Photoniques

N°107

LIGHT AND APPLICATIONS | EOS & SFO JOINT ISSUE

NEWS	BIOGRAPHY	BUYER'S GUIDE	PRODUCTS
Partner news & highlights	Patricia Era Bath	Microscope objectives	In optics and photonics

FOCUS

QUANTUM TECHNOLOGIES

- Generation of quantum states of light in nonlinear AlGaAs chips: engineering and applications
- Towards real-time quantum imaging with single photon avalanche diode cameras
- Semiconductor single-photon sources: progresses and applications
- Diamond-based quantum technologies
- Quantum sensing with nitrogen-vacancy colour centers in diamond

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Quantum Correlations and Entanglement

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Editorial

NICOLAS BONOD
Editor-in-Chief

Welcome to the Quantum World

The year 2021 marks the 100th anniversary of the 1921 Nobel Prize in Physics awarded to Albert Einstein "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect". Einstein introduced the concept of "light quantum" in a seminal paper he submitted on March 17, 1905, at the age of 26, in which he wrote "Each incident energy quantum of frequency ν_1 is absorbed and generates by itself a light quantum of frequency ν_2". Einstein himself did not anticipate how much this term "quantum" would revolutionize physics and change our perception of physical reality. This paper opened a prolific period for theoretical physicists who established the theoretical frameworks of quantum physics in only a few decades. They quickly established revolutionary concepts such as uncertainty and entanglement, which greatly changed our comprehension of physics. Quantum mechanics allowed a deep understanding of the optical and electronic properties of semiconductors. It is remarkable to see how such fundamental and theoretical results have rapidly and profoundly influenced technologies with the surge in the use of transistors and lasers that opened the information age.

But a second quantum revolution is underway. While the pioneers of quantum physics focused their efforts on understanding existing states of matter, researchers are now developing new, man-made quantum systems. Objectives are now to shape complex coherent quantum systems and achieve coherent and entangled quantum states that have never been observed before. This new degree of control over quantum states opens novel routes to reinventing fields such as information processing, computing, communications and sensing. This current scientific challenge goes beyond the improvement of existing classical components and offers a new paradigm in technological applications.

You will discover in this special issue some of the latest advances in one of the most exciting and promising scientific fields of the 21st century: quantum sensing, quantum imaging, diamond-based quantum technologies, single photons sources and engineered quantum states. The back-to-basics article is devoted to quantum correlations and entanglement. Also, do not forget to test your lexical skills in quantum physics with our crossword puzzle! Welcome to the quantum world!

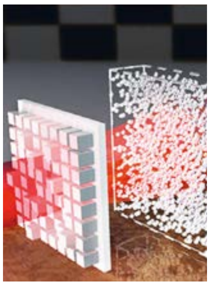
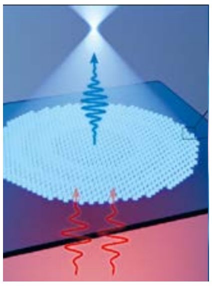
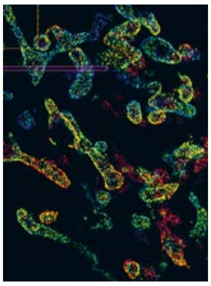




Table of contents

www.photoniques.com N° 107

Advertisers

SFO/EOS forewords

PHILIPPE ADAM
President of the French Optical Society

The important events of 2021 are rapidly approaching. In order to make them as profitable as possible, the implementation of a communication strategy towards the Optics-Photonics community is essential in order to affirm the positioning of the SFO on its choice of commitment for a face-to-face meeting. The mobilization is strong around the OPTIQUE 2021 congress in Dijon in July. We warmly thank those who have already submitted a contribution. The echoes from our community clearly indicate the willingness and impatience of future participants to come together to renew technical and scientific links in a version if not "fully liberated", at least in the as user-friendly format as possible. Even if the situation has not yet stabilized and is evolving day by day, the measures (e.g. gauge limitation), that we have adopted and inherent to the locations chosen, completely reassure us about the relevance of our choice of a face-to-face format.
However, the current period requires us to be vigilant and plan for fallbacks... just in case. For example, the SFO organized remote conferences on Freeform Optical Systems: this event was a great success with more than 150 participants and a flawless digital management.
In conclusion on this event chapter, essential for the life of our Society, I do believe that the OPTIQUE 2021 Congress will take place in Dijon from Monday 05 July to Friday 09 July.
At Dijon, the SFO scientific prizes will be awarded. For the Arnulf Françon price, the selection is under process; for the Fabry - de Gramont prize, the winners are already known. For the Léon Brillouin Grand Prix, the jury selected a winner in a selection with a complete parity.
At the same time, we will participate with enthusiasm in the constitution of French nominations to obtain the much sought-after "EOS fellow" distinction and this for the greater influence of our community: our links with EOS are still active and friendly.
Finally, I am delighted the current issue of Photonics is devoted to quantum technologies. Few fields have seen such rapid and efficient development from fundamental research in the 90s to current industrial activities in the fields of sources, sensors, quantum computing, communications. A revolution is underway; being able to follow these advances in real time is a great opportunity. Photoniques review is actively participating in it.

GILLES PAULIAT
President of the European Optical Society

Research and scientific careers are characterized by uncertainty and doubt. Overcoming these difficulties to move forward together on the subjects that are important to us and the society is an immense satisfaction and one of the pleasures of our professions. Nevertheless, this long-lasting pandemic adds to this insecurity and affects many of us and our relatives. Not to mention the acute health problems, morale and enthusiasm deteriorate.
We learned how to partly compensate for the absence of physical meetings by an extensive use of videoconferencing. These valuable tools are without any doubt good for the planet and for keeping close contacts and collaborations despite the distances. Nevertheless, we are all eager to revive with in-person meetings. These meetings are invaluable for networking, for reconnecting with old colleagues in the corridors, for meeting new ones to build new projects... These meetings are also an opportunity for our younger colleagues to build their career and find new laboratories for their post-docs.
Learned societies are actively preparing these next eagerly awaited in-person meetings. Just to mention a few, the next meetings in July of the French Optical Society, SFO, in Dijon, "Optique Dijon", or in September for the German Optical Society, DGAO, General Assembly in September in Bremen. It is worth reminding that internal agreements signed within EOS allow members of EOS branches to participate to meetings organized by other branches at members rates. For example, DGAO members can benefit for low registration rates at SFO meeting and vice-versa. Similarly, all EOS members, and thus of EOS branches or affiliated societies, benefit for reduced rate in many international meetings of the EOS partner societies throughout the world. Please see the EOS website for more information.
Of course, do not miss the EOS general meeting EOSAM2021. It will be held in Rome, on Sept 13-17, in close collaboration with the Italian Optical Society, SIOF. You will have the opportunity to meet with colleagues from all over Europe and beyond. The meeting covers all topics in photonics, including the bubbling "Non-linear optics and Quantum Optics". The multiple facets of Quantum optics are covered by this issue of Photonics. Enjoy your reading! Keep safe, looking forward to seeing you in-person this year for an ever-renewed European cooperation!

OPTIQUE DIJON 2021: VENEZ À DIJON

The French Optical Society affirms its choice of face-to-face format: OPTIQUE Dijon 2021 will take place in Dijon from the 5th to the 9th of July 2021.

The mobilization is strong around the OPTIQUE 2021 congress in Dijon. We warmly thank those of you who have already submitted.
The echoes from our community clearly indicate the willingness and impatience of future participants to come together to renew technical and scientific links. Even if the situation is not yet completely stabilized, the large spaces of Congrexpo would allow OPTIQUE Dijon to run normally with a 50% gauge. So you are cordially invited to attend and participate in the 8th Congress of the French Optical Society SFO.
OPTIQUE Dijon 2021 will cover a wide range of topics from the fundamental to the applied research, industrial developments and pedagogical innovations. An exhibition area for photonics industry, including start-ups, will be set up at the heart of the congress. This congress provides fertile ground for beneficial exchanges between the actors of optics and photonics.
Professor Gérard Mourou, Nobel Prize in Physics 2018, will deliver the keynote opening plenary speech in this congress. OPTIQUE Dijon 2021 also includes plenary sessions led by guest speakers renowned internationally for their expertise, several thematic conferences and poster sessions.

OPTIQUE Dijon 2021 Prizes, to promote optics and photonics research

To recognize excellence, the SFO awards three Scientific Prizes during this congress. The Léon Brillouin Prize rewards researchers for all their research in optics in France. The Fabry-de Gramont Prize rewards a young researcher (under 40), for the quality, originality and potential impact of his (her) research. The Arnulf-Françon Prize aims to promote outstanding teaching book in higher education or popular science. OPTIQUE Dijon 2021 welcomes for the first time the awarding of the Jean Jerphagnon Prize, which promotes technological innovation and the dissemination of optics and photonics in all fields of application.

Women in Physics committee, to promote parity in Optics

In symbiosis with the commission "Women and Physics, achieve parity in optics" the congress pays a special attention to the number of women working in optics, at all responsibility levels and tends to parity on invited conferences.

PhD students are welcome in OPTIQUE Dijon 2021

Our goal is to allow all PhD students to participate once in the congress during their thesis. 200 students are expected in this congress.

Dijon hosts the 8th SFO congress

The local organizing committee orchestrated by Guy Millot is very happy to host the SFO Congress. They do their utmost to welcome hundreds of participants in the best conditions. The congress facilities at Palais des congrès of Dijon are well located and easy to reach. During our networking program, you will get to know this exciting city in all its aspects.
We invite you to submit and present your research and to make friendships in friendly atmosphere.
Welcome to OPTIQUE Dijon 2021!

OPTIQUE DIJON 2021 IN FEW FIGURES

- 8th edition of the SFO congress
- 600 expected attendees
- 45 stands of companies in the ecosystem of optics and French photonics
- 7 hours of plenary sessions
- 70 hours of specific sessions in parallel
- 5h30 dedicated to the industrial sector.
- 10 Thematic sessions

THEMATIC SESSIONS

- Crystals for Optics
- Optics and Photonics diagnostic
- Optical Fibers and Networks
- Frontiers of Optics
- Lasers and Quantum Optics
- Nanophotonics
- Guided Optics
- Adaptive Optics
- Organic Photonics
- Atomic, Molecular, and Optical Physics (*)

(*) SFP thematic session, PAMO

EEDAL
11th Energy Efficiency in Domestic Appliances and Lighting

The French Optical Society invites you to attend

the 11th International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL'21)
17th International Symposium on the Science and Technology of Lighting (LS:17)
For the first time, the two conferences will be held jointly Toulouse, November 8th to 10th, 2021
https://eedal-ls21.sciencesconf.org/

News from FoodPackLab's SMEs

1) R&D Vision : Artificial Intelligence in aisles
Product layout and visibility in hypermarket aisles (supermarkets, specialised superstores, DIY superstores, wholesalers, etc.) are vital factors for any brand. In this context, improving knowledge on marketing mechanisms and shelf visibility is crucial and this is where R&D Vision developed an Artificial Intelligence (AI) solution to automate the analysis of these photographic records which is based on a combination of a variety of technologies such as Deep Learning, colour and texture analysis, OCR, SIFT matching and correlation.

2) Cénotélie Agricolio is an online crop monitoring solution open to all farmers
Agricolio offers farmers a dedicated solution allowing the traceability of farming practices and field management based on the monitoring of vegetation and absorbed fertilizers. In order to provide these services, Agricolio combines technologies of high resolution satellite images and advanced agronomic knowledge on plant development.

AGENDA

■ **SmartAgriFood Industry Expo**
May 25-26th 2021,
a virtual trade fair-congress that will bring together the leading experts in technological innovation applied to the agrifood sector. The event will showcase different types of innovation that apply to the entire value chain in a transversal way: from raw materials, through the processing industry, to food packaging and distribution. This is the ideal event where you can catch up on innovation trends to solve today's challenges facing tomorrow's industry.

■ **French Business Meetings « Photonics for Foodchain », May 27th 2021, 100% virtual meeting** to discover 6 business cases from French major corporations and unique opportunity to present your solutions during dedicated B2B meetings with them.

Discover the new Quantum Mapping of the Systematic's members

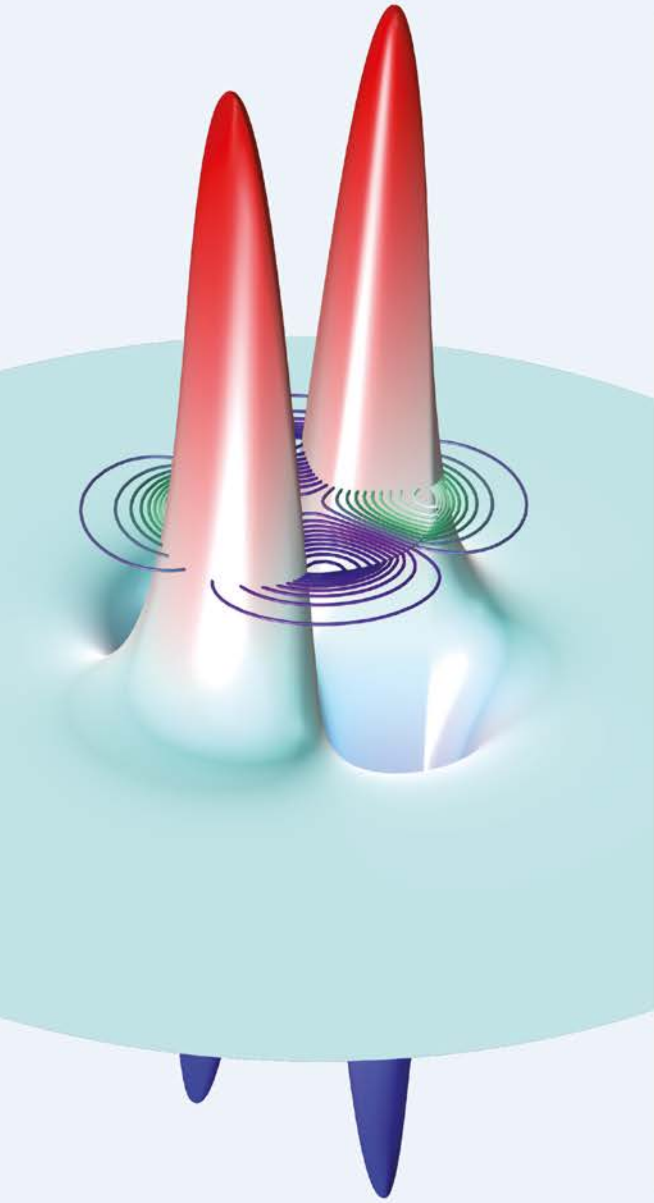
A quantum ecosystem is not something easy to apprehend and sometimes companies struggle to be identified as top quantum-enabler even if they deal with quantum R&D for many years.
Usually quantum technologies, which have wide-ranging applications in optimization, research and cryptography, are driven by these organizations: end-to-end solution providers, quantum hardware builders, software & services companies, research labs and companies that use quantum computers in their business.
At Systematic, we tried to give a more detailed visibility to the tremendous number of our members dealing with quantum and here is our Quantum Mapping we are very proud of!

SYSTEMATIC IS PART OF THE EUROPEAN PROJECT ALLIANCE STRAND 2:
COOPERATION BETWEEN TEXTILES, DEFENCE AND SECURITYFRENCH PHOTONICS DAYS

This project promotes exchanges between the textile sector and the defence and security aspects at a European level. The consortium is led by the TECHTERA cluster. It will create dual technology transfer initiatives between the civilian and military sectors, to bring out innovations, to make our companies leaders in this field, and export these new products, services or processes to international markets. Systematic will specifically be in charge of the missions to US and Canada during the next 2 years, let's give it a GO!

European COSME project FoodPackLab strand 2: new opportunities

FoodPackLab 2 supports you in recruiting new talents and offers you a free slot on WaveJobs! WaveJobs leverages the experience of other industries where job searching and finding the right talent is eased thanks to streamlined descriptions containing the desired level of details, using standard phrases for skills etc.
https://foodpacklab.eu/



Addressing all markets with specific focus on quantum and optical communication

EPIC is the European Photonics Industry Consortium and bit by bit photonics is penetrating all markets. EPIC aims to address all the photonics needs of all the industries. You can see that from the wide range of topics we cover during our EPIC (Online) Technology Meetings that already this year included topics like medical devices, transport and eMobility, textiles and wearables, oil and gas, green energy, security and defence, agriculture and food, robotics, drugs, forensics, and AR/VR. But there are two markets that have received some extra attention: optical communication and quantum technologies.

We started in January with the EPIC Online Technology Meeting on Commercial Challenges for Photonics as 5G Booms and in March we organised the EPIC Online Technology Meeting on Roadmap 2021 for Co-packaged Optics. Both in cooperation with COBO (Consortium for on-board optics) and EA (Ethernet Alliance). We value partnerships with other associations like COBO and EA as they complement the ability to collaborate and work towards common goals. We also had an EPIC Presentation on 5G Requirements Driving Photonic Opportunities and on 21 April we continue with the EPIC Online Technology Meeting on Roadmap 2021 for Beyond 400G Ethernet Optics.

Another booming market is quantum technology. Therefore, EPIC has launched a series of technology meetings specifically focussed on this market. The EPIC Quantum Technology Meetings also cover several markets and topics have so far included qubit generation, quantum computing, security and defence sectors, (tele) medicine, next-generation transport and mobility, secure strategies for communications, and we will close this season the EPIC Online Quantum Technology Meeting on New Opportunities for the Quantum Photonics Supply Chain which will be held on 23 April 2021, so if quantum is a field of your interest, then be sure to register through our website www.epic-assoc.com/events. Besides these new services, EPIC also continues its success with a brand new series of EPIC Online Technology Meetings, monthly EPIC Member Product Releases, and of course our CEO/CTO interviews. Also be sure to keep an eye out for our HR activities, such as the latest jobs (www.jobs-in-photonics.com) and our EPIC Mentors in Photonics program (www.mentors-in-photonics.com). We are here to serve the photonics community and look forward to continuing our efforts in 2021.

SPECIAL NEWS SECTION

EPIC is pleased to welcome Adam Piotrowski and Berthold Schmidt as new EPIC Board Members. Adam Piotrowski is CEO of VIGO System and President of the Polish Technological Platform on Photonics. VIGO System a world leader in the design and manufacture of products for photonics. The offer includes both epitaxial wafers (GaAs and InP based) as well as infrared detectors (HgCdTe, InAs, InAsSb) and detection modules. Berthold Schmidt is CEO at TRUMPF Photonic Components. TRUMPF is market and technology leader in machine tools and lasers for industrial manufacturing. It's a privilege to have these experts join our Board of Directors and to have their expertise and knowledge of the industry onboard to benefit our members and the association as a whole.

AGENDA

- **Upcoming EPIC Online Technology Meetings**
EPIC events are renowned for excellent networking, creating new connections and strengthen existing ones. Connecting EPIC members means building trust within the photonics industry.

- **EPIC Online Technology Meeting on Photonics for Cosmetic and Beauty Industry**
19 April 2021, 15:00 CEST

- **EPIC Online Technology Meeting on Roadmap 2021 for Beyond 400G Ethernet Optics**
21 April 2021, 16:00 CEST

- **EPIC Online Quantum Technology Meeting on New Opportunities Now for the Quantum Photonics Supply Chain**
23 April 2021, 15:00 CEST

- **EPIC Online Technology Meeting on PIC Packaging**
26 April 2021, 15:00 CEST

- **EPIC Online Technology Meeting on Moulded Optics**
3 May 2021, 15:00 CEST

- **EPIC Online Technology Meeting on Advanced Photonics in Urology**
10 May 2021, 15:00 CEST

- **EPIC Online Technology Meeting on Laser Micromachining**
17 May 2021, 15:00 CEST

- **EPIC Online Technology Meeting on Human-centric Lighting and Applications**
31 May 2021, 15:00 CEST

- **EPIC Online Technology Meeting on VCSEL Manufacturing and Applications**
7 June 2021, 15:00 CEST

- **EPIC Online Technology Meeting on Medical Devices for Surgical Procedures**
14 June 2021, 15:00 CEST

- **EPIC Online Technology Meeting on Novel Photonic Solutions for Microscopy**
28 June 2021, 15:00 CEST

- **EPIC Online Technology Meeting on Current and Future Challenges for Laser Cutting**
5 July 2021, 15:00 CEST

Find out about upcoming EPIC events on
www.epic-assoc.com/epic-events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EPIC members are companies and organizations in the field of photonics covering optics, fibers, sensors, lasers, LEDs, detectors, displays. EPIC members are technology leading edge companies, covering the entire value chain from system integrator, components supplier, equipment, materials and service suppliers.
EPIC
European Photonics Industry Consortium

French photonics expertise supported by the Ministry of the Economy

On March 4th, the French Ministry of Economy announced the support to 8 strategic companies of the photonics sector following the call for projects "Resilience". These companies are planning to develop quantum photonic systems, new lasers, OLED micro displays, a "photonic nose" or to support the relocation to guarantee the independence and sovereignty of photonic components. These 8 projects will create hundreds of jobs for operators, technicians and engineers in the region.

PHOTONHUB

Photonics France and these regional clusters members Alpha-Rlh, Photonics Bretagne, Minalogic, Optitec et Systematic are partners of PHOTONHUB (2021 – 2025) that joined 53 european partners within 21 French partners. The other partners are 13 laboratories from CNRS and technological platforms as CEA LETI and Alphanov.

Photonics France is the co-leader to create a leverage effect of the regional contribution and create some Digital Innovation Hub in Photonics in Europe.

TO CONTACT PHOTONICS FRANCE
contact@photonics-france.org
www.photonics-france.org

Photonics Online Meetings #3: an extensive webinar programme

The third edition of the Photonics Online Meetings is coming up in less than 2 weeks and the program is already very busy. Nearly twenty webinars are scheduled. Register for free and discover all the latest news in our industry. Save the date for: "Ready-to-use solution for your photonic and vision needs" by Polytec France, *"Automated scratch-dig inspection – Advantages of replacing manual-visual inspection"* by **DIOPTIC GmbH**, *"Enhanced performance for imaging & sensors with deep-black coatings through stray light optimization"* by **Acktar**, *"IRG Infrared glasses from SCHOTT as the basis for high performance solutions in infrared technology"* by **SCHOTT**, *"How to do effective digital marketing with the RP Photonics Buyer's Guide"* by **RP Photonics**, *"A wide spectrum of wonders: discover Hamamatsu Photonics' scientific cameras"* by **Hamamatsu**, *"SCHOTT in Yverdon – With focus on aspheres for Laser, Cine lenses and Defense applications"* by **SCHOTT**, *"Laser technologies for autonomous driving"* by Lumibird, *"Photon Lines Optical Solution Provider : interference filters vs colored glass filters in automated vision applications"* by **Photon Lines** and *"Packaging partner for microelectronics and optoelectronics"* by **Argotech**.
Join this day to discover all the news of your sector and to meet your future Business & Photonic Projects partners.

MORE INFORMATION ON:
http://onlinemeetings.photonics-france.org/

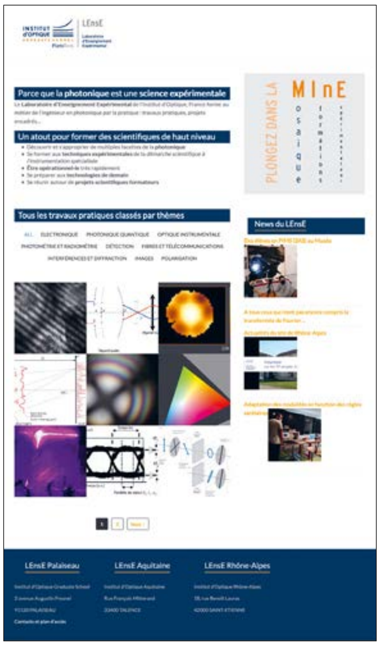
Creation of the coordination of French photonics platforms

Photonics is a vast field that requires multiple highly specialised skills. This has led to the creation of several platforms, each with its own specificities, which today work together, while maintaining their independence. Photonics France, the French Photonics Federation, is responsible for coordinating the links between these different structures. We count among these platforms ALPhANOV, CEA-Leti, FiberTech Lille, IREPA LASER, MANUTECH USD, PHOTONICS BRETAGNE and PISEO.

BESTPHORM

Photonics France is partner of the Bestphorm[21] (2021 – 2024) to support Photonics 21 and the strengthening of photonics in Europe.

INSTITUT D'OPTIQUE GRADUATE SCHOOL ParisTech | université PARIS-SACLAY



More information on the educational website (lense.institutoptique.fr/), where a wide range of resources are shared in free access.

IOGS: a high-level scientific education with a strong practical component

Since the creation of the Institut d'Optique Graduate School (IOGS) in 1917, future engineers in photonics are trained by emphasizing practical work.

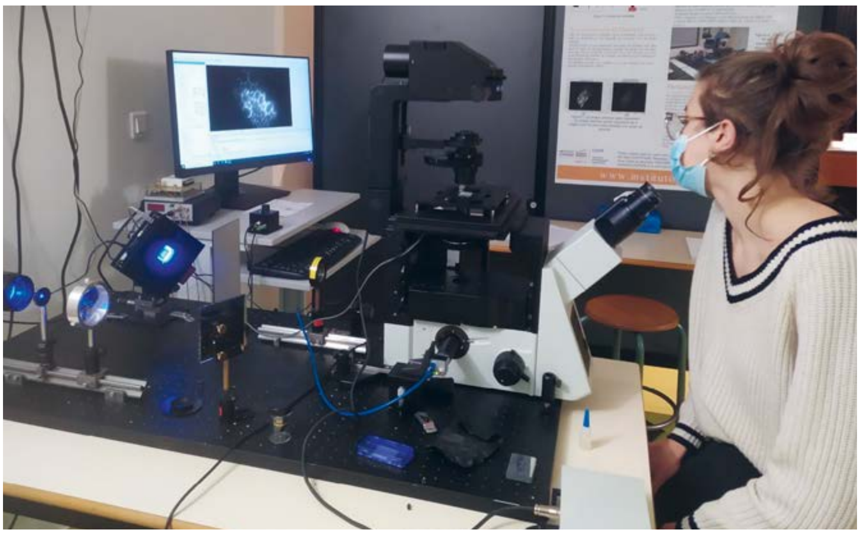
The Experimental Teaching Laboratory (LEnsE, for Laboratoire d'ENSeignement Expérimental) has always been a major structure of the engineering school and offers remarkably strong training that contributes 25% of the total curriculum. It is an impressive structure where students have access to a large diversity of material and human resources to be able to gain the skills to become excellent experimenters recognized in their field.

Currently, the LEnsE has approximately 150 scientific experimentation stations on three sites, which enable the implementation of a rich and stimulating curriculum through experimentation. Future graduates acquire both a technical and scientific culture that allows them to be immediately operational in an industrial R&D or academic lab. Their training is enriched by the confrontation of experimental physics with advanced theoretical models. Practical work and projects are privileged moments to analyze physical phenomena in depth.

The richness of the LEnsE, built up over its long history, is based on its 80 contributors. The teachers, researchers and engineers who participate in the LEnsE education know that they can count on the support and expertise of an engineer and three technicians to launch new scientific, pedagogical and experimental adventures every year! The LEnsE is in constant interaction with research laboratories and industrial companies. As well, the list of experiments proposed to the students evolves each year.

The subjects of the practical curriculum cover all aspects of photonics: production of light (lighting or lasers), measurement (photometry, colorimetry), detection (visible or IR detectors, matrix or not), fundamental properties (wave optics, polarization, quantum optics), manipulation (instrumental optics, optical fibers, non-linear optics), industrial application devices for telecommunications (defense, biomedical, etc.). The training program is always kept up to date, in strong relation with edge-front advances and research in all the fields of optics and photonics (quantum technologies, solid-state photonics, sustainable technologies, ...) - let's for instance point out new experiments in biophotonics that have been designed in 2020. These aspects are complemented by training in modern electronic information processing technologies.

One of the four new experiments in Biophotonics : Structured Illumination Microscopy.



AGENDA
of our Continuing Education service

- **Optics without calculation**
  From May 10 to 12
- **Design of optical systems with commercial components using Zemax®**
  From May 10 to 12
- **Optical design of imaging systems using Zemax® / OpticsStudio - Initiation**
  *From May 25 to 27 *e-learning**
- **Optomechanics**
  From May 25 to 28
- **Understanding laser sources**
  From May 31 to June 4

For more information and complete catalog
www.fc-institutoptique.fr

CONTACT INSTITUT D'OPTIQUE GRADUATE SCHOOL:

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www.institutoptique.fr

Job opportunity at Photonics Bretagne: Business Development Manager wanted!

The main objective of the job is to generate commercial leads and industrial partnerships for the members of the cluster and for the technological platform of Photonics Bretagne. The Business Developer will also federate and animate the strong network of photonics players in the region. Required profile: PhD/Engineer level with a photonics profile and excellent interpersonal and communication skills allowing to quickly create links with potential customers and partners. Sales experience and fluent French/English required. Plenty of photonics jobs available in Brittany due to global growing business!

Do not hesitate to send us your CV if you have good skills in optical fiber/laser/sensor technologies and want to work in an innovative tech environment with sea view! We'll make the link with the perfect company for you!

MORE INFO:
www.photonics-bretagne.com
dmechin@photonics-bretagne.com

Success of our last Photonics and Health workshop

Co-organized by Photonics Bretagne and Biotech Santé Bretagne last February, this workshop brought together more than 60 participants to create links between photonics and health communities and foster innovative collaborative R&D projects. Laboratories and companies presented the latest technological breakthrough and applications of photonics in the health field, from dermatology to surgery, including the detection of pathologies.

OIP4NWE – APPLY NOW TO GET A 50K€ VOUCHER FOR GETTING INNOVATIVE INP PIC TECHNOLOGY

The Interreg NWE project OIP4NWE aims at establishing an open innovation pilot line for the development of generic photonic integration technology. Integrated photonics is the emerging technology where the manipulation of light takes place on a chip, making the components an order of magnitude cheaper, smaller and more energy-efficient compared to today's solutions. By providing these services to SMEs across Europe through a funded voucher scheme, Photonics Bretagne and other partners of the OIP4NWE project have the objective to reduce Photonics Integrated Circuit (PIC) access barriers and strengthen the competitiveness and innovation of European SMEs. Apply now for Innovation Support Fund and get a 50k€ voucher for design verification, manufacturing of PICs, external optics and packaging!

MORE INFO: dmechin@photonics-bretagne.com

First optical fibres made from 3D printing

The Glass & Ceramics team from Rennes Institute of Chemical Sciences (ISCR) with the collaboration of Fresnel institute (university of Aix-Marseille) and Selenoptics company, report the first realization of a microstructured optical fiber drawn from a 3D-printed inorganic glass preform. For this proof of concept, a soft glass such as chalcogenide glass was chosen because of its well-known capability to be shaped at low temperature and its broad mid-IR transparency. Chalcogenide glasses generate a great deal of interest in science and industry, targeting novel applications, like new infrared light sources and civilian thermal imaging, and society-oriented needs in the fields of health and environment with infrared optical sensors.

News in brief

Cailabs continues to grow its business internationally. The deep tech company signed a distribution agreement with Axiom Optics to expand its presence in the United States and a distribution contract for Israel with LAS Photonics, specialist in the distribution of lasers and electro-optics in Israel.

Lumibird has signed an agreement with the Swedish company Saab to acquire its defense laser rangefinder business. It would contribute to consolidating the Lumibird Group's position on the European defense market. The transaction is expected to be finalized for the first half of 2022.

Hytech-imaging, expert in hyperspectral data processing, announces a new partnership with CLS, historical and main supplier of the oil pollution detection service. Thanks to this partnership, it will be possible to process new Earth Observation data to further characterize pollution (density, viscosity, etc.). This will help to create a competitive French industrial force for the development of spectral imagery, in order to address major current environmental challenges.

Hervé FLOCH,

President of the new European association EUCLES

The European Clusters Excellence Labelling Structure (EUCLES), an international non-for-profit associations (AISBL of Belgium rights) was officially created on March 19th, 2021, bringing together national and regional clusters organisations to work for continuous improvement of the European clusters labellisation system and granting of the labels. EUCLES takes over the European Secretariat for Cluster Analysis (ESCA).

With the help of a pool of experts, EUCLES will assess clusters' organisation and management quality in order to award a label of excellence to the recipients (bronze, silver or gold). EUCLES is looking forward to start full operation by summer time 2021.

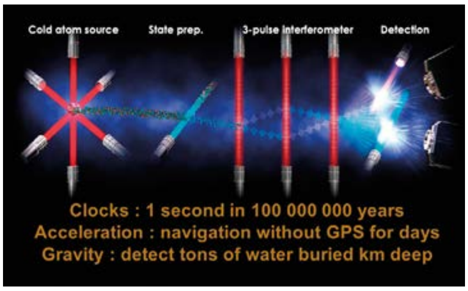
Hervé FLOCH, President of the « Europe » committee of Association Française des Pôles de Compétitivité (AFPC) was elected as the first Chairman of EUCLES during the constitutive general assembly held Decembre 14th, 2020.

UPCOMING INTERNATIONAL EVENTS

- **Photonics Online Meetings #3**
  May 11 - online
- **Minalogic Business Meetings**
  May 27 - online
- **Arab Health**
  June 21-24 - Dubaï (UAE)
- **ECOC "European Conference on Optical Communication"**
  September 12-16 – Bordeaux (France)
- **Vision**
  October 5-7 – Stuttgart (Germany)

Quantum technologies: Is the revolution already underway?

From laser cooling of atoms to quantum entanglement, quantum technologies are becoming increasingly common: sensors, cryptography, computers, simulators. France is a leading country in quantum technology, with pioneering laboratories of excellence in research and world-leading industrial players. But can we speak of a revolution and consider quantum photonics as a key technology of the 21st century?



© Didier Florentz

To answer this question, on January 21, 2021, the ALPHA-RLH cluster organized a webinar with presentations by experts in quantum science and technology: the LP2N (Talence) and XLIM (Limoges) laboratories, and the companies Muquans, Aurea Technology and NVision Imaging Technologies. These presentations highlighted the applications of quantum technologies in the field (sensors, clocks and quantum gravimeters), the contributions of quantum physics to cryptography/data security, and innovations in quantum photonics for space and health.

The NAQUIDIS center gathers Nouvelle-Aquitaine Region, IOGS, CNRS, the University of Bordeaux, the University of Limoges and the ALPHA-RLH cluster to establish an international outreach center for quantum photonics in Nouvelle-Aquitaine. The center was officially launched through a digital event on March 4, 2021. The replay is available on naquidis.com.

ALPHA-RLH INVOLVED IN THE PHOTONHUB EUROPE PROJECT

ALPHA-RLH is a stakeholder of PhotonHub Europe – a new pan-European photonics digital innovation hub – which has been awarded €19 million investment from the EU's Horizon 2020 programme. PhotonHub Europe aims to set up a unique photonics innovation centre that will bring together the technologies, facilities, skills and experience of 53 European partners. PhotonHub Europe will help European SMEs and mid-caps become highly competitive digital businesses through faster and smarter deployment of photonics-based technologies, directly creating over 1.000 new high-tech EU jobs and nearly €1 billion in new revenues and venture capital by 2025. The French photonics competitiveness clusters, including ALPHA-RLH, are united under the leadership of Photonics France, which coordinates the clusters' activities. PhotonHub will provide European companies, in particular "non-photonics" SMEs and mid-caps that are first users and early adopters of photonics, with open access and guided orienteering through the PhotonHub regional contact points, across a broad range of services and capabilities covering:

- training and upskilling supports
- "test before invest" innovation support
- supports to find investment

Dealing with this last item, ALPHA-RLH has a long and successful experience to share in the frame of PhotonHub Europe with its INPHO VENTURE SUMMIT©, the 8th edition will take place in Bordeaux in October 2022 (Inpho-ventures.com).

Uptake of disruptive photonics technologies for a faster post-COVID-19 economic recovery: *Acceleration Programmes* by OPTITEC

The COVID-19 pandemic has upended nearly every aspect of life, from the personal to the professional. Most business executives expect the fallout from COVID-19 to fundamentally change the way they do business over the next years, while also envisaging the crisis will have a lasting impact on their customers' needs. However, the crisis can also create significant new opportunities for growth, depending on the industry. Of course, identifying the emerging opportunities is not the same as being able to seize them.

How is the industry responding? As expected, it is largely focusing on maintaining business continuity, especially in their core. It weighs cutting costs, driving productivity, and implementing safety measures against supporting innovation-led growth. It does not come as a surprise, that innovation investments are not *a priori*ty.

The vast majority of industry sectors – with the exception of pharmaceuticals and medical technologies – will probably not return to pre-crisis innovation-related initiatives before the current business environment stabilises and the path forward becomes clearer.

The rationale of OPTITEC's *Acceleration Programmes*

Assumptions, which were true during the years of stable growth, may no longer be valid. Companies can gain long-term advantages by understanding changing business practices and the opportunities they present.

As an agile innovation and business actor, photonics cluster OPTITEC remains convinced that prioritising innovation during the times of crisis is important for companies.

Therefore we have set-up *Acceleration Programmes* enabling our members to consider and take up actions in order to:

- Adapt the core business to meet evolving customer needs
- Identify and swiftly address new opportunities created by the changing landscape
- Re-evaluate the innovation activities and ensure proper resource allocation
- Building the basis for post-crisis growth

Key elements: time-to-market and external partnerships

The global COVID-19 pandemic has significantly accelerated the pace at which companies are bringing new ideas to market. Given the accelerated pace at which products and services are launched directly into market, it is critically important to ensure that supply chains and other enablers of scale keep pace to meet demand.

OPTITEC's *Acceleration Programmes* focus on specific pre-identified needs from various industrial actors in the end-user sectors such as automotive, agriculture & food and security & defence. It than matches these needs with the state-of-the-art solutions identified within our members' network. This process consists of 3 stages – Open Innovation ACSESS, Open Innovation HUB and Open Innovation FACTORY - and is typically carried out in less than a year since the speed is a key driver of innovation success.

One of the major early lessons of the COVID-19 crisis is that competitors from completely different industries can suddenly become allies. To enable such extensions, organisations need a framework instilling an agile culture and working model that helps mobilise innovation. In some cases, companies can leverage external partnerships to extend their organisation's reach and realise a higher return on innovation investment and mitigate risk.

As a managing entity of *Acceleration Programmes*, OPTITEC provides a platform, including a sandbox component to test and demonstrate identified solutions, and acts as a match-maker and a broker between the solution provider and industry end-user in order to keep the process agile, human-centred and free of red tape as much as possible.

If you are interested in becoming a solution provider or would like to use the services of OPTITEC's Acceleration Programme, please contact Mr Christophe Camperi-Ginestet (Director of Operations - christophe.camperi@pole-optitec.com).

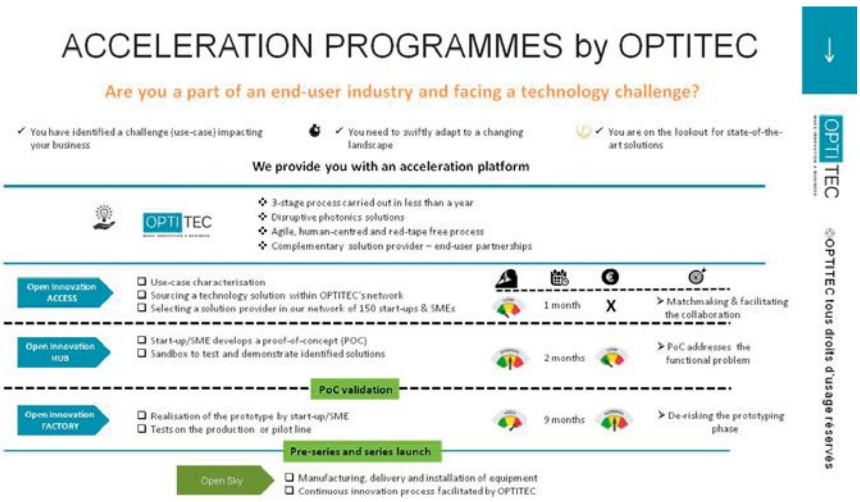


Figure 1: Acceleration Programme functioning

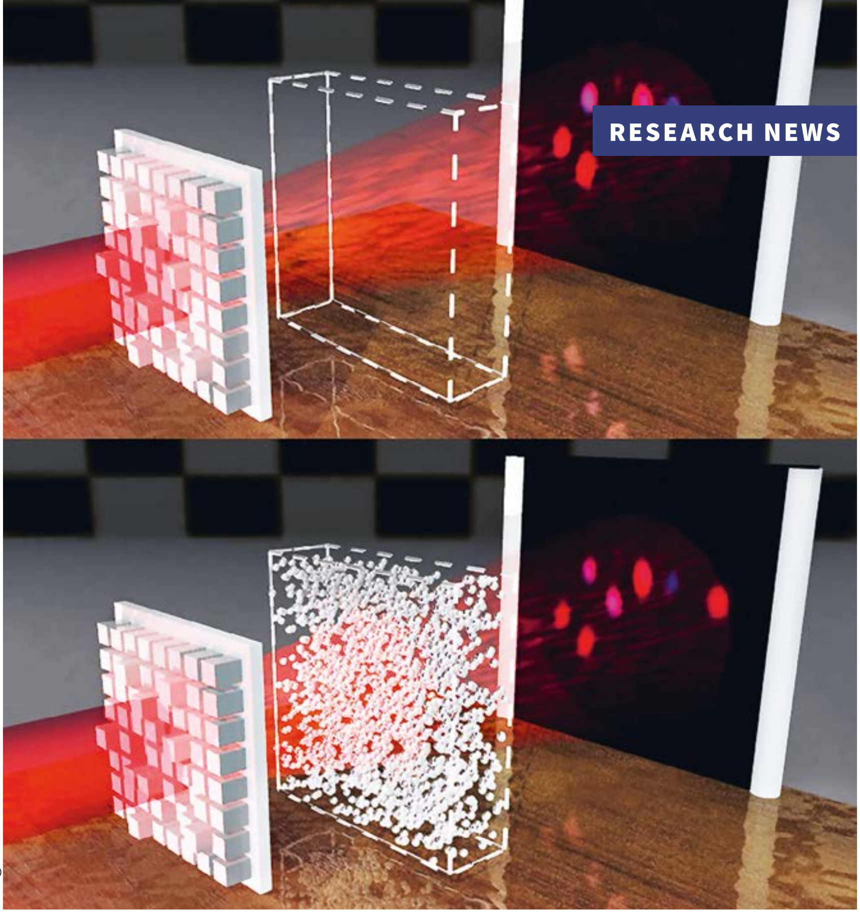


Image credit: Allard Mosk

THE INDESTRUCTIBLE LIGHT BEAM

Why is sugar not transparent? Because light that penetrates a piece of sugar is scattered and deflected in a highly complicated way.

However, as a research team from Utrecht University (Netherlands) and from TU Wien (Austria) has now been able to show, there is a class of very special light waves for which this does not apply: for any specific disordered medium—such as the sugar cube you may just have put in your coffee—tailor-made light beams can be constructed that are practically not changed by this medium, but only attenuated. The light beam penetrates the medium, and a light pattern arrives on the other side that has the same shape as if the medium were not there at all (see figure for a corresponding illustration).

In the experiment in Utrecht, a layer of zinc oxide was used as a light-scattering medium—an opaque, white powder of randomly arranged nanoparticles. First, the transmission matrix of this specific medium was measured interferometrically. With this information at hand, the “scattering-invariant modes” were then determined based on the property that their transmitted field pattern is the same as when they propagate through empty space. This feature was then checked explicitly by injecting the same state through air or through the disordered medium (see top and bottom panel in the figure). The intensity pattern arriving at the screen was observed to be strikingly similar, thereby proving the feasibility of the concept.

In a second step the two research teams also showed that these scattering-invariant modes not only provide interesting new possibilities for imaging across opaque media, but also inside of them. As it turns out, the scattering-invariant modes maintain an unusually strong correlation with the ballistic component of light inside a complex medium, which can be exploited to take a deeper look inside the challenging environment of disordered materials.

REFERENCES

P. Pai, J. Bosch, M. Kühmayer, S. Rotter, A.P. Mosk; Scattering invariant modes of light in complex media, Nature Photonics (2021). https://doi.org/10.1038/s41566-021-00789-9

Link to the freely accessible version: https://rdcu.be/cikbl

ADVERTORIAL

The decisive time and cost factor in the production of PICs is the necessity to repeatedly align signal-carrying glass fibers, active and passive components, and the individual chips.

From wafer probing through chip testing to packaging, this demanding positioning task must be carried out multiple times for each device.

The enabling technology of the active alignment (FMPA = Fast Multichannel Photonic Alignment) developed by PI is the key to speeding up this process immensely: ultrafast, precise, and active alignment where the orientation of the optical components is optimized for best coupling efficiency.

The FMPA system combines a hybrid active alignment mechanism with up to six degrees of freedom in a modular architecture, with fast algorithms that are integrated in the firmware of the controller.

These algorithms provide command-level functions such as the search for first light, local-maximum rejection, and especially the parallel gradient search.

That unique technology enables a fast optimization across multiple inputs, outputs, channels and degrees of freedom between photonic elements, even when these influence each other optically or geometrically.

Leveraging the Possibilities of FMPA

With these groundbreaking tools, already employed by more than two dozen manufacturers of SiPh components, entire SiPh wafers could be tested within hours instead of weeks or months. ●

CONTACT

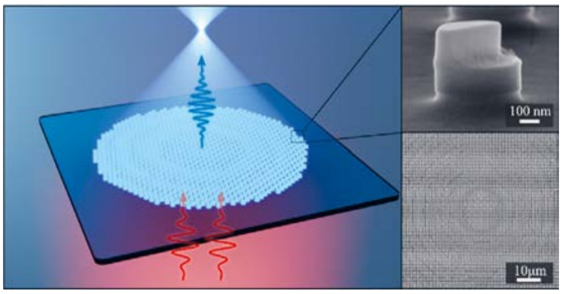
PI France SAS

+33 (0)4 42 97 52 30 - info.france@pi.ws - www.pifrance.fr

A METASURFACE FOR PARAMETRIC OPTICAL GENERATION AND LIGHT MANIPULATION

Nanostructured surfaces can control the propagation properties of incident light within a thickness of the order of its wavelength. Such objects, known as metasurfaces, are now drawing the attention of the scientific community for their potential not only in the miniaturization of optical components such as filters, prisms, lenses and spatial modulators, but also for unprecedented functionalities in light manipulation. This is especially the case of nonlinear optical metasurfaces, which combine the frequency conversion of an optical input with the control of the harmonic beam.

Thanks to a 2D array of semiconductor nanoantennas, the researchers of the MPQ Laboratory (University of Paris & CNRS) have designed and fabricated thin meta-lenses capable of simultaneously generating a second harmonic signal from a laser beam at telecom wavelength, and focusing it at different distances. The building blocks of these metasurfaces are hundreds of aluminum gallium arsenide (AlGaAs) nanostructures with a shape reminiscent of a nanochair.



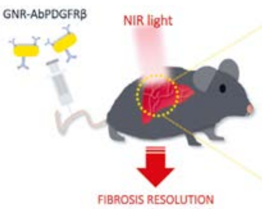
Setting a look-up table of such nanochairs made it possible to impress an arbitrary phase profile on the generated wave, similarly to a phased-array antenna in the radio-frequency domain, while the material chosen resulted in record frequency conversion efficiency (10^{-5}, *i.e.* a million times higher than with plasmonic metasurfaces). This proof of concept paves the way to new nonlinear meta-optics devices unfeasible with bulk components, like nonlinear meta-holograms, and it opens intriguing perspectives for both optoelectronic integration and ultrafast real-time control.

REFERENCES

C. Gigli, G. Marino, A. Artioli, D. Rocco, C. De Angelis, J. Claudon, J.-M. Gérard, and G. Leo, "Tensorial phase control in nonlinear meta-optics," Optica **8**, 269-276 (2021), https://doi.org/10.1364/OPTICA.413329

Towards a new treatment for liver fibrosis enabled by plasmonics

Liver fibrosis occurs when the liver is damaged or exposed to pro-inflammatory stimuli continuously or frequently. In this pathological context, the liver produces internal scarring, and this wound healing is called liver fibrosis. If the wound is small, the liver can heal and return to its normal structure and function. But if the wound is large and occurs continuously, the repair or healing of the damaged area leads to a destruction of the organ's internal structure, which affects its ability to regenerate and function properly, leading to liver diseases such as cirrhosis.
As a first step towards treating liver fibrosis, which is a major cause of morbidity and mortality globally, researchers from IDIBAPS-CIBERehd and ICFO (Spain) designed a pioneering study using targeted photothermal therapy with gold nanorods (GNR). GNR were injected intravenously into fibrotic mice.



These nanoparticles, functionalized with anti-PDGFRβ antibodies, specifically targeted hepatic stellate cells (HSC), which are the main source of extracellular matrix in fibrotic livers. Ten days after the injection, the team irradiated the fibrotic liver with NIR light in order to heat up the GNR via plasmon excitation and specifically kill HSC. After 5 days, treated fibrotic mice showeda significant decrease in liver fibrosis and serum markers of liver damage compared to the different control groups. Another important aspect of this study was the good biosafety profile showed by this therapeutic strategyafter the period of 10 weeks after injection. Despite the very promising results of this study, the clinic's road is still at its infancy. Future studies will focus on optimizing treatment conditions to improve their effectiveness.

REFERENCES
J. Ribera, C. Vilches C, V. Sanz, I. de Miguel *et al.*
"Treatment of Hepatic Fibrosis in Mice Based on Targeted Plasmonic Hyperthermia,"
ACS Nano. (2021), https://doi.org/10.1021/acsnano.1c00988

PUSHING THE LIMITS OF SINGLE MOLECULE LOCALIZATION MICROSCOPY

Revealing the three-dimensional position of molecules with uniform nanometric precision is now possible regardless of the depth inside the biological sample. This result was obtained by teams from Institut des Sciences Moléculaires d'Orsay, Institut Langevin and INSERM research unit 1193, by proposing a new concept in the process of single molecule localization. By substituting the conventionally used uniform illumination of the sample with a structured illumination that varies rapidly over time, the fluorescence emission of the molecules is modulated temporally and its phase intrinsically reveals the position of each molecule. As single fluorescent molecule emits over few milliseconds, researchers developed a demodulation approach that samples the modulated emission in a single camera frame, thus overcoming the limit of the camera frequency. This technique, called ModLoc for "Modulation Localization", achieves axial precision close to the size of the biomolecules (6.8 nm). This new and patented concept allows to determine a parameter from the sample with constant precision on the nanometric scale and can be used to observe information other than the position of the molecules, in particular their orientation.

REFERENCES
P. Jouchet, C. Cabriel, N. Bourg *et al.*, "Nanometric axial localization of single fluorescent molecules with modulated excitation," Nat. Photonics **15**, 297–304 (2021)
https://doi.org/10.1038/s41566-020-00749-9

Photonics:
From European support to industrial technology leadership

Photonics support in the European programmes dates back to the early 90s, though the “Telematics” and “Esprit” initiatives (1983 to 1998) primarily focused on the then emerging field of optical telecommunication, fibre optics, optoelectronic, detectors and III-Vs and semiconductor lasers.

Henri RAJBENBACH, John MAGAN and Werner STEINHOEGL .
European Commission,
Directorate General CONNECT (Communications Networks, Content & Technology),
Unit A3 – Microelectronics and Photonics Industry

"*Photonics is the discipline of photons and electrons working in tandem to create new physics, new devices and new applications”*[1] From our perspective, one could even expand and “Europeanise” this definition, adding: “*... and new industrial opportunities for a green, sustainable and sovereign Europe”*.Photonics support in the European programmes dates back to the early 90s, though the *“Telematics”* and *“Esprit”* initiatives (1983 to 1998) primarily focused on the then emerging field of optical telecommunication, fibre optics, optoelectronic, detectors and III-Vs and semiconductor lasers. In the follow-up Information Society Technologies (IST) initiative (1999 to 2013), it expanded the original ambition to include applications in health, life science, environment, lighting and security and supported a total of 70 photonics projects worth €150 m.The Information and Communication technologies (ICT) initiative (2014 to 2020) has further expanded the support of photonics, supporting Research and Development, but also *“closer-to-market”* Innovation projects.

As a highlight, the programme has set up Digital Innovation Hubs and Pilot lines where new actors, in particular SMEs, can develop advanced photonic-based products, building on the networked expertise of major Research and Technology Organisation (RTOs) across Europe.

[1] T.P. Pearsall, in Quantum Photonics, 2nd ed. Graduate Texts in Physics, Springer-Nature Switzerland AG, 2020; 2020; https://www.springer.com/book/9783030473242

ADVERTORIAL

PHASICS
The phase control company

A SOLUTION FOR EACH METROLOGY PROJECT

Nowadays, the capability to accurately measure optical systems and components is crucial at each development stage: sample qualification, prototype optimization and final integration. Therefore, the test stations need to fit the metrology requirements both in terms of technical specifications, and practical implementation. Technically, the stations should be adapted in terms of wavelength, sampling, accuracy... In practice, some people need a complete, ready-to-use, and turnkey solution, while others are looking for something more flexible.

Leveraging more than 15 years of experience in the development of wavefront metrology solutions, Phasics is answering this challenge with its broad spectrum of measurement tools: **from standalone wavefront sensors to fully integrated test stations, including a new versatile intermediate solution.**

- The **SID4 wavefront sensors** range, available from UV to LWIR, with various samplings. These high resolution achromatic wavefront sensors can easily be integrated in any set-up.

- The **Kaleo Kit**, a brand-new modular and compact solution. Choosing between a large variety of modules (SID4 wavefront sensors, R-cube illumination modules, beam expander, and focusing modules) the user assembles his own test station according to his requirements.

- The **Kaleo MultiWave**, a complete ready-to-use, dynamic interferometer integrating up to 8 test wavelengths on a unique test station. It measures TWE and RWE at the sample design wavelength.

Thanks to all the available options in terms of specifications and implementation, Phasics solutions benefit to a large variety of industries: smartphones, AR/VR, aerospace, autonomous driving, astronomy to name a few.

CONTACT
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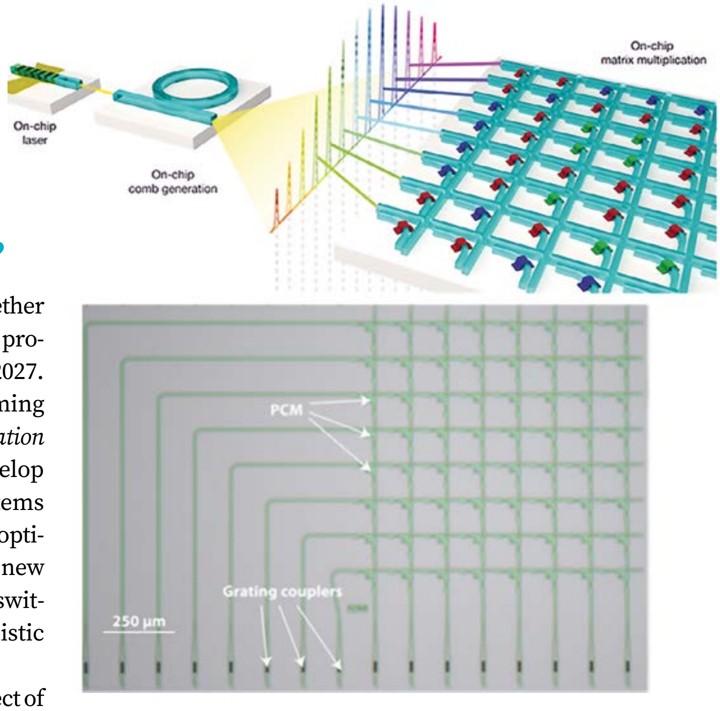
contact@phasics.fr - www.phasics.com

Now comes the future. What is next? What will happen to Photonics between 2021 and 2027?

Electrons and Photons need to work even closer together in ever-miniaturised systems. The Horizon Europe programme is the next horizon, for the period 2021-2027. A few topics will already be called for in the coming two years:In a topic centred on *"Optical communication components"* (26 m€), Innovation actions will develop ultra-dynamic photonic components and subsystems for data communication, using for example new optical wavelength bands, space division multiplexing, new integration schemes, optical switching and new switching paradigms, as solutions for time-deterministic and time-sensitive networks.

Advancing integration technologies will be the subject of the *"PIC topic"* (38 m€). Projects will address the co-integration of photonic and electronic, facilitating new applications in biomedical, environmental and industrial fields, making devices more power-efficient and bringing ground-breaking technologies within reach of entrepreneurial SMEs. Finally, at the crossroad of Photonics and Nanoelectronics, the *"Advanced multi-sensing systems"* topic (47 m€) will be calling for breakthroughs in sensor



The ICT Fun-COMP project develops an all-photonic Matrix-Vector Multiplier (MVM) for neuromorphic, brain-like neural networks. Top shows the system schematic: a micro-comb laser source generates multiple wavelengths modulated according to the vector values and launched into the rows of the MVM array. Bottom shows the fabricated MVM array. Matrix elements are stored in the programmable non-volatile states of phase-change material (PCM) cells; the MVM output emerges at the bottom of the columns. https://fun-comp.org/

The ICT i-Grape project develops fully integrated and connected miniaturised low-cost, standalone micro-spectroscopic smart systems for grape maturation and vine hydric stress monitoring. The detection head integrates UV-VIS-NIR LED sources and photodiode/interference filter arrays at wafer level. It is connected with a IoT processing unit for real-time online processing and monitoring. http://i-grape.eu

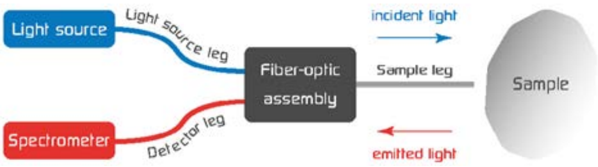
systems by combining component development, system integration, packaging and cost-effective manufacturing processes. They would propose innovative approaches capable of acquiring, processing and interpreting vast amounts or fast changing sensory input data, while reducing significantly overall energy consumption. The sensing functionality builds on technologies related to light and will include integration with microelectronics, micro-nano-mechanical, micro-fluidic, magnetic, radio frequency or bio-chemical technologies.

To take Europe's photonics industry to 2030 and beyond, it will not be sufficient to focus solely on individual research projects. While the EU support for these projects has been of outstanding value and will continue, future focus will be even more closely on creating the ecosystems and markets of tomorrow. That means enabling the transfer of breakthroughs in photonics technology into successful products and services that create new jobs, resolving our most important societal challenges and improving the lives of European citizens. The new Photonic Partnership aims to speed up photonic innovations for a digital, green and healthy future in Europe, securing Europe's technological sovereignty, raising the competitiveness of Europe's economy and ensuring long-term job and prosperity creation. The past has been bright, the future is even brighter!

ADVERTORIAL

FIBER-OPTIC ASSEMBLIES FOR SPECTROSCOPY

SEDI-ATI Fibres Optiques designs and builds fiber-optic based probes aiming at performing and enhancing spectroscopic measurements. Discover 3 different technologies together with their unique benefits.



Basic principle of a fiber-optic probe

MULTIMODE FIBER-OPTIC BIFURCATED BUNDLES

These bundles usually consist of optical fibers in a round or linear configuration combined in an end piece or in an SMA905 connector to match the entrance slit of most spectrometers. This 100% customizable component allows large core fibers up to 1000 µm, large number of fibers, various detection geometries, and a random or coherent mapping.

1X2 HIGH-DIRECTIVITY MULTIMODE COUPLERS

Such couplers have the great advantage of high-directivity which minimizes the light that can directly pass from the injection port to the output port. Also, this solution based on GI50 and GI62.5 µm fibers offers a better spectral resolution than bifurcated bundles. Finally, it is mode insensitive and achromatic over 400-1625 nm wavelength range, allowing broad-band light sources.

MULTIMODE FIBER-OPTIC WDM

The core of this component carries a dichroic filter which is customizable for use in the UV, VIS and IR spectra. It allows to select key wavelengths of interest as well for the incident light to be guided to the sample as for the emitted light to be directed towards the detector. This property makes it ideal for fluorescence detection.

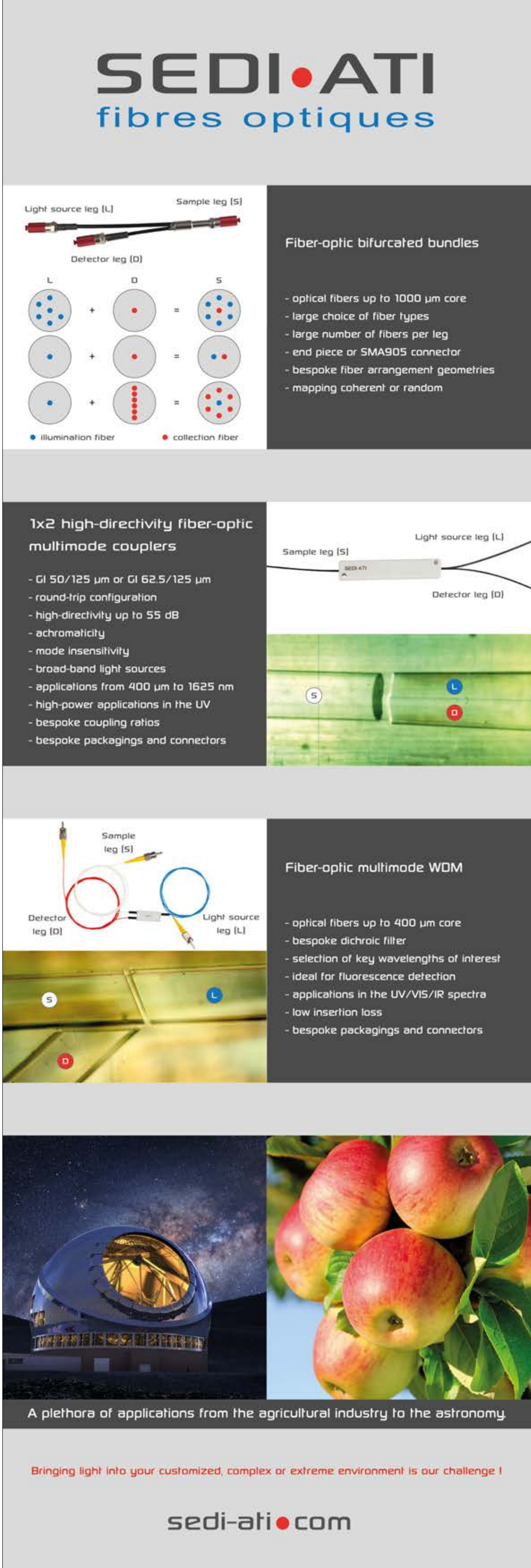
ABOUT SEDI-ATI FIBRES OPTIQUES

With 50 highly skilled and qualified professionals, a strong R&D team, a certified quality system ISO 9001 and ISO 13485, we have in house resources required to adapt and integrate an intrinsically fragile material such as the optical fiber to a wide variety of applications.

SHARE YOUR DREAMS WITH US!

SEDI-ATI is an agile company, creating sustainable and long-term value for its customers. We are always ready to listen to your needs, and to offer you optimal solutions to overcome your challenges. So do not hesitate to consult us!

CONTACT: Pascal SLOBADZIAN / Sales Director
contact@sedi-ati.com / www.sedi-ati.com



BIOGRAPHY

Patricia Era Bath: a community Ophthalmologist

Denis GUILHOT
ExploitDriver, Barcelona, Spain
* denis@exploitdriver.eu

Dr. Patricia Era Bath was not only a medical doctor but also an ophthalmologist, a laser scientist, a surgeon, a researcher, an inventor, an activist, and a humanitarian. She is best known as the inventor of laser cataract removal but also proposed a new discipline in medicine to promote technical, medical, and social aspects of eye care and blindness prevention. As such, she passively and actively allowed millions of people across the world to recover their sight.

https://doi.org/10.1051/photon/202110724

Dr. Patricia Era Bath. © UCLA

Patricia Era Bath was born on the 4th of November 1942, in Harlem, New York City, in the United States of America. Her father Rupert was a merchant seaman from Trinidad who went on to become the first Black motorman for the New York City subway system. Her mother Gladys was a housewife and domestic worker who used to "scrub floors so that her daughter could go to medical school". She is said to have sparked her daughter's interest in science by buying her a chemistry set. This interest, combined with her admiration for both her family physician, Dr. Cecil Marquez, and the humanitarian work of Dr. Albert Schweitzer with lepers in Africa, led her to pursue her ambition to become a medical doctor and help underserved communities. At the age of 16, she received a scholarship from the US National Science Foundation to join a research project on cancer at Yeshiva University. She contributed to the results through her derivation of a mathematical equation for predicting cancer cell growth which was included in a scientific paper presented by Dr. Robert O. Bernard at an international conference held in Washington, D.C.. This led her to win in 1960 one of ten Merit Awards from *Mademoiselle*, a woman's magazine aimed to the smart young woman. She went on to complete high school in two and a half years instead of four, before studying physics and chemistry as an undergraduate at Hunter College, New York City.

In 1964, she enrolled at Howard University College of Medicine in Washington DC, which she graduated from as a medical doctor (MD) in 1968. Dr. Bath joined the Harlem Hospital as an intern and completed

KEY DATES

1958:
Scholarship from the US National Science Foundation.

1968:
Graduates from Howard University as a medical doctor (MD).

1970:
Performs her first major eye surgery.

1976:
Co-founds the American Institute for the Prevention of Blindness.

a fellowship in ophthalmology at the Columbia University. By working in two different eye clinics, so close yet so different, it struck her that the rate of blindness in patients at Harlem Hospital was about twice as high as that at Columbia. She identified that that difference was mainly due to the lack of access to ophthalmic care of the black community, since no surgery was performed at Harlem Hospital. She convinced Columbia professors to perform surgery on blind patients at the hospital for free as part of Dr. Martin Luther King's Poor People's campaign and volunteered herself as an assistant surgeon. She performed her first major eye surgery in 1970 and started drafting her new concept of Community Ophthalmology, which she published in 1979 [2]. This new discipline aimed at promoting eye health and blindness prevention through programs leveraging public health, community medicine, and ophthalmology strategies in chronically underserved communities, and is now operative worldwide. Dr. Bath joined New York University in 1970 and became its first African American resident in ophthalmology. During this final step of her academic training, she married Dr. Beny J. Primm and gave birth to her daughter Eraka in 1972. In 1974, she moved to Los Angeles to simultaneously become an assistant professor in surgery at the Charles R. Drew University and in ophthalmology at the University of California, Los Angeles (UCLA). In 1975, she became the first female faculty member in the Jules Stein Eye Institute and the first African American female surgeon at the UCLA Medical Centre. In 1976, she co-founded the American Institute for the Prevention of Blindness (AIPB), a non-profit organization dedicated to the prevention of blindness through programs designed to protect, preserve, and restore people's sight. It advocates that eyesight is a basic human right and that primary eye care must be a component of basic health services provided for free, when necessary, to everyone. She then established the keratoprosthesis program at UCLA, to remove damaged corneas and replace them with artificial ones. She started experimenting on laser ophthalmology with a Lasag Microruptor II Nd:YAG lasers in single pulse and multiple pulse modes, with 12-ns pulse durations and energy levels between 1.1 and 4.0 mJ. Her experience in this field led her to direct the first national keratoprosthesis study in 1983. That same year, she became the first woman in the USA to head a postgraduate ophthalmology training program as Chair of the King-Drew-UCLA ophthalmology Residency Program. Meanwhile, she started working on a new concept, based on laser technology instead of the standard ultrasound probes, to remove cataract. *"When I talked to people about it, they said it couldn't be done"*, she later recalled. She could not pursue this idea satisfactorily since her funding proposals were not granted and she could not get access to the required lasers. Thus, she decided to take a sabbatical and was accepted as visiting professor on merits in several laboratories. First, she went to the Rothschild Eye Institute of Paris, where she was Dr. Danièle Aron-Rosa's mentee. She worked with her mainly on laser ophthalmology with mode-locked picosecond pulsed Nd:YAG lasers for a summer, before moving on to the Loughborough Institute of Technology, in the UK, and the University of Free Berlin's laser medical centre, Germany, where she began her study of laser cataract surgery and performed her first experiment with excimer laser phaco-ablation in human eyes. She went back to the USA and completed her research in 1986. She was also awarded the US patent No. 47,444,360 for the LaserPhaco probe in 1988, the first medical • • •

**"You can achieve your dreams.
And even though there may never have been a girl or woman in that field, that should not be an obstacle to prevent you from achieving that.
It's the impossible dream that I hope my work will make possible for all girls".**

1979: Publication of the Community Ophthalmology Rationale paper.

1986: Completes research on the LaserPhaco technology.

1988: LaserPhaco probe patent granted.

2000: Ultrasound cataract removal patent granted.

2003: Combination of ultrasound and laser cataract removal patent granted.

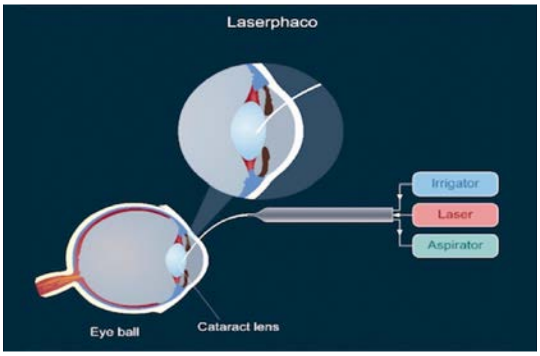


Figure 1. Schematic view of the excimer laser ablation of cataract with the LaserPhaco probe.
Step 1: Laser pulses change the crystalline lens material structure through ablation, fragmentation and/or disruption.
Step 2: Mechanical hydraulics fluid is injected to emulsify the lens fragments.
Step 3: Mechanical suction forces are applied to aspirate the emulsified lens fragments.

patent granted to an African American female doctor. That same year, she was elected to the Hunter College Hall of Fame.
But what is the LaserPhaco probe invention about? Cataract occurs naturally over time, when the lens of the eye, located behind the iris and the pupil, becomes opaque. It is very common amongst the senior population and leads to distorted vision and ultimately blindness. It accounts for more than half of all avoidable blindness cases in the world [3]. Patricia Bath invented the excimer laser ablation of cataract and the LaserPhaco probe, that allows an excimer laser emitting at 308 nm to ablate the cataract through a fibre optic probe and a 1mm insertion into the eye so it can be removed and replaced by an artificial lens. She initially used a Lambda Physik 102 xenon chloride excimer laser and a quartz silica optical fibre (see Fig. 1). This laser was selected over the 193 nm excimer laser since it was more difficult to transmit through optical fibre while there was no evidence that it was preferable for the human eye. The laser was operated with 17-ns pulses at a repetition rate of 1 to 100 Hz, with energy output of 0 to 230 mJ. She discovered that ablation of tissues occurred for human lenses at a threshold of 0.5 J/cm^2. The LaserPhaco technology was a major breakthrough in cataract surgery. It also laid the foundations of all laser-enabled cataract surgery techniques developed since, such as femtosecond Laser Assisted Cataract Surgery (FLACS), the most widely used technology amongst laser cataract surgeons. This has enabled techniques which will account for an estimated 1.1 million surgeries globally per year by 2022 [4]. This represents a 1 billion US dollar market in equipment only.

"Many times, these days, I get asked what do I think my greatest accomplishment has been. Philosophically, I like to think that my greatest accomplishment has to be in those moments when I've helped someone see. [1].

Between 1988 and 1993, Dr.Bath also practiced ophthalmology in the private sector in Santa Monica, California. In 1993, she retired and became the first woman elected as honorary staff of the UCLA Medical Centre. She was also named a "Howard University Pioneer in Academic Medicine".
In 2004, she was dubbed one of "California's Remarkable Women" in an exhibit organised by the California State History Museum.
Even after retiring, Dr. Bath continued her work towards curing blindness in several ways. She performed more top-level research, even receiving more patents in 2000 and 2003. She also started advocating for telemedicine, which led her to be appointed to President Barack Obama's commission for digital accessibility for the blind in 2009. She remained director of the AIPB and travelled on several humanitarian missions in which she taught, donated equipment, lectured, and even restored the sight of countless people through keratoprosthesis, some of whom had been blind for 30 years.
Because of her gender, origins, and ambition, Patricia Bath faced discrimination many times, even in her professional life. When she was growing up, there were no high schools in Harlem. She did not have models of female physicians and surgeons, which were male-dominated professions. Black people were excluded from many medical schools and medical societies. At medical school, women were not allowed to seat in the front row. When she became the first woman faculty member in her department, she was offered to share an office with the secretaries since they were all women, instead of the other all-male faculty members offices. She was also offered an office in the basement, next to the lab animals, which she refused, and succeeded in getting acceptable office space. She also reached a glass ceiling in the

1980s when her research proposals were not funded, and her colleagues would tell her that her idea for laser-enabled cataract surgery would not work. *"I didn't waste time with phone calls or petitions about the unfair and discriminatory practices of the National Institutes of Health or the National Eye Institute"* she said. Instead, she opted for her sabbatical and pursued her research in Europe. She explained in an interview on Good Morning America in 2018: *"I had a few obstacles, but I had to shake it off. That's the noise and you have to ignore that and keep your eyes focused on the prize".*

She died on the 30th of May 2019 at the UC San Francisco medical centre, California, from complications due to cancer. She was granted five patent families (three on the LaserPhaco technology, one on ultrasound cataract removal and one on a combination of laser and ultrasound for cataract removal), 25 patents globally, and co-authored more than 100 scientific papers. In 2020, she was nominated as a candidate to the U.S. Patent Office's National Inventors Hall of Fame. Although she was not one of the 2021 new inductees [5], she is expected to one day become the first Black Woman in this prestigious Hall of Fame.

REFERENCES

[1] Conversation Between Patricia Bath, MD and Eve Higginbotham, MD. The Foundation of the American Academy of Ophthalmology Museum of Vision & Ophthalmic Heritage, Orlando FL, October 23 (2011).

[2] P.E. Bath, Rationale for a Program in Community Ophthalmology, Journal of the National Medical Association **71(2)**, 145-148 (1979).

[3] https://www.cureblindness.org/cause. Retrieved on the 3rd of January 2021.

[4] https://eyewire.news/articles/steady-growth-in-cataract-surgical-procedures-is-expected-over-the-next-5-years/. Retrieved on the 3rd of January 2021.

[5] https://www.invent.org/inductees/new-inductees. Retrieved on the 3rd of January 2021.

GENERATION OF QUANTUM STATES OF LIGHT IN NONLINEAR ALGAAS CHIPS: ENGINEERING AND APPLICATIONS

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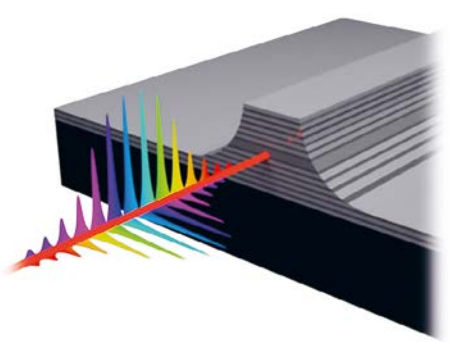

Photonic quantum technologies represent a promising platform for applications ranging from long-distance secure communications to the simulation of complex phenomena. Among the different material platforms, direct bandgap semiconductors offer a wide range of functionalities opening promising perspectives for the implementation of future quantum technologies. In this paper, we review our progress on the generation and manipulation of quantum states of light in nonlinear AlGaAs chips and their use in quantum networks.

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NONLINEAR QUANTUM PHOTONICS IN THE ALGAAS PLATFORM

Integrated quantum photonics is playing a leading role in the development of quantum technologies and significant progress has been made using a wide variety of platforms for the generation, manipulation and detection of quantum states of light. Semiconductor materials, which are already at the basis of current classical communication and computation technologies, are ideal systems for the miniaturization and integration of several quantum components and important achievements have been reached by exploiting both the Si and the III-V platforms. In this context, AlGaAs presents several assets [1,2]: high purity quantum states of light can be generated either using the single emitter approach (quantum dots) or by using nonlinear frequency conversion processes thanks to its strong nonlinearity (χ^2 of GaAs ~ 110 pm/V at 1550 nm). In both cases, the direct band-gap of this material has allowed to demonstrate electrically injected sources, offering a clear advantage over optically driven ones in terms of portability, energy consumption, and integration. Photon manipulation and routing in quantum circuits thanks to electro-optical effects has also been demonstrated; finally, a full on-chip integration of generation, manipulation and detection of quantum states of light has been shown using this platform. In this paper, we focus on the generation of biphoton states exploiting the process of spontaneous parametric downconversion (SPDC) in AlGaAs waveguides; in this process, photons of an impinging pump laser beam of energy $\hbar\omega_p$ can be probabilistically converted into photon pairs, usually called signal and idler, of energy $\hbar\omega_s$ and $\hbar\omega_i$, respectively. In order to have a maximum efficiency in the frequency conversion, both energy and momentum have to be conserved. Despite its nondeterministic nature, this process is widely used to produce photon pairs and leads to devices working at room temperature and emitting photon pairs in the C-telecom band, thus

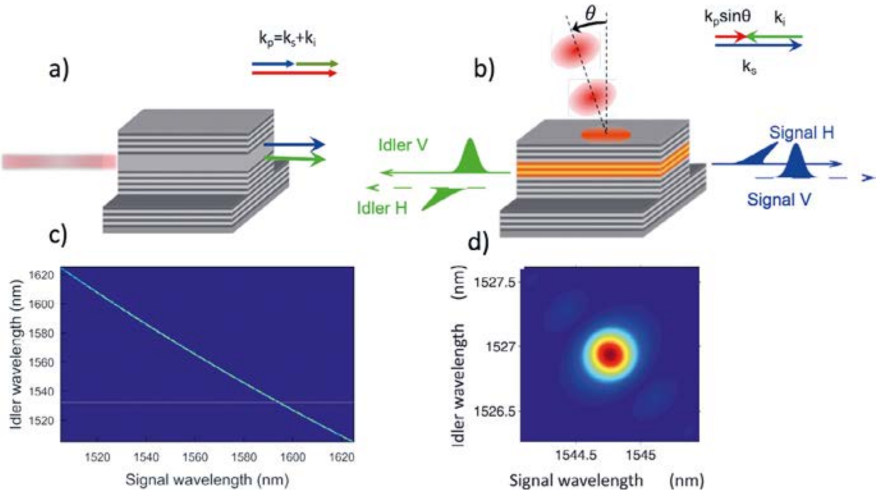
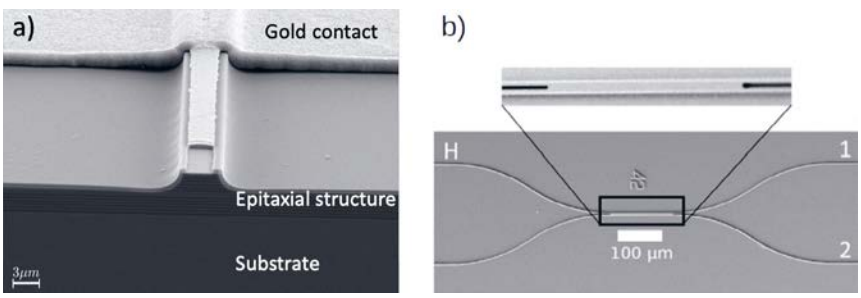


Figure 1. Top: Sketch of AlGaAs waveguides emitting photon pairs by SPDC based on two different phase-matching schemes. (a) Pump, signal and idler are collinear and co-propagating. (b) The pump beam is transverse with respect to the waveguide, and signal and idler are counterpropagating. Bottom: joint spectral intensity corresponding to co-propagating (c) and counterpropagating (d) phase-matching geometry.

facilitating their use in real world quantum information and communication protocols (see also the work done in the group of Prof. G. Weihs in Innsbruck, and Prof. A. Helmy in Toronto). In order to deal with the isotropic structure of this crystal, several solutions have been proposed to satisfy momentum conservation (called also phase-matching (PM) condition) in AlGaAs waveguides. Among these, the most advanced results in quantum states generation and manipulation have been obtained using two phase-matching geometries: a collinear modal PM scheme, in which the phase velocity mismatch is compensated by multimode waveguide dispersion, and a counterpropagating PM scheme, in which photon pairs exit from opposite waveguide's facets (Fig. 1). The choice of the PM scheme has a strong impact on the joint spectrum of the generated photon pairs: in the case of the collinear PM scheme, the photon pairs present a broadband and strongly • • •

Figure 2.
Scanning electron microscopy image of an electrically injected device generating photon pairs by internal SPDC (a) and of a photonic chip integrating a heralded single photon source and a 50/50 coupler (b). In this device, a pump laser beam vertically incident on one of the input guides generates pairs of photons propagating in opposite directions. One photon of each pair is detected in arm H to herald the presence of its twin. The purity of the emitted photons is assessed by analyzing the temporal statistics of the photons transmitted by the waveguides at the output. Figure a) adapted from Technologies **4**, 24 (2016) under CC license; Figure b) adapted from Photoniques 91, 25 (2018) under CC license.



COMPLETE SOLUTIONS FOR QUANTUM APPLICATIONS

Menlo Systems' optical frequency combs and ultra-stable lasers enable the second quantum revolution

Quantum technology lets us exploit the laws of quantum mechanics for tasks like communication, computation, simulation, or sensing and metrology. As the second quantum revolution is ongoing, we expect to see the first novel quantum devices replace classical devices due to their superior performance.

There is a strong impetus to transform quantum technologies from fundamental research into a broadly accessible standard. Quantum communication promises a future with absolute security through quantum key distribution; quantum simulators and computers can perform calculations in seconds where the world's most powerful supercomputers would require decades; quantum technologies enable advanced medical imaging techniques. Further applications will likely arise that we cannot anticipate yet. The global market has realized the huge potential of quantum technologies. Menlo Systems, a pioneer in the field, provides commercial solutions for these novel challenges.

The link between photonics and quantum physics is obvious. Quantum simulation and computation use cold atoms and ions as qubits, labs worldwide use optical frequency combs and ultra-stable lasers in these types of experiments. Quantum communication often relies on single photons, which are generated with precisely synchronized femtosecond laser pulses in the near-infrared (-IR) spectral range. Quantum sensing and metrology require the highest stability and accuracy in frequency comb and laser technology. And – an application worth highlighting – optical atomic clocks are under way to replace the current definition of the second in the International System of Units (SI).

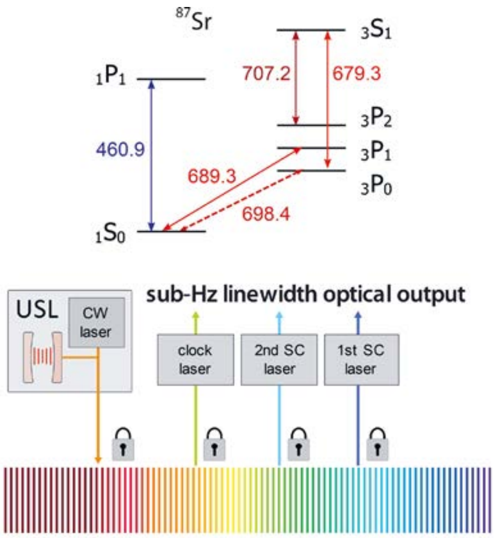


Figure:
The hyperfine transitions in strontium (Sr) atoms with the ultra-narrow clock transition at 698.4 nm (upper part). A commercial FC1500-Quantum system for optical clock applications contains an ultra-stable laser transferring its spectral purity onto an optical frequency comb and all other lasers which are also locked to the comb (lower part).

The transition frequency in optical clocks is on the order of hundreds of terahertz, corresponding to the visible or the ultraviolet region of the electromagnetic spectrum. Counting these optical frequencies is only possible using a frequency comb [1], a mode-locked laser with evenly spaced frequency modes within its optical spectrum. When referenced to a CW laser which is stabilized to a high-finesse optical cavity, the bandwidth of the comb lines narrows down to below 1 Hertz [2], corresponding to a stability of 10^{-15} or better. The newest generation of optical atomic clocks enabled by this technology reach an accuracy of 10^{-18} [3], two orders of magnitude higher than the best cesium atomic clock.

Menlo Systems' FC1500-Quantum is a complete CW laser system with an ultra-stable frequency comb. It provides several CW lasers for atom cooling, repumping, and addressing the sub-Hertz linewidth clock transition in atoms or ions used in optical clocks (see figure). The low phase noise obtained on the comb-disciplined CW lasers is essential for coherent gate manipulation in many atom optical quantum computing schemes and for fast and high-fidelity gate operations. The laser light is delivered *via* optical fiber to the "physics package" consisting of vacuum chamber with all the necessary optics and electronics components and the atoms. Labs no longer need to undergo the time consuming process of designing and building their own ultra-stable lasers. Eventually, the comb itself has two purposes: It acts as reference for all the lasers to maintain their narrow linewidth, and it is the clockwork that transfers the optical frequency's spectral purity to the microwave region, or to a different optical frequency [4].

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REFERENCES

[1] J. Reichert *et al.*, Opt. Commun. **172**, 59 (1999)
[2] R. W. P. Drever *et al.*, Appl. Phys. B. **31**, 97 (1983)
[3] E. Oelker *et al.*, Nat. Photonics **13**, 714 (2019)
[4] M. Giunta *et al.*, Nat. Photonics **14**, 44 (2020)

anti-correlated joint spectrum; in the case of counterpropagating PM scheme the photon pairs are characterized by a narrowband spectrum and their spectral correlations can be engineered through the pump beam profile. One of the important advantages of the collinear PM scheme is its compatibility with electrical injection allowing for the monolithic integration of the pump laser and the nonlinear medium. In this device, working at room temperature, the active medium is a quantum well inserted in the core of the structure; the electrical injection of the device generates the laser emission which is converted in photon pairs in the C-telecom band *via* intracavity SPDC (Fig. 2a). A further step towards a fully quantum integrated photonic circuit has been done by demonstrating the monolithic integration of a heralded single photon source and beamsplitters using the counterpropagating PM scheme; this device has been used to implement an integrated Hanbury-Brown and Twiss experiment confirming the single photon operation (Fig. 2b). The quality of the quantum state generated in both PM schemes has been analyzed through measurements of indistinguishability (using for example Hong-Ou-Mandel interferometers), quantum correlations and entanglement — between the generated photons — in several degrees of freedom like polarization, energy-time and time bins. In this regard we note that the group velocity mismatch between orthogonally polarized photons in the AlGaAs chip is so small that no off-chip walk-off compensation is required to obtain polarization entanglement. This is a key feature enabling the direct use of the emitted pairs at the output of the chip, opening the way to its easy integration into simple and robust architectures.

QUANTUM STATE ENGINEERING

In recent years, entanglement in high-dimensional degrees of freedom of photons has attracted a growing attention as a means to increase the throughput and security of quantum communication and enhance flexibility in quantum computing. In this context, frequency is a particularly attractive degree of freedom thanks to its robustness to propagation in optical fibers and its capability to convey a large amount of quantum information into a single spatial mode. This provides a strong motivation for the development of efficient and scalable methods to generate and manipulate frequency-encoded quantum states. In this respect, the counterpropagating PM scheme allows for an extremely high versatility in quantum state engineering. Indeed, tailoring the spatial profile (intensity and phase) of the pump beam enables the control of the spectral correlations and wavefunction symmetry of the photon pairs directly at the generation stage, without any post-selection. In particular, tuning the pump beam waist allows to produce correlated, anti-correlated and separable frequency states, while modifying the spatial phase profile allows to switch between symmetric and antisymmetric spectral wavefunctions and modify the exchange statistics of the photons (see Fig. 3) [3]. These results could be harnessed to study the effect of exchange statistics in various quantum simulation • • •

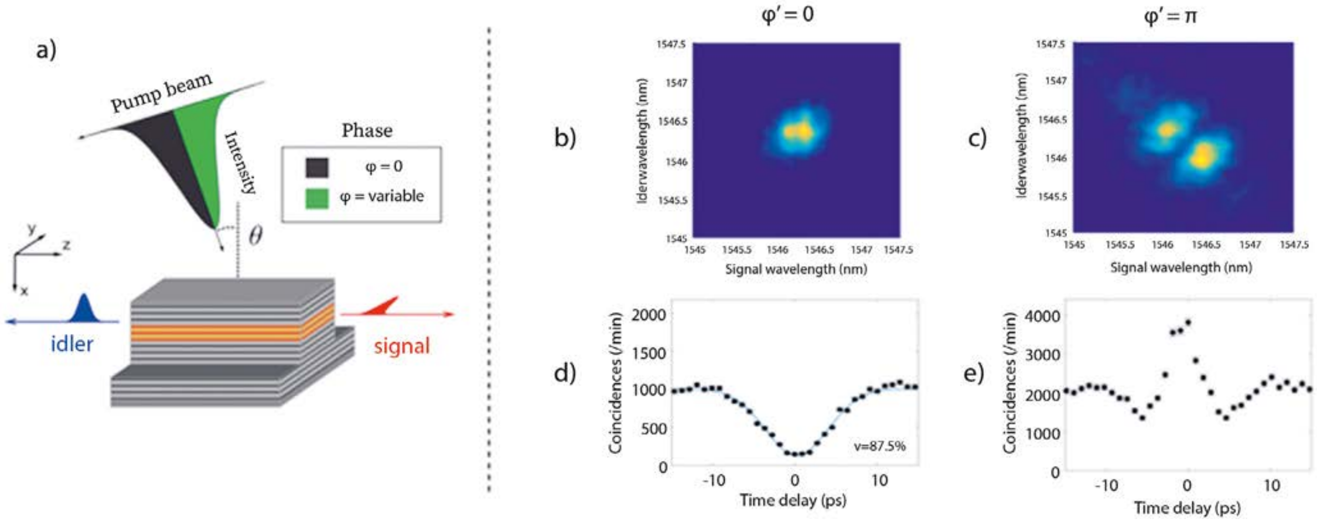


Figure 3:
a) Sketch illustrating the tailoring of the pump profile to engineer the signal/idler exchange statistics in the device based on the transverse pump configuration;
b, c) measured joint spectrum for different values of the phase shift imposed to the pump beam;
d, e) corresponding two-photon interference measured in a Hong-Ou-Mandel interferometer.

problems, and to implement communication and computation protocols exploiting antisymmetric high-dimensional quantum states. Another interesting aspect related to AlGaAs chips is the inherent cavity effect arising from the refractive index contrast between semiconductor and air at the waveguide's facets; in devices based on the collinear PM scheme, this leads to the generation of *biphoton frequency combs* spanning several tens of nanometers (Fig. 4). These states, that have also been generated in integrated nonlinear optical resonators based on third order nonlinear optical processes, consist of discrete spectral modes and are characterized by a biphoton phase coherence guaranteed by the generation process. They constitute entangled *qudits, i.e.* d-level quantum systems, providing promising applications for quantum information processing [4]. In this context, we have shown that the interplay between cavity effects and a temporal delay between photons of a pair allows to switch from symmetric to anti-symmetric high-dimensional states opening the way to the implementation of qudit teleportation, logic gates, as well as dense coding and state discrimination [5].

APPLICATIONS IN QUANTUM INFORMATION AND COMMUNICATION PROTOCOLS

The richness and the quality of the quantum states generated and controlled in AlGaAs chips in terms of degrees of freedom, dimensionality, possibility to have simultaneous entanglement in different degrees of freedom (namely hyperentanglement) opens many perspectives for both fundamental research and for the implementation of future quantum technologies.

For example, continuous degrees of freedom of photons display a perfect analogy with the continuous variables (CV) of a multiphoton single mode of the electromagnetic field, which makes them a promising platform to realize CV •••

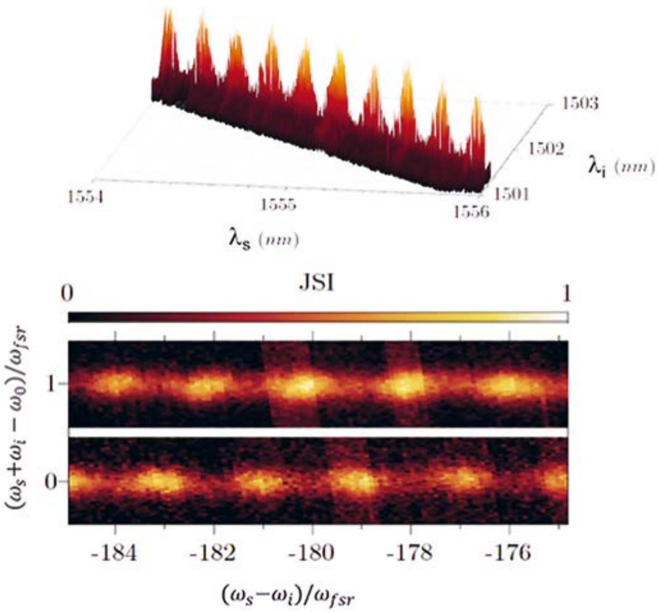


Figure 4:
Top: Experimental measurement of the Joint Spectral Intensity of the state generated by a device based on a collinear phase-matching geometry, showing a frequency comb structure. Bottom: generation of resonant and anti-resonant biphoton frequency combs by tuning the pump beam frequency. This control, combined to the insertion of a temporal delay between photons of a pair, allows to switch from symmetric to anti-symmetric quantum frequency states. Figure adapted from [5] under Creative Common License.

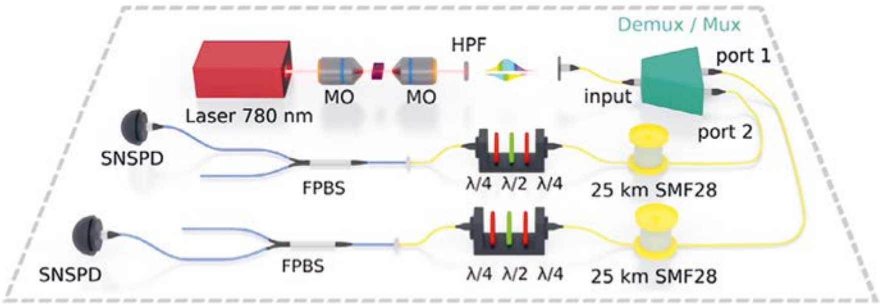


Figure 5:
Sketch of the quantum network architecture exploiting broadband polarization entangled states produced by an AlGaAs chip. The setup consists of three stages: entanglement generation, frequency demultiplexing/ multiplexing of the generated signal, and a distribution stage including fiber links, a polarization analysis stage fibered polarizing beam splitters (FPBS) and superconducting nanowire single photon detectors (SNSPD).

quantum information protocols in the few-photon regime. In this regard, we have shown that biphoton frequency combs can be used to generate, manipulate, and detect grid states encoded in time (t) and frequency (ω). The redundancy of information arising from the periodicity of time-frequency space gives these states a particular robustness against time and frequency shifts, opening the way to the implementation of quantum error correction operations [6]. Also, continuous degrees of freedom of single photons are relatively easy to engineer using spatial light modulators acting on the pump beam as well as measurements and time delays, opening the perspective of extending the range of application of frequency and time degrees of freedom to different quantum information related protocols for continuous variables, as for instance quantum communications and quantum metrology.

In the context of quantum communications, the ability to maintain high quality polarization entanglement over a broad spectral region in the C-telecom band makes AlGaAs sources particularly appealing. Recently, the combination of these devices with industry-grade wavelength division multiplexing techniques has allowed us to build a reconfigurable, fully connected entanglement distribution quantum network between up to 8 users in a resource-optimized quantum network topology (Fig. 5). We have demonstrated that the lower bound on the fidelity of the entangled state generated by our chip with respect to an ideal Bell state stays above 95 % over a 26 nm wide spectral range around biphoton degeneracy and above 85 % over a 60 nm range. The performance of the network has been benchmarked by running an entanglement-based quantum key distribution protocol between two users across fibered optical links of up to 50 km and we extrapolate a positive key rate for distances of up to 75 km in both symmetric and asymmetric configurations opening the way to the implementation of our architecture in metropolitan-scale quantum communication networks [7].

CONCLUSION

Nonlinear AlGaAs devices allow to generate pure quantum states of light in two and higher dimensions with a high level of flexibility and on-chip control; they work at room temperature, telecom wavelength and are compatible with electrical injection. These results open a wide variety of perspectives for the implementation of future quantum technologies. The level of integration can be pushed further by implementing additional on-chip functionalities such as polarizing beam-splitters or photon routers exploiting the electro-optics effect. Hybrid devices integrating a III-V generation stage with Si-based photonics circuits are also promising candidates for fully integrated quantum integrated photonic chips bringing together the best of the two worlds. We also note that recently, entangled-photon -pair generation has been demonstrated using third order nonlinear effects in AlGaAs-on-insulator devices, opening another promising approach for all-on-chip quantum information applications. From the point of view of fundamental research, the obtained level of control and engineering on the biphoton time-frequency phase space opens the way to the generation and manipulation of exotic states, like Schrödinger cat-like state, compass states or grid states which can find interesting applications in metrology or quantum error correction codes. Finally, the recent demonstration of flexible entanglement-based secure communication using AlGaAs chips offers a promising route to the deployment of scalable quantum network architectures which could benefit from other features of the generated quantum states, such as their biphoton comb structure as well as the combined exploitation of both polarization and frequency entanglement.

REFERENCES

[1] C. P. Dietrich *et al.*, Laser Photonics Rev. **10**, 870 (2016)

[2] A. Orieux *et al.*, Rep. Prog. Phys. **80** 076001 (2017)

[3] S. Francesconi *et al.*, Optica **7**, 313 (2020)

[4] M. Kues *et al.*, Nat. Photonics **13**, 170 (2019)

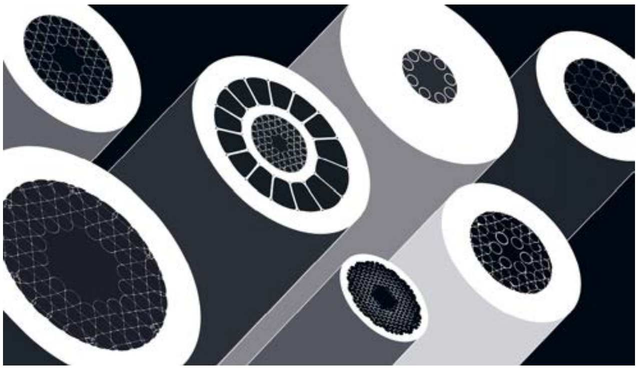
[5] G. Maltese *et al.*, Npj Quantum Inf. **6**, 13 (2020)

[6] N. Fabre *et al.*, Phys. Rev. A **102**, 012607 (2020)

[7] F. Appas *et al.*, arXiv:2102.04835v1 (2021)

ADVERTORIAL

GLOPHOTONICS: AN ENABLING PARTNER IN THE EMERGING QUANTUM TECHNOLOGIES



GLOphotonics (or 'GLO' for short) develops and commercialises photonic components, sub-systems and/or systems built upon its proprietary and disruptive photonic fiber technology.

GLO's technology stands out by its versatility (platform technology) and its enabling powers. This Key Enabling Technology (KET) rests on two outstanding building blocks: The **hollow-core photonic crystal fiber** (HCPCF) and the **photonic microcell**™ (PMC). By a judicious choice of the HCPCF design and the filling gas, GLO functionalizes its PMC to make a variety of unique and value-added devices such as light sources, laser pulse-compressors, spectroscopy-cells and gas detectors. GLO addresses a multi-sector market that covers laser micromachining, bio-photonics, telecom, laser, space and science to mention a few.

GLO has built a unique experience in providing metrology laboratories and space agencies with quantum devices such as optical references and gas-sensing solutions.

GLO is actively involved through collaborations with major universities in developing innovative solutions for quantum information and quantum metrology and sensing. GLO is particularly proud to be part of the new quantum center NAQUIDIS of the French region Nouvelle Aquitaine, and a co-investigator in the European project CRYST³ whose objective is to develop highly miniaturized quantum sensors based on its fiber technology.

Contact us if you are a player in this exciting emerging quantum era, GLO's technology might be the perfect fit for your projects and products.

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TOWARDS REAL-TIME QUANTUM IMAGING WITH SINGLE PHOTON AVALANCHE DIODE CAMERAS

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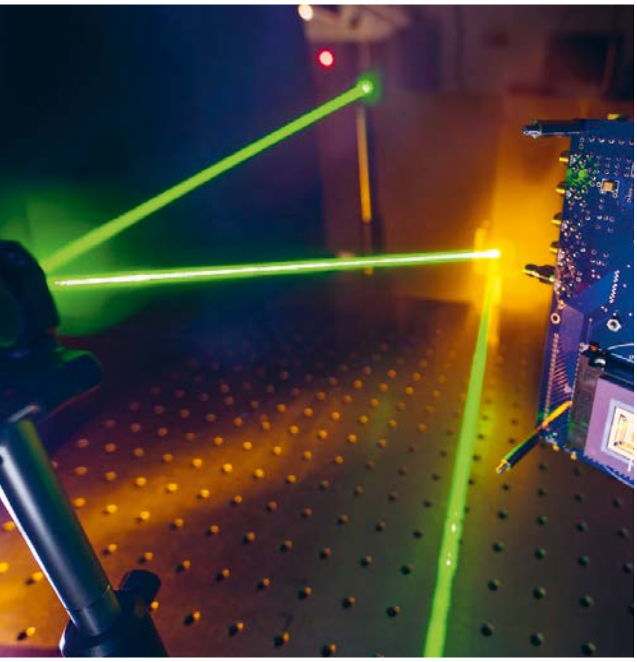

By harnessing the properties of photonic quantum states and their interaction with the environment, quantum imaging promises to go beyond the limits of classical imaging. However, the inherent weakness of detected signals and the fragility of quantum states make their properties difficult to measure in practice. In recent years, the emergence of single-photon sensitive cameras enabled the field to take a step closer to practical applications. In this respect, single-photon avalanche diode (SPAD) cameras are one the most promising technologies as they can detect single photons across many pixels with unparalleled speed, temporal resolution, and very low noise.

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Quantum imaging harnesses quantum properties of light to break the fundamental limitations of imaging. In a typical quantum imaging system, a non-classical state of light illuminates an object from which an image is formed onto a set of photodetectors. The specific measurement performed by the detectors (e.g. single or coincidence detections) combined with the state properties (e.g. single-photon, entangled photon pairs or squeezed states) enables to improve the image quality. Proof-of-principle demonstrations range from super-resolution to contrast-enhanced and sub-shot-noise imaging, leading to the development of unique imaging modalities such as imaging with undetected photons, quantum illumination and non-local imaging [1]. However, despite recent significant advancements in this field, the practical potential of quantum imaging can be questioned. The doubts about applicability arise from a combination of limiting factors including the inherently weak intensity of quantum sources, the fragility of quantum states and the difficulty to measure their properties. While source brightness is likely to keep improving constantly because it is an essential aspect also for other fields such as quantum communications, the efficiency of imagers for quantum light has stalled for several years and impedes the advances in quantum imaging. To highlight how critical this is, it is worth noting that most quantum imaging experiments performed to date used raster-scanning single-pixel techniques to capture images, which is obviously a very photon-inefficient, time-consuming, and non-scalable process.

In recent years, the development of single-photon sensitive cameras such as electron multiplied charge coupled device (EMCCD), intensified Complementary Metal Oxide Semiconductor (iCMOS) and iCCD, enabled the detection of extremely weak optical signals — down to the single photon level — over a large number of spatial positions in parallel. However, single-photon sensitivity is generally not sufficient in quantum imaging experiments because most protocols also require measuring the N^{th}-order optical correlation function ($G^{(N)}$). But it turns out that performing high-order correlation measurements is much more delicate than forming an image by photon accumulation. For example, schemes based on entangled photon pairs reconstruct images by measuring the second-order spatial correlation function. In practice, this is achieved by identifying photons detected in coincidence between different pixels of the sensor in each frame, and then accumulating these measurements. Such a procedure is, however, extremely challenging. Indeed, the presence of spurious detection events due to dark and electronic noise, background light, and the presence of multiple pairs in a single frame strongly hinder the process by producing 'accidental' coincidences *i.e.* coincidences that do not originate from the simultaneous detection of two photons from an entangled pair. This process is also very sensitive to losses because the probability of detecting two photons is the square of that of •••

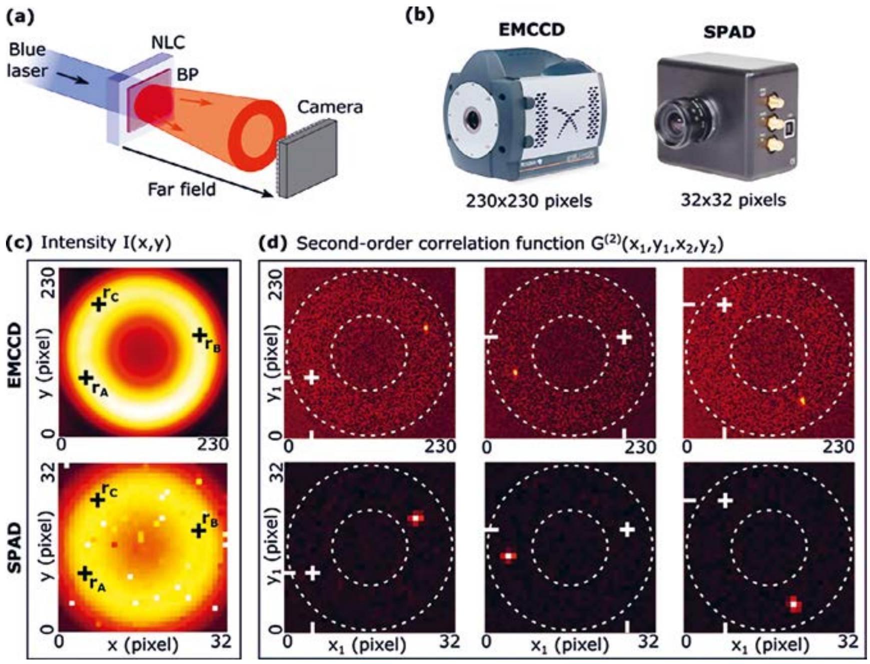

Figure 1. Measuring a spatially resolved second-order correlation function ($G^{(2)}$) under entangled photon pairs illumination. (a) Simplified experimental setup for imaging spatially entangled photon pairs in the far field. Photon pairs are produced by type-I spontaneous parametric down conversion in a 0.5 mm-thick non-linear crystal of β – Barium Borate. (b) Images of the two types of single photon sensitive cameras used in the experiment: EMCCD and SPAD array. (c) Intensity images measured by each camera showing the typical ring shape of photon pairs sources. (d) Spatially resolved second-order correlation functions $G^{(2)}(x_1, y_1, x_2, y_2)$measured by each camera. To visualize this, three projections of $G^{(2)}$ relative to three different references pixels $r_2 = \{ r_A, r_B, r_C \}$ of the sensors are shown: $G^{(2)}(x_1, y_1, x_A, y_A)$ (left), $G^{(2)}(x_1, y_1, x_B, y_B)$ (center) and $G^{(2)}(x_1, y_1, x_C, y_C)$ (right). In each projections, a peak of correlations is visible and centred around the symmetric pixel $r_1 = -r_2$. These symmetric peaks are clear signatures of anti-correlations between photon pairs due to momentum conservation in the pair generation process. $G^{(2)}$ was acquired in 17 hours with the EMCCD and in 140 seconds with the SPAD camera. More details can be found in [2,9]. BP: Bandpass filter; NLC: Non-linear crystal.

the overall detection efficiency of the system. In addition, such a task is even more difficult if one seeks to identify N-fold coincidences to retrieve N^{th}-order spatial correlation functions in the case of quantum states composed of more than two photons. Today, there is no camera that can take a picture of high-order optical correlations in real time.

In recent years, some solutions have been developed to reconstruct spatially resolved second-order correlation function in photon-pairs-based imaging schemes ($G^{(2)}$). One popular approach uses post-processing algorithms with EMCCD cameras to suppress accidental coincidences and retrieve a spatially resolved ($G^{(2)}$) across thousands of pixels [2]. However, this approach requires millions of frames, which in practice corresponds to many hours of acquisition even using the fastest EMCCD cameras on the market (frame rate ~100Hz and ~1ms exposure time). Another method that was developed combines an intensifier and a low-noise scientific CMOS camera to achieve similar results, but is currently limited to few hundreds of pixels and also requires several hours of acquisition [3]. These prohibitive acquisition times result from the fact that currently single-photon sensitive camera technologies, including EMCCD, iCCD, iCMOS, do not have good enough noise properties, temporal resolution and/or acquisition speed to quickly and precisely identify photon coincidences. Even if these devices can still be used in laboratory proof-of-principle experiments and will further improve in the coming years, it is clear that a major step forward is required to go from measurements times of hours to seconds, a major step that SPAD cameras seem capable of achieving.

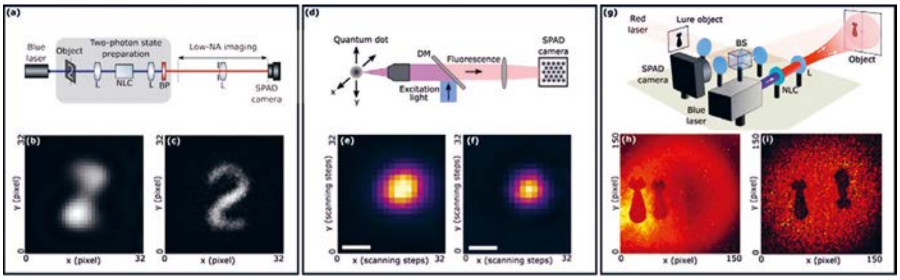

Figure 2. Three experimental demonstrations of quantum imaging with SPAD cameras. (a) Experimental setup used by A. Stefanov's group to achieve super-resolution imaging by measuring a spatially resolved $G^{(2)}$ with a SPAD camera (32×32 pixels) [6]. By measuring second order correlations between photon pairs, an image of the object '2' is retrieved with better resolution (c) than that obtained under classical coherent illumination (b). (d) Experimental setup used by D. Oron's group to perform quantum imaging scanning microscopy using a SPAD array (23 pixels) [10]. By measuring second order photon anti-bunching in single photons produced by a qu antum dot, the width of the point spread function (f) is narrower than that obtained by conventional imaging scanning microscopy (e), which enables super-resolution imaging. (Scale bar: 0.25 μm). (g) Experimental setup used by D. Faccio's group to achieve full-field quantum illumination imaging with a SPAD camera (512×512 pixels) [9]. Images of two cat-shaped objects illuminated by a classical source (red laser) and photon pairs beam are superimposed on the sensor (h). By measuring second order correlations between photon pairs, an image showing only the object illuminated by photon pairs can be retrieved (i). L: lens; NLC: Non-linear crystal; NA: Numerical aperture; BS: beam splitter.

SPAD CAMERA FOR QUANTUM IMAGING

Single-pixel SPADs have long been the detectors of choice in many quantum optics experiments. Their recent implementation in CMOS technology enabled the development of the so-called SPAD cameras, a technology that is currently booming [4]. Like intensified and EM cameras, SPAD cameras offer single photon level sensitivity, but with unparalleled speed, temporal resolution and very low noise. Thus far, these imaging devices have demonstrated their capabilities in many classical optics applications including fluorescence lifetime imaging, light detection and ranging (LiDAR), non-line-of-sight imaging and imaging through scattering media. In the last decade, they also started to be used in quantum optics experiments. In 2016, the group of A. Stefanov at the University of Bern used a 8×16 pixel SPAD camera to perform multi-pixel coincidence measurement under photon-pair illumination [5]. Thanks to the capability to set a very small coincidence window (265ps) and operate at a very high frame rate (250kHz), the SPAD camera was able to detect the presence of spatial correlations between photon pairs in less than 3 minutes by averaging coincidence detections over the pixels. However, it was not efficient enough to retrieve the full spatially resolved second-order correlation function that is key to perform quantum imaging. Furthermore, a post-processing technique had to be used to significantly reduce the accidental background. This ineffectiveness was mainly due to the extremely low photon detection efficiency (PDE= quantum efficiency × fill factor) of 0.57 % of the device and the presence of a significant crosstalk between adjacent pixels. Nevertheless, this study was the first to highlight the potential of SPAD cameras for imaging quantum properties of light.

In the following years, significant technological advances were achieved that improved the spatial resolution, PDE and the pixel crosstalk in SPAD cameras. In this respect, some established companies such as Horiba and Hamamatsu, as well as a handful of start-ups such as *MicroPhotonDevice* (MPD) and *PhotonForce*, even started to release first commercial versions of SPAD cameras. Using a larger chip made of 32×32 pixels, A. Stefanov's group later achieved super-resolution imaging and entanglement characterisation [6,7] by measuring the spatially resolved $G^{(2)}$ under photon pair illumination, but these experiments still required tens of hours of acquisition. In 2020, the group of Prof. D. Faccio at the University of Glasgow made an important step forward in terms of speed by achieving high-dimensional entanglement certification in less than 140 seconds by measuring the full spatially resolved $G^{(2)}$ of spatially entangled photons using a commercial 32×64 pixels SPAD camera from MPD [8] (Fig. 1). In collaboration with the group of Prof. E. Charbon at École Polytechnique Fédérale de Lausanne, they later pushed the limit of resolution by performing photon pair imaging using a prototype of SPAD camera composed of 512×512 pixels [9], but at the cost of many hours of acquisition because the camera speed was not fully optimised. In addition, SPAD cameras have also been envisaged for multi-pixel coincidence counting using different types of illumination than photon pairs. For example, the group of Prof. D. Oron at the Weizmann Institute recently used a SPAD camera to characterise the lack of high order spatial correlation in optical signals produced by single-photon emitters (quantum dots) for super-resolution imaging [10]. All these early proof-of-principle demonstrations have triggered many other research teams to explore SPAD camera for quantum imaging, most of them located in Europe (Fig. 2).

CONCLUSION

SPAD cameras are a rapidly growing technology with enormous potential for quantum imaging. Their single photon sensitivity, very high frame rate (up to 800 kHz) and unmatched temporal resolutions (hundreds of picoseconds) make them very promising for measuring spatially resolved high-order optical correlation functions that are at the basis of many quantum imaging schemes. The drawbacks of current models — including a relatively low fill factor, limited spatial resolution in the 2D pixel arrangement, low quantum efficiency and crosstalk — are being resolved very quickly thanks to the growing interest of these devices to be used in large consumer markets (*e.g.* cell phone cameras). Today, there are already some prototypes made of hundreds of thousands of pixels, with fill factor around 80 % and quantum efficiencies as high as 40 %. In addition, rapid progress in improving their temporal resolution suggest SPAD cameras will enable the measurement of entanglement in time between photons, paving the way towards the development of time-gated quantum imaging applications such as quantum LiDAR and quantum non-light-of-sight imaging. One may thus envisage soon a quantum video camera of the size of a cell phone camera for implementing quantum imaging in real-world applications such as biological imaging, microscopy, radar and sensing.

REFERENCES

[1] P. A.Moreau, E. Toninelli, T. Gregory, M. J. Padgett, Nat. Rev. Phys. **1**, 367 (2019)

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

[3] R. Chrapkiewicz, W. Wasilewski, K. Banaszek, Opt. Lett., **39**, 5090-5093 (2014)

[4] C. Bruschini, H. Homulle, I. M. Antolovic, S. Burri, E. Charbon, Light: Sci. Appl. **8**, 1 (2019)

[5] M. Unternährer, B. Bessire, L. Gasparini *et al.*, Opt. Express **24(25)**, 28829(2016)

[6] M. Unternährer, B. Bessire, L. Gasparini *et al.*, Optica **5**, 1150 (2018)

[7] B. Eckmann, B. Bessire, M. Unternährer *et al.*, Opt. Express **28**, 31553 (2020)

[8] B. Ndagano, H. Defienne, A. Lyons *et al.*, npj Quantum Inf. **6**, 1 (2020)

[9] H. Defienne, J. Zhao, E. Charbon, D. Faccio, Phys. Rev. A (in press), arXiv:2007.16037 (2021)

[10] G. Lubin, R. Tenne, R., I. M. Antolovic *et al.*, Opt. Express **27**, 32863-32882 (2019)

SEMICONDUCTOR SINGLE-PHOTON SOURCES: PROGRESSES AND APPLICATIONS

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Single photons are the cornerstones of many applications in quantum technologies, from quantum computing to quantum networks. A new technology for the generation of single-photons has recently emerged, allowing a ten-time increase in efficiency with near-unity quantum purity. These single-photon sources are based on semiconductor quantum dots in optical microcavities.

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LIGHT IN QUANTUM TECHNOLOGIES

Light, and more precisely quantum light is a key component of the emerging second quantum revolution. Like in classical technologies, light is the ideal support to carry the quantum information from one place to another and develop quantum communications. Such communication is highly sought after as it admits confidentiality guarantees that rely only on the most fundamental laws of physics. They can also be used to network several quantum processors leading to strong increases in computational capabilities. Actually, quantum light is also a highly promising technology for developing a quantum computer, with the unique advantage that photons are non-interacting particles in vacuum and barely suffer from decoherence. This potential is reflected by the creation of start-up companies with the objective of developing the first optical quantum computing machines in the last few years like PsiQuantum in the United States or Xanadu in Canada which have raised several hundreds of millions of dollars, and more recently with QUIX, ORCA computing, and Quandela in Europe, among others. Finally, quantum light can be used to push the limits of sensing, a possibility beautifully illustrated by the introduction of squeezed light in gravitational waves interferometers.

A very appealing property of quantum light for all these applications is that it offers many degrees of freedom to encode the quantum information: wavelength, polarization, path, orbital angular momentum, time... It also makes it possible to encode more than one quantum bit on a single light wavepacket. These possibilities have also led to different approaches to manipulate the quantum information. Some approaches encode the information on single photons (discrete variables), others exploit quantum modes (continuous variables). In the following, we discuss approaches based on discrete variables, an approach where first small-size quantum computing processors have been demonstrated with a defined path toward a universal quantum-computing machine.

SINGLE-PHOTON SOURCES – FIGURES OF MERIT

The ideal single-photon source (SPS) produces light pulses with exactly one photon — no more, no less — in a well-defined spectral and spatial mode of given polarization. In real

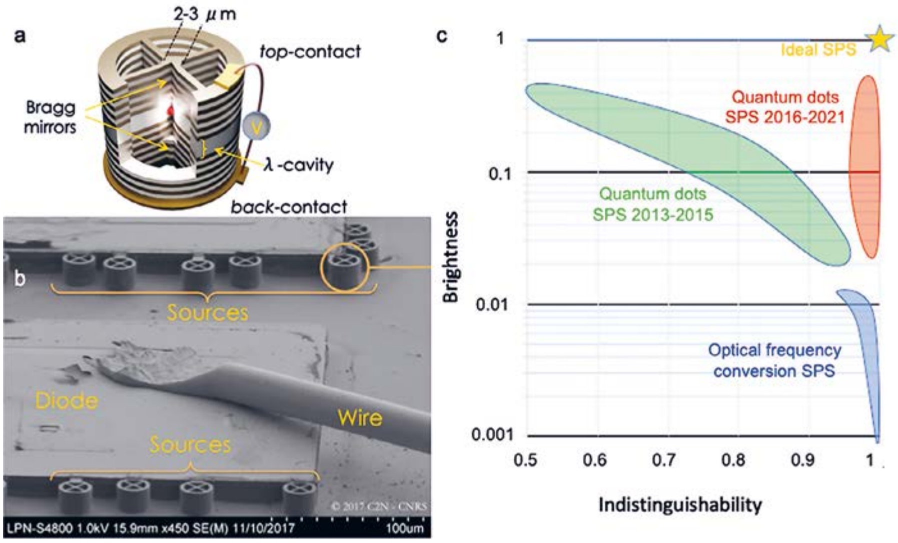

Figure 1. (a) Schematic of single photon source based on an electrically controlled quantum dot in a cavity. (b) Scanning electron microscope image of a semiconductor chip with 11 single photon sources. (c) State of the art in Single Photon Sources (SPS) technologies. The various technologies are presented on a 2D map corresponding to the source brightness and indistinguishability. An ideal source would be at the upper right corner. From 2013 to 2015, important progresses were reported on QD-based single photon sources, but they were either bright or indistinguishable. Since 2016, it is possible to combine both properties.

life, there is always a probability that the light pulse contains more than one photon or no photon at all. A single-photon source is thus characterized by the probability to actually have one photon per pulse, also called the source brightness, as well the probability to have no more than one photon, also called "single-photon purity".

The final criteria, *i.e.* that the same spectral mode is always produced must be understood at the quantum level. In the spectral domain, the single-photon pulse is a quantum superposition of single photon states of various frequencies with complex coefficients: the source should produce always the exact same superposition. This property is crucial for quantum technologies as it allows the implementation of photon-photon gates both for quantum computing or quantum communications. The effective photon-photon interaction relies on a very fundamental quantum effect called "quantum interference": when two single-photon pulses in exactly the same spectral mode are sent at the two inputs of a beam splitter, the two photons will bunch and exit together through the same beam-splitter output, a situation very different from what we would expect from a classical perspective, by which we would expect that with some probability the photons exit by separate outputs. This property, which is used to build two-photon gates with beam splitters, waveplates and detectors, arises from the impossibility of distinguishing the single-photon pulses. A single-photon source is thus also characterized by its degree of indistinguishability.

The early development of optical quantum technologies has relied on single-photon sources based on optical frequency conversion: a laser pulse sent on a non-linear crystal generates photon pairs. The system operates at the threshold for photon-pair generation where most of the time no pair is produced and the probability of generating two pairs is kept below 1%. To operate such source, one photon of the pairs is detected to announce the presence of the other one. Such a source is intrinsically limited to very low brightness (B<1 %), setting strong limitations for scalability.

A NEW GENERATION OF SINGLE-PHOTON SOURCES

In the last few years, a new technology for single-photon sources has emerged based on semiconductor quantum dots (QDs): a nano-insertion of InAs in GaAs. In these nanostructures, electrons (and holes) present discrete energy levels like in a single atom. In 2000, these artificial atoms have been shown to emit single-photons based on the recombination of electron-hole pairs at temperatures around 5 K [1]. To efficiently collect the single photons that are otherwise emitted in all directions of space, the QD is inserted in an optical microcavity that confines light in a volume of the order of λ^3. Fig. 1a presents the • • •

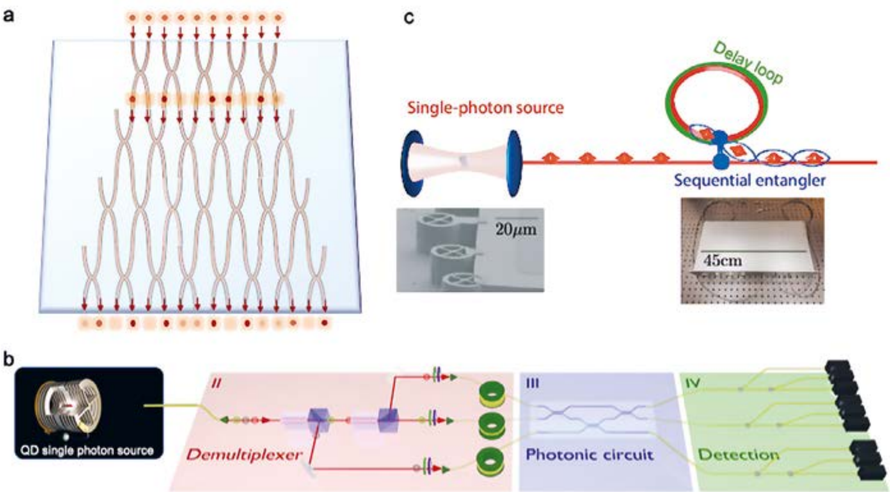

Figure 2. (a) Schematic of an intermediate quantum computing scheme: Boson Sampling. (b) Interfacing a QD single-photon source with a photonic chip to implement a 3-photon experiment. (c) Scheme used to develop light states comprising several entangled single photons from a QD single-photon source.

architecture of such a source where the QDs are precisely positioned at the center of a cavity based on two Bragg reflectors that confine light in the vertical direction. The wheel-shaped structure in the transverse direction confines light in its center, by refractive index contrast. Finally, the device embeds a diode structure that allows controlling the electric field around the QD. To do so, the device is connected to a bigger surface where an electrical contact is defined and a wire bounded (Fig. 1b).

The insertion of the QD in a cavity has multiple effects: first it allows accelerating the emission process into the cavity mode, so that the photons are preferentially emitted in this direction. Single photon sources with a record brightness around 80 % have been demonstrated with this approach in 2013 [2]. Second, it shortens the time the electron-hole pairs remain in the QDs before emitting a photon. This is crucial to obtain indistinguishable photons by strongly reducing the time where the system is subject to the randomness of the semiconductor environment: charge noise, vibrations, *etc.* The charge noise is further suppressed by applying a bias on the diode structure that allows sweeping away any unwanted charge. Combining these various techniques with a resonant excitation approach to perform coherent control of the artificial atom led to a new generation of sources in 2016 [3,4]. These sources were able to produce single photons with a near-unity indistinguishability with brightness in the B = 10–20 % range.

These sources were more than ten times brighter than sources based on frequency conversion for the same degree of indistinguishability (Fig. 1c). Such increase allows a spectacular scaling of optical quantum technologies since the availability of N single-photon qubits scales as B^N.

Since then, the quality of sources has continued improving reaching B>50 % in 2021. In 2019, it was also shown that such devices can provide new types of photonics quantum bits, where the information can be encoded on the photon number [5]: arbitrary quantum superposition of 0 and 1 photon were generated by transferring the coherence that is optically imprinted at the level of the atom to the emitted field.

FIRST APPLICATIONS IN OPTICAL QUANTUM COMPUTING

This new generation of sources has immediately been used to gain important speed-up in some specific quantum-computing tasks. Boson sampling is an intermediate quantum-computing scheme that has been proposed as a path to demonstrate quantum computational advantage. It relies on sending N-single photon quantum bits in a random optical circuit, where the single photons undergo many steps of quantum interferences. At the end of the network, single-photon detectors measure the photon distribution (Fig. 2.a). Predicting the output distribution has been shown to be a computationally hard problem, inaccessible to today's most powerful super-computers as soon as the number of photons would slightly exceed 50. The new generation of single-photon source discussed above led to a 10^{3}-10^{6} speedup of Boson Sampling computing schemes in 2017 with 3-5 photonic qubits [6]. In 2019, the group of Chao-Yang Lu in Hefei University in China brought this number to 20 qubits, using a very similar source technology as the one presented here, setting an unprecedented record in discrete variable optical quantum computing [7].

The above achievements were obtained with optical circuits implemented in free space, with many mirrors, beam splitters, etc, making the approach hardly scalable. However, optical quantum computing can be realized with a fully integrated approach, where single photon sources and detectors, inserted in cryostats to operate in the 2-10 K range, are fiber-pigtailed and fiber connected to photonic chips where the photonic quantum bits are manipulated at room temperature.

QD single photon sources have been used for a first proof of principle for on-chip quantum computation (Fig. 2.b) [8]. The source generates temporal trains of single-photon quantum bits at a clock rate around 80 MHz. A temporal to spatial demultiplexer is used to convert a train of N photons in time, into an input of N photons at the N entries of a photonic chip. The integrated photonic circuit was obtained by femto-second laser writing in glass, a technology that allows very low guide and insertion losses. In this first demonstration, three photons were manipulated at unprecedented rates on chip.

The QD sources are also very interesting from the perspective of creating new photonic states in which several single photons are entangled [9].

Some of these states, such as the so-called "cluster-states" are an important universal resource quantum computing, which offer a scalable path to large-scale, fault-tolerant quantum computing. To obtain such a state, the single photons that are sequentially generated by the source are sent into an entangling apparatus that fits into a simple rack-size box (Fig 2.c). The photons are sent onto an optical gate based on a beam splitter that entangle the second photon with the first emitted one that has been partially stored into a fiber loop. Repeating the scheme with as many photons as desired can be used to generate such photonic cluster state with an arbitrarily high number of photons and was recently demonstrated to entangle 4 photons in a linear cluster state.

FUTURE OPPORTUNITIES

The new generation of single-photon sources based on semiconductor quantum dots open exciting perspectives for optical quantum technologies by providing a disruptive technology on the photon generation side. A similar breakthrough was obtained almost a decade ago on the single-photon detector side with detection efficiency now routinely above 90 %. The commercialization and industrialization of these sources has begun, developing robust and easy-to-use products for the researchers and engineers developing quantum technologies. The best sources currently operate in the 890-950 nm wavelength range. New developments should soon bring this technology to the 700-850 nm range, with great potential for interfacing with atomic-based quantum memories for instance. Finally, the same sources could in the future be used to directly generate photonic cluster states, with unparalleled efficiency.

This relies on exploiting the spin degree of freedom of an electron in a QD. This is the next breakthrough that the quantum dot scientific community is pursuing, a milestone that would open the way toward scalable quantum computing, long distance quantum communications as well as new limits in optical sensing.

REFERENCES

[1] P. Michler, A. Kiraz, C. Becher *et al.*, Science **290**, 2282 (2000)

[2] O. Gazzano, S. Michaelis de Vasconcellos *et al.*, Nat. Commun. **4**, 1425 (2013)

[3] N. Somaschi, V. Giesz, L. De Santis *et al.*, Nat. Photonics **10**, 340 (2016)

[4] P. Senellart, G. Solomon, A. White, Nat. Nanotechnol. **12**, 1026 (2017)

[5] J. C. Loredo, C Antón, B. Reznychenko *et al.*, Nat. Photonics **13**, 803 (2019)

[6] JC Loredo, M. A. Broome, P. Hilaire *et al.*, Phys. Rev. Lett. **118**, 130503 (2017)

[7] H. Wang, J. Qin, X. Ding *et al.*, Phys. Rev. Lett. **123**, 250503 (2019)

[8] C. Antón, J. C. Loredo, G. Coppola *et al.*, Optica **6**, 1471 (2019)

[9] D. Istrati, Y. Pilnyak, J. C. Loredo, C. Antón *et al.*, Nature Commun. **11**, 1 (2020)

DIAMOND-BASED QUANTUM TECHNOLOGIES

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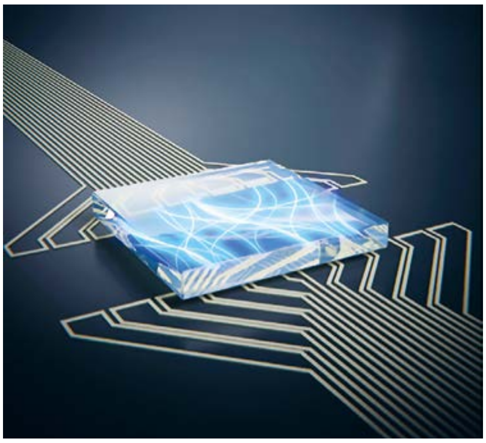
Image credit: Enrique Sahagun, SCIXEL

Optically accessible spins associated with defects in diamond provide a versatile platform for quantum science and technology. These spins combine multiple key characteristics, including long quantum coherence times, operation up to room temperature, and the capability to create long-range entanglement links through photons. These unique properties have propelled spins in diamond to the forefront of quantum sensing, quantum computation and simulation, and quantum networks.

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Over the last decade, the development of quantum technologies such as quantum sensors, computers, simulators and networks has become one of the major goals in science and technology. This envisioned quantum revolution is driven by the potential of quantum systems to outperform their classical counterparts in terms of speed, security, and sensitivity as well as providing functionality beyond what is possible classically. With the launch in 2018 of the Quantum Technologies Flagship (https://qt.eu/), the European Union has made developing quantum technologies a strategic priority. Quantum systems in diamond play an important role in all four pillars of the Flagship - communication, computation, simulation and sensing/metrology [1-4].

Diamond-based quantum technologies revolve around optically active atomic defects in the diamond carbon lattice. The most studied is the nitrogen-vacancy (NV) defect (Fig. 1a), which consists of a substitutional nitrogen atom next to a vacancy (a missing carbon atom). Various other defects such as silicon-vacancy (SiV) and tin-vacancy (SnV) defects are being explored, as well as related systems in materials like silicon carbide, each with their own properties and advantages. The electrons associated with such defects have a magnetic moment called spin, which is sensitive to magnetic fields because of the Zeeman interaction. The quantum mechanical nature of spin enables the creation of quantum superpositions and entanglement. Diamond defect spins offer a unique combination of long coherence times, due to the excellent isolation from their environment by the stiff and pure diamond lattice, and the capability to prepare and measure the spin using optics (Fig 1a). In this article, we discuss the application of spins in diamond for quantum sensing, quantum computation & simulation, and quantum networks.

QUANTUM SENSING

Sensors play a ubiquitous role in our technological society. New capabilities to pick up minute signals in noisy environments is key to opening up new opportunities in fields ranging from medical imaging to nanotechnology. With the drive to develop quantum technologies there is an increasing need for sensors that can probe quantum and biological systems at small length scales. Electronic spins in diamond provide the capabilities to meet this need. The spins are sensitive to temperature, electric fields, and in particular to magnetic fields. Spin-control techniques, similar to those used in MRI scanners and nuclear magnetic resonance, tune their sensitivity from DC to GHz frequencies (Fig. 1b-d). Importantly, these methods work from cryogenic to room temperatures, enabling a diverse range of applications.

In the last decade, magnetometry based on the nitrogen-vacancy (NV) defect in diamond has evolved from demonstrations that focused on its sensitivity and resolution to a microscopy tool that is applied from condensed-matter to biological systems [1-2]. Being particularly suited for probing stray fields close to surfaces, key application areas are magnetism and imaging electrical transport. Because the imaging is magnetic, it enables "looking through" opaque materials such as electrodes on a chip. NV magnetometry has enabled detecting nuclear spins in few-cubic-nanometer volumes and electrical currents in quantum materials such as graphene. A recent application studied by one of us focuses on imaging waves in magnets that transport information with little heat production (Fig. 1 e) [5].

To image a sample's spins and currents, three approaches are common:

1) A diamond with a high-density, thin layer of shallowly implanted NV centers is placed onto a sample (Fig. 1e - top). The simultaneous use of many NV centers yields high imaging speed and sensitivity. Spatial resolution is however limited by the NV-sample distance and the diffraction-limited readout optics.

2) NV-containing diamond nanostructures are deposited onto a sample to achieve nanometer proximity (Fig. 1e - middle). Such nanostructures can also be attached to fibers to realize magnetic endoscopes, or injected into biological samples such as a single cell for in-situ sensing. The temperature-sensitivity of the NV spin can provide insight into a cell's metabolism and transport pathways.

3) An NV in a diamond nanotip is scanned over a sample using an atomic force microscope (Fig. 1e - bottom). While it is a relatively slow technique, it enables a spatial resolution that is only limited by the NV-sample distance (~ 50 nm).

Because of the large application area of high-resolution imaging of magnetic and quantum materials, we anticipate an expanding array of new scientific experiments and an increasingly industrialized use of NV magnetometers.

QUANTUM COMPUTATION AND SIMULATION

Spins in diamond also provide a promising quantum-bit (qubit) platform for quantum information processing [3, 6]. The central elements of diamond-based quantum processors are the optically addressable electron spins of individual defects (Fig. 2). Larger multi-qubit quantum processors are created by coupling these spins together via magnetic-dipole interaction and optical photons (see Fig. 2 and *"quantum networks"*). Additionally, the electron spin can be used to detect, control and measure nuclear and other electron spins in the vicinity, providing more qubits. This network of different types of qubits and connections provides a flexible platform for scalable quantum processors.

Quantum processors with up to 10 fully-connected qubits with coherence times exceeding minutes have been demonstrated [7]. Proof-of-principle quantum algorithms and molecular quantum simulations have been realized. Basic quantum error correction schemes — in which quantum states are encoded in entangled states of multiple qubits so that errors can be detected and corrected — have been realized. Such •••

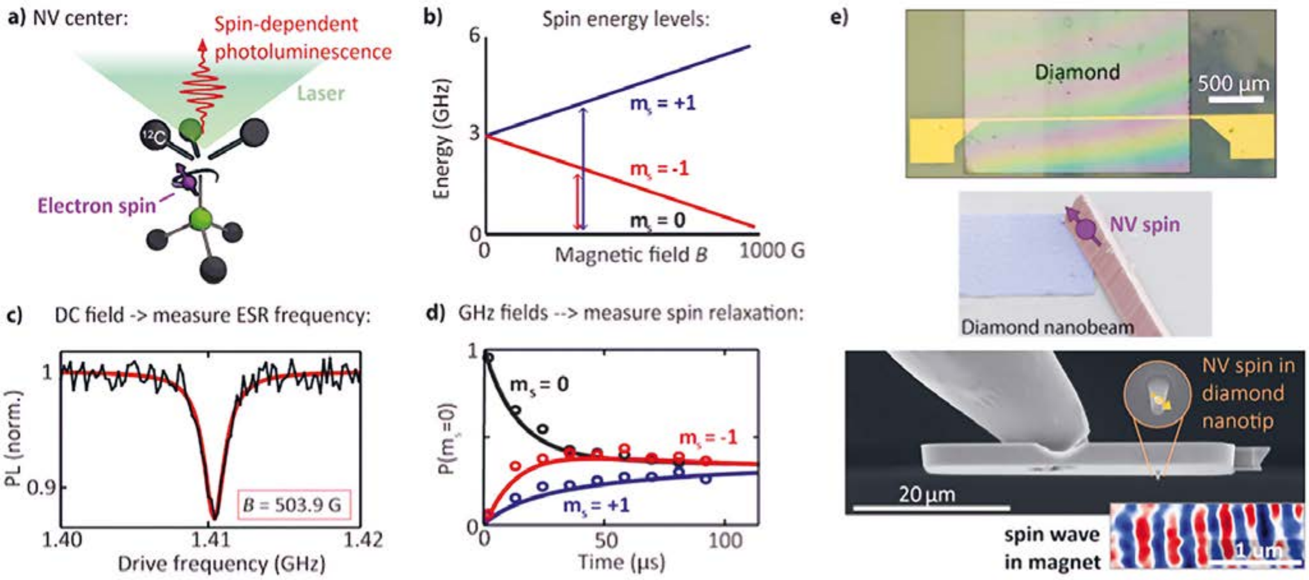


Figure 1. Magnetic sensing with the nitrogen-vacancy (NV) center in diamond. a) The NV electron spin is an atom-sized magnetic field sensor that is initialized and read out optically. b) NV spin energy levels vs magnetic field. c) Optical detection of the NV electron spin resonance (ESR) frequency yields the DC magnetic field B. d) Relaxation measurement that quantifies magnetic fields at the gigahertz ESR frequencies. e) Top: an NV-diamond placed onto a sample (image originally published in [5]). Middle: a diamond nanobeam with an NV positioned onto a nanostructure (image originally published in [2]). Bottom: A diamond tip that enables spatial imaging with nanometer resolution.

quantum error correction protocols are an essential element of future quantum computers.

Now, the key challenge is to scale up to larger systems. A particularly powerful concept is to realize modular quantum processors, in which many small processors such as the one in Fig. 2 are connected optically (see *"quantum networks"*). Scaling up will require a combination of improved materials and fabrication methods, improved control gates to enable error correction, and chip-scale integration of optical and electronic controls. Such efforts are now underway in worldwide collaborations between universities, research centers and industry.

Figure 2. Spin-based quantum processors in diamond. Example showing the different types of qubits and connections available. At the heart of the system are optically active defect centers (shown here : the NV center). The electron spin can be connected to other defect centers over long ranges using photonic channels, as well as over short distances by magnetic coupling (typical 10-50 nm). Additional qubits are provided by nuclear spins, such as carbon-13 isotopes that make up ~1 % of the diamond, and other electron spin defects (shown here : a substitutional nitrogen defect).

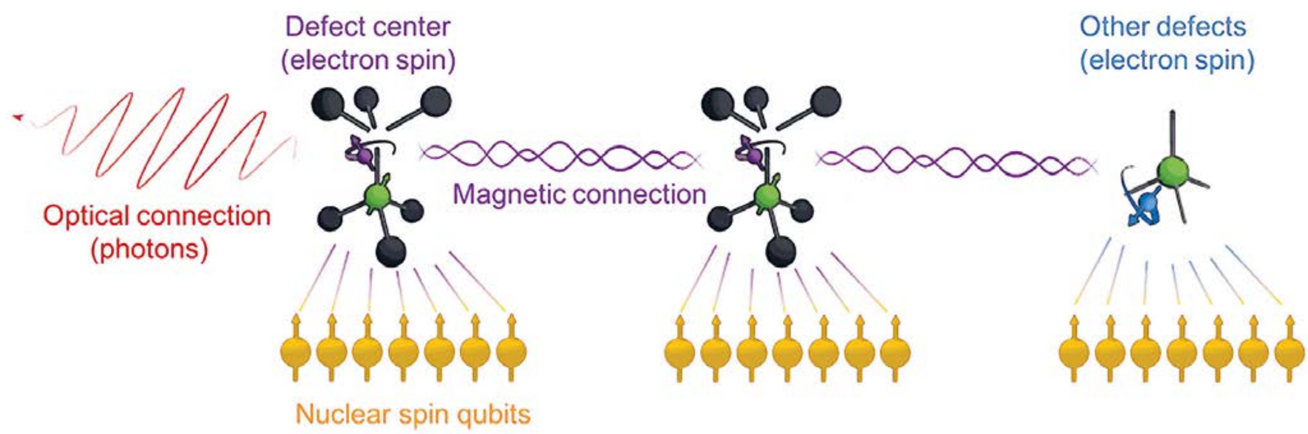


Figure 3. One of the aims of the EU Quantum Flagship program is to realize a pan-European quantum internet. Image credit: SCIXEL and QuTech/ TUDelft

QUANTUM NETWORKS

Information networks, of which the internet is a prime example, have revolutionized the way we share and process information. Realizing a quantum internet is a goal of the EU Flagship program (Fig. 3). Such a quantum network aims to exploit the exchange of quantum information for tasks that are fundamentally impossible with current networks. Several such tasks are already known, such as securing communication through the laws of quantum physics, cloud computation with perfect privacy, and secure leader election [4].

In the past two decades, research has focused on establishing the building blocks for quantum networks and proof-of-principle demonstrations of rudimentary quantum network protocols.

The quantum hardware requires two key capabilities:

1) generating entangled links with distant nodes and

2) storage and processing of quantum information in local registers.

While the field of quantum networks had been the exclusive domain of atomic systems in earlier years, solid-state platforms have taken a leading role in more recent years.

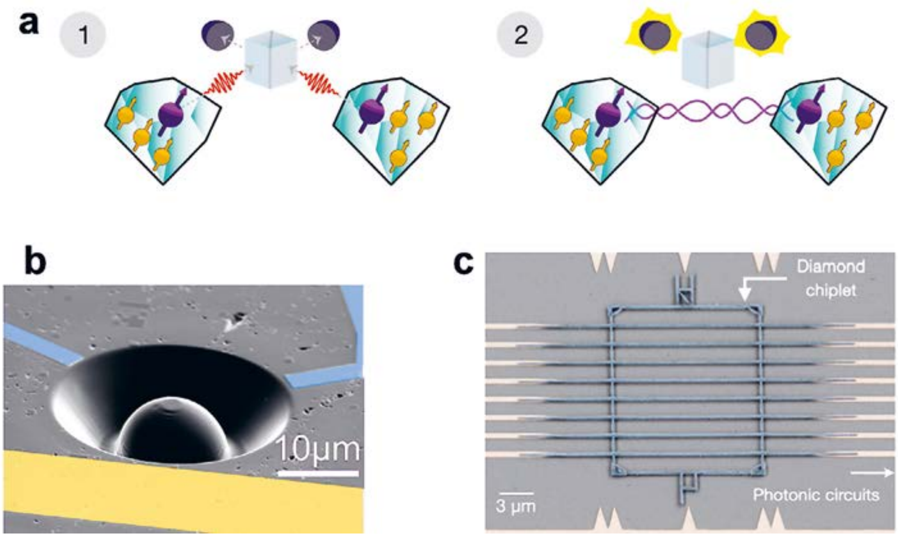


Figure 4. (a) Generating entanglement between remote diamond-based qubits. In step 1, a quantum entangled state between an electron spin and a photonic mode is created, followed in step 2 by single-photon detection behind a beam splitter.
(b) Image of a diamond solid-immersion lens device as used in remote entanglement demonstrations [3]. Image credit QuTech/TUDelft.
(c) Image of an integrated photonics device with a diamond "quantum microchiplet" (blue) containing optical waveguides and defect centers.
Image credit : Noel Wan, MIT [8].

The NV center has been one of the most fruitful platforms, thanks to the combination of well-controlled, long-lived spin states that serve as qubits and a stable optical transition for establishing entanglement with remote nodes (see Fig. 4a for a sketch of the protocol). The first demonstration of entanglement between an NV spin and a photon was reported in 2010. In 2013 two of us reported the first demonstration of entanglement between two separated NV centers using devices as in Fig. 4b. In 2015 we extended the distance between the nodes from a few meters to more than 1 km, and used this setup to measure a violation of Bell's famous inequalities with a minimum of assumptions (often termed loophole-free).

In the past few years research has focused on improving the optical interface and on realizing the first small networks by linking more than two nodes in a single architecture. At the same time, other defect centers, such as the SiV and SnV centers, were found to have promising properties that may enable easier integration into large-scale devices (Fig. 4c) [8].

The near future will see NV centers and similar systems being linked into the first true quantum networks. These networks will still be far from practical for end-users, but they will serve as critical testbeds for development of quantum network protocols, control stack and applications. Research will continue on improving the optical interface by development of cavity systems leading to faster and higher-fidelity entanglement links. Incorporating multiple qubits per network node will enable more functionality. The advances made on quantum computing (see *"Quantum computation and simulation"* above) can often be directly translated to the quantum network nodes.
Besides increasing the number of nodes, their functionality and their performance, large-scale quantum networks also require compatibility of the devices with the existing optical fiber infrastructure. Efficiently converting single photons to match the desired telecom wavelengths is ongoing work. Also, developing a quantum network control stack and interfacing it with the classical networks control is an expanding area of research.

CONCLUSION

Over the last years, spins in diamond have been developed into one of the leading platforms for quantum sensing, computation and simulation, and networks. With several principles demonstrated, a major challenge for the next few years is to realize the broad potential of this platform for basic science and quantum technology. This will bring exciting new opportunities on multiple fronts, from physics to engineering, and from academia to industry. ●

REFERENCES

[1] R. Schirhagl, K. Chang, M. Loretz, *et al.*, Annu. Rev. Phys. Chem. **65**, 83 (2014)

[2] F. Casola, T. van der Sar, A. Yacoby. Nat. Rev. Mater. **3**, 17088 (2018)

[3] D. D. Awschalom, R. Hanson, J. Wrachtrup, *et al.*, Nat. Photonics **12**, 516–527 (2018)

[4] S. Wehner, D. Elkouss, R. Hanson. Science **362**, eaam9288 (2018).

[5] I. Bertelli *et al.*, Sci. Adv. **6**, eabd3556 (2020)

[6] J. Cai *et al.*, Nature Phys. **9**, 168 (2013)

[7] C. E. Bradley *et al.*, Phys. Rev. X. **9**, 031045 (2019)

[8] N. H. Wan *et al.*, Nature **583**, 226 (2020)

PASQAL

HARNESS THE POWER OF QUANTUM COMPUTING

A sketch of the QPU

WHO ARE WE?

Founded in 2019, PASQAL develops and markets scalable Quantum Processing Units (QPUs) that have the potential to address complex computing issues, from fundamental science to real-world grand challenges.
The company is a spin-out from Institut d'Optique Graduate School in Palaiseau (France), one of the leading quantum research centres in the world.

PASQAL is the only European company offering Quantum Processing Units with a number of qubits, level of performance and maturity allowing practical use for both industrial and academic applications as of today.

> We are building multi-purpose quantum processors in the 100 – 1000 qubit range

TECHNOLOGY

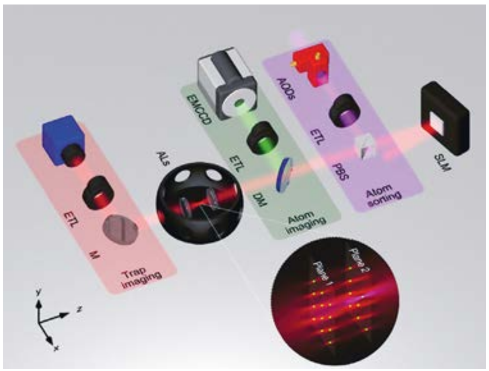
Our QPUs are built around a core of neutral atoms which can be precisely addressed, controlled and arranged in 1D, 2D and 3D geometries, thus providing outstanding flexibility to model and process various use cases and calculations.
100 qubit QPUs are available as of 2021 and 1000 qubit QPUs will be available by 2023.
Our processors are designed as accelerators which integrate easily into High Performance Computing (HPC) Centres, and are operated at room temperature. They come with a full software stack, allowing control from any standard computer.

APPLICATIONS

Our QPUs address complex computing issues, from fundamental science to real-world grand challenges that are out of the reach of today's most powerful classical computers, covering a vast range of topics: Optimisation, Simulation, Quantum Machine Learning (QML), Material Sciences, Quantum Chemistry, *etc.*

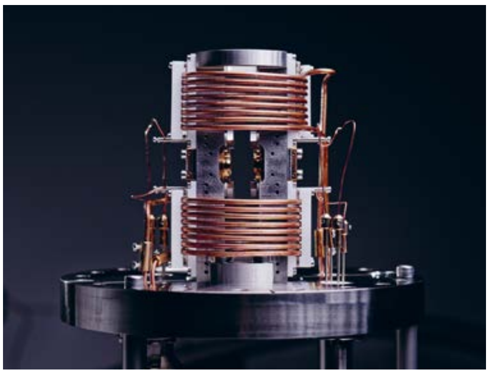
OUR OFFER

- PASQAL's Quantum Computing Power can be made available to our clients:
  - Through appliances in national HPC centres / clients' premises
  - On the Cloud, with QPUs operated at PASQAL (Software as a Service & Platform as a Service)
- Clients also benefit from the support of PASQAL's expert engineers: we build with our partners Proof of Concept (PoC) studies on specific problematics related to their activities. We implement a co-design approach, centred on our partners' needs, as we work closely with them on defining the problems to be solved and benchmarking with classical technics.



Thousands of qubits shaped by light

The core of the QPU



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QUANTUM SENSING WITH NITROGEN-VACANCY COLOUR CENTERS IN DIAMOND

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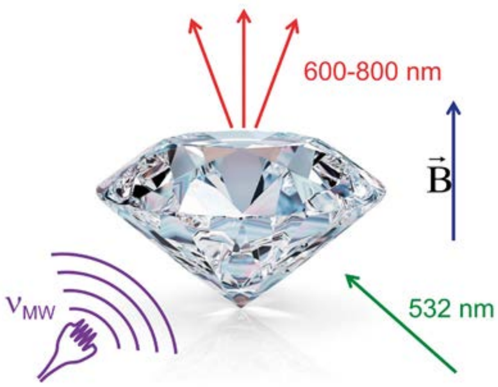

Quantum sensing exploits the possibility of manipulating single quantum objects and of measuring external physical quantities with unprecedented accuracy. It offers new functionalities that cannot be obtained with classical means. Quantum sensors can be based on atomic vapours, cold atoms, dopants in solid-state materials, etc. In the latter category, the nitrogen vacancy centre in diamond has received particular attention in recent years due to its very attractive characteristics.

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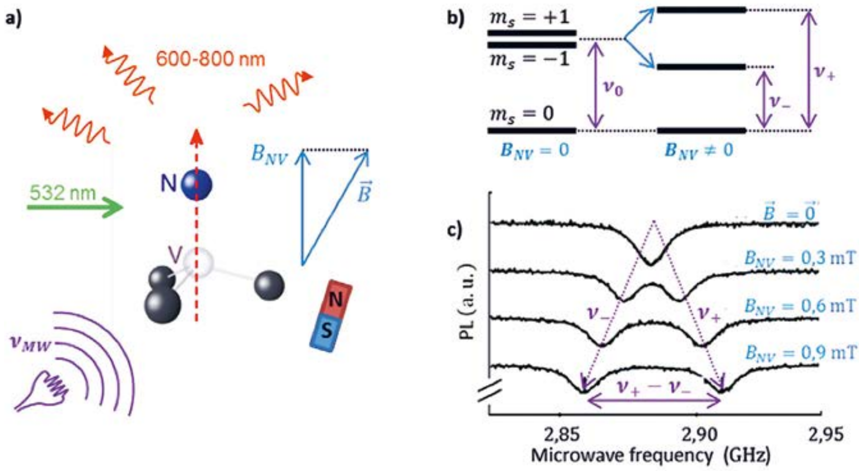
Diamond is a beautiful and well-known jewel. Its ability to trap visible light when properly cut and polished yields its distinctive flashing appearance. Diamond is a crystal made only of carbon atoms, which has many appealing properties. It has excellent transparency across the entire visible spectrum; it is one of the hardest materials known with excellent mechanical properties; it has excellent thermal conductivity with very efficient heat dissipation. It is therefore widely used in industry, and the large-scale production of artificial diamond has motivated a great deal of effort on the part of crystal producers. The first technique consisted of reproducing in growth chambers conditions similar to those existing in the heart of volcanoes. Under high pressure and high temperature, carbon atoms can form diamond crystals similar to natural crystals. However, they generally contain too many impurities for applications in the field of sensing or electronics. In the 2000s, a new growth technique was developed, based on plasma-assisted chemical vapour deposition. Here, carbon atoms are deposited layer by layer, resulting in an almost perfect single crystal with a very low level of impurities. Large diamonds of a few millimetres in size and a few hundred micrometres in thickness can be produced with excellent properties. Artificial diamonds are therefore the ideal material for a large number of new applications. For example, these ultra-pure crystals can be doped in a controlled manner with different species to modify their electronic properties.

Natural diamonds can have defects that give them specific colours and are therefore called colour centres. One of them, the nitrogen vacancy (NV) centre, produces a red luminescence that yields a pink colour. In a perfect diamond lattice, a nitrogen (N) atom is substituted for a carbon (C) atom. A missing carbon nearby creates a vacancy (V). The nitrogen and the vacancy form what is called the nitrogen vacancy centre (NV). Nitrogen vacancy centres can exist as isolated colour centres in the diamond. A first application in quantum technology was to use them as single photon emitters. Such single photons can then be used to perform quantum cryptography experiments to establish a secret key between two parties [1].

BASICS

To better understand the properties of the nitrogen vacancy centre, it is necessary to study its atomic structure (See Fig. 1). The NV centre can exist under different states of charge. The neutral state NV^0 has an unpaired electron. The negatively charged state NV^- captures an additional electron and therefore has two unpaired electrons. The latter is of particular interest for quantum sensing and we will only consider this one, now referred to as NV for the sake of simplicity. The NV centre is similar to an atom nestled in a solid-state matrix. It has energy levels with well-defined spin properties which naturally couple to the magnetic field. In typical experiments, the NV centre is optically pumped, usually with a green laser beam at a wavelength of 532 nm. This induces optical transitions between ground and excited states, resulting in the emission of red fluorescence around 637 nm. As a result of this process, the NV centre resides in its lowest ●●●

Figure 1. Figure 1. (a) The NV center of diamond is constituted by a nitrogen atom (N) substituted to a carbon atom, and a vacancy in an adjacent site. This quantum object absorbs light in the green (at 532 nm in our case) and emits a perfectly stable photoluminescence in the red domain (between 600 to 800 nm).
(b) Energetic diagram associated to the internal electronic spin of the negatively charged NV center. The degeneracy between the state of zero spin ($m_s = 0$) and the states of non-zero spin ($m_s = \pm1$) is lifted by the spin-spin interaction. The presence of an external magnetic field (in blue), lifts the degeneracy between the states $m_s = -1$ and $m_s = +1$ through the Zeeman effect. The frequency difference is proportional to the projection of the magnetic field on the NV axis, B_{NV}.
(c) Electron Spin Resonances (ESR) spectrum. Resonances between the state $m_s = 0$ and the states $m_s = \pm1$ induced by a microwave field (in purple) can be detected optically by a decrease of the photoluminescence intensity. The frequency difference between the two resonances is directly related to the value of B_{NV}. (taken from A. Nowodzinski *et al.*, Microelectronics Reliability **55** (2015) 1549–1553)

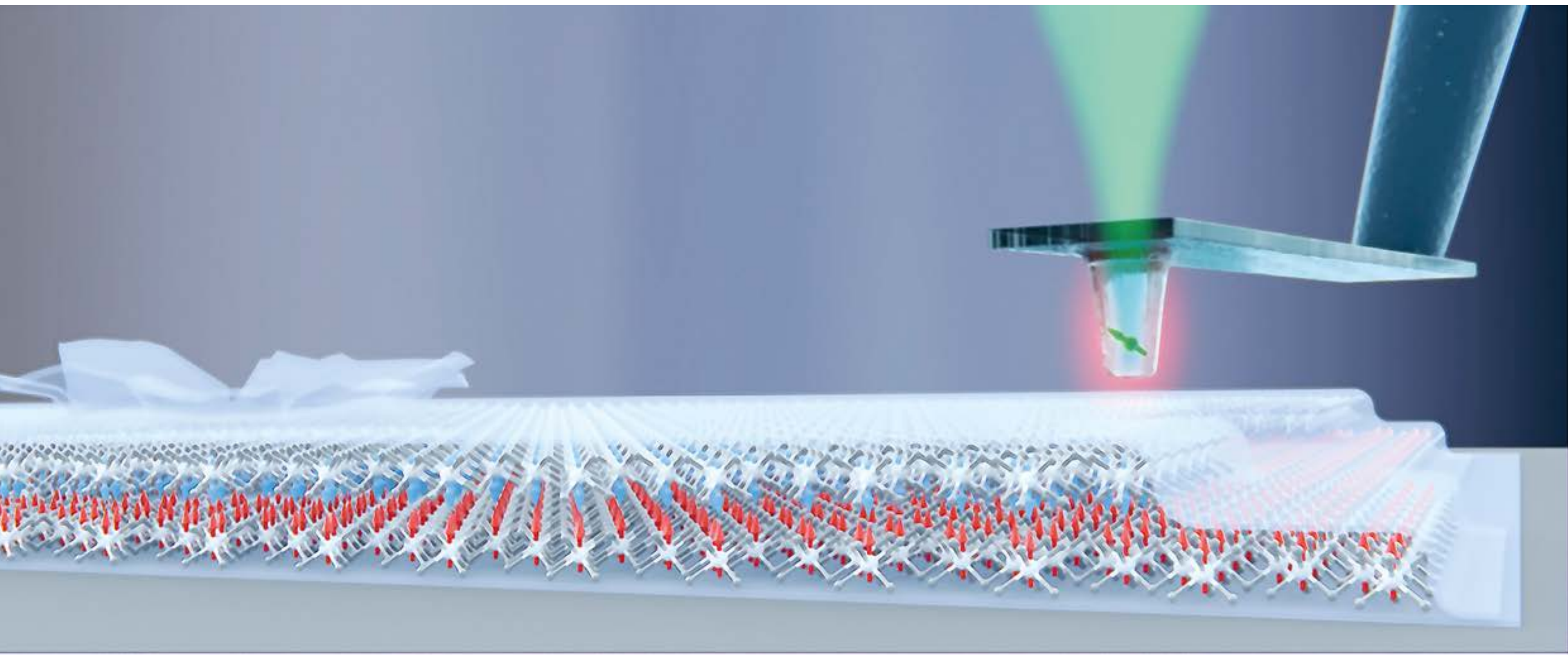


> the NV centre in diamond is similar to an atomic size magnet capable of measuring an applied magnetic field with nanometer scale resolution.

energy level. The NV centre is therefore polarized in a well-defined quantum state. A similar polarization can be achieved when cooling the sample to cryogenic temperature. Here, however, neither cryostat nor heavy equipment is required and the NV centre can be used under ambient conditions in a standard laboratory environment. This is a major advantage over other techniques and it greatly facilitates the use of NV centres outside the laboratory for a variety of applications. Being in a well-defined quantum state, the NV centre can then be coherently manipulated as an elementary quantum object. This is at the heart of the so-called second quantum revolution. The energy difference between the levels of lowest energy corresponds to a frequency of 2.87 GHz. Applying a microwave radiation at this frequency induces a resonant transition between those levels. Therefore, the NV center, initially in the lowest energy level, is now partly in a higher energy level. This results in a decrease of the fluorescence intensity that can be explained by the properties of the transitions between the energy levels. By sweeping the microwave frequency, a decrease in the fluorescence spectrum can be observed which indicates the transition from ground level to higher levels, very similar to what happens with ordinary atoms. This Optical Detection of Magnetic Resonance (ODMR) is the main property of the NV centre used as a quantum sensor [2].

To go further with the properties of NV centres, it should be noted that the levels involved in the transitions have a well-defined spin state, *i.e.* an intrinsic magnetic moment that can couple with an external magnetic field. Consequently, the application of an external magnetic field induces a shift in the energy levels (Zeeman shift) which results in a change in the frequencies of the magnetic resonance transitions. By measuring those frequencies, the value of the applied magnetic field in the direction of the N-V axis can be obtained directly. In addition, the use of an ensemble of NV centres makes it possible to measure both the magnitude and direction of the magnetic field. Therefore, the NV centre in diamond is similar to an atomic size magnet capable of measuring an applied magnetic field with nanometer scale resolution. Other physical quantities can be measured with NV

Figure 2: Example of a scanning NV magnetometer. A diamond tip with a single NV center at its end is held by an AFM tuning fork. The NV center is excited by a green pump laser. The NV fluorescence is guided by the tip acting as an optical waveguide and then collected by a microscope objective. Measuring the level of luminescence allows retrieving the magnetic field value below the tip. The magnetization distribution is measured with a spatial resolution of 50 nm when scanning the tip over the magnetic sample. (Courtesy of the Quantum Sensing Group, University of Basel)



centres. For example, the application of pressure or thermal heating causes a change in crystal lattice size which can induce a shift in the resonances of the NV centre. This gives access to the measurement of these quantities.

APPLICATIONS IN SENSING

The versatile sensing capabilities of NV centres, combined with their simple operating conditions, make them very attractive for applications in various fields such as the automotive industry, communications or medical applications. This is why European research groups in this field launched the European project ASTERIQS whose objective is to develop new sensors with optimal sensitivity and resolution that exploit the quantum properties of nitrogen vacancy centres in diamond. The first example is NV scanning magnetometry (see Fig. 2). A diamond tip with a single NV centre located at its end is positioned at the end of an AFM tuning fork. Scanning the tip a few tens of nanometres above a magnetic sample allows its structure to be recovered with a typical spatial resolution of 50 nm. This is a new tool that makes it possible to study structures such as antiferromagnetic domains with unprecedented resolutions and opens up entirely new fields in spintronics and nanomagnetism. This research is being carried out by several laboratories including the CNRS, ETH Zurich and the University of Basel [3]. This technology is currently being transferred to start-ups such as QNAMI and QZABRE.

In a second example, NV centres are used to monitor the behaviour of matter under high pressure (see Fig. 3). The high pressure is achieved in a cell consisting of two diamond anvils which are pressed against each other. One of these anvils contains NV centres near its surface which monitor the magnetic field in the cell. This is a new tool for studying the transition of a material from its normal phase to its superconducting phase under high pressure, which results in a change in its magnetic properties [4]. This work carried out by ENS Paris-Saclay has been transferred to Attocube in order to develop an instrument capable of making measurements under high pressure and at cryogenic temperatures.

The EC Quantum Flagship program [5] targets the development of a European industry in the field of quantum technologies. Several companies are active at different stages of the value chain. Element 6 is now capable of producing large "quantum grade" diamond samples with very low residual stress and a high concentration of NV centres of the order of a few ppm; this is necessary to develop high-sensitivity sensors. Attocube is developing new platforms that will enable magnetic materials to be characterised at the nanometre scale and at cryogenic temperature. Thales is developing a NV-based spectrum analyser that converts microwave frequencies into an optical signal. It can instantaneously monitor a wide spectrum of frequencies, which is necessary for recent developments in the field of communications, such as 5G and cognitive radio, or for radar applications over a wide frequency band. Bosch is targeting the electric car market. It is developing a magnetometer with a miniaturised NV-based sensor head that is capable of monitoring the electric current in a car battery with both high dynamics and high sensitivity.

NV centres offer many other application perspectives. Significant progress is being made in the analysis of the chemical structure of a single molecule. To do this, the molecule rests on the surface of a diamond crystal containing •••

This is a new tool for studying the transition of a material from its normal phase to its superconducting phase under high pressure, which results in a change in its magnetic properties

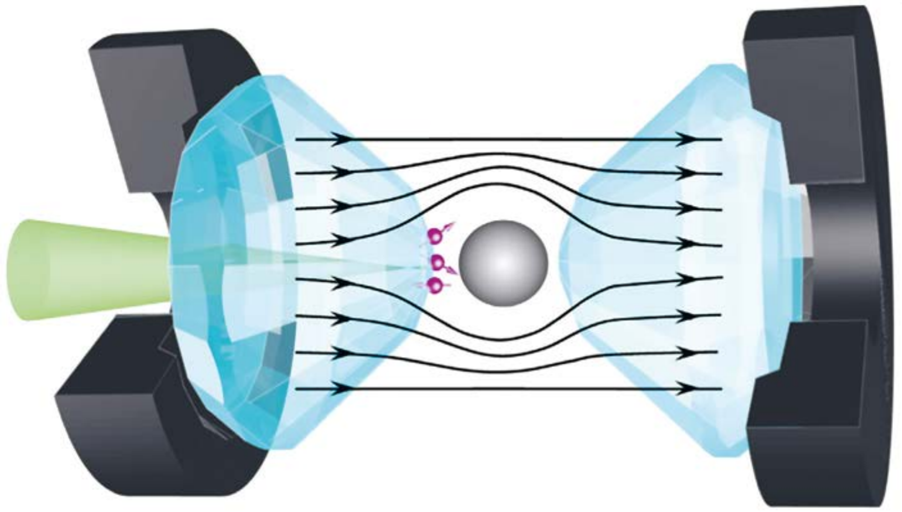


Figure 3: A high pressure cell is composed of two diamond anvils facing each other. The material under study (MgB_2), represented by the grey sphere, experiences a pressure of 7 GPa inside the cell. A uniform external magnetic field is applied through the cell. The NV centers (pink spheres) implanted close to the surface of one of the anvils can measure the magnetic field inside the cell when pumped by a green laser beam sent through the anvil. For temperatures below 28 K at a pressure of 7 GPa, the MgB_2 sample becomes superconductor and then produces a magnetic field that compensates exactly for the magnetic field inside it (Meissner effect). This induces a change in the overall magnetic field outside the sample that is measured by the NV centers. (Courtesy Lesik/Roch/ENS Paris-Saclay)

a single NV centre located a few nanometres below the surface. Such a small distance makes the NV centre sensitive to the magnetic field of a single nucleus, which can be detected using nuclear magnetic resonance techniques. This makes it possible to monitor the chemical shifts induced by neighbouring nuclei and to obtain information about the structure of the molecule. On the basis of similar techniques, a functional nuclear magnetic resonance spectrometer is currently being investigated. It would make it possible to develop a lab-on-a-chip for much more efficient drug analysis and improved medical diagnostics. Another medical application of NV centres is being developed within the framework of the METABOLIQS quantum flagship project. NV centres are used to efficiently polarise molecules used as markers in magnetic resonance imaging (MRI) devices. A gain of four orders of magnitude in the spin polarisation efficiency is expected. This would make it possible to manufacture MRI machines that are much smaller and cheaper than existing machines, which would lead to a wider diffusion of this technique for medical diagnostics.

PERSPECTIVES AND CONCLUSION

The NV centre applications described so far are based on the optical detection of magnetic resonance. However, the photoelectric detection of magnetic resonance has recently been demonstrated. Electrons excited in NV centres are picked up by an electrode deposited on the diamond surface and produce a current which can be directly used as a measurement signal. This opens up the possibility of developing much more compact and efficient devices, as the detector is directly deposited on the diamond crystal.

The NV centre in diamond is the most advanced example of a solid-state spin defect. However, there is a large class of other related defects which have very interesting characteristics. The silicon vacancy defect in diamond is another colour centre that can be used as an excellent source of photons for photonic integrated circuits. Tin vacancy and germanium vacancy are new colour centres currently under investigation. Other substrates such as silicon carbide or two-dimensional materials such as hexagonal boron nitride can host defects similar to the NV centre. In particular, silicon carbide defects have the interesting characteristic of emitting in the transparency window of optical fibres and are therefore well suited for telecommunication applications.

As we have shown previously, the NV centre in diamond and more generally solid-state spins are quantum objects with spectacular applications in the field of quantum sensing. In addition, they also hold great promise for quantum communications and quantum computing. We are only at the beginning of their application in a wide variety of fields. Many other applications, as yet unknown, are still to come and the future of these quantum sensors is very promising.

REFERENCES

[1] A. Beveratos, R. Brouri, T. Gacoin *et al.*, Phys.Rev. Lett. **89**, 187901 (2002)

[2] A. Gruber, A. Dräbenstedt, C. Tietz *et al.*, Science **276**, 2012 (1997).

[3] L. Thiel, Z. Wang, M. A. Tschudin *et al.*, Science **364**, 973 (2019).

[4] M. Lesik, T. Plisson, L. Toraille *et al.*, Science **366**, 1359 (2019).

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QUANTUM CORRELATIONS AND ENTANGLEMENT

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In 1935, Schrödinger introduced the word "entanglement" to describe a situation examined in the famous Einstein-Podolsky-Rosen paper published a few months before. The proper nature of quantum correlations that exist when a two-partite system is in an entangled state was a subject of controversy. In contrast to many other subjects, the debate about the nature of entanglement came quite recently to an end.

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After a period of gestation in the first quarter of the XX$^{\text{th}}$ century, Quantum Mechanics, as a comprehensive *ab initio* theory that could be applied to any physical situation, opened up a new era of physics, as it was able to describe in a quantitative and accurate way many systems: atoms, molecules, solids, electromagnetic fields ... Because of this amazing success, there was no doubt among the community of physicists concerning the validity of quantum theory and of its predictions. But this was not the case for the precise understanding of the concepts introduced, which have been, and are still, the object of debate [1]. Schrödinger, as a start, introduced the wavefunction $\psi(\mathbf{r})$ without knowing the exact nature of it. Born postulated that its square gives the probability of presence at point $\mathbf{r}$ and stressed the fundamental stochastic character of the measurement in quantum mechanics. He wrote it in a short footnote at the bottom of his paper [2], and for these few words he was rewarded with the Nobel prize! This in turn raised a wealth of questions: does the wavefunction, and more generally the state vector $|\psi\rangle$, describe a single particle or an ensemble of particles? Is the intrinsic randomness of the measurements a fundamental feature of the quantum world, or the reflection of our present ignorance? These questions, and many others, were the object of intense discussions, in particular between Einstein and Bohr, at the occasion of the Solvay meetings, and contributed to clarify, if not solve, the issues at stake. Following the 1935 "EPR" paper of Einstein, Podolsky and Rosen [3], and the reactions to this paper by Schrödinger [4] and Bohr, • • •

the discussion focussed on the description of two-particle states and on the characterization of correlations between the measurements performed on these particles, their analogies and differences with the classical ones.

Let us take as an example the polarization states of two photons, labeled 1 and 2. We note $|V_1\rangle|V_2\rangle$ the quantum state of two photons of vertical polarization, and $|H_1\rangle|H_2\rangle$ the state of two photons of horizontal polarization. A basic feature of Quantum Mechanics is the superposition principle, which states that any linear combination of quantum states is another bona fide quantum state. It has been popularized by Schrödinger with his famous cat, superposition of a dead cat and an alive cat. We can therefore consider the state

$$|\psi_{12}\rangle = \frac{1}{\sqrt{2}}(|H_1\rangle|H_2\rangle + |V_1\rangle|V_2\rangle)$$

It is easy to show that this state cannot be written as a product of separate polarization states for each photon, so that is not possible to ascribe any polarization state to them separately. The two-photon state must be considered globally. If one measures the polarization of photon 1 using a polarizer of vertical orientation we have 50% probability of finding him with polarization V or H. If we find H for example, the measurement projects the quantum state of photon 1 on state $|H_1\rangle$ and therefore the global state $|\psi_{12}\rangle$ collapses on state $|H_1\rangle|H_2\rangle$. We are therefore sure that the polarization of photon 2 is also H, even when the two photons have been detected very far from each other. The same reasoning is true for a V measurement. There is therefore a perfect correlation between the measurements made on the two photons. For this reason the state $|\psi_{12}\rangle$ is named an entangled state, the english translation of the German word "Verschränklung" introduced by Schrödinger, who coined this property, "not as ONE, but rather as THE characteristic trait of quantum mechanics". This puzzling behaviour does not require any physical link between the two photons, just the application of basic quantum mechanics rules. The argument can be extended to measurements using polarizers of different orientations than vertical and horizontal that also exhibit correlations.

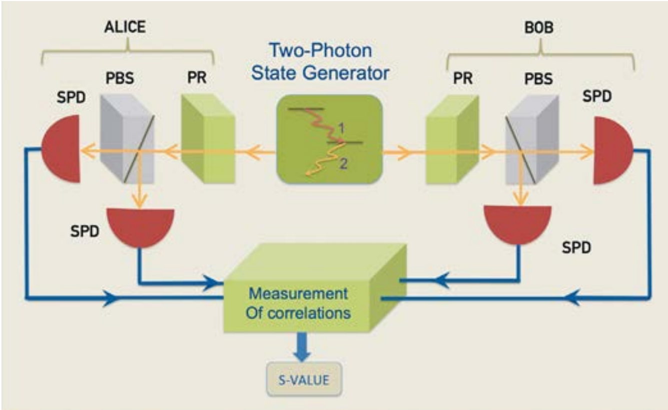


Figure 1: Sketch of an experimental set-up testing Bell inequality on a polarization-entangled two photon state. PR: polarization rotator; PBS: polarizing beamsplitter; SPD: single photon detector.

Of course, correlations do exist also in the classical world. They are even often the basis of scientific approach in many domains of science, for example in sociology, where correlations between apparently unconnected parameters constitute a privileged way to find causal chains. Let us consider the following classical situation: a jeweller, named J, has a stock of earring pairs, 50% in silver, 50% in gold. J randomly choses one pair and sends one earring of the pair to Alice (A) in Australia, and the other to Beatrice (B) in Brazil. When A receives her earring, she finds that it is for example a gold one. She then immediately knows, whatever the distance between them, that B will receive also a gold one. This is a classical case of perfect correlations. Though it seems that some kind of information has been transmitted instantaneously, there is no superluminal effect, because the information that A has on B's jewel is "private". The information is effective and measurable only when A sends a mail to B to communicate him the list of earrings she has received, so that Bob can effectively compare to its known list and measure the correlation.

The classical and quantum situations that we have just described seem at first sight quite similar. This is however not the case: in the classical example, each earring sent by J is made of a definite metal, a "solid" property that is carried all along by the earring. In the quantum example, there is no predetermined value of the spin orientations at the level of the entangled state generation. In addition, the randomness of measurements in the classical example arises from the random choice of earring pairs made by J, not from the probabilistic nature of quantum measurements.

A tempting resolution of the puzzling aspects of the quantum case is to mimic the classical situation by introducing for the two components of each photon pair a "tag" that identifies their common polarization and is carried all the way to Alice and Bob detectors. The value of this tag, named "hidden parameter", is not controlled, so that one has access only to averages over the values of this parameter. This simple picture leads to values of polarization correlations that are identical to the quantum prediction.

The introduction of a supplementary variable implies that the present state of quantum physics is not complete. The possible future mastering of this parameter would eliminate the random character of the quantum measurements. This interpretation of Quantum Mechanics was defended by Einstein (every physicist has in mind his famous statement: "The Old One does not play dice").

In 1964, John Bell made two astonishing discoveries [5]:

- He proved mathematically that the existence of hidden variables is not just a philosophical position. It indeed implies a constraint on measurement results. It showed more precisely that the introduction in the theory of local (i.e. attached to each photon) supplementary variables has indeed a physical consequence: it implies a maximal value of 2 for a well-defined combination, labeled S, of correlations between polarization measurements made by Alice and Bob with two different settings of the polarizer orientations. This is the famous "Bell inequality", which shifted the debate about hidden variables to the domain of experimental physics.
- He also exhibited specific experimental situations for which, according to the ordinary laws of quantum mechanics, one predicts a value of S bigger than 2 (Note that many entangled states do not violate Bell inequality).

Bell's discovery triggered a whole series of experiments [6,7]. In the oldest ones, performed in the 1970's, the entangled state was created by cascaded spontaneous emission on two successive atomic transitions, with two possible paths to the ground state. Most pairs of photons were lost because spontaneous emission is not directional, giving rise to a poor signal to noise ratio. One of the first experiments gave even an unexpected value of S smaller than 2. In experiments performed later in Berkeley and Houston, at the end of the 1970's, the use of laser excitation and improved detection schemes gave S values well above the noise floor. In the beginning of the 1980's the experiment by A. Aspect and coworkers yielded values of S unquestionably above 2, by more than 40 standard deviations. At the end of the 1990's spontaneous parametric down conversion in $\chi^{(2)}$ nonlinear crystal replaced cascades to generate the two-photon polarization entangled states. Phase matching conditions give rise to signal and idler photons emitted in small solid angles, resulting in a significant increase in the quantum efficiency of detection. Nowadays, Bell inequality is strongly violated, and in a short integration time, in photonic systems, but also using two spin 1/2 entangled particles [9].

Such experimentally proven violations of Bell inequality convinced an overwhelming majority of physicists to reject local hidden variables. The debate was actually closed in the 80's, after the Orsay experiments including a fast change of polarization settings during the photons time of flight. However, some theorists raised objections related to the unavoidable imperfections of the experimental protocols. These objections, named "loopholes", are sound from a purely logical point of view, and as such deserve to be examined, but they imply very improbable behaviours of the experimental set-up (a kind of "detector conspiracy") that are very unphysical. Objections concern the possibility of interaction information exchange between Alice and Bob polarization detectors, and a possible "unfair sampling" of the data that were detected, considering the limited collection efficiencies of the photon pairs. Starting from 1981 more and more sophisticated experimental set-ups strived to close this loopholes.

Finally in 2015, the results of 3 "loophole-free" experiments were published [8-11]. Let us briefly describe the one performed by M. Giustina and co-workers in A. Zeilinger's group in the basement of the Hofburg castle in Vienna [10]: the entangled state is generated by spontaneous parametric down conversion in a periodically poled nonlinear crystal and collected in two single mode fibers, at a rate of 3000 pairs per second. While the photons are in flight, fast random number generators choose the two polarization measurement settings. The distances between Alice, Bob, and the entangled state generator, of 30m, are large enough to prevent any kind of causal physical link between them. The detector quantum efficiency is 98%, thanks to the use of TES supraconducting Single Photon Detectors amplified by SQUID. In these optimized experimental conditions, Bell inequality is violated by 11.5 standard deviations on a sample of $3,5.10^9$ photon pairs.

After these experiments no serious physicist can now object that the hypothesis of local realistic hidden variables is ruled out by experiments and that an entangled state must be considered as a global, inseparable, entity whatever the distance between its two parties. In addition we must admit that the randomness of Quantum measurements cannot be related to our lack of knowledge about the system. The non-existence of random hidden parameters tells us that it will not be possible to predict for example when exactly an atom will decay by spontaneous emission: the quantum randomness is intrinsic.

Let us finally stress that Bell inequality violating entangled states are not only objects of basic theoretical interest. They are now privileged quantum resources used in applications, such as Quantum Key Distribution and Quantum Teleportation.

RÉFÉRENCES

[1] F. Laloe, Do we really understand Quantum Mechanics?, Cambridge University Press (2019)

[2] M. Born, Zeitschrift für Physik **37**, 863-867, (1926)

[3] A. Einstein, B. Podolsky, N. Rosen, Phys. Rev. **47**, 777 (1935)

[4] E. Schrödinger, Proc. Am. Philos. Soc. **124**, 323-338 (1935)

[5] J. Bell, Physics **1**, 195-200 (1964)

[6] A. Aspect, Bell theorem: a naive view of an experimentalist, in Quantum (un)speakables: from Bell to quantum information, (R. Bertlmann, A. Zeilinger editors, Springer) (2002)

[7] G. Grynberg, A. Aspect, C. Fabre, Polarization-entangled photons and violation of Bell inequality, in Introduction to Quantum Optics, Complement 5C, Cambridge University Press (2010)

[8] J. Miller, Phys. today **69**, 1-14 (2016)

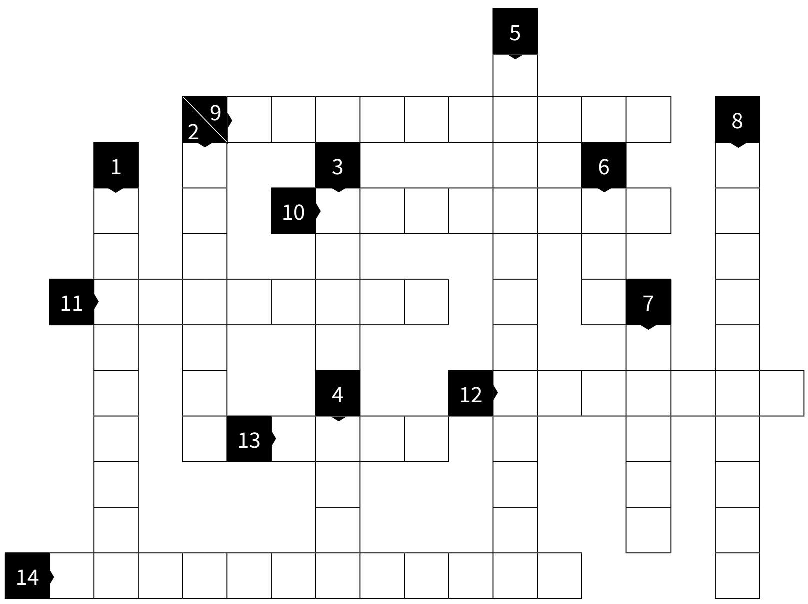
[9] B. Hensen et al., Nature **526**, 682 (2015)

[10] M. Giustina et al., Phys. Rev. Lett. **115**, 250401 (2015)

[11] L. Shalm et al., Phys. Rev. Lett. **115**, 250402 (2015)

CROSSWORDS ON QUANTUM TECHNOLOGIES

SOLUTION ON PHOTONIQUES.COM



1 Property of a quantum operator
2 Big atoms
3 Up or down
4 Inequality
5 Obeys the Schödinger equation
6 Paradox
7 Bob's friend
8 Only with bosons
9 Physical quantity that can be measured
10 States with less uncertainty in one quadrature
11 First condensate
12 Doppler, Sisyphus or evaporative
13 Basic unit in quantum computing
14 Only in quantum mechanics

MICROSCOPE OBJECTIVES

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Microscope objectives are key components of optical microscopes, but they also equip experimental set-ups to focus laser beams or to collect photons emitted from any physical events to analyze or to diagnose. There are properties to take into account about their specifications and their usage for selecting the right microscope objective. They are used in a wide range of applications, from life sciences to material sciences, in laboratories and in industries and each application requires a specific microscope objective.

https://doi.org/10.1051/photon/202010459

The microscope objective is a complex multi-lens assembly that collects light from the sample. It plays a key role for the primary image formation and determines the quality of the image that the microscope, or the optical set-up, provides.
Although the first compound microscope was invented in the 17th century [1], microscope objectives are still high-technology items and among the most sophisticated optical components to design and to assemble. High-class microscope objectives can be composed of a set of individual lenses, lens doublet and triplet groups that are cemented together in order to reach the optical specifications that are designed for. Some lenses are still manually manufactured and result from a high level of know-how and skills. The microscope manufacturers offer a wide range of objectives providing different features as regards the optical aberrations correction, the illumination conditions and most generally the applications and the conditions of operations. Their costs can vary according to those characteristics, from hundreds to dozens of thousands of Euros.

Microscope objectives specifications can easily be found *via* the writings and the signs engraved on their barrel (see Fig. 3). But finding the right objective for each specific application is not obvious. According to the specimen type and the set-up, the requirements may change. There are microscope objectives for a wide range of applications such as live sample imaging, metallography, petrography...
A first point to consider is to select the right type of objective according to the device, the equipment or the set-up which will accommodate it. Microscope objectives feature different sizes, weights but also different optical configurations that can limit their integration.

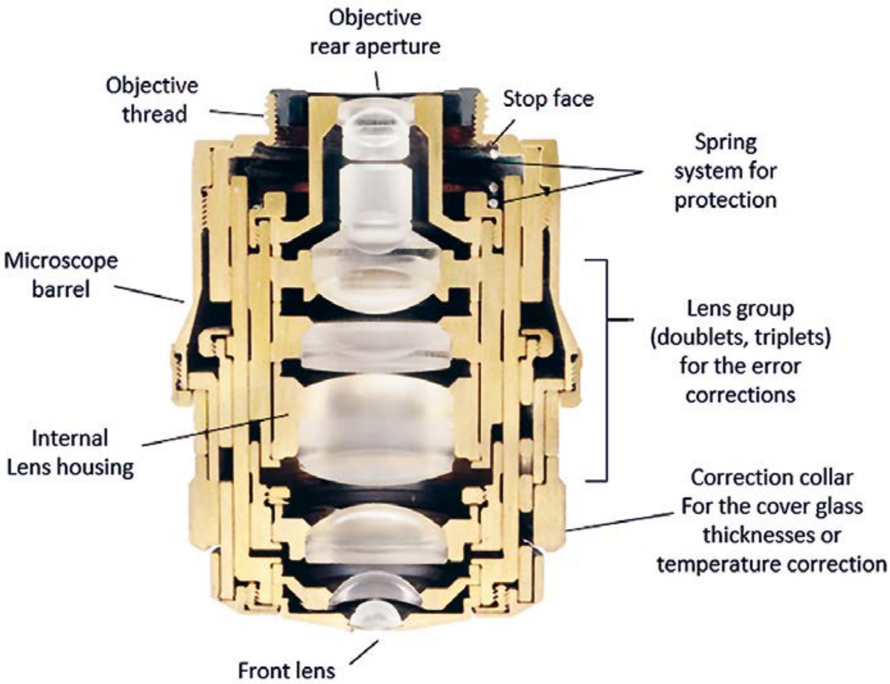


Figure 1. Cross-section of an apochromat objective showing the lenses and the main parts of the item.

A FINITE-CONJUGATE OR INFINITY-CORRECTED MICROSCOPE OBJECTIVES?

The finite-conjugate microscope objectives are designed to project a diffraction-limited image at a fixed plane, the intermediate image plane. They are mainly used for simple compound microscopes or OEM integration, or as focusing objectives. Because they are generally composed of two or three lenses, including an achromatic lens, they have a smaller size and a lower weight than higher classes of objectives [2]. However, they are limited as regard the color and the chromatic error corrections.
The infinity-corrected objectives are designed to project incoming rays to infinity and they require a specific

MANUFACTURER	TUBE LENS FOCAL LENGTH (MILLIMETERS)	PARFOCAL DISTANCE (MILLIMETERS)*	THREAD TYPE	INFINITY-CORRECTED DESIGNATION
Leica	200	45	M25	HC system (Harmonic Compound System)
Nikon	200	60	M25	CFI (Chrome-Free Infinity).
Olympus	180	45	RMS	UIS (Universal Infinity System)
Zeiss	165	45	RMS and M27	ICS (Infinity Color Corrected System)
Mitutoyo	200	95	M26	

Table 1: Common manufacturer's specifications standard on the objective design. Adapted from [4]. For home-built optical set-up, microscope objective threading adapters exist.

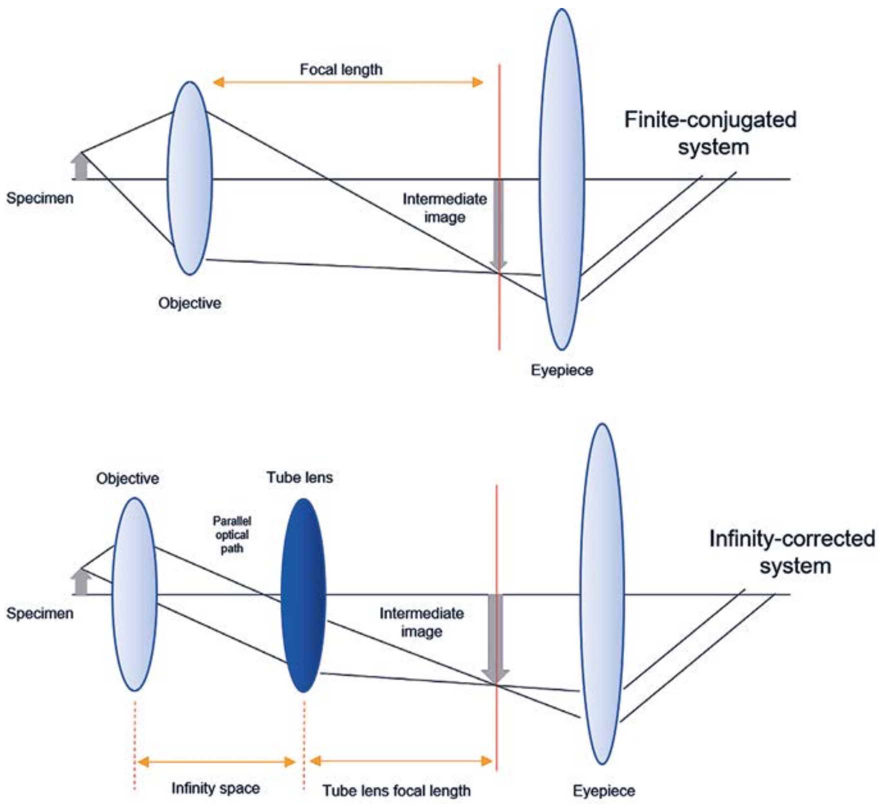
*The parfocal distance is the distance between the objective lens mounting plane and the specimen.

RANGE	OBJECTIVE MAGNIFICATION	MAIN COMMENTS
Low	1× to 5×	It gives a large overview image of the sample. The illumination homogeneity can be compromised.
Medium	10× to 40×	It offers a good trade-off between the field of view and the spatial resolution.
High	60× to 100×	It is used for small samples and to image fine structures. Image brightness can be weak.

Table 2. The main magnification ranges. Adapted from [5].

tube lens (or a secondary lens) to focus the image at the intermediate image plane. Infinity-corrected and finite objectives are consequently not interchangeable and can only be accommodated in specific microscopy systems, according to the focal length of the tube lens and the parfocal distance used by the manufacturer. A secondary lens is not needed for laser focusing applications. Infinity-corrected objectives are composed of a higher number of optical elements (see Fig.1) and have larger sizes and weights than finite-conjugate objectives. However, they provide better optical performances. Another consideration is the objective pupil diameter. The effective exit pupil diameter (D) necessary to achieve a given numerical aperture is D=2NA×f where NA is the numerical aperture and f is the objective focal length. The limited factor within the objective is the thread size which differs from the manufacturer. There are two categories: the RMS having a thread size of 20.32 millimeters with a pitch of 0.71 mm, and the M25 & M27 having

Figure 2. Simplified diagram of the finite-conjugate and infinity-corrected optical configurations. Adapted from [3].



OBJECTIVE CLASS	SPHERICAL ABERRATION	CHROMATIC ABERRATION	FIELD CURVATURE	TYPICAL DESIGNATIONS
Achromat	1 Color	2 Colors	No	Achro
Plan Achromat	1 Color	2 Colors	Yes	Plan Achro
Fluorite	2-3 Colors	2-3 Colors	No	Fluor, FL
Plan Fluorite	2-3 Colors	2-3 Colors	Yes	Plan Fluor, FL Plan
Plan Apochromat	2-3+ Colors	3+ Colors	Yes	Plan Apo

Table 3. Summary of the different types of optical aberration corrections. Adapted from [3-5]

respectively thread sizes of 25mm and 27mm with a pitch of 0.75mm. Some microscope objectives are designed with a larger thread size (M32 or M40) in order to provide a longer working distance and a wider field of view. The parfocal distance is also longer than conventional objectives.

Manufacturers employ different combinations of parfocal distance, tube lens focal length and thread size to overcome the optical limitations which may occur along the optical path and to meet the requirements for the design of new models of objectives. Current specifications used by the main microscope objective manufacturers are summarized in Table 1.

READING THE OBJECTIVE BARREL: A CLOSER LOOK TO THE WRITINGS

Resolution versus magnification

The linear magnification M and the numerical aperture NA are the two main specifications needed when seeking for an objective. The first gives the ability of the objective to magnify small objects while the second is related to the spatial resolution. The objective magnification is usually classified in three ranges as indicated in Table 2.

Another important parameter is the numerical aperture (NA) which indicates the incoming light acceptance angle of the microscope objective. This parameter determines the light collection, the resolution and the depth of field of the objective. The resolving power or the spatial resolution (in microscopy) is the minimal distance at which two distinct points of the object can still be discriminated from each other. In other words, it estimates the lateral resolution that can be calculated in conventional light microscopy by the formula presented by Ernst Abbe in 1873 : Abbe resolution = $\lambda/2NA$, where λ is the illumination wavelength. The higher the NA, the better the resolution. But it is important to know that the specimen and refractive index of the medium between the objective's front lens and the sample surface can also influence the resolution.

CORRECTION OF THE OPTICAL ABERRATIONS

Light is composed of different wavelengths which are not associated with the same refractive index of lenses. Color aberrations may therefore occur when light is transmitted through a lens. There are different degrees of color corrections which lead to different types of objectives (Table 3).

The achromatic objective is the least expensive type. Those objectives are corrected for axial chromatic aberrations in two wavelengths (typically blue and red). They are additionally corrected for spherical aberrations in the green color.

The next level of corrections and type is the fluorite or semi-apochromat objective. They are, axially corrected for two colors. They are additionally corrected of spherical aberrations for two or three colors. They usually have higher NA and yield brighter images and higher contrasts.

Apochromat objectives provide the highest level of spherical and chromatic corrections. They are corrected for at least three colors, typically blue, green and red, and spherically corrected for two or three wavelengths. Images are free of color fringes. They are the most complex and expensive objectives as they result from specific combinations of different glass materials with opposite dispersion properties.

Lenses in microscope objectives are curved, convex or concave, resulting in image curvature. The higher the magnification, the worse this curvature effect. To eliminate the field curvature, a specific optical design must be considered. Objectives with flatness correction are called "plan" or "planar".

IMMERSION MEDIA	REFRACTIVE INDEX (N)	ABBREVIATIONS	CONVENTIONAL LINEAR MAGNIFICATION RANGE	CONVENTIONAL NUMERICAL APERTURE RANGE
Air	1.00	Dry	1× – 100×	0.04 – 0.9
Water	1.33	W, Water	10× – 100×	0.3 – 1.27
Silicon oil	1.40	Sil	25× – 100×	1.05 – 1.35
Glycerol	1.47	Glyc	10× – 93×	0.5 – 1.3
Oil	1.515	Oil	20× – 100×	0.4 – 1.49

Table 4. Main properties of a set of immersion media. Multi-immersion objectives exist with a specific adjustable collar to select the refractive index of the immersion media.

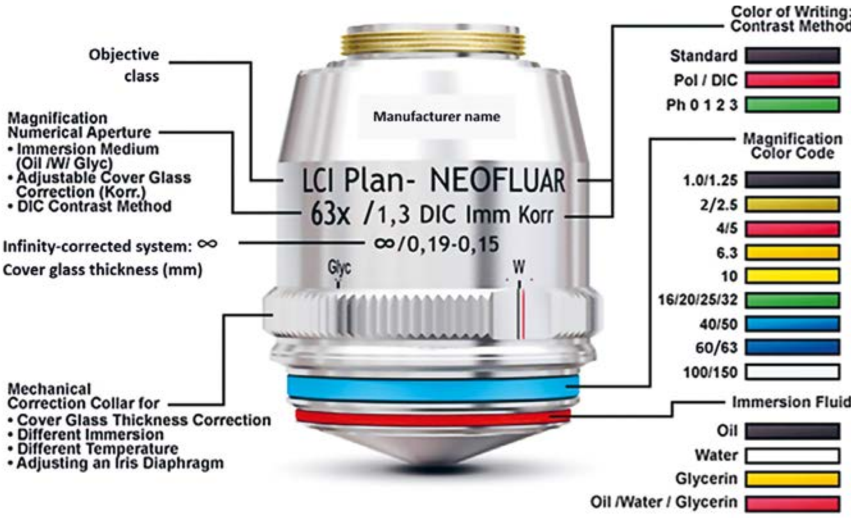


Figure 3 – Color Codes – The microscope manufacturers label their objectives with color codes which allow for a rapid identification of the magnification and the requirements of any specialized immersion media. The figure lists the current magnification and imaging media color codes. Other specifications marked on the objective barrels can be also found.

IMMERSION OBJECTIVE: HOW TO REACH A NA HIGHER THAN 1?

The typical maximum achievable numerical aperture for dry objectives is 0.95. It is possible to increase the numerical aperture by including an immersion media between the objective lens and the specimen. To increase the resolving power, typical immersion liquids are used such as synthetic immersion oil, glycerol, water or silicone oil (Table 4).

WORKING DISTANCE

The working distance is the distance between the objective front lens and the top of the specimen (or the cover glass) when the specimen is in the focus plane. The working distance decreases as the magnification (and the numerical aperture) increases. This specification is not always engraved on the objective barrel. It is mentioned when the objective provides specific working distance characteristics. Three categories of working distances can be identified: conventional working distance (not indicated on the objective barrel), long working distance (abbreviated as L, LL, LD, and LWD) and extra-long working distance (abbreviated as ELWD (extra-long working distance), SLWD (super-long working distance), and ULWD (ultra-long working distance).

Those features will affect the size and consequently the weight of the microscope objective. A higher magnification will make a longer and larger objective. At a given linear magnification, the diameter will not be identical according to the color correction and the working distance characteristics.

PHOTON EFFICIENCY

A high photon efficiency (or transmittance) can be required, *e.g.* in fluorescence microscopy techniques, at a given range of the optical spectrum, for instance at the extrema of the visible spectrum and even in the near-infrared (NIR) and near-ultraviolet (NUV) domains. That is why manufacturers offer specific objective series with specific photon efficiency performances, depending on the antireflective coatings and materials used for the lenses.

OBJECTIVE LENSES BEYOND THE UV AND THE NIR

Specific objectives designed in specific glass materials can be manufactured to be compatible with the X-ray and the IR domains. UV microscope objectives can be found in the semiconductor industry, X-ray objectives in X-ray microscopes or facilities like synchrotrons. IR objectives can be found in laser processing systems and used for laser beam focusing.

CLEANING AND MAINTENANCE

Microscope objectives are very sensitive materials. They must be carefully manipulated to maintain their performances. It is important to follow the manufacturer recommendations for the microscope objective cleaning and their conditions of usage and storage. It is also important to pay attention to the type of reagent the microscope objective can be in contact with. Some reagents might be aggressive and dissolve the glue used to seal the lenses within the microscope objective. Besides, it is advised to store microscope objectives in their dedicated casing when they are not mounted in order to prevent any shocks which could move lenses within the objective and affect their quality. Some objectives can be equipped with a spring-loaded assembly that protects the front lens elements and the specimen from collision damage. With the correct conditions of usage and storage, the performances of the microscopy objective can be maintained for a very long period as it has no wearing parts.

CONCLUSION

The main microscope objective specifications have been introduced in this article. That list is not exhaustive and other specifications can be used to characterize other significant features in link with the application. The microscope objective, as a fundamental component in the laboratory, is an optical component that demands continuous R&D efforts, motivated by the development of new imaging and microscopy techniques as well as the specific end-users' requirements.

REFERENCES

[1] Wikipedia | Albert Van Helden; Sven Dupré; Rob van Gent (2010). The Origins of the Telescope. Amsterdam University Press. pp. 32–36, 43. ISBN 978-90-6984-615-6.

[2] https://www.edmundoptics.fr/knowledge-center/application-notes/microscopy/understanding-microscopes-and-objectives

[3] Zhang, Yueqian & Gross, Herbert, Advanced Optical Technologies **8** (2019), 10.1515/aot-2019-0002.

[4] https://www.microscopyu.com/microscopy-basics/infinity-optical-systems

[5] https://application.wiley-vch.de/Microscopy_for_Dummies/

For further pieces of information about the microscope objectives and the microscopy techniques, please consult the educational resources made by the manufacturers:

https://www.leica-microsystems.com/science-lab/science-lab-home/ | Leica

https://www.microscopyu.com/ | Nikon

https://www.olympus-lifescience.com/en/microscope-resource/ | Olympus

http://zeiss-campus.magnet.fsu.edu/ | Zeiss

MANUFACTURER	APPLICATION / PRODUCT	DEALER	CONTACT
Nikon	Life Sciences (LS)	Nikon Healthcare	https://www.nikon.com/products/microscope-solutions/inquiries/index.htm
	Materials Science (MS) Industrial Microscopy (IM)	Nikon Metrology	https://www.nikonmetrology.com/en-gb/contact-us/find-a-sales-or-distributor
Olympus	Life Sciences (LS)	Olympus Life Science	https://www.olympus-lifescience.com/en/contact-us/
	Materials Science (MS) Industrial Microscopy (IM)	Olympus IMS	
Leica	Life Sciences (LS) Materials Science (MS) Industrial Microscopy (IM)	Leica Microsystems	https://www.leica-microsystems.com/contact/contact-us-online/
Zeiss	Life Sciences (LS) Materials Science (MS) Industrial Microscopy (IM)	Zeiss Industrial Quality & Research	https://www.zeiss.com/microscopy/int/service-support/microscopy-contact.html
Mitutoyo	Industrial Microscopy	Mitutoyo Europe GmbH	https://mitutoyo.eu/en_us/contact
Thorlabs	Microscope objectives (LS, MS and IM), reflective objectives, UV, visible & NIR focusing objectives.		https://www.thorlabs.com/locations.cfm
Edmund Optics	Microscope objectives (LS, MS and IM), reflective objectives, UV, visible & NIR focusing objectives.		https://www.edmundoptics.com/contact-support/
OptoSigma	Microscope objectives (LS, MS and IM), reflective objectives, UV, visible & NIR focusing objective.		https://www.optosigma.com/eu_en/contact-us?___from_store=us_en
Jenoptik	Customized and Standardized Objective Lenses (LS, MS and IM)		https://www.jenoptik.com/contact

PHOTONIC CO-PROCESSOR FOR AI COMPUTING

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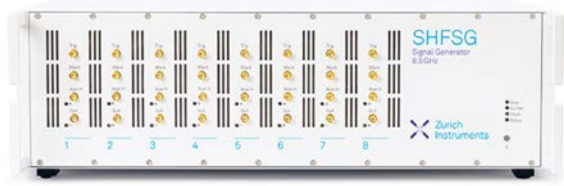
https://lighton.ai/

Signal generator for complete qubit control



Zurich Instruments launches the SHFSG, a signal generator specially designed for superconducting and spin qubits. The SHFSG can output signals from DC up to 8.5 GHz without the need for mixer calibration, and provides a clean and low-noise signal in a bandwidth of 1 GHz. The SHFSG can be programmed to generate complex pulse sequences. The SHFSG is available in two variants, one with 4 channels and one with 8 channels.

https://www.zhinst.com/

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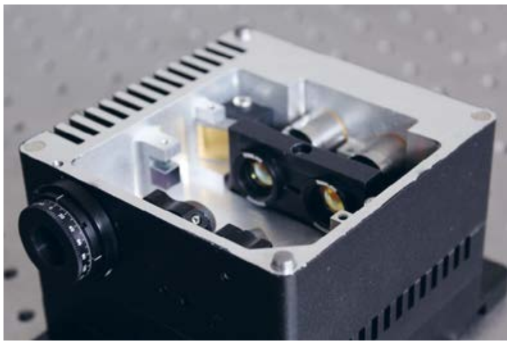
Coupled with ultra-low noise laser controllers, the QubeDT differential detector opens a wide range of possibilities for advanced spectroscopy. Two models are available: QubeDT-S: DC-coupled (0-2 MHz BW) detector, designed for spectroscopic applications such as Polarization Spectroscopy ; QubeDT-F: AC-coupled, high BW (>100MHz) detector, designed for hetherodyne detection and RIN-immune beat-note acquisition.

https://www.ppqsense.it/



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Ultra-Compact UV Nanosecond Lasers

The Explorer One HP HE 355-200 offers >200 µJ of UV pulse energy, pulse widths of <15 ns, and user-adjustable repetition rates from single shot to 200 kHz. The laser's advanced E-Track™ active pulse-energy control features a closed-loop algorithm that enables dynamic pulse energy adjustment with various gating operations for optimal process control.

https://www.spectra-physics.com