means it can be transported by a cable car to the summit of Saentis, which is not accessible by car. The first two years of the project were devoted to the development of the laser by Trumpf, and to the study of lightning events at the Mont Saentis in the absence of laser.

Achieving an energy of one joule per pulse proved more difficult than expected, due to the strong thermal effects that occur at high power. In the end, including 5 amplification stages, the laser still achieved a record energy of 720 mJ at 1060 nm. After two years of development, the first tests with the laser were carried out at the former Orsay Linear accelerator laboratory in France, to characterize and optimize the filaments produced at 150 m using an enlarging telescope. Stopped for almost a year by the COVID pandemic, the project then resumed in 2021 for the final experiment, where the laser and its transport and focusing device were installed at the top of Mount Saentis.

The lightning experiment

Supervised by the University of Geneva, this 4-month installation on the top of Mount Saentis proved to be particularly complex. On the one hand, the laser had to be installed in an air-conditioned environment with filtered air, because at high average power, dust in the amplifiers can easily damage the entire chain. It •••

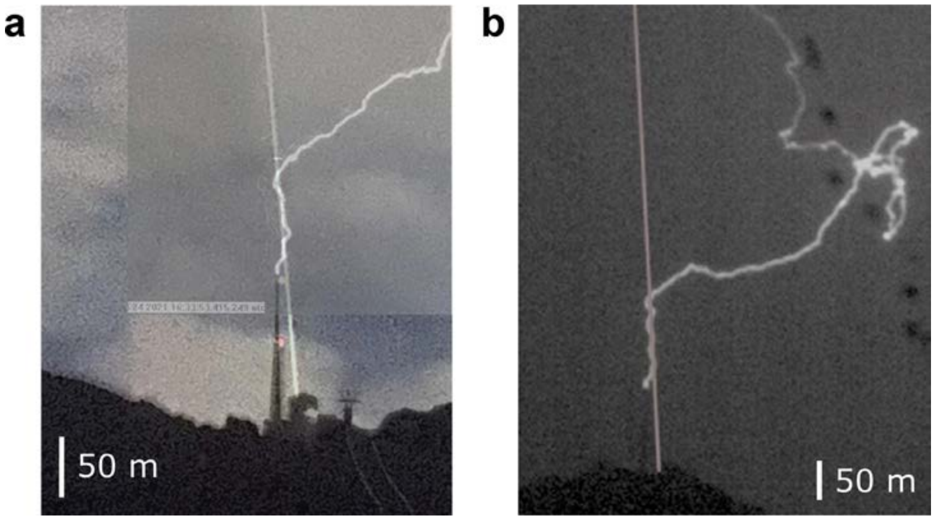


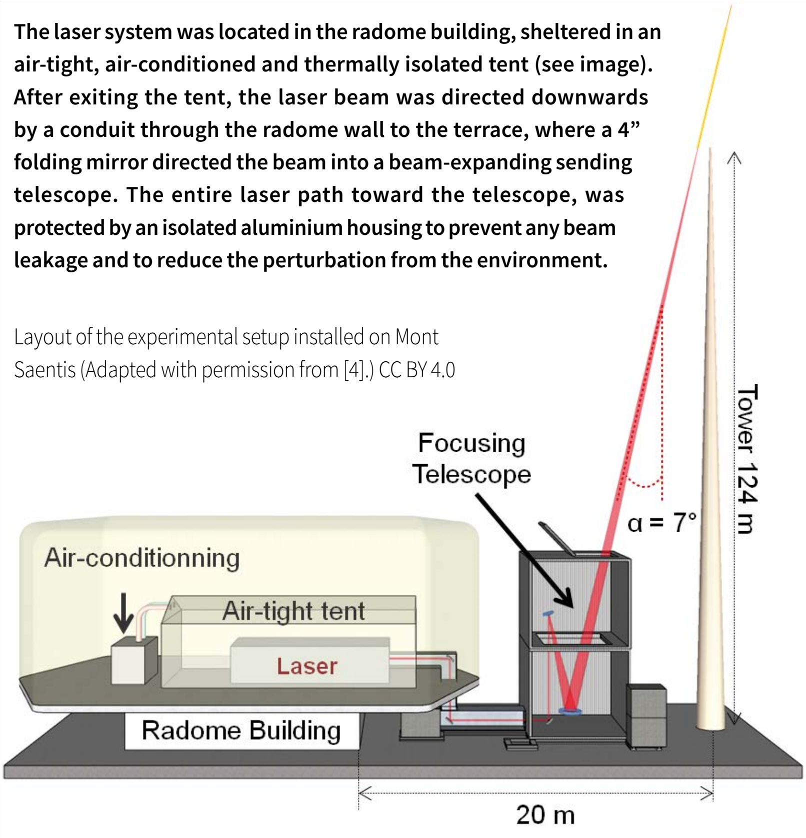
Figure 3. Images of the laser guided lightning flash recorded by two cameras over Mont Saentis on July 24 2021. Reproduced from [4]. CC BY 4.0

was also necessary to build a 3 m high telescope shelter to direct and focus the laser beam, and to cover the entire laser path between the building and the sending telescope. The installation of this shelter required the helicopter transport of two 10' high containers and 20 tons of concrete to stabilize the structure, which had to withstand winds of 80 km/hour. In addition, a special device was designed to protect the telescope's exit optics from the heavy rain that accompanied the storms, and the whole experiment had to be connected to a generator during each storm, to protect against frequent power cuts. The laser was then activated whenever thunderstorm activity was forecast, between July and September 2021. Beforehand, the area had to be closed to air traffic for a 5 km radius around the laser beam.

Once all these problems had been resolved, the experiment could begin in mid-July 2021. A week later, the first bolt of lightning struck the tower while the laser was in operation. Luckily, that evening, the cloud ceiling was very high and the lightning was perfectly visible from the neighboring peaks. Using two high-speed cameras positioned at different angles, the images shown in Figure 3 were recorded. It can be clearly seen that over 60 m, the lightning bolt, which starts at the top of the tower, follows the path of the laser beam. This is precisely the length over which the laser beam produces plasma filaments with this telescope configuration. Subsequently, a similar guiding effect was observed during three other lightning events, using a VHF detector capable of tracking the movement of lightning tracers in clouds, when the cloud prevents the lightning from being seen with a camera (see Figure 4).

This experiment therefore demonstrated that an intense ultrashort laser beam was capable of repeatedly guiding lightning over a distance of more than 60 m, even under difficult weather conditions, as the mountain was regularly shrouded in dense fog. Many questions remain unanswered, concerning the reproducibility of this effect, or the ability of the laser to stimulate the number of lightning discharges. But these questions

The laser system was located in the radome building, sheltered in an air-tight, air-conditioned and thermally isolated tent (see image). After exiting the tent, the laser beam was directed downwards by a conduit through the radome wall to the terrace, where a 4" folding mirror directed the beam into a beam-expanding sending telescope. The entire laser path toward the telescope, was protected by an isolated aluminium housing to prevent any beam leakage and to reduce the perturbation from the environment.



Layout of the experimental setup installed on Mont Saentis (Adapted with permission from [4].) CC BY 4.0

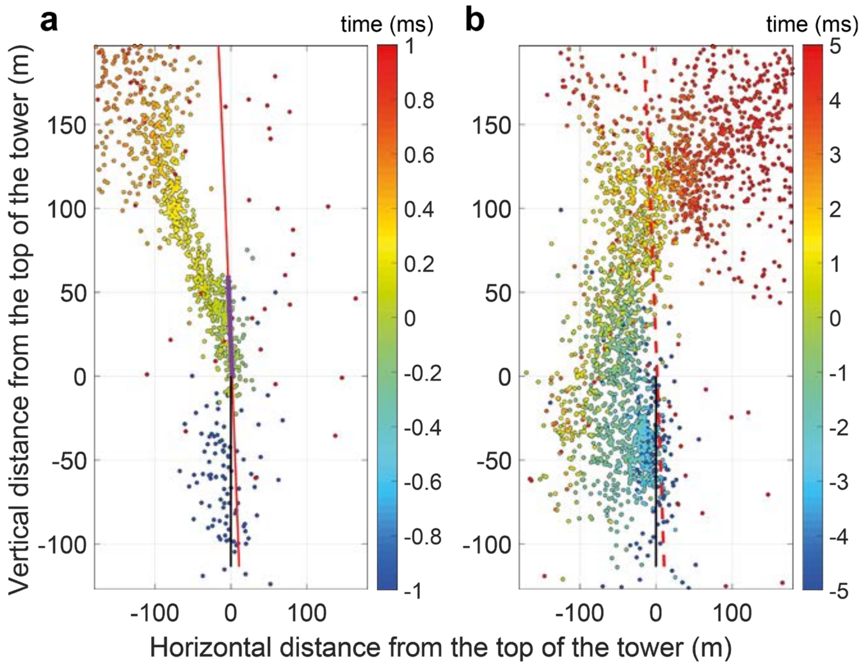


Figure 4. 2D maps of the VHF sources emitted during a lightning event with the laser on (a) and without laser (b). The laser path is shown in red. Reproduced from [4]. CC BY 4.0

would need more statistics to be answered, and installation difficulties meant that we were unable to take advantage of a large proportion of the season's lightning events. Therefore, additional experimental campaigns would be necessary to qualitatively assess the guiding efficiency of the laser filaments.

Conclusion

The Laser lightning rod experiment demonstrated that a high-repetition rate terawatt laser could guide lightning over 60 m by forming plasma filaments in the air. For lightning protection applications, the next step is to increase the length and guiding efficiency of the laser filaments, for example by doubling the laser frequency to obtain more energetic photons. Another important topic in the control of lightning will consist in the demonstration of lightning triggering with lasers. This should require the formation of long-lived conductive plasma channels, but their formation over long distances remains a real challenge [5].

REFERENCES

[1] S. Uchida, Y. Shimada, H. Yasuda, *et al.*, J. Opt. Technol. **66**, 199 (1999)

[2] X. M. Zhao, J.C. Diels, C. Yi Wang and J.M. Elizondo, IEEE J. Quantum Electron. **31**, 599 (1995)

[3] A. Mysyrowicz, J.P. Wolf, Photoniques **127**, 32 (2024)

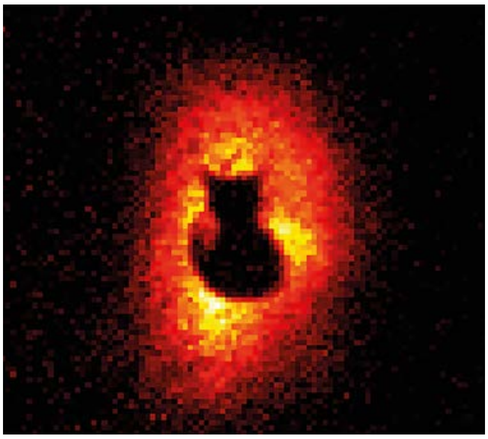
[3] C. Herkommer, P. Krötz, R. Jung, *et al.* Opt. Express **28**, 30164 (2020)

[4] A. Houard, P. Walch, T. Produit, *et al.* Nat. Phot. **17**, 231 (2023)

[5] T. Produit, J. Kasparian, F. Rachidi *et al.* Rep. Prog. Phys. **87**, 116401 (2024)

ENCODING AND DECODING IMAGES IN QUANTUM OPTICAL CORRELATIONS

Chloé VERNIÈRE[1], Baptiste COURME[1,2], Hugo DEFIENNE[1,*]
[1] Sorbonne Université, CNRS, Institut des NanoSciences de Paris, INSP, F-75005 Paris
[2] Laboratoire Kastler Brossel, ENS-Universite PSL, CNRS, Sorbonne Université, Collège de France, 24 rue Lhomond, 75005 Paris, France
***hugo.defienne@insp.upmc.fr**



Quantum correlations, such as those existing between photons produced by spontaneous parametric down-conversion (SPDC), are ubiquitous in quantum photonic technologies. To develop applications, they must be precisely tailored and efficiently measured, which is often challenging in practice. This article presents an image encoding-decoding method based on the quantum correlations of photon pairs, highlighting recent advances in detecting and controlling these correlations for imaging and sensing applications.

https://doi.org/10.1051/photon/202513142

Quantum imaging exploits non-classical optical properties to surpass the performance of classical systems or to develop new imaging modalities [1]. Building on quantum metrology and sensing, this field has developed over the past 40 years. Advances in detector and source technologies, combined with conceptual progress in quantum phenomena such as entanglement and non-locality, have gradually paved the way for practical applications. Notably, the past five years have seen the first proof-of-principle demonstrations of quantum microscopes employing squeezed light [2], single-photon emitters [3] and entangled photons [4].

Among quantum imaging techniques, many leverage photon correlations to enhance imaging performance. Photon correlations in so-called 'twin beams' were first observed in 1970 in light emitted from $\chi(2)$ nonlinear crystals [5]. Since then, this nonlinear optical process, known as spontaneous parametric down-conversion (SPDC) [6], has been extensively studied. Today, it underpins most non-classical light sources used in modern experiments and applications, particularly those that produce entangled photon pairs.

SPONTANEOUS PARAMETRIC DOWN CONVERSION

SPDC is a non-linear process in which a photon from a high-energy (e.g. blue) pump laser is converted into two lower-energy (e.g. infrared) photons called signal and idler (Fig. 1a). It is a very inefficient process, as most of the pump photons pass through the crystal unperturbed, with only a small portion (10^{-5} to 10^{-12}) producing a pair of down-converted photons. When operating in the low gain regime, for example by using a continuous-wave pump laser with hundreds of mW intensity, the probability of generating a double-pair is negligible and the output state is well described by a two-photon state of the form

$$|\psi\rangle \approx C_0|0\rangle + C_1\sum_{k,l}\Psi_{kl}a_k^{\dagger}a_l^{\dagger}|0\rangle, \quad (1)$$

where C_0 and C_1 are normalization coefficients ($C_0 \gg C_1$), $a_k^{\dagger}$ is the creation operator of a photon in the mode k of the electromagnetic field (spatial, spectral, and polarization) and Ψ_{kl} is the two-photon wavefunction.

The properties of Ψ_{kl} – and thus those of the quantum correlations of the photons emitted by the source – are entirely determined by the characteristics of the pump laser and the crystal used. On the one hand, engineering the crystal parameters allows modification of the phase-matching conditions (Figs. 1b and c), thereby changing the properties of the state. This is the case, for example, when using periodically poled crystals [7]. On the other hand, one can also modify the properties of the pump laser, such as its wavelength or spatial structure. This latter approach, known as pump shaping, is particularly attractive since it allows for adaptive and dynamic control of the two-photon state. Over the past years, many research teams have started using it to optimize their states for specific applications [8]. In this article, we describe an approach that exploits this idea to tailor the spatial correlations between photon pairs in the form of arbitrary objects.

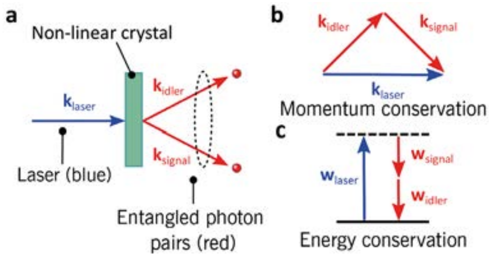


Figure 1. a, Illustration of the spontaneous parametric down conversion (SPDC) process. b, Momentum and c energy conservation in SPDC.

ENCODING AND DECODING IMAGES

A key feature of SPDC is the transfer of the pump beam first-order spatial coherence to the down-converted photon pairs' second-order coherence. Our approach, illustrated in Figure 2a, leverages this property by placing an object and a thin nonlinear crystal at the front and back focal planes of a lens. In such a configuration, the crystal is effectively illuminated with a pump that has the shape of the transverse spatial Fourier transform of the object. Due to momentum conservation (Fig. 1b), the structure of the photon pairs spatial correlations • • •

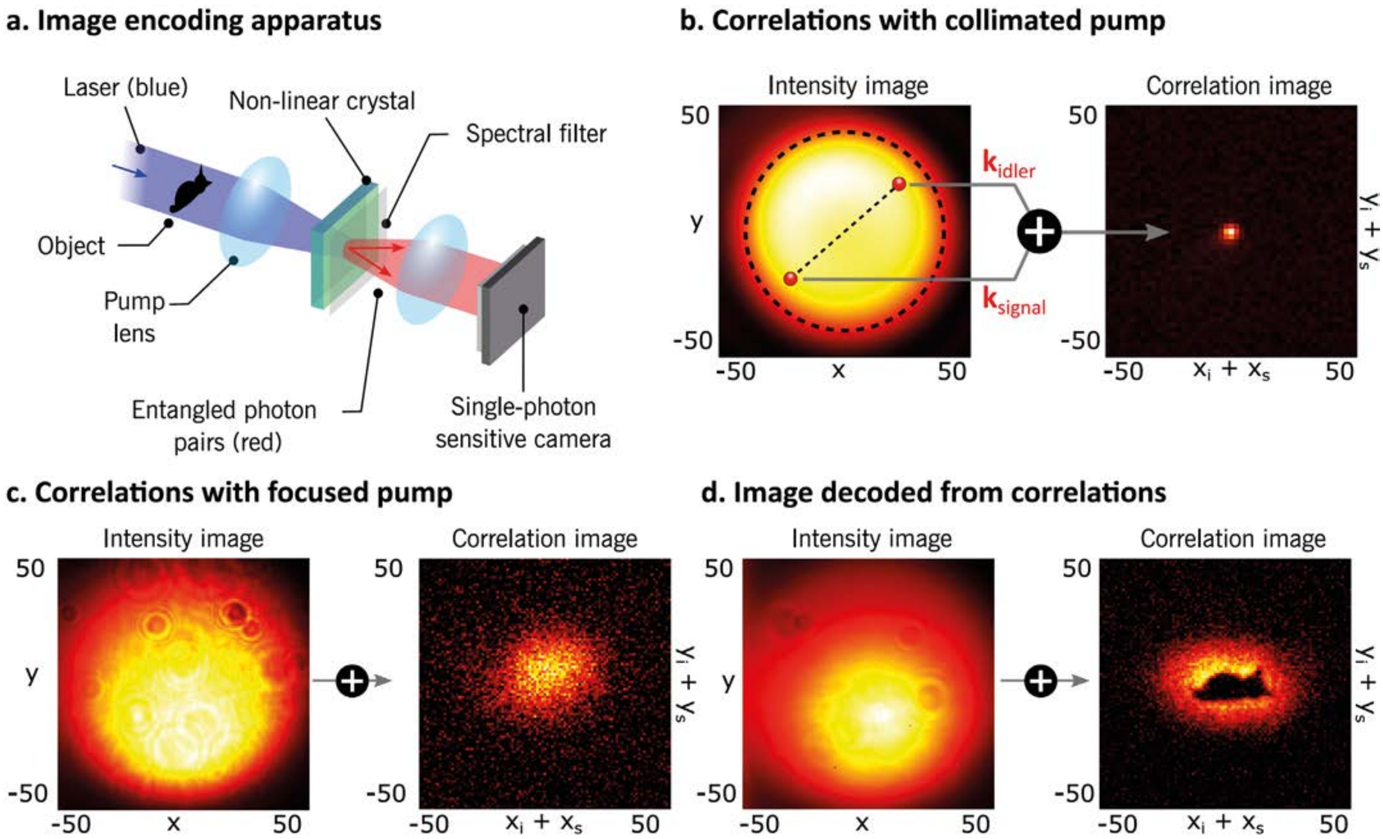
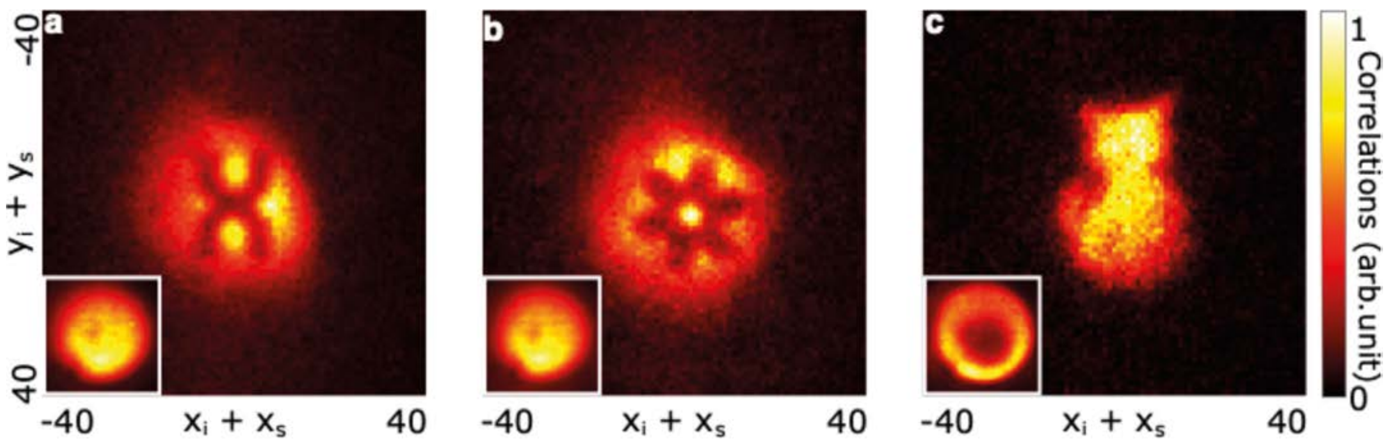


Figure 2. a, Simplified experimental setup. A collimated blue continuous-wave diode laser (405 nm) illuminates an object, which is Fourier imaged by a lens onto a β-Barium-Borate nonlinear crystal (0.5 mm thick). The down-converted photon pairs have the same wavelength (810 nm) and polarization (perpendicular to the pump). A spectral filter after the crystal removes the pump photons. A second lens Fourier images the crystal onto a single-photon-sensitive camera, here an Electron Multiplied Charge-Coupled Device (EMCCD) camera. b, Intensity and correlation images without the object and the lens in front of the crystal. c, Intensity and correlation images with only the lens. d, Intensity and correlation images with both the lens and the object.

Figure 3. Preliminary results obtained by replacing the EMCCD by a Tpx3cam camera in the quantum encoding-decoding image scheme described in Figure 1a. a,b et c, Correlations images of three different objects (cross, flower and standing cat) reconstructed from 10 seconds of acquisition. Direct intensity images are shown in inset.



is consequently modulated. Specifically, the associated two-photon wavefunction, expressed in the momentum basis, takes exactly the form of the object:

$$\Psi_{\mathbf{k}_s\mathbf{k}_i} = t(\mathbf{k}_s + \mathbf{k}_i),$$

where $\mathbf{k}_s$ and $\mathbf{k}_i$ are the momenta of the signal and idler photons, respectively, and t is the object. These correlations are measured by Fourier imaging the down-converted field onto a single-photon-sensitive camera and detecting coincidences between all pixel pairs [9]. Note that in our experiment, the crystal is cut to produce frequency-degenerate (810 nm) photon pairs with the same polarization (Type I SPDC).

To intuitively understand the shaping of correlations, we first consider the case without the object and lens before the crystal. The collimated pump at the crystal implies a near-zero transverse momentum ($\mathbf{k}_p \approx 0$), leading to strong anti-correlations between the signal and idler photons momenta: $\mathbf{k}_s+\mathbf{k}_i \approx 0$. Each time a photon is detected at a certain position on the camera (placed in the Fourier plane of the crystal), its twin appears in the symmetrical position. These strong anti-correlations form a sharp central peak in the measured correlation image (Fig. 2b), constructed by summing the signal and idler photon positions for each detected pair ($\mathbf{k}_s+\mathbf{k}_i$).

With the lens, the pump is focused on the crystal, broadening its transverse momentum ($\mathbf{k}_p = \Delta\mathbf{k}$, with $|\Delta\mathbf{k}| >> 0$). Momentum conservation now gives $\mathbf{k}_s+\mathbf{k}_i = \Delta\mathbf{k}$, reducing the strength of anti-correlations and widening the correlation peak (Fig. 2c). Note that only the spatial correlations are affected - the direct intensity remains uniform.

Placing an object (e.g. a 'sleeping cat') in the back focal plane of the lens projects its Fourier transform onto the pump field at the crystal. Conversely, this means the pump field transverse spatial momentum in the crystal plane has exactly the cat shape. Momentum conservation effectively 'encodes' the cat shape into the photon pairs spatial correlations. Then, measuring coincidences in the Fourier plane 'decodes' the cat in the correlation image, while the intensity image remains uniform. Our approach enables shaping photon-pair correlations into arbitrary objects, without any information appearing in the intensity image.

CORRELATION-BASED IMAGING

A key aspect of this approach is the ability to reconstruct correlation images by measuring photon coincidences across all camera pixel pairs. In the work presented above and reported in Ref. [10], we used an EMCCD camera, requiring 2 to 10 hours to reconstruct a high-quality correlation image, depending on the object complexity. While suitable for proof-of-principle demonstrations, this duration is impractical for real-world applications.

In recent years, new technologies have emerged, significantly accelerating this process. Among them, single photon avalanche diode (SPAD) cameras or intensified • • •

The TPX3CAM is an advanced intensified hybrid Complementary Metal-Oxide-Semiconductor (CMOS) sensor designed for single-photon detection. This sensor is based on technology originally developed for particle detection at CERN. An optically sensitive silicon sensor is bonded to a specialized fast readout chip. This combination results in a sensor featuring 256×256 pixels, each measuring 55µm × 55µm, with exceptionally high quantum efficiency. To achieve single-photon sensitivity, the incoming signal must be amplified. This is accomplished by placing a photon intensifier in front of the sensor. The intensifier consists of a photocathode that converts the incoming light into an electron beam. This electron beam is then amplified using a multichannel plate (MCP) and subsequently converted back into photons by a scintillator. The intensifier has a quantum efficiency of 20% at 810nm. The photon flash produced during the amplifying process hits more than one pixel on the camera, but centroid algorithms resolve this by identifying the central pixel based on spatial distribution and timing. This sensor distinguishes itself from others on the market with its event-based operating mode, in contrast to the frame-based approach used by most other cameras.

The high-speed readout chip records each pixel individually, assigning a time tag to each photon that strikes the sensor with sufficient energy. Each time tag corresponds to a detection event. The detection process operates as follows: each pixel has its own electrical threshold Vth, and only pixels that exceed this threshold trigger the readout process and time measurement. The chip records the Time of Arrival (TOA) with a precision of 1.56 ns and the Time Over Threshold (TOT) with a precision of 25 ns. These two time tags are subsequently used in the centroid process, enabling single-photon sensitivity. This new technology makes it straightforward to detect temporal coincidences between photons. In post-processing, a temporal correlation window of width ΔT is applied across the entire dataset. Within this window, all pixel positions corresponding to detection events are examined. If at least two events occur within the same temporal window, the pixel positions of these events are identified and recorded. By repeating this process for all time intervals in the dataset, a spatial coincidence map is constructed. This map highlights the positions of pixels where coincident detections occurred, enabling the recovery of spatial correlations between photons with high precision.

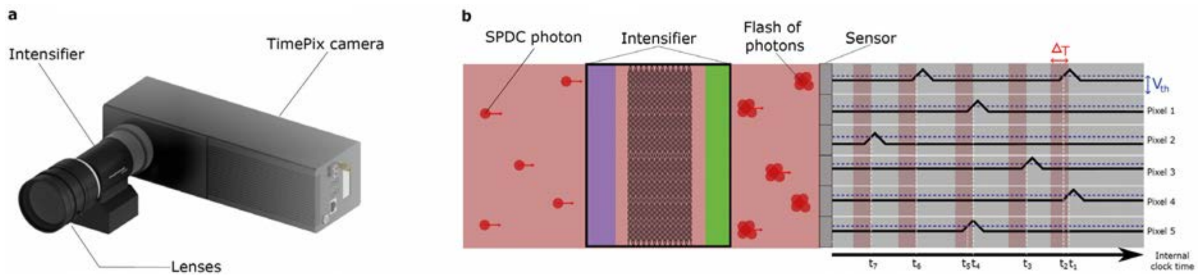


Figure 4. a, Tpx3Cam camera setup configuration (the computer is not represented). b, The incoming SPDC photons interact with the intensifier resulting in a flash of photons. Those are detected by the CMOS sensor and the electronic signal is recorded by the fast readout electronics embedded in the sensor. Post processing enable the correlation measurement between the pixels.

time-stamping cameras, such as the Tpx3Cam (see box), are extremely promising. They benefit from a much higher temporal resolution, typically 1-10 ns, higher frame rates - up to 8.10^5 frames per second - and can operate in an event-based detection mode, which considerably simplifies output data processing. Integrated into our experiment, the Tpx3cam enables, for example, the acquisition of correlation images in under 10 seconds with quality comparable to those obtained with the EMCCD, representing a 1000-fold reduction in acquisition time. Preliminary results obtained with this camera are shown in Figure 3.

These new camera technologies will facilitate the use of our encoding-decoding imaging scheme and gradually lead it towards potential applications. For example, promising avenues we are exploring include the possibility of transmitting images in an absolutely secure manner, bridging the fields of quantum key distribution and imaging. Another key direction is improving image transmission through complex or aberrating media, such as atmospheric turbulence, fog, or biological tissues, where quantum light demonstrates greater robustness than classical signals.

CONCLUSION

As seen through the example described in this paper, correlation-based quantum imaging approaches - a subcategory of optical quantum imaging and sensing schemes - represent a new form of imaging with significant potential. However, it is also evident that substantial technological efforts are still required for these proof-of-principle experiments to transition to real-world applications and compete with classical imaging systems. Among the most critical are the limited photon detection efficiency of single-photon sensitive cameras - rarely exceeding 30 % - and the inherent inefficiency of SPDC in generating correlated photons. While these limitations are still manageable when working with two-photon states, the scaling rapidly deteriorates for generating and detecting N-photon states: both photon detection efficiency and conversion probability decrease exponentially with N.

Despite its current limitations, recent progress in quantum imaging is encouraging. Alternative photon sources to SPDC, such as semiconductor quantum dots [11], are being actively developed and show promise. Simultaneously, event-based cameras with higher quantum efficiency and improved temporal resolution are advancing, often driven by consumer market demands – such as the integration of SPAD cameras in smartphones. As these technologies continue to evolve, quantum imaging remains most relevant for specialized applications, including biological imaging of photo-sensitive samples [4] and imaging in challenging wavelength ranges [12].

REFERENCES

[1] H. Defienne, W. P. Bowen, M. Chekhova, G. B. Lemos, D. Oron, S. Ramelow, N. Treps, and D. Faccio, Nat. Photonics **18**, 1024 (2024)

[2] C. A. Casacio, L. S. Madsen, A. Terrasson, M. Waleed, K. Barnscheidt, B. Hage, M. A. Taylor, and W. P. Bowen, Nature **594**, 201 (2021)

[3] R. Tenne, U. Rossman, B. Rephael, Y. Israel, A. Krupinski-Ptaszek, R. Lapkiewicz, Y. Silberberg, and D. Oron, Nat. Photonics **13**, 116 (2019)

[4] P. Cameron, B. Courme, C. Vernière, R. Pandya, D. Faccio, and H. Defienne, Science **383**, 1142 (2024)

[5] D. C. Burnham and D. L. Weinberg, Phys. Rev. Lett. **25**, 84 (1970)

[6] C. Couteau, Contemp. Phys. **59**, 291 (2018)

[7] O. Yesharim, S. Pearl, J. Foley-Comer, I. Juwiler, and A. Arie, Sci. Adv. **9**, eade7968 (2023)

[8] A. Mair, A. Vaziri, G. Weihs, and A. Zeilinger, Nature **412**, 313 (2001)

[9] H. Defienne, M. Reichert, and J. W. Fleischer, Phys. Rev. Lett. **120**, 203604 (2018)

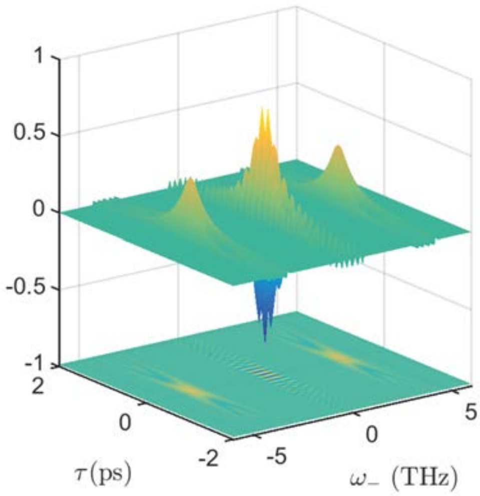
[10] C. Vernière and H. Defienne, Phys. Rev. Lett. **133**, 093601 (2024)

[11] J. Loredo *et al.*, Nat. Photonics **10**, 340 (2016)

[12] D. P. Ryan, K. Meier, K. Seitz, D. Hanson, D. Morales, D. M. Palmer, B. Hanson, P. M. Goodwin, R. Newell, R. M. Holmes, *et al.*, Optica **11**, 1261 (2024)

LIGHT AND COLOR: PHOTONIC RESOURCES FOR QUANTUM METROLOGY

Pérola MILMAN*, Eloi DESCAMPS, Othmane MESKINE
Laboratoire Matériaux et Phénomènes Quantiques, Université Paris Cité, CNRS, UMR 7261 – 10, rue Alice Domon et Leonie Duquet, 750
***perola.milman@u-paris.fr**



https://doi.org/10.1051/photon/202513148

A finite precision is always associated with the estimation of a parameter, whether it is time, length, or a rotation angle. What does fundamentally limit this precision, given a fixed amount of resources—such as total energy—that are used in parameter estimation? The answer depends on whether classical or quantum strategies are employed. In this paper, we explore the fundamental precision limits of metrological protocols, with a focus on how quantum optics and photonic devices can achieve a quadratic improvement in precision compared to classical setups while using the same amount of resources. We analyze both theoretical aspects and experimental demonstrations, highlighting the respective roles of field statistics and spectral properties in enhancing precision.

BASIC PRINCIPLES OF QUANTUM METROLOGY

Precision plays an essential role, not only in technology, but also in our daily life. Optimizing precision is particularly important when it relates to time measurements: time is considered by some as our most precious resource - or the most important parameter. In optical setups, the precision associated with time (or temporal delay) measurements, is often related to the field's spectral properties. For instance, for classical monochromatic fields, the time estimation precision limit is roughly said to be the inverse of the field's frequency. However, in quantum optics, light is characterized not only by its modal properties - such as spatial or frequency modes - but also by the statistical distribution of photons. This dual nature encapsulates the interplay between the wave-like and particle-like aspects of light. The study of parameter estimation and the associated precision is called metrology. In this contribution, we will discuss how quantum optical strategies can be applied to this field.

We start by recalling the basic principles of metrology, and its quantum counterpart. We will focus throughout this contribution into time estimation precision, but the description provided is valid for other parameters as well. The steps of a parameter estimation protocol are outlined in the pink squares of Box 1, that we will further explore in the context of quantum optics. The first step of the protocol involves generating a quantum state, such as a squeezed state or an entangled multi-photon state—both of which will be examined in greater details later in this article. This initial state serves as a probe, incorporating both modal and statistical properties.

In the "Evolution" step, information about the parameter to be measured (denoted τ) is imprinted onto the state. For instance, in the case of time estimation, this can occur through the free evolution of the field, which depends on the parameter (time) and is governed by a Hamiltonian (specifically, the free-field Hamiltonian). Next, a measurement is performed, yielding an outcome x with probability $P_\tau(x)$, which depends on the parameter to be estimated τ. From these outcomes, we define an estimator—a function that maps measurement results to the estimated parameter. The average value of this estimator over many experimental runs provides an estimate of the parameter's value, with a certain precision. Naturally, the higher the precision, the more accurate the measurement.

The precision limit can be calculated using the Fisher information, defined as $\mathcal{F} = \sum_i^M \frac{1}{P_\tau(x_i)}\left(\frac{\partial P_\tau(x_i)}{\partial \tau}\right)^2$, where x_i are the possible measurement outcomes of the experiment. Given a state and a parameter, there are a number of different measurements that can be implemented to infer the value of this parameter, leading to different probabilities $P_\tau(x_i)$. Using $\mathcal{F}$, we see that the precision associated with the measurement of the parameter τ is limited by $\delta\tau \geq \frac{1}{\sqrt{N\mathcal{F}}}$, where N is the number of repetitions of the experiment. This precision limit is known as the Cramér-Rao bound.

Increasing the precision of a given parameter estimation protocol involves finding measurement strategies such that $\mathcal{F}$ is as large as possible. But how large can $\mathcal{F}$ be? By optimizing the precision over all possible measurement strategies, we can define the quantum Fisher information (QFI): $\mathcal{Q} = max\,\mathcal{F}$, leading to the quantum precision limit, $\Delta\tau \geq \frac{1}{\sqrt{N\mathcal{Q}}}$, called the quantum Cramér-Rao bound. Hence, the best possible precision occurs when $\mathcal{F} = \mathcal{Q}$. And what limits the QFI ? For pure states undergoing Hamiltonian evolution (see Box 1), the QFI takes a relatively simple form: $\mathcal{Q} = 4\Delta^2\hat{H}$, where $\hat{H}$ is the Hamiltonian that generates the parameter dependent evolution into the state considered as a probe. Hence, given a Hamiltonian, the maximal achievable precision depends entirely on the choice of probe state. This is where quantum resources may offer advantages over classical ones.

Indeed, if we consider a system composed of K qubits, we have that each qubit can be prepared not only in states $|0\rangle$ and $|1\rangle$, the analogous of the classical bits 0 and 1, but also in states as $|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$, which

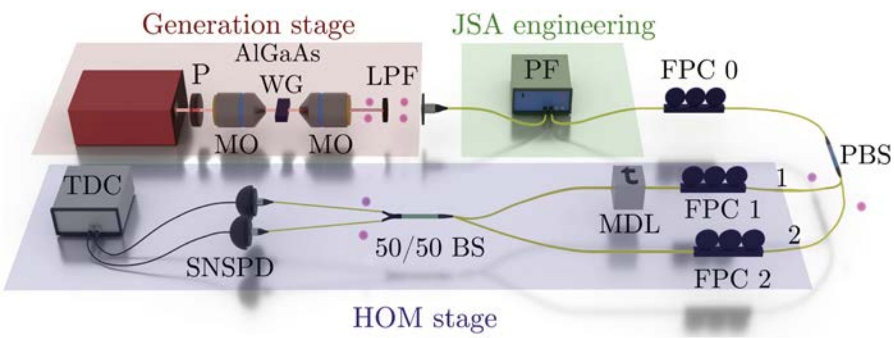


Figure 1. Experimental setup for investigating the metrological performance of the Hong-Ou-Mandel (HOM) experiment, showing the generation, joint spectral amplitude (JSA) engineering, and HOM interferometer stages.

is a quantum superposition of the values 0 and 1 with no classical analog. By combining $K > 1$ qubits, more complex states can be created. We can either produce separable states, as $|\Psi_1\rangle_1|\Psi_2\rangle_2...|\Psi_K\rangle_K$, where the qubits are independent from one another, or entangled states, as $\frac{1}{\sqrt{2}}(|0\rangle_1|0\rangle_2...|0\rangle_K+|1\rangle_1|1\rangle_2...|1\rangle_K)$. This state, analogous to a Schrödinger cat states, has no classical counterpart. While for separable states it has been shown that the QFI scales as $\mathcal{Q}\leq K$, for entangled states we have that $\mathcal{Q}\leq K^2$, so such states can lead up to a quadratic enhancement of precision. This is also the maximal possible precision enhancement that can occur in quantum metrology, and it is called the Heisenberg limit. Importantly, this enhancement occurs without increasing the resources which are, in the present case, the number of qubits. We now see how these results manifest in the context of quantum optics.

USING QUANTUM OPTICS FOR QUANTUM METROLOGY

We now detail the specific case of time precision limits in quantum optics. The free evolution leads to a time dependent phase to photon states, and temporal delays can be easily implemented in interferometers by creating a path length difference between two propagation modes. The recombination of the propagation modes leads to interference, which enables the measurement of this delay. The QFI associated with the estimation of temporal delays can then be calculated from the free propagation Hamiltonian and the state used as a probe. For a single frequency mode field, the free propagation Hamiltonian is given by $\hbar\omega\hat{n}$ where ω is the field's frequency and $\hat{n}$ an operator counting the number of photons of the field. However, it takes a slightly more complex form in the general case, when the field can be decomposed into different frequency modes. In this case, we can still obtain an intuitive expression for the QFI, which reads, for a single mode state, $\mathcal{Q} = 4(\Delta^2\omega\bar{n}+ \Delta^2\hat{n}\bar{\omega}^2)$, where $\Delta^2\omega$ is the frequency variance of the mode, $\bar{\omega}$ is average frequency, $\bar{n}$ is the average number of photons, and $\Delta^2\hat{n}$ the photon number variance. In general, the total photon number is not fixed, and paradigmatic states, as Gaussian states (squeezed and coherent states), consist of superpositions of different photon numbers. The expression of the QFI for a single mode is elegant, for treating symmetrically modal (frequency variables) and statistical (photon number variance) properties of the field.

In early quantum optics metrology, only single-mode states were considered. Coherent states, which are classical-like states, are an example of a single-mode state. They are a special case of Gaussian states for which the photon number follows a Poissonian distribution. The QFI of a coherent state is given by $\mathcal{Q} = 4\bar{n}\bar{\omega}^2$. We see that the average photon number appears here as the analog to the number of qubits K, and we recover the known classical result that the precision in time estimation is limited by the inverse of the frequency for monochromatic fields. Photons in a coherent state behave as independent particles, explaining the observed analogy with the separable states of qubit systems described earlier.

If we fix the average field's energy as the available resource (i.e.,$\hbar\bar{n}\bar{\omega}$), how can we obtain the quadratic scaling in precision observed in qubit-based quantum metrology? It has been shown [1] that the optimal metrological strategy concentrates all resources into a single mode. In this case, the frequency variance appears as a classical-like quantity, and doesn't play a role in the scaling of precision enhancement. However, some non-classical states can enable $\Delta^2\hat{n}=\bar{n}^2$ Again, the average photon number plays the same role as the number of qubits, leading to a quadratic precision enhancement—the Heisenberg limit.

The previous results assume that modal properties (frequency) and statistical properties (photon number) are independent. However, this is not always the case. A key example is photon pairs, commonly used in Bell inequality experiments [2]. These states exhibit mode and particle entanglement and cannot be described as single-mode states. Frequency modes can also be entangled for photon pairs [3], and in this case, the QFI must be modified to account for mode correlations.

To explore this scenario, let us consider a system with K photons and K propagation modes. Each mode can host a single photon with its own frequency distribution. The free evolution Hamiltonian now depends on both propagation direction and frequency distribution in each mode. For a single propagation mode, the QFI follows from the single-mode expression: $\mathcal{Q}_i=4\Delta^2\hat{\omega}_i$ (where we have used the general expression for the QFI of a single mode, labled i, in the case where $\bar{n}_i = 1$, one photon per propagation mode). For K independent photons (in independent propagation modes), if we suppose, for simplifying reasons and without loss of generality, that all the variances are the same, the total QFI is given by $\mathcal{Q}=\sum_i^K \mathcal{Q}_i=4\Delta^2\hat{\omega}\, K$. This result resembles the QFI of coherent states and separable qubit states, since the precision scales linearly with the number of photons.

We can now consider a system of maximally entangled photons, both in frequency and in propagation direction. An example of such a state is $\frac{1}{\sqrt{2}}(|\omega_1\rangle \ldots |\omega_K\rangle + |\omega'_1\rangle \ldots |\omega'_K\rangle)$, where $\omega_i \neq \omega'_i$ for all values of i, that labels auxiliary modes. This state is the generalization of a pair of polarization entangled photons, where each photon is on a different propagation mode. For this state, the frequency variance in each mode is $\Delta^2\omega_i=\frac{1}{4}(\omega_i-\omega'_i)^2$. If the variance is the same for each propagation direction, the QFI becomes $\mathcal{Q}=\Delta^2\omega K^2$. Then, analogously to the case of entangled qubits, we recovered the quadratic scaling of precision with the number of particles (here, photons instead of qubits). However, now precision is also proportional to the frequency variance for each mode. Interestingly, in this case, we observe at the same time a wavelike behavior of the scaling and a particle-like one.

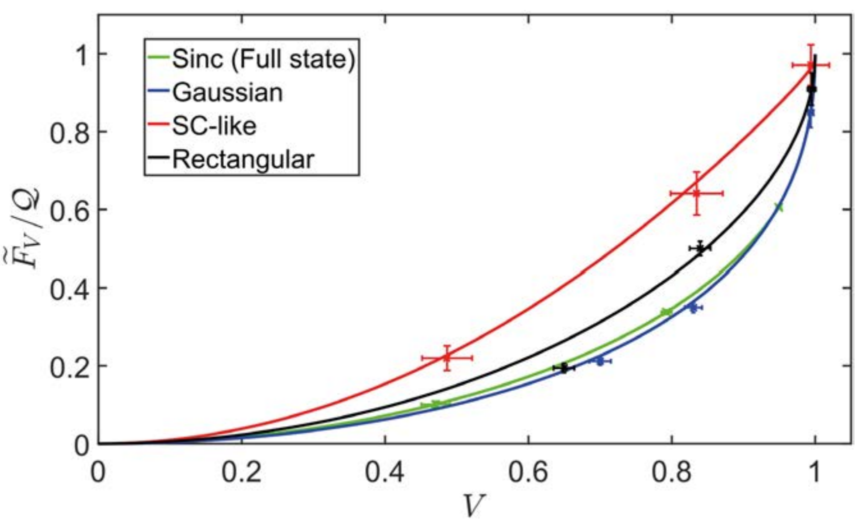
We have provided a broad picture highlighting how both modal correlations and particle statistics can lead to precision enhancement in quantum optics [4]. Nevertheless, two natural questions appear: the first one is, how can one engineer frequency entangled states, that permit achieving the Heisenberg precision limit ? On the other hand, what is the optimal measurement strategy, for which the Fisher information is equal to the QFI for this type of system ? We discuss these two questions in the next section.

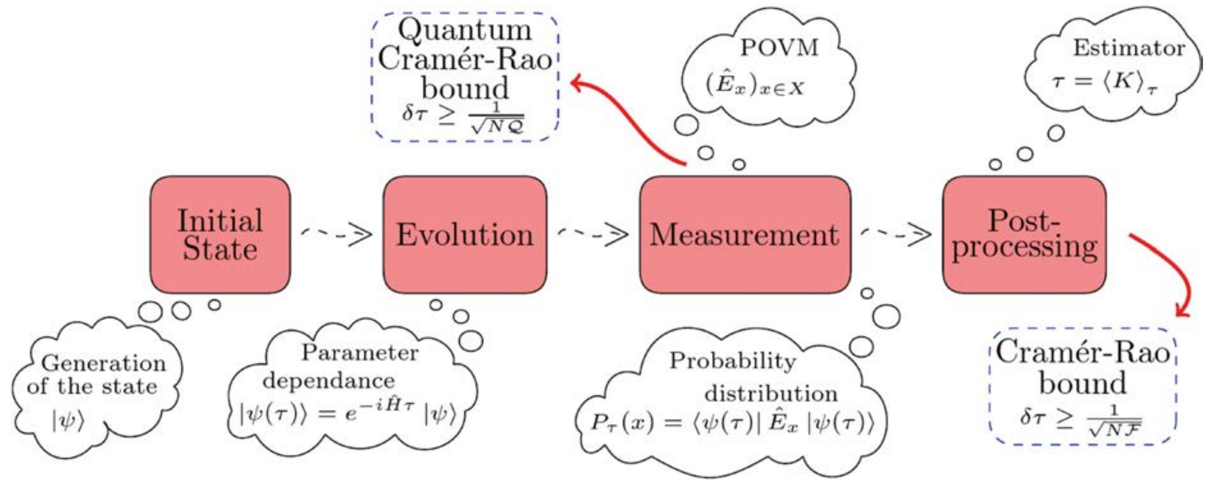
QUANTUM METROLOGY USING THE HONG-OU-MANDEL EXPERIMENT

Theoretically, the Hong-Ou-Mandel (HOM) interferometer [5] was shown to be an optimal measurement tool as it allows the quantum Cramér-Rao bound to be reached under ideal conditions of perfect visibility, where photons either perfectly bunch or anti-bunch. Not only it enables reaching the QFI, but also, in principle, the Heisenberg scaling of precision (even though this type of experiment is limited to two photons, precision is proportional to the square of the number of photons). Several experiments have shown the approach to this optimal precision using different two-photon frequency entangled states [6].

However, in reality, perfect visibility is unattainable due to experimental limitations. Interestingly, the •••

Figure 2. Scaling of the ratio $\tilde{F}_V/\mathcal{Q}$ for different biphoton states with respect to the HOM visibility V. For SC-like states a maximal value of $\tilde{F}_V/\mathcal{Q}$ is attained for $V = 99.4\%$.





Basic principles (pink boxes) of a metrological protocol, using classical or quantum resources. The boxes and thought bubbles correspond to relevant actions of quantities which are specific to quantum protocols. The "generation of the state" is considered as a black-box outputting a given quantum optical state (as an entangled or squeezed state). In "Evolution", a unitary operator generates a parameter depending evolution, and the resulting state now depends on the parameter to be estimated (τ in the example). The "Measurement" step can also be formalized as the application of Positive Operator Valued Measurements (POVMs), and the probability of obtaining an outcome x depends on the parameter τ. In the post-processing, this probability can be used to infer, by using an estimator K, the value of the parameter κ from the probability distribution $P_\tau(x)$ obtained from the measurements. The precision $\delta\tau$ associated with this procedure on the obtained value of τ can be computed using the Cramér-Rao bound, where N is the number of repetitions of the experiment and $\mathcal{F}$ is the Fisher information (details in the main text). The Fisher information depends on the measurement performed (the POVM $\hat{E}_x$). An optimization over all possible measurements leads to the quantum Fisher information $\mathcal{Q}$ and to the quantum Cramér-Rao bound, which can be up to quadratically smaller than the Cramér-Rao bound (depending on the chosen initial state), leading to a better-than-classical precision.

consequences of this fact are extreme: a finite visibility leads to the impossibility of reaching the QFI under any circumstances in this experiment. It is however possible to understand the approach to the maximal possible Fisher information in this set-up: the effects of a finite visibility highly depend on the spectrum of the entangled two-photon state (and not on its variance, as previously). In order to better understand these points, we recall the basic principles of the HOM experiment and interpret it as a metrological protocol.

In the HOM setup, two photons in two different propagation modes (as in the previous model) are injected into the two input ports of a 50/50 beam splitter. One of the modes is temporally delayed with respect to the other: this delay is the parameter to be measured, and the free propagation Hamiltonian is the time (parameter) dependent generator of the evolution. After the beam-splitter, either both photons exit through the same port (bunching effect), or they exit through opposite ports (anti-bunching effect). Coincidence detection at the outputs determines whether the photons have bunched or not. The time delay in one path changes the distinguishability of the photonic modes, altering the coincidence detection probability and enabling measurements of time or path differences. The precision we compute is associated with this measurement, and the idea is to optimize the Fisher information associated with this quantity.

We have demonstrated in [7] how the spectral properties of the quantum state affect the scaling of precision with visibility. To explore this, we engineered various types of frequency entangled two-photon states and tuned the visibility of the HOM interference. The quantum source employed is an AlGaAs Bragg reflection waveguide, which generates polarization-entangled photon pairs *via* type-II spontaneous parametric down-conversion. As illustrated in Fig.1, a continuous-wave laser with a wavelength of 772.42 nm pumps the waveguide, producing pairs of horizontally and vertically polarized photons that are collected in single-mode fibers and directed to a programmable filter. This filter enables the engineering of the spectral distribution (joint spectral amplitude) of the photons. This step corresponds to the "Initial state" preparation in Box 1. At the filter output, the photon pairs are separated - the "Evolution" step in Box 1 - with horizontally and vertically polarized photons entering the HOM interferometer through arms 1 and 2, respectively. Precise control over polarization distinguishability—and consequently, HOM visibility—is achieved using two polarization controllers (FPC1 and

FPC2), which allow for arbitrary polarization transformations. The temporal delay between the photons is controlled using an optical delay line (MDL) placed in arm 1. The two paths are recombined and separated by a 50/50 beam-splitter (BS). Finally, the photons are sent to superconducting nanowire single photon detectors (SNSPD) - the "measurement" step in Box 1. Temporal correlations between the detected photons are analyzed by a time-to-digital converter (TDC).

The experimental results display an excellent agreement with the theoretical predictions: a quadratic behavior is observed for the ratio between the maximal Fisher information $\tilde{F}_V$ and the QFI, $\tilde{F}_V/\mathcal{Q}$. The curvature of the parabola depends on the state, and we confirm experimentally that for spectral distributions corresponding to Schrödinger cat-like states (states of the type $\frac{1}{\sqrt{2}}(|\omega_1\rangle_1|\omega_2\rangle_2+|\omega_2\rangle_1|\omega_1\rangle_2)$, precision decreases slower with visibility than for states with a Gaussian spectral distribution is $\int d\omega p(\omega)|\omega\rangle_1|\omega+\delta\rangle_2$, where is a Gaussian distribution and is a constant frequency. The experimental results are shown in Figure 2.

Figure 2 illustrates the evolution of the ratio between the maximum of the Fisher Information $\tilde{F}_V$ and the quantum Fisher Information $\mathcal{Q}$ as a function of visibility V for four engineered states. The results reveal that the Schrödinger Cat (SC)-like state exhibits the most favorable scaling behavior, outperforming the Gaussian state. For instance, at a visibility of approximately 99.4%, the $\tilde{F}_V/\mathcal{Q}$ ratio is 0.97 for the SC-like state and 0.85 for the Gaussian state. Notably, the experimentally achieved ratio of 0.97 relative to the quantum limit is the highest ever reported, establishing a new benchmark in the field.

CONCLUSION

In conclusion, we have presented the fundamental ideas and concepts of quantum metrology in quantum optics, along with recent efforts to establish a unified framework for quantum metrology ranging from single photons in different modes to many photons in a single mode. This approach highlights the respective roles of field statistics and of modes of the field, which vary depending on the specific quantum state. Additionally, we have described an experiment that explores the metrological potential of a two-photon system, along with its limitations. A careful analysis of these limitations has led to a strategy for optimizing the ratio between the Fisher information and the quantum Fisher information in this type of experiment. Quantum metrology in quantum optics remains a rapidly evolving field. A more comprehensive understanding of the interplay between modes and states will be essential for fully harnessing the capabilities of quantum optics to reach ultimate precision limits.

REFERENCES

[1] O. Pinel *et al.* Phys. Rev. A **85**, 010101(R) (2012).

[2] A. Aspect, P. Grangier et G. Roger, Phys. Rev. Lett. **49**, 91 (1982); A. Aspect, J. Dalibard et G. Roger, Phys. Rev. Lett. **49**, 1804 (1982).

[3] F. Appas *et al.* npj Quantum Information **7**, 118 (2021).

[4] E. Descamps *et al.* Phys. Rev. Lett. **131**, 030801 (2023).

[5] C. K. Hong, Z. Y. Ou, L. Mandel, Phys. Rev. Lett. **59(18)**, 2044 (1987). Voir aussi: B. Vest and L. Jacubowiez, Photoniques **125**, 24 (2024).

[6] Y. Chen *et al.* npj Quantum Information **5**, Article number: 43 (2019); A. Lyons, Science Adv. **4**, vol. 5 (2018).

[7] O. Meskine *et al.* Phys. Rev. Lett. **132**, 193603 (2024).

QUANTUM IS IN THE EYE OF THE BEHOLDER

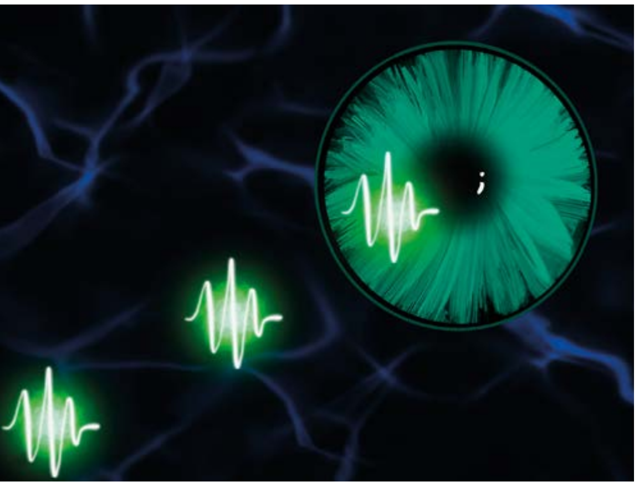
Gabriele BIZZARRI[1], Assunta DI VIZIO[1], Matteo ROSATI[2], Ilaria GIANANI[1], Marco BARBIERI[1,3,*]

[1] Dipartimento di Scienze, Università degli Studi Roma Tre, Rome, Italy

[2] Dipartimento di Ingegneria Civile, Informatica e delle Tecnologie Aeronautiche, Università degli Studi Roma Tre, Rome, Italy

[3] Istituto Nazionale di Ottica – CNR, Florence, Italy

*** marco.barbieri@uniroma3.it**



The evolving understanding of the limits of human visual perception has advanced the development of optical devices that not only correct visual defects but also help manage changes in certain eye structures. As modern optical technologies allow precise control of the quantum properties of light, recent endeavours have started testing the quantum capabilities of human eye perception, proving that they can detect single photons. This paves the way for the application of quantum metrology and cryptography to medical imaging, with potential increase in precision and security.

https://doi.org/10.1051/photon/202513154

Vision is the primary means for exploring the world. In the animal kingdom, we observe a variety of eye systems as different as the segment eye of insects, to the complex arrangements of some crustaceans [1]. In comparison, the human eye appears as a fairly simple system, with its three kinds of cones for colour vision, and its high density of receptors in the central fovea for spatial resolution. Yet, despite millennia of scrutiny, its structure and functions keep revealing unexpected subtleties. For instance, the peripheral retina is now held responsible for driving a feedback mechanism for the axial eye growth. Based on this hypothesis, improved corrections of myopia in young individuals have been realised, slowing its progression [2].

This demonstrates how a deeper scientific understanding of the eye can have profound implications for health and well-being. This has been made possible, until now, by steady technological progress that has resulted in novel instruments for diagnostics and analysis. Thanks to the efforts invested in enhancing imaging tools, we can now depend on fundus cameras, corneal topographers, and ocular aberrometers, to name a few, for the benefit of eye health and visual comfort. The current frontier in optical systems is beginning to expand its reach beyond issues in classical optics, exploring quantum aspects [3]. Advancements made in the last three decades now enable us to control light at the quantum level, including the ability to produce single photons with finely tuned spectral, temporal, and spatial properties.

These observations raise the question of whether quantum photonics can offer solutions for examining the eye, possibly down to the single photon level. We review results that establish this as a viable option, although with plenty of stimulating challenges ahead.

QUANTUM LIGHT AND THE EYE

Studies of the intensity threshold for human vision date back to the late 1800s, but fully reliable results were obtained much later, in the 1940s, through the pioneering work of Hecht *et al.* [4]. This research accounted for what the authors defined as "the best physical and physiological conditions." By using filtered light, both in wavelength and intensity, and paying meticulous attention to the calibration of absorptions in the eye media and rhodopsin, the authors established that "to see, it is necessary for 1 quantum of light to be absorbed by 5 to 14 retinal rods" [4]. The technology available at that time did not allow for control over the photon number. Subsequent investigations demonstrated the capability of retinal cells to detect single photons, thanks to a combination of four factors highlighted in [5]: 1. high efficiency, 2. low noise, 3. significant amplification, and 4. reproducibility of the signal waveform.

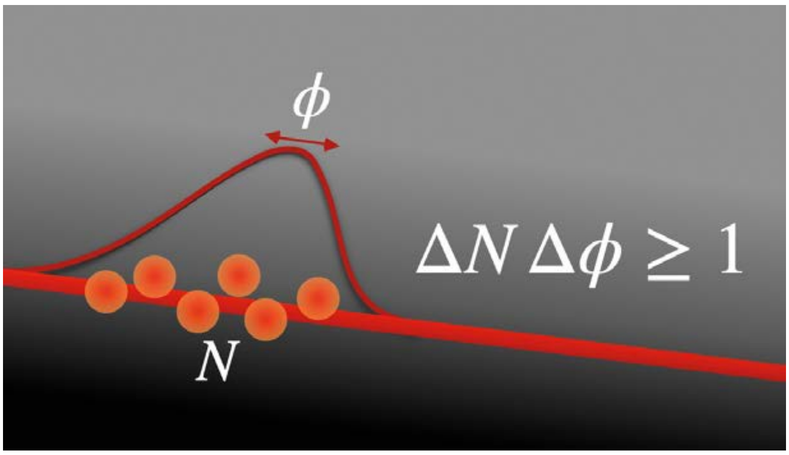
The advent of quantum photonics now allows for the production of single photons with an excellent degree of approximation, and this has led to experiments conducted with superior control. In particular, Phan and coworkers reported in 2014 [6] that ex-vivo retinal cells from Xenopus toads could produce a detectable signal when illuminated with single photons at 532 nm – the reported value of the second-order correlation $g^{(2)}(0)=0.08$ corresponds to a multiphoton suppression by a factor 12 with respect to classical light of equivalent intensity. The signal from individual cells, collected by means of an electrode, confirmed the presence of those remarkable detection properties.

The mere presence of such a physiological capability does not imply that this is then actually used in the visual function. In fact, a complex arrangement of neural cells processes the signal emerging from the receptors before this is transmitted over the optical nerve, and then there is the active interpretation of the stimulus by the brain. The confirmation that humans can actually see single photons directly – i.e. that they can be perceived by the visual system – has been published in 2016 by Tinsley et al. [7]. The authors have asked subjects to give a yes/no answer upon the stimulation from a single-photon source and to rate their confidence in their response. The probability of seeing a photon was found to exceed the random guessing baseline ($p_{see} = 0.516\pm0.010$), reaching even higher significance for high-confidence events ($p_{see} = 0.60\pm0.03$).

Using sub-Poissonian statistics for investigating vision is an intriguing exploration, partly connected to the question of whether and how quantumness is preserved in energy transduction in biosystems [8]. This however barely strokes the surface of the potential quantum photonics may hold for these investigations. There exists a much richer toolbox that can be put to good use. The eye can be considered as a quantum detector, thus its description can be elaborated in terms of detector tomography. This idea was first presented by van der Reep et al., considering the domain of the intensity response [9]. They showed that, even taking in due consideration the limitations of subjective responses from psychophysical tests and the • • •

QUANTUM CRYPTOGRAPHY AND QUANTUM METROLOGY

All quantum objects must satisfy Heisenberg's relation $\Delta x \Delta p \geq \frac{\hbar}{2}$ accounting for how the uncertainty on the quantity x limits the one on the conjugated quantity p. Photons can thus be prepared in quantum states with enhanced precision for measurements with respect to classical light, by suppressing the intrinsic fluctuations in one quantity by increasing those of another: this applies to polarization, to orbital angular momentum and to phase ϕ and photon number N, using the proper units. This implies, for instance, that a beam with suppressed phase fluctuations would show increased fluctuations of its intensity, and vice versa. In addition, an eavesdropper attempting to read the value of x would be caught, since it necessarily produces an increase in Δp. By exploiting the opportunities granted by Heisenberg's relation and turning its limitations to our advantage, it could be possible to combine precision and security in a single cryptographically protected scheme.



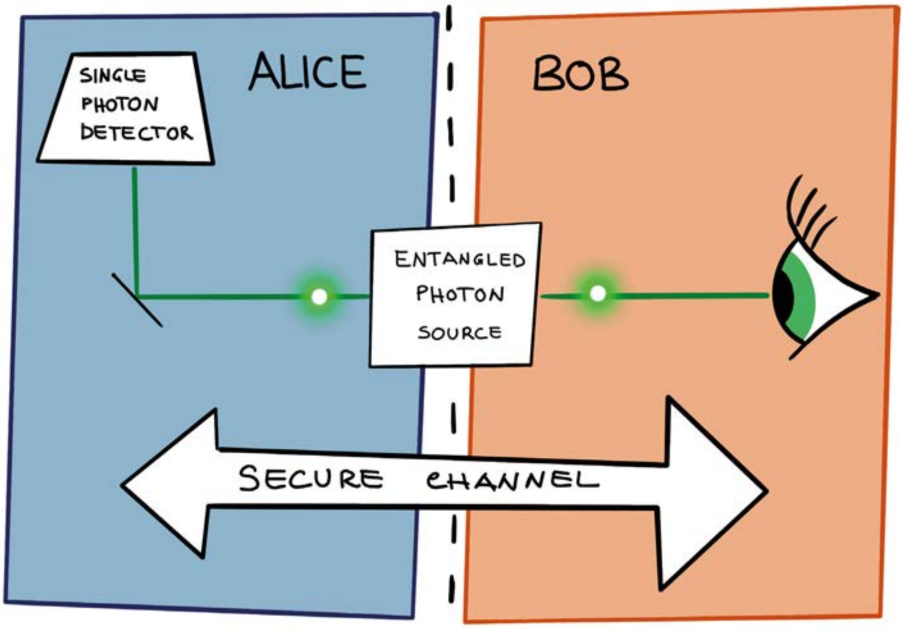
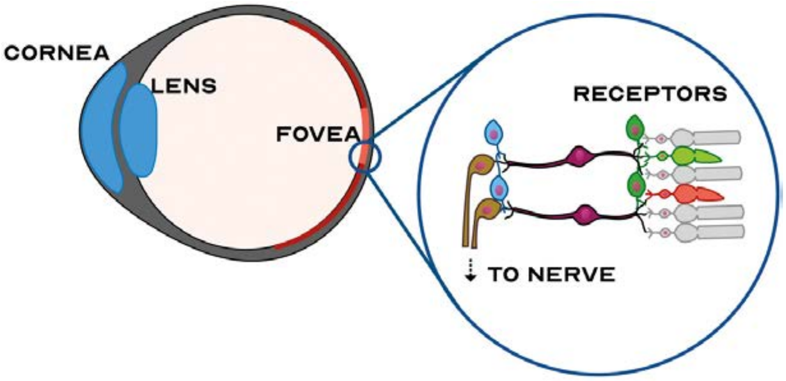


Figure 1. Quantum technologies may usher in a new way of performing measurements of the eye while ensuring secure transmission. Light controlled at its ultimate quantum level can be prepared in a state showing entanglement, ***i.e.*** a connection among its constituents beyond what is possible by purely classical means. These correlations can be so strong that, while the overall state is specified, each partition carries limited information. This is only retrieved when access is granted to the whole state. Measurement performed remotely by Alice on Bob's eye can thus be made secure by the use of entangled photons since verifying the integrity of their correlations provides a way to certify the integrity of the measurement itself using protocols of quantum cryptography. Light can thus serve as the means to observe and encrypt at the same time.

RETINA AS A DETECTOR

The eye can be considered as a detector with its entrance focussing elements (the cornea and the crystalline lens) and an active layer. This is composed of receptor cells containing rhodopsin or iodopsin molecules that undergo activation upon absorption of light by a phototransductive mechanism. This signal is conveyed to the brain via the optical nerve, but it passes first through a network of specialized neural cells. Different kinds of photoreceptors have a distinct spectral response and their density changes with the relative position to the central region of the fovea.



limited available time, an accurate reconstruction can be achieved. It could be interesting to extend those considerations also to the spatial domain, envisaging techniques to infer the spatial distribution of low-light sensitivity in individuals. Many ocular pathologies, especially those affecting the retina and the optical nerve, become manifest as alterations of vision with the appearance of blind spots. Typically, the disease at its onset exhibits a distinct spatial profile of the alteration. Tests at very low illumination levels that have access to the spatial resolution on the retina may uncover such pathologies at an earlier stage.

Loulakis and coworkers have introduced the intriguing idea of using quantum parameter estimation as a tool for biometric recognition [9]. Their original idea concerned the estimation of the transmissivity of the ocular medium as a marker based on "the photon-counting principles of human rod vision" [10]. This concept can also be extended to other ocular structures, such as the corneal surface or specific spatial characteristics of the pupillary frill and the optic nerve on the retina. Differently from the usual setting in quantum sensing, however, this valid proposal is faced with the challenge of taking into account the natural variability of those parameters. For instance, the opacity of the eye media is influenced by hydration. A good balance should be found between the required accuracy and precision demanded by biometry on the one side and the tolerance demanded by physiology.

The appeal of quantum light in such applications not only resides in its sensing power but also in the fact that it may become possible to combine the recognition protocol with secure data transmission. Controlling the quantum state of light is the key aspect that permits improved performance for precision measurement, but also what ensures security in quantum cryptography. Combining the two tasks in one system taking up both roles is a challenge that is emerging as a novel direction for quantum technologies [11]. The system that can be envisioned may consist in a two-beam state exhibiting quantum entanglement, linking the subject Bob to an operator Alice carrying out a measurement remotely. This ensures that Alice, by only sending one half of the total state, gives out limited information to the external world, but her additional knowledge from the second half provides her with means for measuring.

The detailed design of the scheme will demand addressing several trade-off conditions. The first concerns the quantum state itself that will need to be able to measure accurately and precisely as well as to protect the available information by revealing intrusions. A fine balance in its quantum properties should be met for the state to remain robust against imperfections such as loss and, at the same time, testable for security. The second aspect is related to the fact that data transmission typically uses infrared wavelengths, but these have limited applicability to measurements of the retina. This may require sophisticated photonics solutions for the realisation of efficient frequency converters.

CONCLUSION

Quantum metrology and cryptography are among the most promising quantum technologies to date, having led already to practical demonstrations and technological applications. Recent investigations into the single-photon detection capabilities of the human eye pave the way for wider usage of quantum-mechanical features in such systems while at the same time calling for considerable steps forward to balance traditional performance measures with medical safety. In taking up this challenge, it will be crucial not to forget the lesson that the best physical and physiological conditions should be met, and genuine progress would only emerge from collaborative, multidisciplinary efforts.

This new frontier of quantum-assisted medical imaging might advance both our fundamental understanding of human vision and our diagnostic capabilities, thanks to the use of lower-intensity signals achieving higher measurement precision and enabling the acquisition of medical data with privacy guaranteed by quantum-mechanical laws.

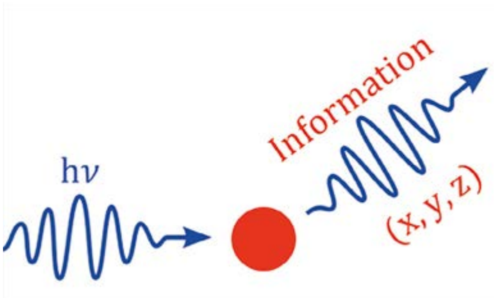
REFERENCES

[1] S. Kleinlogel, and A.G. White, PLoS ONE 3: e2190 (2008)
[2] A. Russo, A. Boldini, D. Romano *et al.*, J. Ophthalmol. **2022**, 1004977 (2022)
[3] E. Polino, M. Valeri, N. Spagnolo, and F. Sciarrino, AVS Quantum Sci. **2**, 024703 (2020)
[4] S. Hecht, S. Shlaer, and M. H. Pirenne, J. Gen. Physiol. **25**, 819 (1942)
[5] F. Rieke and D. A. Baylor, Rev. Mod. Phys. **70**, 1027 (1998)
[6] N.M. Phan, M.F. Cheng, D.A. Bessarab, and L.A. Krivitsky Phys. Rev. Lett. **112**, 213601 (2014)
[7] J.N. Tinsely, M.I. Molodtsov, R. Prevedel, *et al.*, Nat. Commun. **7**, 12172 (2016)
[8] Q. Li, K. Orcutt, R.L. Cook, *et al.*, Nature 619, 300-304 (2023)
[9] T. H. A. van der Reep, D. Molenaar, W. Löffler, and Y. Pinto, J. Opt. Soc. Am. A **40**, 285 (2023)
[10] M. Loulakis, G. Blatsios, C. S. Vrettou, and I. K. Kominis, Phys. Rev. Res. **8**, 044012 (2017)
[11] Z. Huang, C. Macchiavello, and L. Maccone, Phys. Rev. A **99**, 022314 (2019)

(QUANTUM) FISHER INFORMATION IN LOCALIZATION MICROSCOPY

Thomas JUFFMANN[1,2,*], Stefan NIMMRICHTER[3], Francisco BALZAROTTI[4] and Jonathan DONG[5]

[1] University of Vienna, Faculty of Physics, VCQ, A-1090 Vienna, Austria
[2] University of Vienna, Max Perutz Laboratories, Department of Structural and Computational Biology, A-1030 Vienna, Austria
[3] Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Siegen 57068, Germany
[4] Research Institute of Molecular Pathology (IMP), Vienna BioCenter (VBC), Campus-Vienna-Biocenter 1, Vienna 1030, Austria
[5] Biomedical Imaging Group, École Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland
***thomas.juffmann@univie.ac.at**



https://doi.org/10.1051/photon/202513158

The precise localization of particles yields structural and dynamical information in applications ranging from fundamental physics to molecular biology. Here, we discuss how the concept of (Quantum) Fisher information can guide the development of localization techniques. Starting from dipole scattering, we discuss imaging based on elastic and inelastic (e.g. fluorescence) scattering and present experimental designs that increase the information obtained per detected photon.

Microscopy and its ability to precisely localize and track single particles has become indispensable in biosciences, material science, and medicine. Most notably, single-molecule localization lies at the heart of many super-resolution fluorescence microscopy techniques, with applications in structural and cellular biology. Recently, elastically scattering particles have also gained attention, as the almost instantaneous scattering rates enable high speed and precision.

The precision in such applications is limited by the finite signal-to-noise ratio in the recorded data. While the signal depends on the properties of the sample and the chosen imaging technique, the noise comprises technical contributions, such as camera read-out noise, and quantum contributions, such as shot noise or backaction noise. The precision of a given technique can often be increased by averaging N consecutive frames. For N independent measurements, this increases the signal-to-noise ratio by $\sqrt{N}$, and improves the precision accordingly. However, this is not always possible. A desired temporal resolution or long-term setup stability might preclude longer averaging times. Furthermore, phototoxicity, heating, or camera limitations might preclude the recording at higher light intensity.

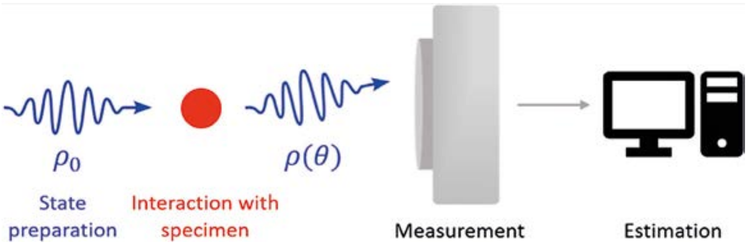
It is then crucial to obtain as much information per detected photon as possible. In estimation theory [1,2], one quantifies this in terms of the Fisher information (FI). It sets the Cramér-Rao bound (CRB) on the achievable estimation precision regarding a parameter of interest, such as particle location, in a given measurement scheme (see info box). The quantum Fisher information (QFI), defined as the maximum FI over all possible measurement schemes, then sets the more fundamental Quantum Cramér-Rao bound (QCRB) on estimation precision. It depends only on the properties of the probe light and the specimen. The FI and the QFI can thus guide the development of even more precise localization and tracking schemes.

Here, we discuss recent advances in the estimation-theoretical analysis of localization techn<iques. We start with the textbook example of localizing an elastically scattering particle in the near and the far field [3]. The much simpler far-field treatment gives rise to the intuitive picture of Fisher information flux [4]. Based on this framework, we assess the localization precision in interferometric scattering (iScat), dark-field [5], and fluorescence microscopy [2,6,7]. Finally, we discuss MINFLUX microscopy [8,9], which increases the information content per detected photon using adaptive measurements, prior knowledge, and tailored probe beams [10].

RESULTS

When illuminating a small non-absorptive particle with a plane wave, the light field induces an oscillating dipole that elastically scatters photons, which carry information about the particle's location (Fig. 1A). A quantum description of this dynamic interaction predicts transient peaks of the QFI in the near field [3]. The QFI oscillates at the optical frequency, indicating that information flows back and forth between the field and the internal degrees of freedom of the particle. The peaks can surpass the QFI accessible in the far field by orders of magnitude (Fig. 1B). It remains to be explored •••

Microscopy can be understood as a parameter estimation process [1,2]: First, a probe state of light ρ_0 is generated. This state could be as simple as a plane wave, have structured amplitude and phase, or involve entanglement or squeezing. Second, the probe state interacts with the sample, which encodes information about a parameter of interest θ into the probe state $\rho_0 \rightarrow \rho(\theta)$. Third, a measurement is performed on $\rho(\theta)$. Finally, one estimates the parameter from the outcome. As measurements are noisy, the estimate varies randomly and deviates from the true value θ. In the absence of bias, the standard deviation σ quantifies the error of the estimate and obeys the CRB $\sigma^2 \geq FI^{-1}$, where the FI quantifies the sensitivity of the measurement outcome distribution to deviations of θ. An estimator that saturates the CRB is called efficient. In the limit of many measurements, maximum-likelihood estimation is both unbiased and efficient. The QFI quantifies the sensitivity of $\rho(\theta)$ to θ-deviations and upper-bounds the FI for any measurement, which implies the QCRB $\sigma^2 \geq QFI^{-1}$. Both the FI and the QFI grow linearly with the number of independent measurements, which for classical light equals the number of detected photons N_d – hence the shot noise limit $\sigma^2 \propto N_d^{-1}$ in efficient and optimal measurements.



to what extent one can realize this potential in existing and future near-field microscopy schemes.

As the light propagates onward and no longer interacts with the particle, its information content about location saturates to the QFI predicted by far-field scattering theory. It is conserved upon free propagation, and its flux density can be calculated from the derivatives of the electric and magnetic fields with respect to the parameters of interest [4], in close analogy to the Poynting vector describing the energy flux density. For coherent probe light, the QFI is given by a simple expression [10] and results in QCRBs proportional to λ^2/N_s (or in terms of the minimal standard deviation, $\sigma \propto \lambda/\sqrt{N_s}$), reflecting the base resolution given by the photon wavelength λ and the detection shot noise over N_s independently scattered photons. Crucially, the elastic dipole scattering process is coherent, and the QFI lies not only in the scattered field, but also in its phase with respect to the excitation light. Such considerations are essential when designing a measurement that maximizes FI. For a given measurement, the FI can be calculated from the detected intensities and their derivatives with respect to the parameter of interest. In the absence of technical noise, it is limited by detection shot noise [2].

These concepts have been applied to various imaging scenarios. In iSCAT, the light scattered by a nanometric object is imaged onto a camera, where it interferes with the light reflected from the microscopy coverslip (see Fig. 1C). The resulting image holds information about the 3D position and the polarizability (mass) of *e.g.*, a protein or nanoparticle [5]. The QCRBs turn out to be $\sigma_x/\lambda \approx 0.13/\sqrt{N_d}$ in lateral, and $\sigma_z/\lambda \approx 0.04/\sqrt{N_d}$ in axial direction, with $N_d < N_s$ detected scattered photons. The excellent axial precision is due to the dependence of the resulting interference pattern on the path length difference between the scattered and reflected light. This advantage is lost in techniques without reflected reference, as the axial QCRB from the scattered light alone is $\sigma_z/\lambda = 0.19/\sqrt{N_d}$. The same formalism also gives an intriguingly simple precision bound for estimating the mass of a scattering protein: $\sigma_m/m = 1/2\sqrt{N_d}$.

In fluorescence microscopy, localization is based on inelastically scattered light. While typical microscopes yield an anisotropic localization precision, FI can guide engineering the wavefronts of the detected light to balance this anisotropy [6]. It also guides the design of complex imaging schemes that saturate the 2π collection QCRB [7], which is obtained when collecting light with a single high numerical aperture objective ($\sigma_{x,y}/\lambda \approx 0.11/\sqrt{N_d}$, $\sigma_z/\lambda \approx 0.29/\sqrt{N_d}$). Notably, interferometric detection of light collected with two objectives reaches the 4π collection QCRB ($\sigma_{x,y}/\lambda \approx 0.11/\sqrt{N_d}$, $\sigma_z/\lambda \approx 0.07/\sqrt{N_d}$). The increase in axial precision is now due to the relative phase between the fields collected in the forward and backward direction.

All schemes discussed so far assumed plane-wave illumination. Shaping the excitation beam profile can further boost localization precision, and the optimal shape can be calculated if the scattering matrix of the specimen and its

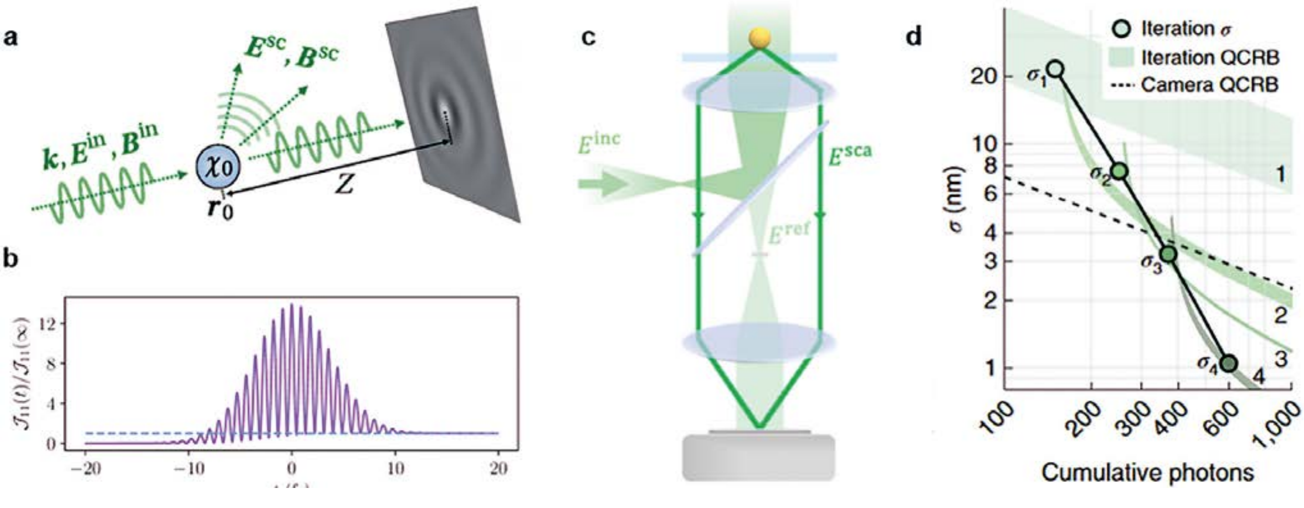


Figure 1. a) Elastic scattering generates electric and magnetic fields that carry information about the position and polarizability of the scatterer (adapted from [3]). b) While a light pulse interacts with a scatterer, the QFI is enhanced and oscillates before it ultimately approaches a constant value once the pulse has propagated to the far field (adapted from [3]). c) In an interferometric scattering microscope, the scattered fields interfere with fields reflected at the coverglass, leading to exceptionally high axial localization precision (adapted from [5]). d) In MINFLUX, one iteratively adapts the excitation beam shape in order to boost localization precision, which can surpass the QCRB for non-iterative, non-shaped excitation (taken from [9]).

dependence on the parameter of interest is known [10]. One practical example is MINFLUX [8], which improves the localization of fluorophores using an excitation beam that features an intensity zero, and that sequentially illuminates various spots within a region of characteristic size L. The CRB of MINFLUX scales as $L/\sqrt{N_d}$, which is independent of the diffraction limit. Furthermore, "iterative" MINFLUX [9] dynamically reduces L as photons are collected, enhancing the localization precision. Doing so in K steps yields an overall CRB scaling of $L/N_d^{K/2}$, which can beat the QCRB of non-adaptive schemes (see Fig 1D). MINFLUX typically reaches an isotropic CRB of $\sigma_{x,y,z}/\lambda \approx 0.06/\sqrt{N_d}$.

CONCLUSION

Treating microscopy as a parameter estimation task allows us to systematically benchmark and optimise imaging schemes based on rigorous statistical quantities. Does the error in my position estimate of a specimen reach the CRB for my measurement scheme? Does the FI of my measurement scheme reach the QFI of the probe state? These are questions every experimentalist can use to optimize the experiment. However, reaching the QCRB should not be seen as a final step. We discussed how the clever interferometric design in iScat yields an axial QCRB far better than other axial localization techniques. We have also seen how shaping the incoming light can yield better QCRBs, and how adaptive measurements in MINFLUX can even bypass the $1/N$ scaling of the QCRB. Further pathways to increased QFI can be found using quantum resources [1], such as entangled or squeezed states, or cavity-enhanced imaging [11]. Including prior knowledge can further guide the design and analysis of experiments and drastically improve results. We thus conclude that, as with many ultimate or fundamental bounds, it is important to know the underlying assumptions and to search for ways to overcome them.

REFERENCES

[1] L. Pezzè and A. Smerzi, At. Interferom. **188**, 691 (2014)

[2] J. Chao, E. S. Ward, and R. J. Ober, J. Opt. Soc. Am. A **33**, B36 (2016)

[3] L. Kienesberger, T. Juffmann, and S. Nimmrichter, Phys. Rev. Res. **6**, 23204 (2024)

[4] J. Hüpfl, F. Russo, L. M. Rachbauer, D. Bouchet, J. Lu, U. Kuhl, and S. Rotter, Nature Physics **20**, 1294 (2024)

[5] J. Dong, D. Maestre, C. Conrad-Billroth, and T. Juffmann, J. Phys. Appl. Phys. **54**, 394002 (2021)

[6] Y. Shechtman, S. J. Sahl, A. S. Backer, and W. E. Moerner, Phys. Rev. Lett. **113**, 133902 (2014)

[7] M. P. Backlund, Y. Shechtman, and R. L. Walsworth, Phys. Rev. Lett. **121**, 023904 (2018)

[8] F. Balzarotti, Y. Eilers, K. C. Gwosch, A. H. Gynnå, V. Westphal, F. D. Stefani, J. Elf, and S. W. Hell, Science **355**, 606 (2017)

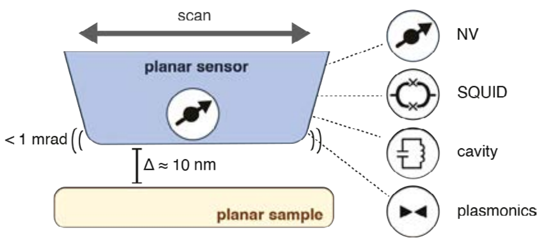
[9] K. C. Gwosch, J. K. Pape, F. Balzarotti, P. Hoess, J. Ellenberg, J. Ries, and S. W. Hell, Nat. Methods **17**, 217 (2020)

[10] D. Bouchet, S. Rotter, and A. P. Mosk, Nat. Phys. **17**, 564 (2021)

[11] T. Juffmann, B. B. Klopfer, T. L. I. I. Frankort, P. Haslinger, and M. A. Kasevich, Nat. Commun. **7**, 12858 (2016)

PLANAR SCANNING PROBE MICROSCOPY – THE ART OF LOW-LEVEL FLIGHT AT THE NANOSCALE

Friedemann REINHARD[1,2]
[1] University of Rostock, Institute of Physics, Rostock, Germany
[2] University of Rostock, Department of Life, Light and Matter, Rostock, Germany
***friedemann.reinhard@uni-rostock.de**



https://doi.org/10.1051/photon/202513162

An unorthodox optical approach to scanning probe positioning is opening a realm of novel applications in various fields of research. By using optical interferometry to carefully align a sensor parallel to a sample, even millimeter-sized sensors can be brought into nanometer-scale proximity of samples. Extended circuits and massively parallel arrays of sensors can thus be used as a scanning probe, a feat that would be impossible using established sharp tips.

For decades, scanning probe microscopy has been probing surfaces with various forms of sharp tips. Sharp conductive tips extract a tunnelling current from a sample in scanning tunnelling microscopy (STM). Sharp mechanical tips literally touch and feel the surface of a sample to reveal its topography in atomic force microscopy (AFM), similar to the needle of a vinyl record player. In both techniques the sharpness of the tip is critical for the spatial resolution that can be obtained, so that sharp tips have become considered a strict necessity for any kind of scanning probe approach. Interestingly, this paradigm remained unchallenged when a new generation of nano-sensors emerged in the past decades and promised to greatly expand the range of quantities that can be measured with nanoscale resolution. These sensors comprise nitrogen-vacancy colour centers few nanometers beneath the surface of a diamond to measure magnetic fields, plasmonic optical antennas for near-field microscopy and microfabricated microwave cavities to measure electron spin resonance. All these novel sensors share a central challenge. The sensors themselves are natively planar devices, microfabricated circuits on a substrate or defects under a crystal surface, but the established approach to scanning probe positioning requires the sensor to be a tip to provide force-feedback and to approach the sample as close as possible. Much effort has been spent to merge these incompatible worlds and fabricate extended sensors onto tip-like structures, *e.g.* by anisotropic dry etching of diamond sensors into nanopillars, or sophisticated evaporation of superconducting films onto

Figure 1. If an extended (10 µm – millimeter)-sized planar sensor is carefully aligned parallel to a planar sample, the sensor and the sample can be brought into nanometer-scale proximity of each other.

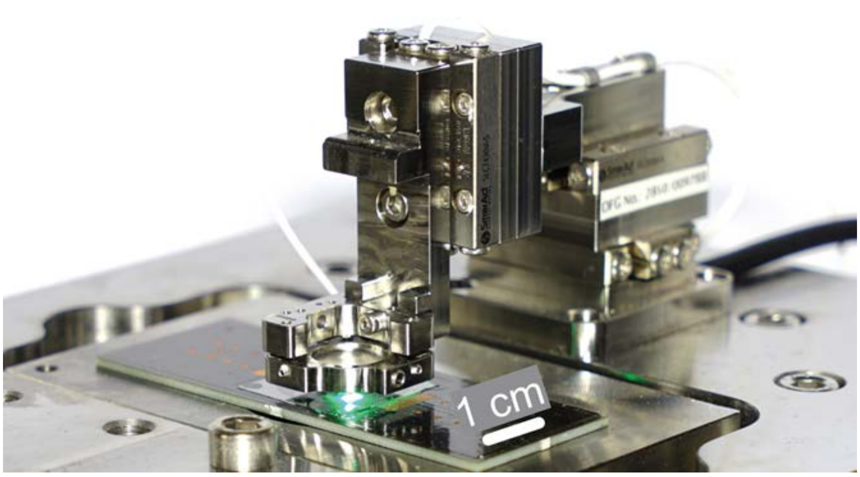
pulled glass nanofibers. In many cases, however, nanofabrication severely degrades the sensor quality and creates additional constraints on sensor layouts that can be fabricated.

We might, however, ask a radical question: do we really need a tip to do scanning probe microscopy? Surprisingly, the answer is negative. It is remarkably practical to bring an extended, (10 µm to millimeter sized), planar sensor surface nanometers close to a planar sample, if the sample is planar itself and free from any protruding contamination. Ensuring these constraints over a micron-to-millimeter large contact surface sounds like a daunting challenge, but is surprisingly well feasible. Already in the 19th century, optical machine shops mastered the technique of optical contact bonding, where two glass surfaces are ground to sub-nanometer scale smoothness and planarity, so that they can then be joined into optical contact and will hold together by intermolecular forces. Every hard drive in a computer employs a similar trick: the read-head slider is a millimeter-sized flat device which flies in nanoscale proximity to a planar recording medium, levitated by an air cushion. While the fly height can vary over the footprint of the slider, *e.g.* due to tilt, it reaches a minimum of only few nanometers at its trailing edge, where the read head is located. Preparing sufficiently flat and smooth surfaces thus is a century-old well-established technique. While even millimeter to centimeter scale surfaces can be machined with the necessary precision, in many applications it is preferable to restrict the planar surface to a smaller region, for example by fabricating the sensor or the sample into a 10-100 µm sized pedestal to relax the demands on alignment and contamination.

Mechanically aligning two flat surfaces with nanometer-scale precision parallel to each other is easily accomplished by commercial tip/tilt-positioners (Fig. 2). The key challenge is thus to measure the sensor-sample tilt and distance with sufficient accuracy to perform feedback control when aligning and approaching the sensor and the sample. It turns out that this is readily feasible for several optical schemes, even if this gap is only few nanometers small.

One straightforward choice for this task is interferometric microscopy. Conveniently, it can be implemented without an external reference arm by using reflection interference microscopy, a differential scheme where light reflected from the sensor-air interface interferes with light reflecting at the sample surface creating "Newton rings" [1,2] (Fig. 3). This differential scheme largely suppresses common-mode vibrations of the sample and the sensor. An alternative approach uses nanofabricated chirped optical gratings fabricated on the sensor and • • •

Figure 2. The positioning setup for planar scanning is a small modular add-on that can be installed on an inverted optical microscope.



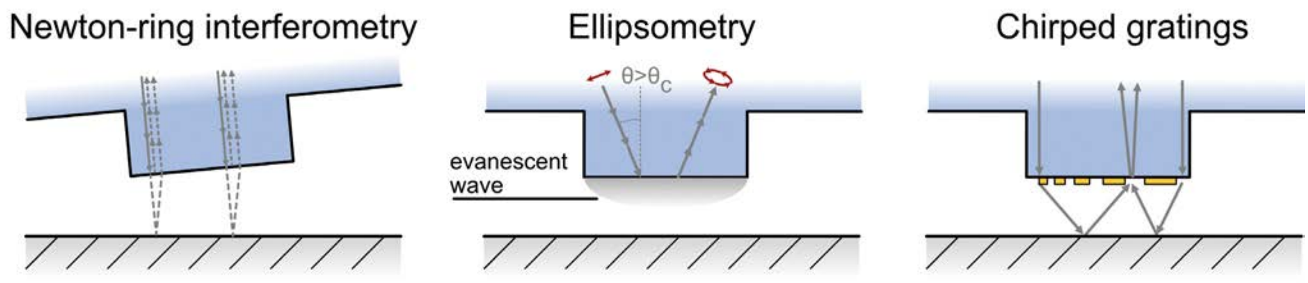


Figure 3. The tilt and the gap distance between the sensor and the sample can be measured by various optical schemes. θ_c critical angle.

the sample which create a far-field interference pattern that sensitively depends on the gap distance [3].

For sensor-sample gaps smaller than around 100 nm, the absolute value of the sensor-sample gap can also be measured by measurements based on optical polarisation, reminiscent of optical ellipsometry [2]. The sensor-air-sample multilayer is a dielectric multilayer system, similar to spin-coated photoresist films in nanofabrication, where ellipsometry is equally a workhorse technique to measure sub-wavelength film thickness. A suitable polarisation-sensitive imaging scheme is Brewster angle microscopy, where a polarized beam of parallel light is totally internally reflected off the sensor surface. If the gap is sufficiently small, the light can tunnel across it and instead reflect off the sample surface, giving rise to an altered polarisation. Crucially, this process can be modelled analytically, so that the gap can be quantitatively inferred from the polarisation rotation, similar to a film thickness measurement in ellipsometry. Notably, this measurement does not require to move the sensor and sample into contact to calibrate the zero-distance point, in contrast *e.g.* to "lift-mode" AFM. The sensor can thus be flown at a controlled height without ever physically touching the sample, enabling work with fragile sensors.

THE PAST – THE SURFACE FORCE APPARATUS AND EARLY PRECURSORS

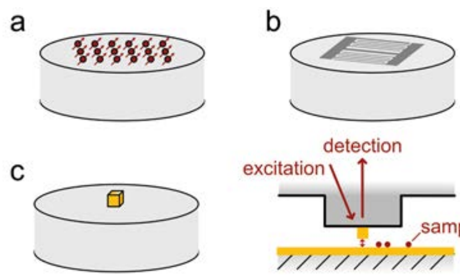
Approaching two planar surfaces into nanoscale proximity under optically controlled feedback has been explored in different contexts in earlier decades. One notable example is the "surface force apparatus" extensively used in nano-tribology. In this setup, two cylinders are approached into nanometer-scale proximity of each other under interferometric optical distance control to study forces between them. The use of cylinders greatly simplifies the design, because it ensures that the surfaces are parallel to each other at the contact point even without control of the tilt angle. Interestingly, even a scanning probe microscope with interferometric distance feedback has been demonstrated in the nineties to perform optical near-field microscopy [4]. Similar to the cylinder trick employed in the surface force apparatus, the sensor here was not planar but a hemispherical surface so that no tilt alignment was needed. However, the technique appears to have fallen out of fashion and to have been superseded by tip-based positioning schemes like shear-force feedback.

THE PRESENT – NANO-FLUIDICS, NEAR-FIELD OPTICS AND MAGNETOMETRY

The idea of aligning two planar surfaces parallel to each other and approaching them into nanoscale proximity has re-appeared in very different fields of research in the past decade, demonstrating its versatility and timeliness. Extensive work has been performed in the field of near-field optics, where it has been employed to position plasmonic antennas in plasmonic nano-lithography and study radiative heat transfer in nanoscale gaps [3], which is orders of magnitude faster than expected from blackbody theory for reasons still under discussion. The technique made an independent appearance in nano-fluidics where the planar setup is known as the "nanofluidic confinement apparatus" [1]. Here, the planar surfaces themselves are less of an interest than the fluid confined between them, which can be confined to a channel of constant and tuneable height by controlling the tilt and the distance of two planar plates. This approach has been employed to study the diffusion of nanoparticles in "Brownian ratchets", tooth-shaped surfaces where an alternating driving force together with random diffusion is rectified into a directed motion of the nanoparticles [5].

Finally, planar scanning probe microscopy has been introduced to the field of NV centers in diamond [2], where both defect-based near-field microscopy [2] and magnetometry [6]

Figure 4. Future possible sensors. a) arrays of NV centers. b) superconducting microcavities. c) plasmonic nanoparticles which can be operated as scanning nanogap cavities (right picture).



have been demonstrated with an extended planar bulk diamond. The technique here solves an outstanding challenge: NV centers have ideal properties when they are under a well-defined planar surface, but these properties easily degrade if nanofabrication is performed in their vicinity, *e.g.* plasma etching required to shape a nanoscale tip. Also, fabrication of a planar probe is considerably simpler than nanofabrication of nanoscale tips.

THE FUTURE – DIFFERENT SENSORS AND MASSIVE PARALLELISM

The most interesting question, however, is: what will we be able to do with planar scanning probes that could not be done with a scanning tip? One answer could be the wide variety of sensors that can potentially be used. Many emerging sensors are extended circuits, for example microfabricated superconducting magnetic resonance cavities which have recently become sufficiently sensitive to detect single electron spins. Even for pointlike sensors the ability to augment them by extended circuits is attractive. For instance, nitrogen-vacancy centers could be augmented by switchable nanomagnets to perform gradient-based magnetic resonance imaging of samples.

Another answer could be the ability to scan at a controlled nanoscale fly height without ever touching the sample. This could pave the way to using fragile nanoparticles as scanning probes, *e.g.* solution-synthesized epitaxial nano-cubes which have excellent plasmonic properties and promise much higher plasmonic enhancement than top-down-fabricated structures. Notably, arrangements of these nanoparticles, *e.g.* in the form of particle-on-mirror nanogap cavities, have achieved spectacular performance in stationary nano-fabricated assemblies, amplifying luminescence by up to four orders of magnitude and confining light to atomic scales [7]. Turning these plasmonic arrangements into a scanning probe scheme would open the door to optical microscopy with atomic resolution. Finally, massive parallelism is an attractive perspective. More than one sensor can be embedded into a single planar probe and can be operated in parallel. This is especially promising for sensors like NV centers, which suffer from a slow readout. Using massively parallel arrays of centers could enable scanning at high resolution (e.g. 4K pixels) and/or large (10 µm-mm) field of view, while fully preserving the nanometer-scale resolution of scanning defect centers. At a high density of NV centers, scanning could even be replaced by superresolution microscopy. Simultaneous scanning with multiple centers could also enable imaging of spatial correlations of signals by correlating the signal of different centers or even by creating quantum entanglement between them, which would open a new window into transport phenomena and spatial correlations in solid-state physics.

REFERENCES

[1] S. Fringes, F. Holzner, A. W. Knoll, Beilstein J. Nanotechnol. **9**, 301 (2018)

[2] S. Ernst, D. M. Irber, A. M. Waeber, G. Braunbeck, F. Reinhard, ACS Photonics **6**, 327 (2019)

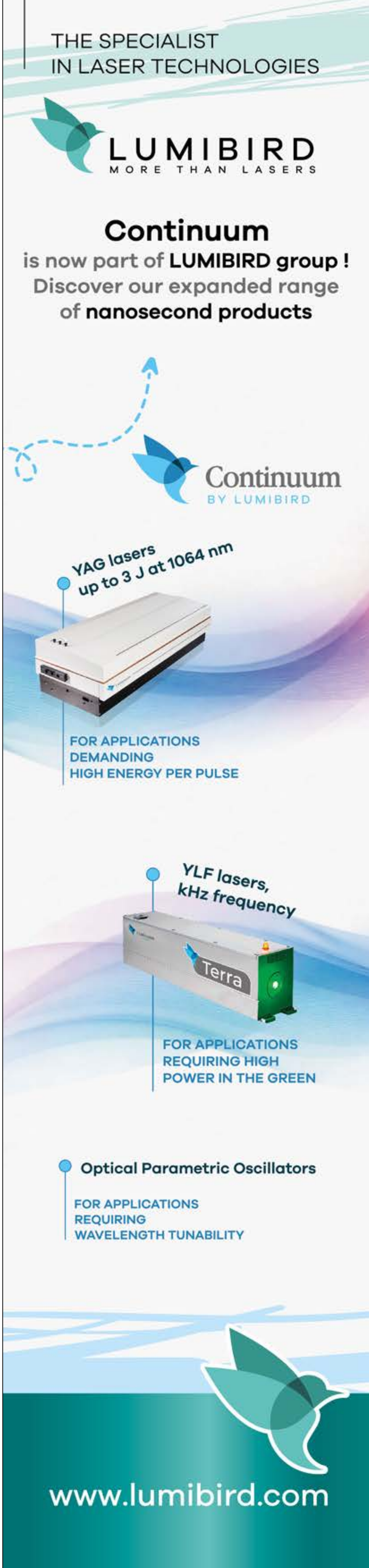
[3] H. Salihoglu *et al.*, Nano Lett. **20**, 6091 (2020)

[4] T. J. Silva, S. Schultz, D. Weller, Appl. Phys. Lett. **65**, 658 (1994)

[5] M. J. Skaug, C. Schwemmer, S. Fringes, C. D. Rawlings, A. W. Knoll, Science **359**, 1505 (2018)

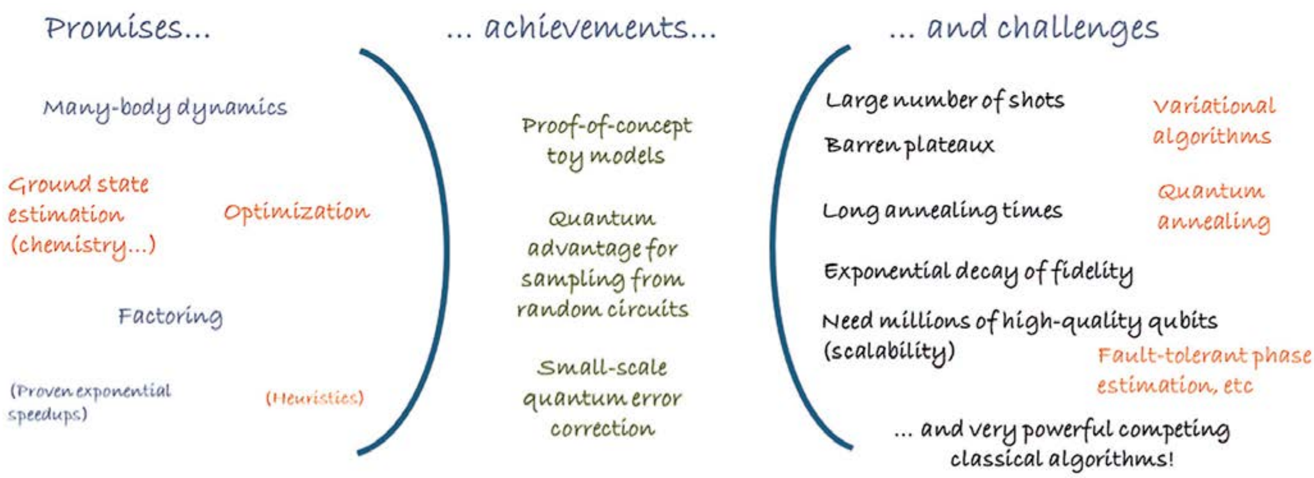
[6] P. Weinbrenner *et al.*, Quantum Sci. Technol. **10**, 015037 (2024)

[7] J. J. Baumberg, J. Aizpurua, M. H. Mikkelsen, D. R. Smith, Nat. Mater. **18**, 668 (2019)



QUANTUM COMPUTING: PROMISES, ACHIEVEMENTS AND CHALLENGES

Thomas AYRAL
Eviden Quantum Lab, 78340 Les Clayes-sous-Bois, France
thomas.ayral@eviden.com



Quantum computers regularly make the headlines, with optimistic claims (often issued by companies large and small) alternating with pessimistic rebuttals (often by academic labs): sometimes they supposedly solve outstanding hard computational problems, sometimes their performances are dwarfed by classical machines. The goal of this article is to shed light on this back-and-forth, and explain what quantum computing could really be useful for.

https://doi.org/10.1051/photon/202513166

WHAT IS A QUANTUM COMPUTER?

The term of quantum computer encompasses a large variety of physical implementations. All have in common the (more or less precise) manipulation of individual objects with quantum properties: the spin of electrons, the energy levels of atoms, the polarization of photons, or even current loops in electrical circuits. Most quantum computing systems are engineered so that only two states — usually called $|0\rangle$ and $|1\rangle$ — of these individual objects are reachable during a computation. What is quantum about these objects is that they can not only be in state $|0\rangle$ or in state $|1\rangle$ (as would be the case for classical bits), but also in an arbitrary superposition of both: $|\psi\rangle = \alpha|0\rangle + \beta|0\rangle$, with α and β two complex numbers.

More importantly, these two-level systems, usually called qubits (for quantum bits), can be coupled to one another by special operations: two neighboring atoms can be coupled *via* a van der Waals interaction, two electrical circuits by a capacitive coupling, for instance. This coupling generates a quintessentially quantum property called entanglement: the joint state of two entangled qubits cannot be described by specifying the individual state of each qubit. Hence, the state of two qubits, described by the superposition $\alpha_0|00\rangle + \alpha_1|01\rangle + \alpha_2|10\rangle + \alpha_3|11\rangle$ can in general not be factorized as $(\alpha_1|0\rangle + \beta_1|1\rangle)(\alpha_2|0\rangle + \beta_2|1\rangle)$. n qubits are thus described by 2^n coefficients. Conversely, N complex numbers could *a priori* be stored in $\log_2 N$ qubits! This exponential storage capacity can be leveraged in some algorithms, with an important caveat: reading out the information stored in the coefficients is not straightforward. Indeed, measuring a qubit in state $\alpha|0\rangle + \beta|1\rangle$ will only return 0 or 1 with respective probabilities given by the squared modulus of α and β. More than that, it will project the state to $|0\rangle$ or $|1\rangle$. Learning the precise value of α and β thus requires more work than meets the eye.

HOW TO PROGRAM A QUANTUM COMPUTER?

A quantum program is a list of instructions that evolve the state $|\Psi\rangle$ of the quantum computer from an initial state to a desired final state, which one can subject to quantum measurements in order to read off the solution to the problem at hand. From a physical perspective, these instructions essentially define a time-dependent Hamiltonian which, through Schrödinger's equation, completely determines the evolution of the system. The sequence of these instructions is commonly represented as a quantum circuit: a diagram whose horizontal lines represent qubits, and boxes represent the instructions, aka quantum gates that act on one, two or more qubits (lines) in a given order. For instance, the circuit used to implement a Fourier transform on a quantum computer is displayed in Fig. 1 for five qubits. Some gates (like the so-called Hadamard gate H) act on one qubit, corresponding to physical operations that act only on one qubit. They can put the qubit in a superposition state, but do not create entanglement. Some others (like the controlled-phase gates), act on two qubits, and may create entanglement.

A major theoretical advantage of quantum computers is that their quantum properties — superposition and entanglement — should afford them a computational advantage over classical processors. We can look at the Fourier transform circuit of Fig. 1 to understand this. On a quantum computer, executing a gate corresponds to a single operation, while on a classical computer, a generic quantum gate corresponds to a matrix-vector multiplication $U \cdot |\psi\rangle$. Since the vector in question is generally represented with size 2^n • • •

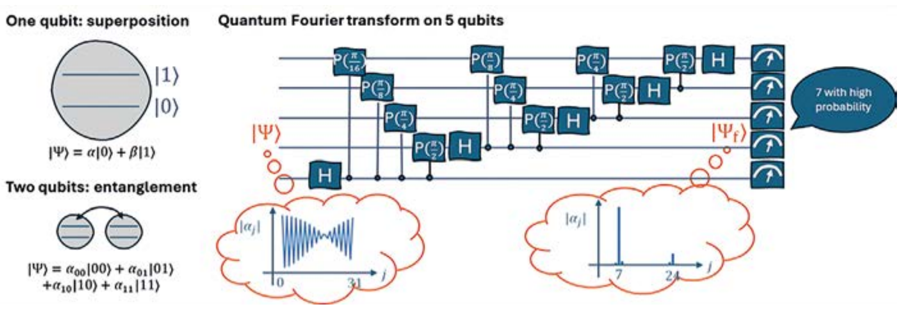
in a classical computer memory, this operation has an exponential cost in the number n of qubits. Bookkeeping all operations in the circuit, we arrive at a cost that scales as $n2^n$ on a classical computer (the cost of a fast Fourier transform), while it scales as n^2 on the quantum computer: this is an exponential gain!

Yet, this impressive gain has strings attached, with a theoretical limitation and a practical one. Let us first dwell on the theoretical one. Supposing the coefficients α_0, α_0,..., α_{2^n-1}, of the Fourier transformed state $|\psi\rangle$ correspond to the values of pixels of an image we would like to recover. Given the probabilistic nature of quantum measurements, to obtain these very coefficients, we need at least 2^n readouts to learn the histogram (which, in fact, is only enough to learn the modulus of the α_i's)... And because of the projective nature of quantum measurements, this means repeating the circuit at least 2^n times... causing us to lose the exponential advantage. This rule has only one exception: if, from all the coefficients, only a few (let us say only one, the kth one, α_k) are nonzero, then the result of reading out the final state is always the same: it returns k with probability 1. Thus, only one circuit execution and readout are required. If moreover, the solution of our problem was to find k, then we have indeed obtained a speedup. In other words, in many quantum algorithms, acceleration can be reached only when the final distribution of coefficients is highly skewed (peaked), and the solution can be read off the peaks of the distribution. This is typically what Peter Shor's famous factoring algorithm does [1]. This is also what makes it difficult to invent efficient quantum algorithms for machine learning: it usually involves reading out a lot of information (in additional to loading a lot of training data, which is also costly) [2].

The second limitation is practical: quantum states are fragile to external classical influence. This means that the longer a computation, the more likely it is to be destroyed by external influence. This deleterious influence, called decoherence, degrades the quality of quantum states, called fidelity, exponentially with the number of gates. Hence, with current processors, only 100-1000 gates can be applied before too much harm happens. The quantum Fourier transform we mentioned above, with its n^2 gates, is already out of reach: with $n = 100$ qubits, it would require about 10 000 gates!

The art of quantum algorithmics thus boils down to finding creative ways to extract computational advantage despite these limitations.

Figure 1. Quantum bits and quantum circuits. Top left: a single qubit can be in superposition of $|0\rangle$ and $|1\rangle$. Bottom left: two qubits can be entangled. Right: Quantum circuit representing a Fourier transform on $n = 5$ qubits, corresponding to a classical discrete FT on a vector of $N = 32$ points. The input wave function requires a potentially long preparation circuit. The output wavefunction (which contains the Fourier spectrum) is not directly accessible: only probabilistic measurements give access to the largest amplitudes.



WHAT USES FOR QUANTUM COMPUTERS?

The first concern of Richard Feynman, when he advocated the use of machines with quantum inside, was however not these intrinsically quantum limitations, but those of classical computers [3]. He had in mind a major conundrum of modern physics called the many-body problem. Ubiquitous in materials science, quantum chemistry, or nuclear physics, this problem arises in systems where interactions between particles matter. For instance, in solids, interactions between electrons are suspected to be the main origin of high-temperature superconductivity. Yet, interactions are also precisely the reason why these problems are difficult to tackle with classical computers: so-called mean-field approaches fail, and the more advanced methods that have been developed in the last fifty years all reach an exponential wall in some regime. For instance, tensor network techniques are sensitive to the amount of entanglement in the problem: their price scales exponentially with this entanglement. Monte-Carlo methods suffer from so-called sign problems that lead to statistical errors that diverge exponentially with system size or at low temperature [4].

Feynman pointed out that quantum computers, on the other hand, would be free from those ills, as information is directly stored in the system, and time evolution happens naturally through Schrödinger's equation, not *via* costly matrix vector multiplications (as in tensor networks) or high-dimensional integrals (computed in Monte-Carlo algorithms). In a way, by trying to simulate directly, namely with an artificial many-body system, the many-body physics that one is interested in, one does away with the problems of classical processors [5].

Quantum many-body problems are thus often believed to be among the first applications of quantum computers. As it turns out, outstanding computational problems

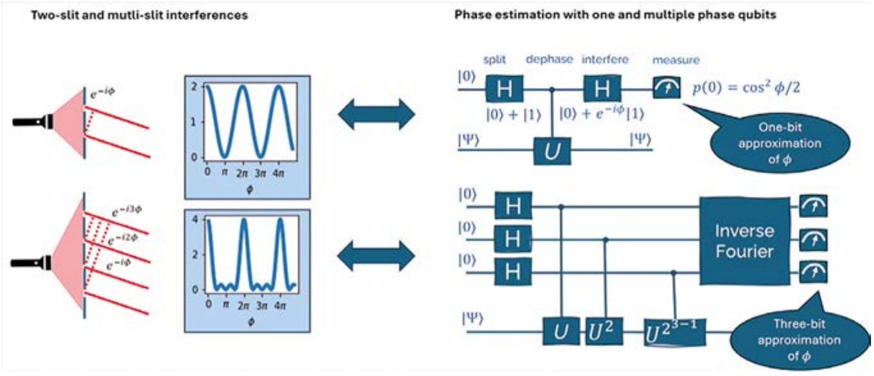


Figure 2. Analogy between interferometry in optics and quantum phase estimation with a quantum circuit. Left: interference between more waves leads to enhanced accuracy (sharper peaks) in the determination of the phase. Likewise, more phase qubits lead to a better precision.

outside of physics can also be regarded as many-body problems: a number of challenging optimization problems, like the famous travelling salesperson problem (find the shortest route to visit each city once and only once in a road network), can also be expressed as "interacting" Hamiltonians. Here, instead of physical interactions, interactions translate the fact that the different conditions on the sought-after solutions are interdependent. Thus, quantum time-evolution algorithms that relax the system to its resting state — which is hopefully the solution to the problem — were developed in this field of combinatorial optimization. Specialized computers called quantum annealers were even specifically constructed for tackling these very problems, with a major limitation: in principle, reaching the resting state takes very long times...

A second large class of quantum algorithms combines the natural time evolution afforded by quantum processors with another central physical phenomenon called interference: as in optics, adding two (or more) coherent waves yields a signal where the phase difference between the waves is easy to read out (see Fig. 2). Likewise, quantum computers engineer interferences between two (or more) signals whose phase difference contains the solution to a hard problem [6]. This algorithm, called quantum phase estimation, underlies Shor's factoring algorithm: the fact that the final distribution is peaked, as mentioned earlier, is a direct result of having many signals interfere in a smart way. Surprisingly, this phenomenon can also be used to invert systems of linear equations $Ax = b$. In this algorithm, the inversion is realized in a time that is exponentially faster than inverting the same linear system with classical algorithms [7]. Since linear systems are central to many application fields like solving partial differential equations, this has prompted many industrial companies to enter the field of quantum computing.

WILL QUANTUM COMPUTERS BEAT CLASSICAL COMPUTERS?

With the increasing availability of prototype quantum processors at the turn of the 2010s, these optimistic ideas were put to the test of reality in the last decade. In particular, practical implementations all face the exponential fidelity wall that we discussed above. With the error rates of current prototypes, between 1% and 0.1%, the number of gates that can be executed before decoherence sets in is limited to a few hundreds or thousands. This rules out all algorithms based on interference, which use a quantum Fourier transform and/or long, and therefore gate-intensive, time evolutions: applications like factoring numbers or inverting linear systems of equations are out of reach due to current (and mid-term) noise levels. In fact, even drastic improvements will not • • •

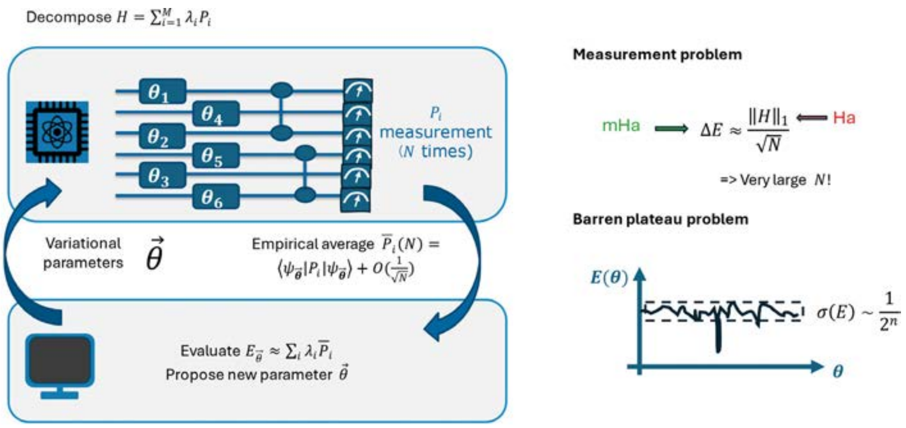


Figure 3. The variational quantum eigensolver algorithm... and its challenges. Left: VQE is a hybrid algorithm where the quantum processor (top) prepares a parameterized quantum state and measures the average values of the various Pauli terms that are contained in the Hamiltonian of the problem. These averages are combined into an estimate of the energy, which is used by a classical optimization algorithm to propose new parameters. The empirical average comes with a statistical error *ΔE* that leads to the so-called measurement problem of VQE (top right): the number *N* of samples required to reach chemical accuracies (1mHa) is very large. The energy landscape tends to be very flat for deep enough variational circuits, leading to trainability issues: this is the barren plateau problem (bottom right).

help much without the help of quantum error correction, a concept that Peter Shor borrowed from classical computers in the mid-1990s to fight against decoherence [8], and that we will touch on later.

CAN WE NEVERTHELESS SALVAGE SOMETHING FROM CURRENT PROCESSORS?

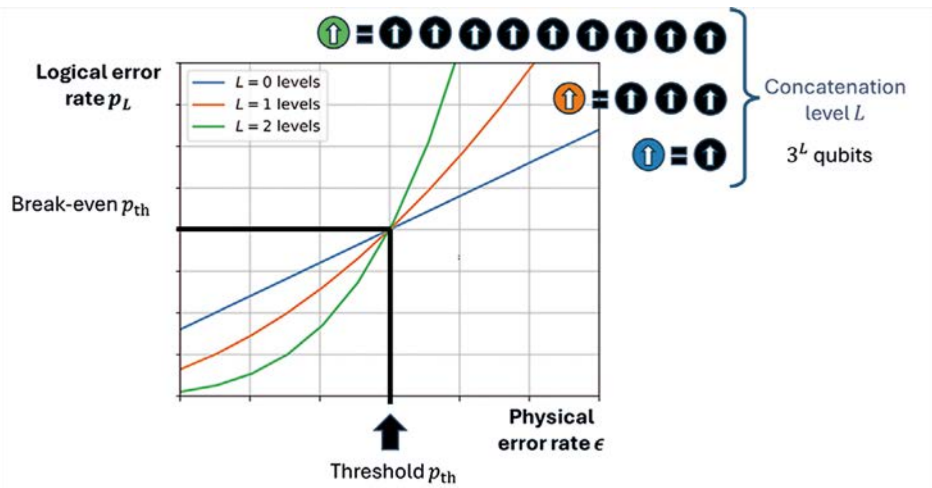
This goal is pursued by many researchers and engineers, with efforts to create algorithms that are short enough to beat decoherence, while at the same time overpowering classical processors.

To this aim, an old method, the variational method, was revisited with a quantum twist: to minimize the energy $\langle\psi(\vec{\theta})|H|\psi(\vec{\theta})\rangle$of a family of parameterized states, one uses a quantum computer to prepare a state $|\psi(\vec{\theta})\rangle$ and measure its energy, and a classical processor to propose new parameters $\vec{\theta}$ to reach a minimum of the energy landscape, as illustrated in Fig. 3. If the quantum computer can prepare states $|\psi(\vec{\theta})\rangle$ that are out of the reach of the best classical algorithms and measure their energy with high accuracy, this method, dubbed the variational quantum eigensolver (VQE [9]), could lead to some practical advantage. VQE, however, comes with two intrinsic limitations (in addition to decoherence): the probabilistic measurement of the energy requires many samples, and the training itself of the variational parameters turns out to be plagued with plateaus and hence exponential slowdowns [10].

The difficulties of VQE did not prevent "quantum advantage" claims on current processors. In fact, they were made without using VQE. For instance, the Google company resorted to random quantum circuits — which are known to produce very entangled states with a small amount of quantum gates — to argue they had reached "quantum supremacy" over classical machines [11]. Their first claims were rebutted by tensor-network based computations [12], but the newest generation of processors likely reached the initial goal [13]. This is however very far from any useful application.

Claims for useful quantum advantage were made by the IBM company in 2023 on a dynamical evolution problem [14], but they were quickly rebutted by classical computations, some of which were also based on tensor networks [15]. The relative ease with which classical computations reproduced or surpassed quantum computers can be attributed to the fact that physical systems usually obey constraints (like symmetries, conservation laws) that limit the growth of correlations or entanglement, and therefore make them tractable by classical algorithms, up to a certain point. Currently, the point where classical algorithms cease to work is

Figure 4. Principle of quantum error correction: by grouping several physical qubits into one logical qubit, one makes more noise-robust qubits, provided the physical (individual) error rate is lower than a certain threshold.



still beyond the point where decoherence makes quantum algorithms useless.

This mixed situation of current devices has prompted intense experimental efforts to make quantum error correction (QEC) work on the leading hardware platforms. QEC consists in protecting qubits against decoherence by spreading the information of one "logical" qubit over many "physical" qubits, and performing regular local measurements to detect and then correct local errors (see Fig. 4). Such a procedure is beneficial — the so-obtained logical qubit is better than the individual physical qubits — only if the individual qubits' error rates are below a certain threshold. Recent experiments have shown error rates below this threshold, opening perspectives for future QEC. However, the number of physical qubits required to implement algorithms such as time evolution, phase estimation or Shor's algorithm exceeds one million, far from the number of qubits (100-1000) available in today's prototypes. Going to these numbers will pose formidable scalability issues that make any prediction as to the first QEC-enabled quantum advantage a very tall order [16].

Whether near-term, uncorrected hardware will already provide quantum advantage on niche applications like many-body dynamics, or if this will be achieved by quantum error corrected hardware with the more traditional, gate-intensive quantum algorithms, is an open question. In fact, it could very well be that a clever blend of both paradigms delivers on the promises of quantum computers.

REFERENCES

1] P. W. Shor, Proceedings 35th Annual Symposium on Foundations of Computer Science **1**, 124 (1995), https://doi.org/10.1109/SFCS.1994.365700

[2] M. Schuld, N. Killoran, PRX Quantum **3**, 030101 (2022), https://doi.org/10.1103/PRXQuantum.3.030101

[3] R. P. Feynman, Int. J. Theor. Phys. **21**, 467 (1982). https://doi.org/10.1007/BF02650179

[4] T. Ayral, C. R. Physique **26**, 25 (2025). https://doi.org/10.5802/crphys.229

[5] T. Ayral, P. Besserve, D. Lacroix, E. A. Ruiz Guzman, Eur. Phys. J. A **59**, 227 (2023), https://doi.org/10.1140/epja/s10050-023-01141-1

[6] R. Cleve, A. Ekert, C. Macchiavello, M. Mosca, Proc. R. Soc. A **454**, 339 (1998), https://doi.org/10.1098/rspa.1998.0164

[7] A. W. Harrow, A. Hassidim, S. Lloyd, Phys. Rev. Lett. **103**, 150502 (2009). https://doi.org/10.1103/PhysRevLett.103.150502

[8] P. W. Shor, Phys. Rev. **A 52**, R2493 (1995). https://doi.org/10.1103/PhysRevA.52.R2493

[9] A. Peruzzo, J. McClean, P. Shadbolt, M.-H. Yung, X.-Q. Zhou, P. J. Love, A. Aspuru-Guzik, J. L. O'Brien, Nat. Commun. **5**, 4213 (2013). https://doi.org/10.1038/ncomms5213

[10] M. Larocca, S. Thanasilp, S. Wang, K. Sharma, J. Biamonte, P. J. Coles, L. Cincio, J. R. McClean, Z. Holmes, M. Cerezo, "A Review of Barren Plateaus in Variational Quantum Computing," arXiv:2405.00781 (2024). http://arxiv.org/abs/2405.00781

[11] F. Arute et al., Nature **574**, 505 (2019). https://doi.org/10.1038/s41586-019-1666-5

[12] T. Ayral, T. Louvet, Y. Zhou, C. Lambert, E. M. Stoudenmire, X. Waintal, PRX Quantum **4**, 020304 (2023). https://doi.org/10.1103/PRXQuantum.4.020304

[13] A. Morvan et al., Nature **634**, 328 (2024). https://doi.org/10.1038/s41586-024-07998-6

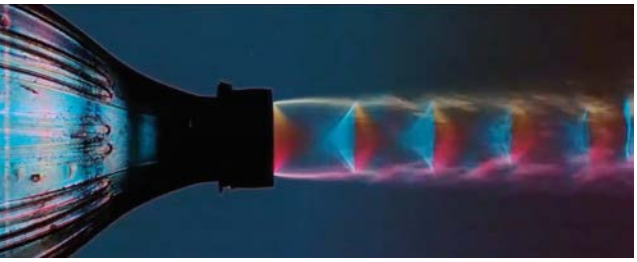
[14] Y. Kim et al., Nature **618**, 500 (2023). https://doi.org/10.1038/s41586-023-06096-3

[15] J. Tindall, M. Fishman, E. M. Stoudenmire, D. Sels, PRX Quantum **5**, 010308 (2024). https://doi.org/10.1103/PRXQuantum.5.010308

[16] M. Mohseni et al., "How to Build a Quantum Supercomputer: Scaling Challenges and Opportunities," arXiv:2411.10406 (2024). http://arxiv.org/abs/2411.10406

SCIENTIFIC HIGH-SPEED CAMERAS: APPLICATIONS & TECHNIQUES

Kyle D. GILROY
AMETEK - PHANTOM Vision Research, 100 Dey Road Wayne, New Jersey 07470, USA
***kyle.gilroy@ametek.com**

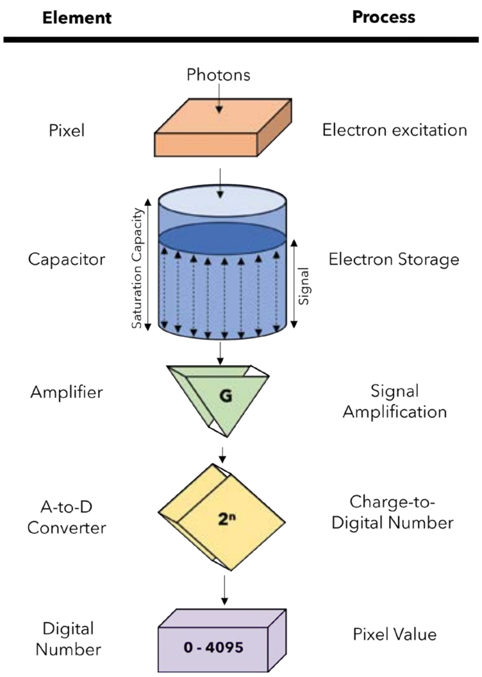


This article discusses the progression of high-speed cameras, along with some of the key working principles, key definitions, the means by which high-speed CMOS sensors are characterized, and the wide diversity of applications and techniques high-speed cameras are used within.

https://doi.org/10.1051/photon/202513172

High-speed cameras have become a cornerstone of modern research and development, serving as key scientific components that have been enabling scientists, engineers, and technicians to both visualize and measure high-speed phenomena. Much like how a microscope provides the ability to finely divide space for human visual inspection, a high-speed camera acts as a "time microscope" allowing researchers to leaf through ultrashort slices of time that occur on timescales otherwise imperceptible to the human eye & mind. In this article, we will discuss the current state of commercial high-speed scientific cameras, together with the basic working principles & emerging features, and then highlight some of the new and exciting high-speed applications.

Figure 1: Schematic illustration of the conversion of incident photons to a resulting pixel value.



PRINCIPLE OF OPERATION

There are a range of different types of high-speed cameras, with the most common type (and the focus of this article) utilizing complementary metal-oxide semiconductor (CMOS) sensors. CMOS sensors consist of an array of photodiodes that convert incident photons into electrical charges, with each photodiode unit corresponding to a 'pixel' in a resulting image. When photons are absorbed by the pixel, a proportional charge is generated and then highly parallelized A/D converters subsequently convert the charges to digital data, as either 8, 10 or 12-bits (typical for high-speed cameras), an abbreviated workflow is shown in Figure 1. To capture color images, a Bayer filter array is placed over the sensor, allowing pixels to capture only either red, green, or blue light; and the color information is reconstructed through interpolation. Once digitized, the image data is rapidly written to onboard RAM that exists as a circular memory buffer under the first-in, first-out (FIFO) method. This technique permits users to record up to tens of gigabytes per recording (generally seconds of record time), with available image systems trending toward terabyte-sized onboard RAM.

TECHNOLOGICAL PROGRESSION OF SENSOR THROUGHPUT

One of the most critical performance metrics in the high-speed camera market is sensor throughput, which is the product of the max sensor resolution and the max frame rate (at the resolution), expressed in gigapixels per second (Gpix·s^{-1}). To date, high-speed sensor offerings generally range from either 1, 4, or up to 9 Mpix. Over the past decade and a half there has been rapid progress, as shown in Figure 2, where clear improvements in throughput have been made for both 1 and 4 Mpix cameras systems. To give a clearer picture, the 40- and 75- Gpix·s^{-1} systems can achieve frames rates of ~10 kHz at 4 Mpix and ~76 kHz at 1 Mpix, respectively. High-speed sensors can also generally be 'windowed' to achieve faster frame rates. A 75 Gpix·s^{-1} system can achieve frame rates of ~1.75 MHz at 41 Kpix (i.e., 1280 × 32).

BSI TECHNOLOGY & SENSITIVITY

The high-speed camera industry, in part, has recently transitioned to Backside Illuminated (BSI) sensor technology, over the traditionally implemented Front-side illuminated (FSI), see Figure 3 for comparison. In short, BSI sensors are designed with the photoactive layer un-occluded by the metal layer, enabling more efficient light collection. Going to BSI was recognized as a requisite for the continued development of camera systems with exceedingly fast framing rates (and low integration periods) due to the fact that as the integration gets shorter there is a direct linear reduction in light-gathering ability (i.e., less signal, lower SNR). Thus, the large improvement in Fill Factor, going from 50-60% to now upwards of >90% with BSI was critically important. Note: Pixel response to incident light is directly proportional to pixel area × quantum efficiency × fill factor. The improvement ●●●

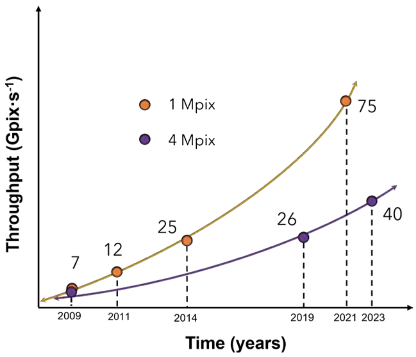
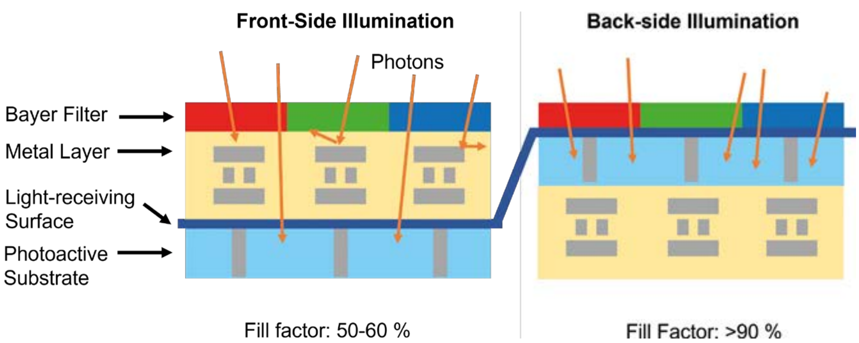


Figure 2: This graph compares the sensor throughput, measured in Gigapixels per second (Gpix·s^{-1}), of two high-speed sensor platforms: one with a 1 Mpix resolution and the other with a 4 Mpix resolution since 2009.

Figure 3: Comparison of FSI (Front-Side Illuminated) vs BSI (Back-Side Illuminated) Sensor Architectures. In the FSI architecture (left), photons (represented by orange arrows) must pass through the metal wiring and other layers before reaching the photodiode, which leads to light loss due to obstruction and reflection. In contrast, the BSI architecture (right) allows photons to enter directly into the photoactive region of the pixel, improving light capture efficiency.



in pixel responsivity has allowed the incorporation of ultrashort exposure times, now down to 38 ns.

SCIENTIFIC APPROACH TO SENSOR PERFORMANCE

Some camera manufacturers use the EMVA 1288 standard to characterize image sensors. This is a scientific approach and currently is the best means for guiding camera users to an optimal image sensor for a given imaging application. Some of the key terms derived from EMVA testing are in Table 1.

SNR VS SIGNAL PLOT

The Signal-to-Noise Ratio (SNR) versus signal plot, as defined by the EMVA 1288 procedure, is a crucial evaluation method for assessing the performance of image sensors. According to the EMVA 1288 standard, this plot is constructed by measuring the SNR at various signal levels, typically obtained from a series of test images captured at different light intensities (irradiances). The irradiation level is plotted on the x-axis, while the SNR is plotted on the y-axis. The SNR is calculated by the ratio of the signal amplitude (usually the mean pixel value) to the respective noise at that signal level. This plot reveals several critical values, namely the absolute sensitivity threshold or AST. This demarks precisely how many photons (at 50 µs integration) are required to produce an SNR = 1, Figure 4, blue arrow. This is the key specification for low-light applications, like in fluorescence, bioluminescence, screen imaging, or applications demanding ultra-short exposure times. This plot also provides an SNR across the 'mid-gray' region of the sensor, and thus users can discern precisely how sensitive the sensors are to change at any light-level, Figure 4, green arrow. Lastly, this plot also provides how many photons are required to bring the pixel to saturation, which is critical information for those who are characterizing scenes with wide 'scene-dynamic-ranges', see Figure 4, purple arrow. The higher the saturation capacity, and the lower the absolute sensitivity threshold, the larger the sensor dynamic range, Figure 4, red arrow.

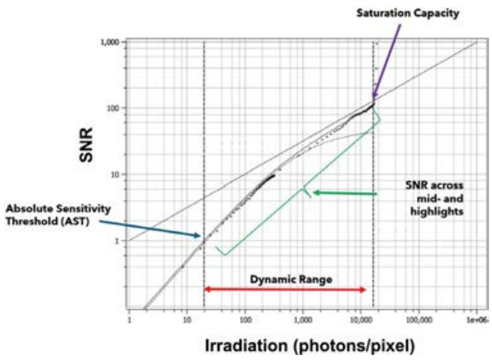


Figure 4: The EMVA 1288 plot illustrates the relationship between the Signal-to-Noise Ratio (SNR) and incident irradiation on a sensor. The curve demonstrates four key performance characteristics: AST (absolute sensitivity threshold), Dynamic Range of the sensor, SNR at all irradiation levels, and the Saturation Capacity.

TEMPORAL, SPATIAL, AND LIGHT-LEVEL RESOLUTION

The sensor specifications should always match or exceed the requirements of the imaging application. To ensure the sensor performance is at least minimally viable (in terms of temporal, spatial, and gray-scale resolution), it always helps to utilize the Nyquist rate (f_{Nyquist}) to define the minimum frame rate needed to prevent aliasing of the event rate (f_{event}), where:

$$f_{\mathrm{Nyquist}} = 2 \times f_{event}$$

The Nyquist rate mandates that the event or entity being measured is sampled at 2× the rate of the event. For

Table 1: Scientific Sensor Specifications (EMVA 1288)

TERM	UNIT	DESCRIPTION
Quantum efficiency (QE×FF)	%	Percent of photons incident on a pixel that get converted to electrons at the specified wavelength (λ). EMVA bundles QE and fill factor (FF) value together, and a singular QE x FF-value is generally reported, where λ ~ 532 nm. This term has a direct linear correlation to sensor responsivity.
Temporal dark noise (TDN)	e-	Noise present in an image when there is no incident light on the sensor (i.e., lens cap on). This value is signal-independent, and represents the lowest noise value on a sensor, and is also traditionally known as 'Read Noise'. This term is paramount for defining sensor effectiveness in low light applications.
Signal-to-noise ratio (SNR_{max})	ratio dB bits	Maximum signal-to-noise (SNR) ratio a pixel can produce. This value is extracted from the highest pixel response (i.e., right before saturation) since SNR trends with the square root of the signal. A higher value indicates better image quality and higher light-level-resolution in the mid-gray and bright parts of an image.
Absolute sensitivity threshold (AST)	p	Quantity of photons (p) required for a pixel to generate a signal that is equal to the noise (SNR = 1). This is measured for integration times of 50 µs and fixed wavelength (i.e., 532 nm). The lower the number, the more sensitive the sensor, and the better a given sensor will perform in low-light applications like fluorescence, bioluminescence, ill-lit scenes & ultra-short exposure times.
Saturation capacity	Ke- Kp	Amount of charge (Ke-) or photons (Kp) a pixel can take just before saturating. This is also known as Full Well Capacity (FWC). Since most sensors are Shot noise limited, the SNR_{max} generally directly correlates with square root of the saturation capacity.
Dynamic range	ratio dB bits	Ratio between the max pixel signal measurable to the lowest signal resolvable. Represented in ratio as saturation capacity (SC) : temporal dark noise (DN) OR SC:TDN; in units of dB as -20 log (SC/TDN), or in units of bits or 'stops' we have n = $\log_2$(SC/TDN) .

APPLICATIONS	TECHNIQUES	POST PROCESSING
Ballistics and Range	Schlieren & Shadowgraph	Object Tracking
Materials Analysis	Microscopy Imaging	Digital Image Correlation
Microfluidics	Optical Tomography	Particle Image Velocimetry
Automotive and Rail	Polarization Imaging	Size & Shape Analysis
Combustion Imaging	Spectral Imaging	Vibrational Analysis
Life Sciences & Biomechanics	Image Intensification	High Dynamic Range
Welding Imaging	Laser Imaging	Image-to-Spectrum
In-line Inspection	Extending dynamic range	Background Oriented Schlieren
Commercials/Media	Tracking Mounted	Optical Tomography
Aerospace & Wind Tunnels	Scintillator Imaging	Upscaling & Denoising
Nuclear Reactions	Stereophotogrammetry	Edge Detection
Plasma Imaging	Data Synchronization	Kinematic Analysis

Table 2: Where and How High-speed cameras are Used

example, if an event occurs at 1 kHz, the minimum frame rate required is 2 kHz. To collect the highest quality recordings, generally users sample the event 10 - 20× the event frequency, thus frame rates of 10 - 20 kHz are often used to visualize smooth temporal transitions. The same approach is viable for spatial resolution, where if one is looking to characterize small subject matter (i.e., 10 µm features or particles), the magnification of the system must be high enough to provide at least 2 pixels to span the subject, hence a minimum image resolution would be 10 µm / 2 pixels, or 5 µm / pix. Like temporal resolution, having 10 - 20× higher produces cleaner data. Lastly, if the event of interest is expressed as very small fluctuations in irradiance, one needs to ensure that the noise level (at that signal level) is less than the incident signal-delta you aim to characterize. Thus, analyzing the SNR vs signal plot in the EMVA 1288 is essential.

SPECTRAL RESPONSIVITY

In addition to the key specifications laid out in the EMVA 1288 report, also of importance is the pixel behavior across the entire UV-visible-NIR spectrum. In general, the EMVA 1288 testing procedure is carried out at one specific wavelength (i.e., 532 nm with noted FWHM), while spectral responsivity plots provide the pixel response (Amps-per-Watt) versus wavelength. A sample spectral response curve is shown in Figure 5a for a red, blue, green, and monochrome pixels from 300 - 1100 nm.

RADIOMETRY

The sensor spectral response curves can be used to perform radiometric measurements for irradiance measurements, spectroscopic measurements, or optical pyrometry. If the incident spectrum I(λ) and S(λ) are known, the pixel response (PR) is simply:

$$PR = k \times \int_{\lambda min}^{\lambda max} I(\lambda) \cdot S(\lambda) d\lambda$$

For a simple monochromatic source incident on a sensor, one can approximate the pixel response, or back out the incident irradiance, Φ_λ by utilizing the following equation:

Pixel Response [e–] =

$$\Phi_\lambda \left[\frac{p}{\mu s \cdot \mu m^2}\right] \times \text{PA } (\mu m^2) \times \text{QE}_\lambda \left[\frac{e}{p}\right] \times \text{FF} \left[\frac{ActivePixelArea}{TotalPixelArea}\right] \times \text{ET } [\mu s]$$

FSI VS BSI

With the introduction of BSI to high-speed cameras, we now have a marked increase in fill factor and thus pixel response. Before this transition, it was common to estimate pixel relative responsivity purely by pixel size, however, this is not great practice any longer. The spectral responses of a 28 µm FSI pixel and an 18.5 µm BSI pixel are plotted in Figure 5b. Notice that despite the much smaller pixel, the BSI pixel will outperform the FSI pixel substantially. ●●●

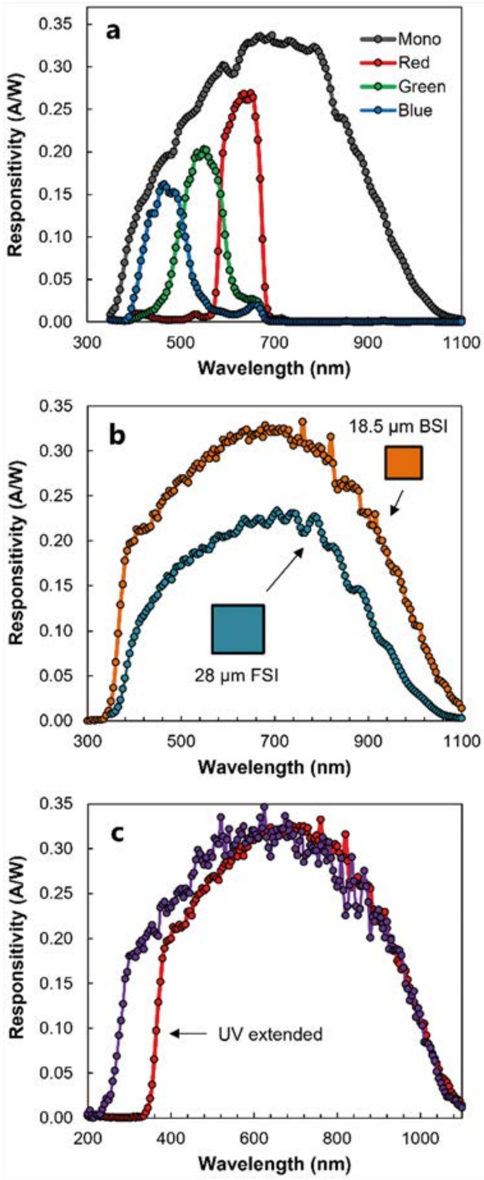
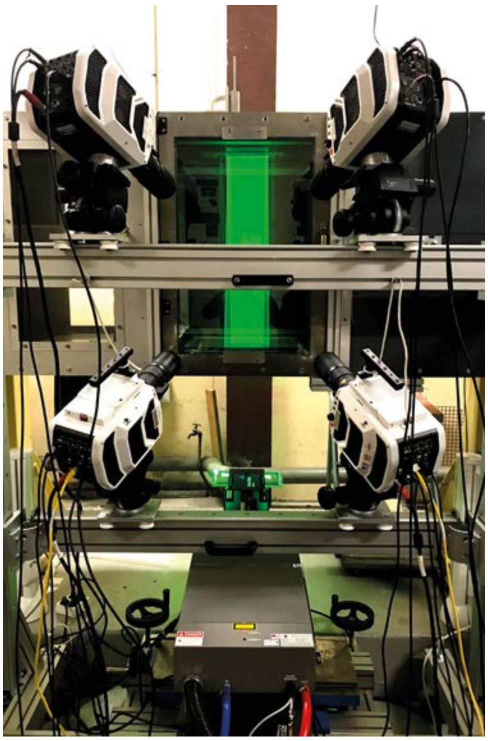


Figure 5: The spectral responsivity curves for: (a) typical sensor with red, green, blue, and monochrome pixels, (b) BSI vs FSI pixels, and (c) UV-Extended *vs.* non-UV-extended sensor spectral response.

Figure 6: A series of still images extracted from high-speed videos to illustrate the wide range of applications high-speed cameras are involved in. Still-images generated from Phantom high-speed cameras, provided by Kyle D Gilroy & co (Vision Research, AMETEK).

Figure 7: A four-camera setup for performing volumetric PIV studies. TOMO-PTV-4D Study of Hybrid electroactive morphing European Projects, IMFT, LAPLACE & FERMAT federation. Using integrated actuator-sensor design to improve aircraft wings aerodynamic performances HORIZON-2023-2027-PATHFINDER-Open-Project N° 101129952-BEALIVE-"Bioinspired Electroactive multiscale Aeronautical Live skin".



UV EXTENSION

The transition to BSI has also resulted in improved sensitivity in the UV region, where sensors can achieve over 70% QE at 300 nm. This is due both to the avoidance of glass microlenses (which absorb UV) and with the addition of a UV-transparent cover glass on the sensor. Figure 5c illustrates the spectral difference between the same sensor, one with cover glass and the other with UV-transparent cover glass. This makes UV-BSI sensors highly effective for applications that require UV sensitivity down to 250 nm, such as UV/Vis spectroscopy, combustion research (OH* imaging), fluorescence imaging, and others.

A MEASUREMENT TOOL

High-speed cameras have evolved from simple imaging devices into sophisticated scientific instruments capable of performing precise measurements on recorded video, see Figure 7 for a high-speed imaging setup with four synchronized cameras performing volumetric PIV analysis (PIV – particle image velocimetry). Modern image sensors, which measure the amount of light hitting each pixel, allow high-speed cameras to function as powerful radiometric *and* photogrammetric tools. As such, high-speed cameras can be used to transduce (from images) displacement, speed, acceleration, strain, vibration, temperature, and also density & flow gradients with Schlieren optics.

APPLICATIONS & TECHNIQUES

High-speed cameras are currently being deployed in increasingly advanced imaging applications across academic, industrial, and government research laboratories. Listed below are some common and emerging applications and techniques of high-speed cameras. Figure 6 shows a small subset of examples of how high-speed cameras are being used.

CONCLUSION

High-speed cameras have become indispensable tools in research and development across academia, government, and industry, enabling groundbreaking advancements in fields such as materials science, biomechanics, aerospace, and automotive engineering. As high-speed camera technology continues to advance, we will be sure to witness improved frame rates at higher sensor resolutions, together with improved sensor performance to ensure the highest possible data quality.

FABRICANT	SITE INTERNET	REVENDEUR FR
Ametek	https://www.phantomhighspeed.com	Ametek
Kron Technologies	https://www.krontech.ca	via internet
Aos	https://www.aostechnologies.com	Acal Bfi
Photron	https://photron.com	vm^2
Fastec	https://www.fastecimaging.com	Clara vision
IX	https://ix-cameras.com	IX cameras
IDT	https://idtcameras.com	Integrate design tools

Multichannel Event Timer & TCSPC Unit

The HydraHarp 500 is designed for advanced research areas such as quantum communication, quantum entanglement, quantum information, the characterization of single-photon sources and time-resolved spectroscopy. Different trigger options to support a wide range of detectors, from single-photon avalanche diodes (SPADs) to superconducting nanowire single-photon detectors (SNSPDs) maximize flexibility in instrumentation.
https://www.picoquant.com/products/category/tcspc-and-time-tagging-modules/hydraharp-500-high-resolution-multichannel-event-timer-tcspc-unit

EMBEDDED DEFORMABLE MIRROR

The Embedded Deformable Mirror –eDM- from Bertin Alpao is a compact and cableless solution with no external electronics. eDM is available with up to 97 actuators, an integrated cooling system to prevent temperature variations, and low SWAP (Size, Weight, and Power) for optimized integration.
https://www.alpao.com/products-and-services/deformable-mirrors/

Ultra-narrow linewidth laser

The SLIM LINER is a single-frequency, ultra-narrow linewidth laser, based on a Self-Adaptive Photonic Oscillator (SAPO) technology developed by the Institut Foton at Université de Rennes in France. A pump laser is optically locked onto a cavity using stimulated Brillouin scattering that offers an extremely narrow gain bandwidth, naturally favoring a high spectral purity without mode-hops. The frequency noise is better than 0.0005 Hz^2/Hz at 200kHz offset frequency and limited by the measurement.
www.silentsys.com

MINI FREE-SPACE OPTICAL ISOLATORS

Mini Free-Space Optical Isolators are designed around a less than $1cm^3$ form factor with an incorporated Faraday Rotator while maintaining a superior performance with high isolation, transmission, and power densities. These isolators effectively reduce feedback in the external cavity of diode laser systems and blocks reflections from free-space fiber coupling. Mini Free-Space Optical Isolators increase power stabilization in optical systems and also eliminate feedback-induced damage to sensitive optical components. These isolators are ideal for quantum technology applications such as quantum communication, simulation, cryptography, sensors, computing, and networks.
https://www.edmundoptics.fr/f/mini-free-space-optical-isolators/40151/#

Optical power meter modules

The AQ2300 Series is Yokogawa's advanced test solution for silicon photonics, semiconductors, optical fibers, passive components, and optical communications equipment. It builds on the AQ2200's performance with faster processing, higher module density, improved data transfer speed and storage capacity. With a new optical power meter module and SMU synchronization, the AQ2300 is designed to boost measurement efficiency and meet the demands of automated testing with precision and speed. Main features include 3-slot and 9-slot frame controllers, a synchronized trigger I/O by frame or module.
https://tmi.yokogawa.com/solutions/products/optical-measuring-instruments/multi-application-test-system/aq2300_series-test-platform/