Photoniques

N°134

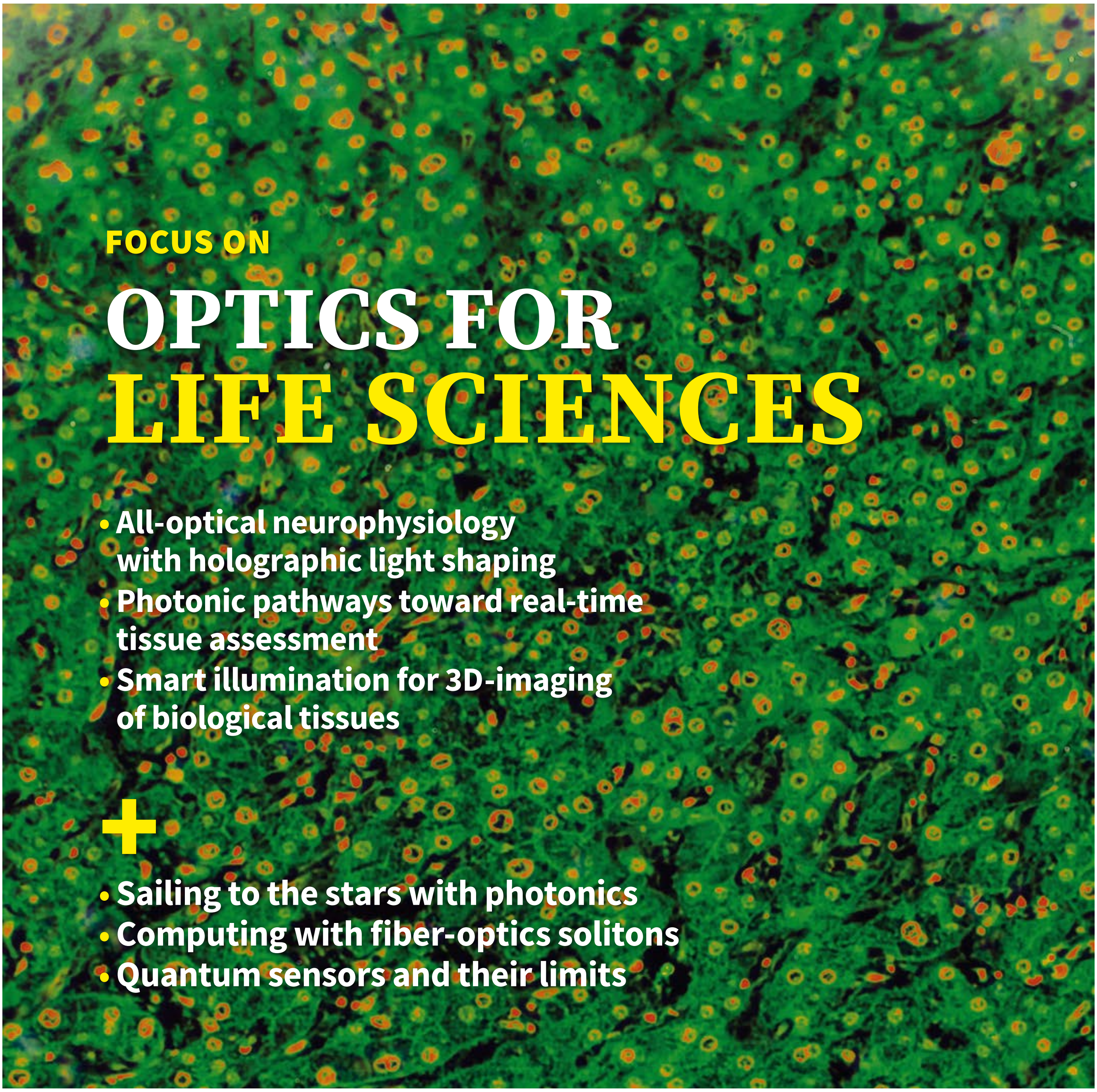
LIGHT AND APPLICATIONS | EOS & SFO JOINT ISSUE

INTERVIEWS
Rachel Grange, Rainer Erdmann

ZOOM
Photonics in Sweden

EXPERIMENT
Optical Coherence Tomography

PRODUCTS
Instruments for bioimaging



FOCUS ON

OPTICS FOR LIFE SCIENCES

- All-optical neurophysiology with holographic light shaping
- Photonic pathways toward real-time tissue assessment
- Smart illumination for 3D-imaging of biological tissues

\+

- Sailing to the stars with photonics
- Computing with fiber-optics solitons
- Quantum sensors and their limits

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Editorial

NICOLAS BONOD
Editor-in-Chief

Optics for Life, A Life for Optics

Copenhagen, 15 August 1932. Niels Bohr, one of the founding figures of quantum physics, steps onto the stage to deliver the opening lecture of a conference devoted to phototherapy. In his lecture, entitled *Light and Life*, he questions whether physics might help in understanding living systems. Among the audience sits Max Delbrück, who would eventually shift from physics to molecular biology, a choice that ultimately led him to the 1969 Nobel Prize in Physiology or Medicine awarded for his discoveries on viral replication and genetic structure. His trajectory illustrates how physics and the life sciences have much to offer one another.

Light and life are intrinsically intertwined. Light ignites the emergence and growth of living organisms, and it provides an exceptional probe for investigating their inner mechanisms.

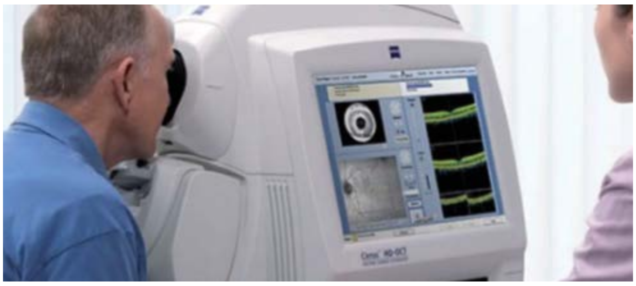
In this issue, we explore the most advanced optical methods for imaging and addressing the living world and life sciences. This issue features three articles that address all-optical neurophysiology, real-time tissue diagnostics, and smart illumination schemes for 3D biological imaging.

We are delighted to inaugurate here a new section, *Perspectives*, dedicated to forward-looking viewpoints on what photonics can bring. The inaugural article, *Sailing to the Stars with Photonics*, captures this spirit perfectly: envisioning high-power lasers propelling ultrathin reflective sails to significant fractions of the speed of light across the cosmos. The second contribution explores the very appealing field of photonic computing with fiber-optic solitons, while the third is devoted to quantum sensing, in resonance with the 2025 International Year of Quantum Science and Technology.

To celebrate the tenth anniversary of the first detection of gravitational waves, this issue features not one but two complementary articles on gravitational wave detectors. The first provides a complete introduction to kilometer-scale laser interferometers that can detect and triangulate the sources of gravitational-wave events occurring billions of light-years away; the second focuses on the implementation of squeezing techniques for quantum noise reduction.

All these topics illustrate how light opens pathways for exploring our world: from deciphering the intricate architectures and mechanisms of life to probing the most powerful events in the universe.

Within the photonics community, we all stand together in this scientific and cultural adventure, placing light at the forefront of knowledge and progress: Optics for life, a life for optics.



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SFO/EOS forewords

FRANÇOIS SALIN
President of the French Optical Society

Standing on the shoulders of giants

Since 2018, we have been organizing a residential school in partnership with the **École des Houches**. This program, initiated by Pierre Chavel, is now thriving, success rooted in a set of proven strengths. The first is the legendary École des Houches, founded by Cécile DeWitt-Morette in 1951. It is legendary in two ways: first, its breathtaking location—a mountain chalet facing Mont Blanc, an ideal environment for brainstorming; and second, its rich history. Since its inception, 59 Nobel laureates have participated, including E. Fermi, W. Lamb, R. Feynman, N. Bloembergen, R. Glauber. And, as a touch of French pride, P.G. De Gennes, C. Cohen-Tannoudji, A. Fert, Haroche, G. Mourou, A. Aspect, A. L'Huillier, P. Agostini, and M. Devoret also stand out.
Building on this heritage, the SFO schools at Les Houches established an excellent reputation based on core values. Among these are the organization by renowned experts in the field, whose dedication we sincerely appreciate; the active involvement of internationally acclaimed professors; the topics which are always at the forefront of scientific excitement. For example, the last four schools included: Optomechanics & NanophoNonics (2023, R. Braive, D. Lanzillotti-Kimura), Waves in Complex Media (2023, S. Gigan, N. Cherroret, A. Aubry), Thermics and Nanophotonics (2024, P. Bouchon Y. de Wilde), and Thin Film Lithium Niobate (2025, K. Bencheikh, A. Boes, R. Grange, and A. Mitchell). A distinctive feature of each SFO school is its comprehensive scope, addressing the continuum from fundamental science to technology and applications enriched by the active participation of industry colleagues.
Over the years, these SFO schools have attracted students from all continents. The upcoming school (March 2026) on Ultrafast Sources of Coherent Light, by Marc Hanna and Aurélie Julien, will also be a great success. It will mark the return of Anne L'Huillier to Les Houches for the first time since she was awarded the Nobel Prize.

Ariel Levenson[1], **François Salin**[2], **Antoine Godard**[3],
[1] Directeur de recherche CNRS, Past-President of SFO,
[2] President and CEO Ilasis Laser, President of SFO
[3] Directeur scientifique du domaine physique – ONERA, future President of SFO

EMILIANO DESCROVI
President of the European Optical Society

EOSAM in Delft: optics at its best

With a slight shift from recent tradition, the EOS Annual Meeting was held this year from August 24 to 28, in Delft. The city's picturesque canals and a mild late-summer climate offered a perfect setting for the EOS's flagship event, hosted at the TU Delft Conference Center. This edition, chaired by Omar El Gawhary (ASML & TU Delft) and Stefan Witte (TU Delft), with the support of EOS members Elina Koistinen, Ignacio Moreno, and myself, introduced interesting novelties.
Building on the successful experience of EOSAM 2024 in Naples, the EU session was expanded and promoted to a plenary format. Delegates from Photonics21, PhotonHub, Phortify, and PIX Europe presented the latest European initiatives and engaged the audience in a lively Q&A session on the future perspectives in the 10th Framework Programme. Another highlight was a joint session co-organized with the Chinese Optical Society (COS). A panel of speakers shared their perspectives on EU–China collaborations, illustrating ongoing research activities and personal experiences. This initiative was warmly welcomed and is likely to be repeated in the future, possibly in cooperation with other partner societies. In addition, an industrial podium supported by EPIC brought together experts from academia and industry to discuss human resource strategies. Recruitment of young talent, career expectations, and professional motivations were among the central themes addressed.
Overall, EOSAM 2025 attracted 440 participants from more than 30 countries, featuring 10 plenary sessions, 54 parallel session, 290 oral presentations, 82 posters, and 19 exhibitors.
As tradition dictates, a topical issue on EOSAM 2025 is launched on the open-access journal JEOS-RP. We are pleased to see JEOS-RP continuing to strengthen its impact, while offering EOS members significant APC discounts.
Next year, EOSAM will move further north, to Tampere, Finland, from August 24 to 28. Save the dates, follow our newsletter and social channels, and visit https://www.europeanoptics.org/

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

AGENDA

■ **Ultrafast sources of coherent light**
Current research and emerging applications
The Houches Physics School, France

23 - 27 March 2026

70 attendees expected

The application deadline is October 31, 2025 (short motivation letter + CV)

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

06 - 10 july 2026

+ 670 participants expected

The application deadline is February 15, 2026

■ **The International Award**
SFO LUMIÈRES Arnulf-Françon

The application deadline is February 26, 2026

OPTIQUE BFC 2026: call for contributions

The biennial Congress of the French Optical Society will be held in Dijon from 6 to 10 July 2026 – Palais des Congrès, Dijon, France. Presentations are accepted both in English and in French.

The French Optical Society (SFO) is organizing its biennial congress OPTIQUE BFC 2026, to be held from 6 to 10 July 2026 at the Palais des Congrès in Dijon. This major event in optics and photonics will bring together more than 650 researchers, PhD students, and industry experts from across Europe and beyond.
The 2026 edition will open with an inaugural lecture by Anne L'HUILLIER, Nobel Prize in Physics 2023. Under the scientific co-chairmanship of Bertrand Kibler (ICB, CNRS) and Daniel Brunner (FEMTO-ST, CNRS), and the local chairmanship of Guy Millot (ICB, IUF), the congress will highlight the vitality of all areas of optics and photonics: lasers, silicon photonics, quantum optics, optical materials, biophotonics, nanophotonics, optical sensing, AI, and many others.
An industrial exhibition will host more than 45 companies and start-ups, providing a unique opportunity to showcase innovations and equipment, and to strengthen synergies between academic research and industry.
The SFO invites the scientific community to submit contributions (oral communications or posters). The Conftool platform will open for submissions on 15 November 2025, with a deadline set for 15 February 2026.
Submissions will be evaluated by SFO scientific committees, composed of more than 120 experts covering all fields, ensuring both quality and diversity of the program.
PhD students and postdoctoral researchers are strongly encouraged to participate. "I will take part in a major congress in my field at least once during my PhD!" — this is the commitment of the SFO, which works to keep registration fees accessible so that every PhD student can present their work.
The congress will feature a strong international dimension (50% of plenary speakers will be from outside France, and more than 30% of participants are expected from abroad) and a firm commitment to gender parity.

Plenary Lectures at OPTIQUE BFC 2026

11 plenary lectures will be given by world-renowned experts:
√ **Hatice Altug** (EPFL, Switzerland)
√ **Anne Amy-Klein** (LPL, France)
√ **Roel Baets** (Ghent/IMEC, Belgium)
√ **John Dudley** (FEMTO-ST, France)
√ **Sylvain Gigan** (ENS Paris, France)
√ **Anne L'Huillier** (Lund, Sweden, Nobel Prize in Physics 2023)
√ **Hélène Perrin** (LPL, France)
√ **Carlo Sirtori** (ENS Paris, France)
√ **Birgit Stiller** (MPL, Germany)
√ **Giovanni Volpe** (University of Gothenburg, Sweden)
√ ... and the lecture by the 2026 Léon Brillouin Grand Prize laureate.

SFO Awards at OPTIQUE BFC 2026

The SFO will present its prestigious awards:
🏆 **Léon Brillouin Grand Prize** – lifetime achievement,
💡 **Jean Jerphagnon Prize** – technological innovation and outreach,
✨ **Fabry-de Gramont Prize** – young researcher of international recognition,
📚 **Lumières Arnulf-Françon Prize** – pedagogical or outreach production,
🎓 **SFO Thesis Prize** – five annual prizes, including one with industrial partnership.

REOD at OPTIQUE BFC 2026

The Meetings on Optics Education and Didactics (REOD) will foster exchanges between teachers, didacticians and physicists. Three sessions will address:
. **Optics teaching in primary and secondary education**
. **Optics teaching in higher education**
. **Didact tools, LightBox, SHIRE, ...**

OPTIQUE BFC 2026 in Numbers

✓ +650 participants
✓ +45 industrial exhibitors
✓ 5 awards presented by the SFO
✓ +7h30 plenary sessions
✓ +80h thematic sessions
✓ +250 oral presentations
✓ +200 posters
👉 More information: www.sfoptique.org


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French optical society
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2026
www.sfoptique.org

Switzerland:
SSOM Microscopy Section Fall Meeting
Bern, 18 November 2025

Norway:
Norwegian Electro-Optics Meeting 2026
Moss, 22–24 April 2026

Finland:
Optics & Photonics Days, OPD
Jyväskylä, 26-28 May 2026

France :
OPTIQUE BFC 2026
Dijon, 6-10 July 2026

Portugal:
7th International Conference on Application of Optics and Photonics
Lisbon, 7-10 July 2026

United Kingdom:
Photon 2026
Newcastle University, Newcastle-upon-Tyne, 31 August – 3 September 2026

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EOSAM 2025 in Delft, the Netherlands

EOSAM was attended by 440 attendees, including top researchers, key leaders, students, and industry experts from over 30 countries worldwide. EOSAM 2025 was organized in collaboration with TU Delft. With 10 plenary sessions, 12 tutorials, 54 technical sessions, 82 posters, networking events, and an exhibition featuring 19 companies, the conference week was packed with opportunities to engage, gain valuable insights into the field of photonics, and share knowledge.

JOIN EOSAM 2026, 24-28 AUGUST IN TAMPERE, FINLAND

Save the date and join the EOSAM to connect, catch up, and network alongside the intriguing conference program. Join and explore the latest topics and emerging trends featured at the next EOSAM, held in Tampere, Finland, 24-28 August 2026. Submission opens at the end of 2025.

Journal of the EOS - Rapid Publications: Impressive new metrics

JEOS-RP Journal of the EOS European Optical Society

JEOS-RP is a valued and trusted publication among the optics community. EOS is delighted to see this reflected once again in both the 2025 Journal Citation Reports™ by Clarivate Analytics, and the Elsevier's CiteScore rankings. The Impact Factor is now 3.2, the immediacy index reaches 0.9, and the CiteScore increased to 3.6! These improvements are achieved without losing the fast publication times of JEOS-RP. Ready to publish in JEOS-RP? Find out more about the Journal: jeos.edpsciences.org

Explore Your Future in Photonics with CARLA Career Camps

CARLA career camps offer students a unique platform to discover the diverse opportunities within the field of photonics. Following EOSAM 2025, TU Delft hosted a dynamic two-day CARLA Camp that highlighted career paths in both industry and academia. Don't miss the chance to explore your future in photonics — join the upcoming CARLA Camp, organized by EOS with local partners, in Grenoble, 23-25 March 2026.

360 Carla Photonics Career Development Programs

Exploring the wonders of light: Institut d'Optique opens its doors for the "Fête de la Science"

In 2025, the Institut d'Optique organized two events for the first time as part of "Fête de la science*": one on its Paris-Saclay campus and the other on its Bordeaux campus. The Institut d'Optique thus reaffirms that sharing and disseminating science is at the heart of its mission.

Paris-Saclay Campus

On Saturday, October 4, and Sunday, October 5, the Institut d'Optique was pleased to welcome nearly 300 visitors to its Paris-Saclay campus.
These two days gave the general public the opportunity to visit the Laboratoire Charles Fabry and experiment with engineering students in workshops on human vision, optical communications, and lasers. Visitors also took part in games and interactive activities, created for the occasion, to better understand the amazing world of photonics.

Bordeaux Campus

From October 9 to October 11, the Institut d'Optique and ALPhANOV joined forces at Institut d'Optique d'Aquitaine to offer a comprehensive overview of the photonics sector to more than 340 visitors.
The first two days were dedicated to high school students, who were invited to discover the world of photonics in a hands-on way: immersion in laboratories and discussions with professionals about lasers, optical fibers, quantum physics... It was a great opportunity to illustrate the concepts taught in class in a practical way... and, who knows, perhaps inspire a few future careers!
On Saturday, the general public was invited to visit the LP2N and ALPhANOV laboratories, attend demonstrations, and participate in a conference led by Philippe Lalanne, physicist, on the famous Young's double-slit experiment.

These two events had a dual purpose: make the science of light accessible to everyone, and highlight the wide range of training opportunities, the diversity of careers, and the enthusiasm of an entire community committed to passing on their passion for photonics.

** French national event promoting science to all.*

THE STARLIGHT+ JOINT LABORATORY CELEBRATES ITS 10th ANNIVERSARY

Laboratoire Photonique, Numérique et Nanosciences (LP2N, CNRS/Institut d'Optique/Université de Bordeaux) and TOPTICA Photonics SAS celebrated the 10th anniversary of their joint laboratory, Starlight+, which was founded in 2014.

Specializing in fiber lasers and amplifiers, TOPTICA develops high-precision technologies for industry and quantum computers. Its lasers are based on rare-earth-doped fibers, offering power, stability, and low noise. To measure and further reduce the noise of its lasers, TOPTICA partnered with LP2N, whose complementary expertise was decisive.
Their collaboration, initially planned for three years, has been successfully extended for more than a decade. Their partnership has resulted in 25 publications, four CIFRE theses, and numerous awards. With the growing need for lasers for quantum computing, Starlight+ intends to continue this collaboration for at least another ten years!

Source : CNRS

In brief

Congratulations to Christophe Salomon, laureate of the 2025 Balzan Prize for his research on ultra-cold atoms, which led to the development of atomic clocks that revolutionized time measurement. Christophe Salomon is Director Emeritus of Research at the CNRS at the Kastler Brossel Laboratory. He is also a member of the French Academy of Sciences and Chairman of the Board of Directors of the Institut d'Optique.

AGENDA

- **Optics without calculations** December 02-04th
- **Optical Design with Zemax® / OpticStudio - Introduction** December 02-05th
- **Optical Design with Zemax® / OpticStudio - Advanced** Decmber 09-11th
- **Low-light vision and photon-counting imaging** December 15-18th
- **Basics of optics** March 11-13th
- **Optical manufacturing and optical metrology** March 17-20th and March 31 to April 04
- **Wavefront sensing** March 19-20th
- **Design of optical imaging systems** March 24-27th

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From Cochin to Troyes: Student Voices

From the southern part of India, students from the Cochin University of Science and Technology (CUSAT), have enrolled as exchange students at the Université de Technologie de Troyes (UTT), Troyes as part of the Memorandum of Understanding (MoU) between the universities. With exuberant attitudes and a passion for learning, these students have jointed the NANO-PHOT graduate school and are here to give it their all and explore the French culture.

"Our journey from Cochin to Troyes has given us a glimpse on the vast difference in the environments, enabling us to become autonomous, resilient and harmonious with other peers in a multi-cultured environment." says, one of the students from CUSAT.

CUSAT is one of the top leading universities in India offering structured courses on engineering, business, arts, and sciences, especially photonics. The students are equipped with skills on problem-solving, communication and collaboration and a deep theoretical knowledge on the basics regarding the subjects while maintaining a curiosity for the students to explore further.

The exchange students have relished their first taste in the French university. They believe that the lectures and training offered in the labs are valuable, as they help build confidence for their future careers in photonics. They also feel that coming to UTT was an excellent decision, as it has allowed them to surpass their own expectations.

National award for a researcher working in our graduate school

A specialist in optical sensors and two-dimensional materials, Shuwen Zeng explores the interactions between light and matter at scales invisible to the naked eye. From Singapore to Troyes, her research career combines physics, engineering, and new technologies. Now a CNRS research fellow at the L2n Lab, she designs ultra-sensitive sensors to detect minute traces of molecules, with potential applications in health, the environment, and security. Shuwen Zeng has just been awarded a bronze medal by the CNRS.

MID-TERM EVALUATION OF NANO-PHOT

An international jury has evaluated NANO-PHOT 5 years after its launch. The report is extremely positive, with pertinent and constructive recommendations.

This evaluation enables NANO-PHOT to take a decisive step forward: maintaining the funding and confidence of the Ministry within the framework of the national PIA program, and continuing the ambitious development of the graduate school. Thank you to all those involved at UTT and URCA, and especially to the students!

News

- 20 new master students from all over the world have joined NANO-PHOT and started their academic year in Sept. 2025
- NANO-PHOT has co-organized/sponsored the 27th General Meeting of the French Physical Society. https://cgsfp2025.sciencesconf.org/?forward-action=index&forward-controller=index&lang=en that took place at UTT on June 30-July 4, 2025. An exceptional congress with the participation of two Nobel Prize winners
- NANO-PHOT researchers and students have attended the META conference https://metaconferences.org/META25/index.php/META/index in July 2025 in Spain
- From October 8 to 12, 2025, during the science festival, more than 65 workshops led by 120 people were presented, including nano-sculpture supported by NANO-PHOT: https://www.fetedelascience.fr/nanosculptures

AGENDA

- **Prof. Alexander Govorov from Ohio University will visit UTT for 2 months from November 2025. He will be hosted by NANO-PHOT**
- **NANO-PHOT will participate and hold a booth at the Master trade show in Paris in January 2026. https://salon-masters-ms-et-mba-paris.salon.letudiant.fr/**

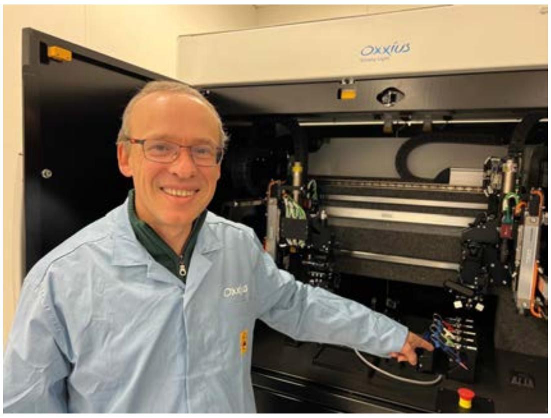
CONTACT

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

Monolithic Design Is Transforming the Laser Market

In this article, Jérémy Picot-Clémente, EPIC's Photonics Technologies Program Manager, talks to Thierry Georges, President and Technical Director at Oxxius, a French designer and manufacturer of advanced laser systems.

What are the advantages of your laser systems?



Since we were founded in 2002, we've developed a range of continuous and modulated monolithic diode pumped solid-state (DPSS) lasers that incorporate a proprietary monolithic resonator that integrates all critical optical components—such as the gain medium, frequency conversion crystals, and resonator mirrors—into a single, ultra-low-loss optical block.

The advantages of our lasers are that compared with conventional ion and gas lasers they eliminate the need for alignment. Additionally, they are more compact, more reliable, more stable, and more robust – making them ideal for a wide range of applications such as interferometry, Raman spectroscopy, and fluorescence microscopy.

What is your added value compared to your competitors in the DPSS laser market?

What sets our lasers apart from our competitors is the lifetime of our products. The typical lifetime of a DPSS laser is up to 40,000 hours. In comparison, the lifetime of our monolithic DPSS lasers is up to 100,000 hours - due to the robust monolithic design, no alignment-sensitive components and the use of long-life diode pumps and high-quality crystal bonding.

What are your main business challenges?

Our main customers are instrument makers, *e.g.*, microscopes and Raman spectrometers. The problem with these types of companies is that they make a new generation of products only every 5-8 years, and when they do, they have to decide whether to keep their existing laser supplier or look for a new one. Consequently, the window of opportunity to get new customers is only once every five or eight years.

How do you see the future?

Two years ago, we launched a fourth generation of product that allows the use of nonlinear crystals that are good for short wavelengths and high power. Having little or no limitations in either wavelength or power means we will be able to develop a lot of new products in the UV and blue wavelengths. So, over the next 4-5-years we expect to at least to triple our revenue and increase production of our laser systems from 1,500 to 5,000.

What's your main piece of advice to the next generation of entrepreneurs?

If you make a product or you have an idea, don't keep it in your lab, think about how you can turn it into a company. You may not be successful the first time, but you will learn a lot of things. In the recent past, failure was seen as very negative in France. But now, fortunately, you are allowed to fail. In the worst case scenario, you can go back to university or become an advisor to a company.

SAVE THE DATE

- **EPIC Technology Meeting on Microelectronics & Photonics – Two Sides of One Coin at attocube**
  17 November 2025. Munich, Germany
- **EPIC Technology Meeting on Cancer Pathology, Therapy and Surgery at Gustave Roussy**
  3-4 December 2025. Paris, France
- **EPIC Technology Session at OPTRO – Defense Photonics: Technology, Integration and Applications**
  4 February 2026. Marseille, France
- **EPIC Technology Meeting on Integrated Photonics and Packaging at PHIX**
  24-25 February 2026. Enschede, The Netherlands
- **EPIC Technology Meeting on Photonics for Defense: Securing the Future at Exosens**
  11-12 March 2026. Toulouse/Brive, France
- **EPIC AGM & SUMMIT 2026**
  28-30 April 2026. Juan Les Pins, Nice, France
- **EPIC Technology Meeting on Optical Fiber Sensors at Airbus**
  19-20 May 2026. Hamburg, Germany
- **EPIC Technology Meeting on Photonics for Quantum Technologies at Fraunhofer HHI**
  16-17 June 2026. Berlin, Germany
- **EPIC Technology Meeting on Photonics for AR: the Tipping Point at EssilorLuxottica**
  13-14 October 2026. Milan, Italy
- **EPIC Technology Meeting on New Developments for Laser Microprocessing at Amplitude**
  4-5 November 2026. Talence, France

NEW MEMBERS

Welcome to our new members:
Milexia France has been marketing high-tech scientific instruments since 1981. The company specializes in microscopy and analysis.
Polytech Paris-Saclay is the engineering school of the Université Paris-Saclay, It trains students in 4 specialties (Electronics, Computer Science, Materials and Photonics).
Ausmosys designs and manufactures high-precision mechatronic and robotic systems for advanced semiconductor tools, metrology platforms, and scientific instruments.
Iota Metrix develops non-destructive optical metrology solutions for surface and volume characterization with a resolution of less than 100 nm.
Themis Technologies is a manufacturer of special-purpose machines integrating various laser processes in all sectors of activity.
Join Photonics France and benefit from a wide range of services to help you develop your professional network and activities. It also means contributing to the strong representation of the French photonics industry in dealings with public authorities.

AGENDA

- **French Photonics Days**
  November 6-7 – Orsay
- **SPIE Photonics West**
  January 17-22 – San Francisco
- **Photonics France Annual Meeting**
  April tbc - Paris
- **SPIE Photonics Europe**
  April 12-16 – Strasbourg

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www.photonics-france.org

Photonics France annual meeting

Last September, Marc Ferracci, Minister of Industry, welcomed representatives from Photonics France to the Ministry of Economy. They were accompanied by Éric Bothorel, Member of Parliament for Côtes-d'Armor.

The discussion focused on French excellence in the field of photonics. Member companies of Photonics France raised the issue of the world's geopolitical situation that are hampering their international development. They requested the support for the Position Paper of Photonics 21 which proposes €2 Billion of funding for photonics technologies in the next Framework Programme (FP10) for Research and Technological Development (PCRD) created by the European Union.
Representative companies from the photonics sector were present: Safran, Thales, EssilorLuxottica, Exosens, HEF Groupe, Amplitude Laser, Bertin Technologies, Oxxius, Imagine Optic and Fiber Optics Group.

PHOTONICS BENEFITS
FROM SIGNIFICANT FUNDRAISING

Several recent photonics projects, including members of Photonics France, have just announced fundraising initiatives that demonstrate the excellence of the French industry.

French startup Scintil Photonics has raised €50 million with the support of NVIDIA. Originally from CEA-Leti in Grenoble, the company manufactures integrated photonic circuits on silicon. It plans to use this Series B funding to recruit in France and abroad and accelerate production of its "Leaf Light" laser source.
Cailabs, a global specialist in advanced photonics, has announced a €57 million financing round to strengthen its industrial development and international expansion. This round combines €37 million in financing from the European Investment Bank (EIB) and €20 million from various investment funds.
The STARLight project is based on a consortium of 24 technology companies and universities led by STMicroelectronics, representing 11 EU countries. The CEA, Thales, and ALMAE TECHNOLOGIES are part of the project. The goal is to make Europe a leader in the field of silicon photonics.

Photonics PhD Days:
Inspiring the Next Generation of Photonic Entrepreneurs

The 4th edition of the Photonics PhD Days took place in Lannion, co-organised by Photonics Bretagne, Anticipa Technopole, ENSSAT and the Foton Institute, from September 24th to 26th. This unique 3-day, English-speaking event gathered French and international PhD students to explore careers and entrepreneurship in photonics. Centred around our signature "PhD to Start-Up" workshop, the programme included conferences, PhD pitches, a poster session, one-to-one meetings with company founders and leaders, and visits to local actors such as IDIL Fibres Optiques, Kerdry – HEF Group, Orange Innovation, Foton Institute, and Photonics Bretagne. The event's goal was to awaken the entrepreneurial spirit of young researchers. Mission accomplished, as several participants are now considering launching a start-up! The 2025 edition once again offered everyone a wonderful and memorable experience, against the backdrop of the Breton coast and under a radiant sun.

Highlighting Photonics Innovation
at ECOC 2025 in Copenhagen

Photonics Bretagne was proud to attend ECOC, the European Conference on Optical Communication, in Copenhagen from September 28th to October 2nd. The event gathered the global optical communication community, and it was a pleasure to meet so many of our members on-site, including BKTEL PHOTONICS, Data-Pixel, Ekinops, Orange Lannion, Exail, Idea Optical, Wavetel, ALPhANOV, Tematys, and Le Verre Fluoré. Their strong presence at ECOC once again highlights the dynamism of the Breton and French photonics ecosystem. At our booth, visitors had the opportunity to discover our portfolio of specialty optical fibres, designed for the most advanced telecom and sensing applications. These include our anti-resonant fibre for low-latency transmission and power delivery, our hollow-core fibre optic cables for ultra-low latency data transmission, our bismuth-doped fibre for O-Band amplification, and our multi-core fibres (2, 7, or 12 cores) dedicated to sensing, telecom, and laser systems. Photonics Bretagne was also honoured to be invited as a speaker and panellist at the workshop "Is Hollow-Core Fibre Ready for 6G? – Technologies and Standards." This was a great opportunity to exchange ideas on the challenges and future perspectives of hollow-core fibres and cables in next-generation telecom networks.

OPEN DE L'INDUSTRIE:
CONFERENCE BY PHOTONICS BRETAGNE, MAUPERTUIS INSTITUTE, KERDRY

The Open de l'Industrie is THE annual event for Breton manufacturers and was held this year in Lannion. As a partner and exhibitor at the event, Photonics Bretagne also gave a presentation alongside the Maupertuis Institute and Kerdry – HEF Groupe on the many interesting opportunities that photonics technologies offer to all sectors of industry.

Cailabs Secures €57 M and Partners
with SES to Advance Optical Communications

Cailabs has raised €57 million to accelerate the industrial scale-up of its optical ground stations and expand globally. In parallel, Cailabs has partnered with SES, a leading space solutions company that wants to test Cailabs' optical ground stations to send data from space using laser beams instead of radio waves. Thanks to optical communication, SES will be able to boost data transmission speeds, provide more secure links, and help alleviate congestion in increasingly crowded radio frequency bands. Using its Multi-Plane Light Conversion technology, Cailabs is able to maintain a clear and powerful laser signal despite atmospheric turbulence. The partnership marks a major step forward for optical communications, which use light beams to transmit data at speeds of up to 10 gigabits per second—about 100 times faster than typical home internet. Unlike traditional radio signals, laser beams are nearly impossible to intercept or jam, making them ideal for secure government and business communications.

AGENDA

- **Up & Space**
  9 December, Lannion (France)
- **France Innovation Defence, Security & Aerospace Meetings**
  11 December, Online [Ask for your discount code]
- **Photonics West**
  17-22 January, San Francisco (United States)

Guiding and filtering crystallization of phase-change materials to program nanophotonic devices

Integrating designer nanostructures on a chip opens up unprecedented functionalities for microelectronics and photonics, for various applications ranging from lightspeed data communications and calculations to beam shaping and focusing with optical metasurfaces. Passive photonic integrated circuits now provide the full control of nearly all aspects of light at the nanoscale, and can now readily be included in complex microelectronic chips. Research on large-scale systems for optical datacoms, metalenses, and neuromorphic computing is now close to leaping industrialization but requires tunable building blocks. In that context, photonic integrated devices are progressively evolving beyond passive components into fully programmable systems, notably driven by the progress in chalcogenide phase-change materials (PCMs) for non-volatile reconfigurable nanophotonics. Recently, Sb_2S_3 emerged as an alternative PCMs with experimentally demonstrated large refractive index changes upon crystallization and ultra-low extinction coefficients from the visible range to infrared. However, the stochastic nature of their crystal grain formation and subsequent uncontrolled growth results in strong spatial and temporal crystalline inhomogeneities, leading to inefficient and lossy devices.

In this work, researchers propose the concept of spatially-controlled planar guided crystallization, a novel method for programming the crystal growth of optically homogeneous low-loss Sb_2S_3 PCM, leveraging the seeded directional and progressive crystallization within confined channels.

By strategically designing crystallization reservoirs and channels, the guided crystallization enables precise control over the temporal and spatial evolution of crystals on the chip, as well as their overall quality. This enables controlling where and when the PCM will crystallize on a chip and, under certain conditions, filtering the planar growth to produce quasi-monocrystals!

This guided crystallization method is experimentally shown to circumvent the current limitations of conventional PCM-based nanophotonics in two different devices: a programmable optical phase shifter and a reconfigurable metasurface. By patterning an Sb_2S_3 patch onto one arm of a Mach-Zehnder interferometer, ten distinct phase shifts were successfully programmed, leveraging the refractive index change of the PCM during crystallization, all while maintaining negligible optical absorption. Going beyond conventional phase-change modulation, the concept of in-plane guided growth of 'filtered' optically homogeneous Sb_2S_3 crystals was shown, analogous to a planar and spatially-controlled version of conventional single crystal production processes such as grain selection in directional solidification or the Czochralski growth. The ability to precisely control the phase transition of Sb_2S_3 between amorphous and optically homogeneous states was leveraged in reconfigurable metasurfaces, enabling a 100 nm spectral modulation of a bound state in the continuum (BIC) mode, while preserving the metasurface functionalities, including optical coherence across a large area of the device.

Precisely controlling the phase transformation of PCMs to ensure optically uniform crystalline properties across devices is a cornerstone for the industrial development of non-volatile reconfigurable photonic integrated circuits. These results establish a new platform for high precision and efficient programmable nanophotonic devices. ●

RÉFÉRENCE

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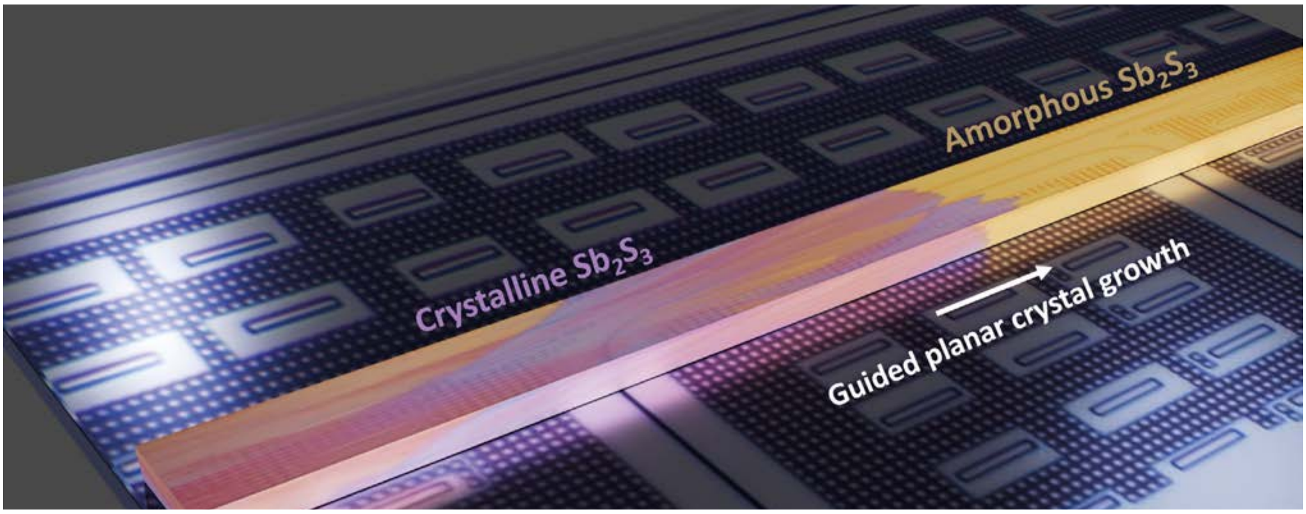

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Interview with Rachel Grange

Professor at ETH Zurich, expert in optical nanomaterials, nonlinear optics and integrated photonics.

https://doi.org/10.1051/photon/202513413

During your early years, when did science become meaningful to you?

I think back to that critical age between 12 and 15, when you are already asked to pick a high-school track. I chose Latin because I loved history and French, I read a lot. I didn't have a scientific heroine; my "heroes" were athletes, especially the Swiss-German skiers winning all the medals, and even a Swedish skier who was incredibly strong. I don't come from a scientific family, but I loved visiting my father's mechanical workshop, where he repaired trucks. That hands-on, practical side of things fascinated me. I already liked the idea of "doing" science.

How did you end up specializing in physics?

In high school there was a reinforced math and physics track, I took it. Physics was exciting but very abstract. A math teacher from high school showed us mathematics from a useful angle, such as probability, statistics, and conics, which convinced me that at EPFL, science would be concrete and useful. I chose physics more for the challenge than out of a calling. I considered moving to the German-speaking part of Switzerland, but adding a language barrier on top of the difficulty of physics felt like too much. So I chose EPFL in Lausanne, in the French-speaking region. I also liked chemistry and almost ended up there, but on the open day, after visiting the physics section, I stopped to chat at the café and never made it to chemistry!

How long was the training at EPFL?

It was still the diploma system, four and a half years. First, two propedeutic years, like an accelerated preparatory cycle; then two and a half years with more specialized courses, either theoretical or applied physics, and the diploma project. EPFL remained fairly generalist, which suited me. I took everything experimental and avoided overly abstract classes.

Where do optics and materials come in?

We often start with optics in high school, sometimes even before mechanics. At EPFL I wanted something practical, so a teaching assistant helped me get into a lab where I worked on some of the first multicore fibers, measuring their polarization. That's when optics really took hold for me, and it never left. I also hesitated about nuclear physics. The campus has a mini-reactor for lab classes, and seeing fuel rods up close is impressive. The broader energy debate convinced me we needed good physicists to avoid disasters.

How did the move to Zurich for your PhD happen?

I graduated at the end of 2001, with the formal certificate in February 2002, wanted to do a PhD, and thought learning German would help a career in Switzerland. I applied to Ursula Keller's group because I liked the topic and because she was a woman leading the lab, something I had never experienced. My PhD focused on semiconductor saturable absorber mirrors (SESAMs). I didn't grow the materials, colleagues did the epitaxy, but I handled the design, clean-room processing, and linear and nonlinear optical characterization. The group pursued record-setting lasers at telecom wavelengths and titanium-sapphire. I built and ran the setups to measure recovery time and saturation fluence for passive mode-locking, a SESAM replacing a mirror with a Bragg stack plus absorber. I started in March 2002 and defended in March 2006.

What were your expectations after your PhD defense?

I had poured so much into the lab that I needed to step back. Despite good conditions, I was burned out and had never dreamed of becoming a professor. My husband was finishing his medical specialty, and I didn't want to leave Switzerland at that time. I looked for a job in industry, but the telecom sector was in crisis, and my applications didn't pan out. I even tried the patent office. I then joined the Swiss State Secretariat for Education and Research, working a year and a half on research policy and OECD indicators. It was interesting, but I missed the lab within six months.

What brought you back to the lab?

Colleagues told me that Demetri Psaltis had moved from Caltech to EPFL as dean. I thought, "Caltech comes to me," and it seemed the perfect opportunity to work in an international group without moving to the US. That is why I joined his lab as a postdoc in nonlinear optics and microfluidics. It was a great topic after my PhD because it bridged laser-building and laser-enabled applications. We set up new labs with equipment arriving from Caltech, bought an optical table, restarted old titanium-sapphire lasers. A small team of three to four people worked very efficiently. I stayed about three years, around 2007 to 2010, and two children were born during that time. I had always received a great support from my supervisor. The • • •

research topic was a niche field but we managed to publish solid work, though not "super high-impact."

What was the next step to build on this successful position?

I applied to many positions in Europe and I got 2+2-year fellowship in Jena that had exactly the infrastructure I needed: two large optical tables, the right laser, and clean rooms, so I could invest in people. I carried out research in nonlinear nanophotonics, frequency conversion, and microfluidic integration for on-chip analysis. Our third child, my daughter, was born in 2012 in Weimar. The lab was very well equipped, and the four years went by quickly.

How did you transition to ETH Zurich?

I obtained an SNSF Professor position at ETH, a four-year, non-tenure-track appointment, hosted by Jérôme Faist. After three years, the department opened a women-only call, and three of us were hired on tenure track in 2018. I was fast-tracked, became associate professor in 2021, and full professor in August 2025.

What was your research program at ETH?

Scientifically, I remained focused on nonlinear materials and moved into thin-film lithium niobate, TFLN. Early films, homemade in Jena, would break, so I sonicated damaged chips to make nanowires and nanoparticles for nonlinear optics. Back in Zurich, in 2015, we first tried to fabricate films ourselves, and then obtained commercial films around 2016. The obvious first demo on TFLN is the electro-optic modulator based on a Bragg design to add a twist to the typical Mach-Zehnder ones. ETH's critical mass of researchers matters a lot: other labs had 100-GHz test benches with unique, very high-end setups. That ecosystem is essential for a young group to ramp up.

What are your main research lines today?

I tend to run two main axes and let good ideas in as long as they touch χ(2) nonlinear materials. That is my core and it keeps the group curious and agile rather than locked into a single track. The first track is a very applied, fabrication-intensive axis: integrated photonics on TFLN, that spans from classical electro-optic modulators to integrated quantum photonic devices with many options of technology transfer into start-ups. The second is a more fundamental axis, nonlinear nanophotonics including scattering in disordered nonlinear media, lighter on fabrication but rich in physics. ETH's base funding let us sustain both. And I have always enjoyed writing grants, it is my creative moment, building the architecture, blending ambitious and safer goals, distributing roles, setting milestones. Experimental discovery is wonderful, but the making of a research idea is also very stimulating.

How are those axes organized in practice?

Integrated photonics on χ(2) materials mainly relies on state-of-the-art nanofabrication, to achieve on-chip periodic poling and electro-optic modulation. We work with monolithic integration rather than hybridizing with other materials, at least for now. Target applications are telecom, classical and quantum optics. The platform is transparent from the visible to the mid-IR, which let us go far beyond 1.55 µm. This is all top-down in-house fabrication in our cleanrooms. I recruit PhD students who are willing to dedicate time in the cleanroom to fabricate for themselves and others. We do not keep know-how with one technician. We pass it peer to peer, from senior PhDs to newcomers, which naturally forms a 4 to 5 person subteam that handles training and handover of process flows.

Second, for the bottom-up approach, we do not synthesize nanoparticles and we have a long-running informal collaboration with a team in Italy. Those χ(2) particles allowed us to study absolute nonlinear responses in complex media, which is unusual because films and random assembly often hide geometry and volume effects. We are also working on solution processing of nonlinear materials suitable for integrated photonics, which represents a convergence of our two research areas.

How do you achieve absolute measurements in scattering media?

We wanted to control the probed volume and the structure, not just average over an uncertain film. Classical drop-cast layers suffer from coffee-ring and thickness uncertainty. We therefore built self-assembled microspheres from the particles, measured their volume by electron microscopy, and even made cross-sections to estimate filling fraction and porosity. With precise volume and geometry, we could model the signals and, demonstrate random quasi-phase matching.

I am proud that we pursued absolute nonlinear measurements under femtosecond pumping and then matched them to models we developed in-house when no one wanted to do the theory. There was skepticism from colleagues trained on bulk crystals who expected random media to wash things out. Getting the numbers right was a long, careful process, but it convinced people.

How did this expertise in nonlinear optics feed back into integrated photonics?

In integrated photonics I initially wanted to stay with electro-optics only, not frequency conversion. One PhD student kept pushing for periodic poling. I resisted, thinking there were groups with decades of head start. This PhD student convinced me eventually and we developed a poling setup. It took about three years to make the process robust. After that, conversion efficiencies were strong, CW operation became natural, and we achieved spontaneous parametric down conversion (SPDC) on-chip. In parallel we built the quantum benches, which also took two to three years to reach the level we wanted. Such a sensitive setup with low temperature detector in the near infrared allowed us to explore SPDC from III-V nanowires, whose nonlinear tensors are roughly one order of magnitude larger than $LiNbO_3$. A single nanowire a few microns long and a couple of hundred nanometers wide can already generate a high rate of entangled photons, which is conceptually very appealing.

$LiNbO_3$ remains the best suited material for frequency conversion. It is not deposited as single crystal by pulse laser deposition (PLD) or epitaxy, so we purchase TFLN wafers and then do top-down processing. $BaTiO_3$ is attractive for electro-optics and can be deposited or grown more easily, though for frequency conversion $LiNbO_3$ is clearly ahead.

You have strong expertise in $LiNbO_3$ and $BaTiO_3$, how do they compare for your projects?

$LiNbO_3$ remains the best suited material for frequency conversion. It is not deposited as single crystal by pulse laser deposition (PLD) or epitaxy, so we purchase TFLN wafers and then do top-down processing. $BaTiO_3$ is attractive for electro-optics and can be deposited or grown more easily, though for frequency conversion $LiNbO_3$ is clearly ahead. Rather than trying to beat performance records in this very competitive environment, we often differentiate our research by original design and features. For instance, we pushed Bragg modulators rather than only standard Mach-Zehnder layouts. Another recent development of those materials in my team, is their synthesis as solution processed films that can be easily nanoimprinted without the needs of complicated etching process. We just demonstrated metasurfaces and metalenses with frequency conversion and electro-optic effects.

Do you impulse collaborations with industry?

When we were temporarily unable to apply to certain European calls from Switzerland, I deliberately diversified funding with industry-funded PhDs, always under conditions that protect the student's ability to publish, speak at conferences and finish a thesis. A good illustration of this partnership starts when a start-up wanted a compact, no-moving-parts spectrometer for space payloads, since bulk optical spectrometers are heavy. We developed an electro-optic on-chip broadband spectrometer. The original idea was theirs, but we did the full device and characterization.

After the ETH News website offered us a space to highlight our research, on nonlinear metasurfaces, several companies reached out. One possible collaboration is related to solar energy where metasurfaces could concentrate light onto small, very efficient cells to power small devices.

How do you position your group in the quantum optics landscape?

We build enabling technology for quantum sciences. Miniaturization is the challenge: integrated sources from nonlinear media for entangled-photon generation, combined with superconducting detectors, with demanding high-speed and cryogenics performances. I do not believe there will be a single winning platform. Silicon, $LiNbO_3$, $BaTiO_3$, III-V each have a their advantages. Some companies are raising hundreds of millions round of financing. We will not compete on scale and record performance. Nevertheless, we may contribute original designs, clean proofs of concept, and robust building blocks.

How do you handle tech transfer and spin-offs from the lab?

I try to support young founders from my team by providing the infrastructure they need to incubate deeptech projects for one to two years, helping to remove pressure from them. If their first attempt doesn't succeed, they can pivot to something new and still benefit from the knowledge and experience they have gained. We currently have three startups in motion, including Versics, founded in 2022, which develops telecom modulators in the 60 to 110 GHz range. I am a co-founder, but I focus on scientific support and infrastructure. I leave business execution to those who want to live it every day. ●

Interview with Rainer Erdmann,

Co-founder and CEO of PicoQuant

https://doi.org/10.1051/photon/202513116

Can you describe your scientific background?

It goes back more than 36 years. I grew up in East Germany and studied physics at Humboldt University in Berlin. While I was working on my diploma thesis, the reunification happened, which completely changed academic life as well as everything else.

At first, I intended to work after my studies in biomechanics supporting professional athletes. But due to the political changes, I eventually switched to the Academy of Sciences, where I began working on single-photon counting techniques and related fluorescence topics in DNA sequencing, which were still very new at the time. My professor was highly enthusiastic and managed to attract a few students to this topic despite the usual competition between universities and research institutes.

How did you create PicoQuant?

For almost five years, I had to survive under extremely difficult financial conditions out of passion for the subject. I worked without a contract, relying on short-term mini-grants from a non-profit association. Later, I joined a company that aimed to develop time-resolved fluorescence products, but it had barely any sales and eventually couldn't pay salaries for several months. Everything took place on the Adlershof campus, and we collaborated with strong groups in Heidelberg, Göttingen and key PIs in the US (e.g. Joe Lakowicz, Dick Keller, W. E. Moerner – later a Nobel laureate) and gained a lot of experience and knowledge about the needs of these labs but stability was very hard to achieve. However, we believed in our ideas the whole time, and finally I founded our own company together with three former colleagues in August 1996. We wanted to make complex instrumentation more accessible to researchers. That was the beginning of PicoQuant.

What were your objectives and motivations when creating the company?

Our first major R&D contract developing a UV microscopic detection system came in December of that year with the University of Jena. Our very first serial product was a picosecond pulsed compact laser at 670 nm. Within half a year, we were selling these units, which helped immediately many researchers substituting their large dye or TiSa lasers. We had our first profitable fiscal year in 1997. In mid of 1997, we received our first BMBF start-up grant supporting the professional development of a wider spectrum of pulsed diode, including wavelengths around 405nm.

Later, we also developed our own time-correlated single photon counting electronics, which simplified together with the diode laser experiments that previously required large, complex setups. By 1999, we had a complete set of components enabling turnkey experiments. This was the basis to expand our portfolio also to complete fluorescence systems. In 1999 we installed our first time-resolved fluorescence spectrometer at the Université Catholique de Louvain (Leuven, Belgium).

In late 2002, we installed our MicroTime 200 - a single molecule sensitive confocal microscope at the Chinese Academy of Science in Beijing. Around 2005, we began collaborating closely with Stefan Hell, providing customized depletion lasers that contributed to his STED microscopy. That collaboration eventually brought us close to the Nobel Prize story of 2014, where I was even invited to the Nobel ceremony.

How has the company grown over the years?

We started with four people in 1996. Today, we are about 120. On average, we have grown by four employees per year—steady, organic growth, not a sudden expansion. We never relied on external venture capital. Growth has always been financed by our own profits. That makes us very different from startups that expand too fast and then collapse.

How did PicoQuant expand from lasers to photon counting and systems?

We have always described our products as generic tools. Our picosecond lasers can be used in many areas: life sciences, material sciences, quantum, communications, lidar, biomedical imaging, and more. Likewise, our timing electronics became a reference worldwide. A majority of labs doing TCSPC now use our products and almost every synchrotron benefits from our precise timing electronics monitoring 24/7 important beam parameters. Our HydraHarp 400, for example, was the first scientific device that used USB 3.0 for high data throughput. Then we expanded into systems, mainly focused on life sciences and fluorescence applications. Today, the system-related products generate the largest part of PicoQuant´s turnover. But every system includes lasers and timing electronics which allows us a nice vertical integration and to customize our systems to the special needs of the research labs. We have about 30 PhDs, not only working in R& D with many dedicated to application support, sales, customer training, and joint experiments with users. In recent years, we also entered material science, applying our tools to solar cells, LEDs, micro-displays, and other advanced materials.

How did you manage to combine such different areas of expertises ranging from electronics to life science within your team?

From the very beginning, we recruited people with both technical expertise and scientific experience. Many of them had just finished their PhD and wanted to bring their knowledge from academia into industry. Over the years, we built a very multidisciplinary team: physicists, electrical & mechanical engineers, chemists, biologists, and software developers.

It's true that electronics and optics require very different skills, but our culture has always been based on collaboration and listening to customers. That helped us create a coherent company spirit and deliver complete solutions rather than isolated components.

How balanced are your activities between lasers, electronics, and systems?

Since the early 2000s, we have maintained a good balance between the three. I often compare it to a table with three legs: it may not be perfectly flat, but it is stable. Some years lasers perform better, some years systems, some years electronics. This diversification has been the key to our stability.

Geographically, our sales are also balanced: roughly one-third in Europe, one-third in the US, and one-third in Asia. That gives us resilience against changes in funding or politics in any one region.

One specific feature of your company is its annual scientific workshop. Why is this so important?

The workshops are part of PicoQuant's DNA. Already in 1995, before the company existed, we organized the first meeting on single molecules with about 50 participants. Here I want to give big kudos to my long-term friend Prof. Joerg Enderlein, now a professor in Göttingen who had very early the strong vision about the importance of single molecule research in the future. He continuously motivated us and we continued with the workshops because the feedback was so positive.

Today, our annual Single Molecule Workshop is the leading international event in this field and we just celebrated our 30th anniversary with 250 participants last month. It is not a commercial conference but a genuine scientific meeting. For us, it's a way to stay connected to the community, to get inspiration, and to give something back to our users. It is also a place where many of our collaborations and product ideas were born.

Who are your main customers: academia or industry?

About 85% of our applications are academic. We sell to many universities and research institutes worldwide. Some large companies, like Nikon or Zeiss, buy our modules to upgrade their microscopes, but in the end the users • • •

are academic researchers. Industry accounts for less than 15% of our business, often in internal R&D labs. Many of them are major technology companies, but due to confidentiality we cannot disclose names.

Which scientific domains are the most important for PicoQuant today?
Life sciences were central from the beginning, even before the term biophotonics existed. Our first instruments were designed to study fluorescent molecules and biological tissue. Materials science has grown strongly in the last decade with the soar of solar cells, displays and semiconductors. Quantum technologies are also important: our lasers and timing electronics are used for single-photon source characterization, quantum communication, and quantum optics experiments. I would roughly say: 40% life sciences, 40% material science, 15% quantum, and 5% metrology.

How have you dealt with the rise of quantum technologies?
As mentioned PicoQuant is mainly engaged in the field of enabling technologies for the quantum market. Since our lasers and time tagging electronics are not tied to a certain application, it very often only needs small modifications to make these products even more attractive to other user groups. To achieve this, we are in close contact with the community to include their needs into the next generation of our products or in the addition of specialized features for this user group. One very successful example is the development of a dedicated software interface “snAPI” as well as a specialized GUI for our time taggers because the needs as well as the language in this field is different compared with life science applications.

How do you organize the R&D activities?
Before we start an R&D project, we naturally need very good ideas. We draw these ideas from many sources and try to use a good mix of technology push and market pull. The wealth of experience of our employees is particularly helpful in this regard, but the feedback from our users, discussions at conferences and our workshops, and a regular review of specialist literature are also very important. A third source is cooperation projects with leading international and national research institutions. Of course, we cannot implement everything, so we use a software tool in which all ideas are discussed, moderated and evaluated. Our experts then examine particularly risky aspects in preliminary projects to assess their feasibility before the actual development projects begin. We achieve the best results in these projects when the teams are highly interdisciplinary, and we also obtain feedback from key opinion leaders during the prototype phase.

Is Berlin a great city to establish a company in optics and photonics?
Definitely. Berlin is one of the top campuses worldwide, with strong universities and research institutes. It’s also a very attractive city for young people, which helps us recruit talented scientists and engineers.

What challenges do you face today?
Tariffs and trade barriers are currently a burden, especially with the US market, which represents one-third of our business. We try to absorb some of the costs ourselves and share the rest with our partners and customers. More generally, forecasting for the future has become difficult in recent years. But we continue to invest in new microscopes, new lasers, and new timing electronics. Life sciences and materials will remain strong; quantum is more uncertain, especially quantum computing, where we have decided not to engage in system-level projects but rather in the enabling technology sector with our laser and time-tagging solution.

Looking back over the last 30 years, what do you consider your greatest achievements?
On a personal level, being part of the Nobel Prize story in 2014, even with a tiny contribution, was very emotional. On a company level, I would say our greatest achievement is having created a stable, independent company that has lasted almost 30 years, supporting science worldwide. I am no longer the main technical expert, but my role is to support our 120 people, give them resources, and make sure PicoQuant will still be here in 20 years. Above all, I am proud that we have stayed true to our long-term vision: remaining independent, fostering our scientific spirit, and supporting the community by making complex instrumentation more accessible for a broader field of researchers.

How do you see the future of photonics?
Photonics will remain a fantastic field to investigate. There are so many opportunities: from quantum technologies to new materials, from advanced displays to medical diagnostics. For young researchers, I can only say: it’s a great opportunity to build a career in optics and photonics because light will remain central to solving key challenges in society. ●

PHOTONICS – A KEY ENABLING TECHNOLOGY IN THE QUANTUM WORLD

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

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

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

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

▼ A small form vapor cell from Hamamatsu

HAMAMATSU PHOTONICS: A TRUSTED PARTNER IN QUANTUM TECHNOLOGIES

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

VAPOR CELL TECHNOLOGY: A FLAGSHIP INNOVATION

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

These vapor cells, when integrated with light sources, detectors, optics, and electronics, become the core of quantum sensors. A notable example is Hamamatsu's optically pumped magnetometer (OPM), unveiled at Photonics West 2025 [2]. This compact sensor

▲ OPM detection heads for MEG application

(under 8.5 cm^3) achieves a magnetic field sensitivity of 20 fT/√Hz, making it well-suited for biomedical functional imaging [3].

A BROADER QUANTUM PORTFOLIO

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

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

LET'S COLLABORATE

Our engineers welcome one-on-one discussions about quantum innovations and custom solutions. To explore collaboration or learn more, reach out at info@hamamatsu.eu.

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OPTICAL COHERENCE TOMOGRAPHY

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Optical coherence tomography (OCT) has become a critical imaging tool in medicine owing to its non-invasive imaging capability of tissues with micrometer-level details. From its initial experiments in the 1980s to now, the adoption of OCT has been facilitated not only by scientific innovations but also advances in fiber optic telecommunications and photonics, as well as industry and government support. This review highlights key milestones that have contributed to the clinical adoption of OCT, as well as current and future trends.

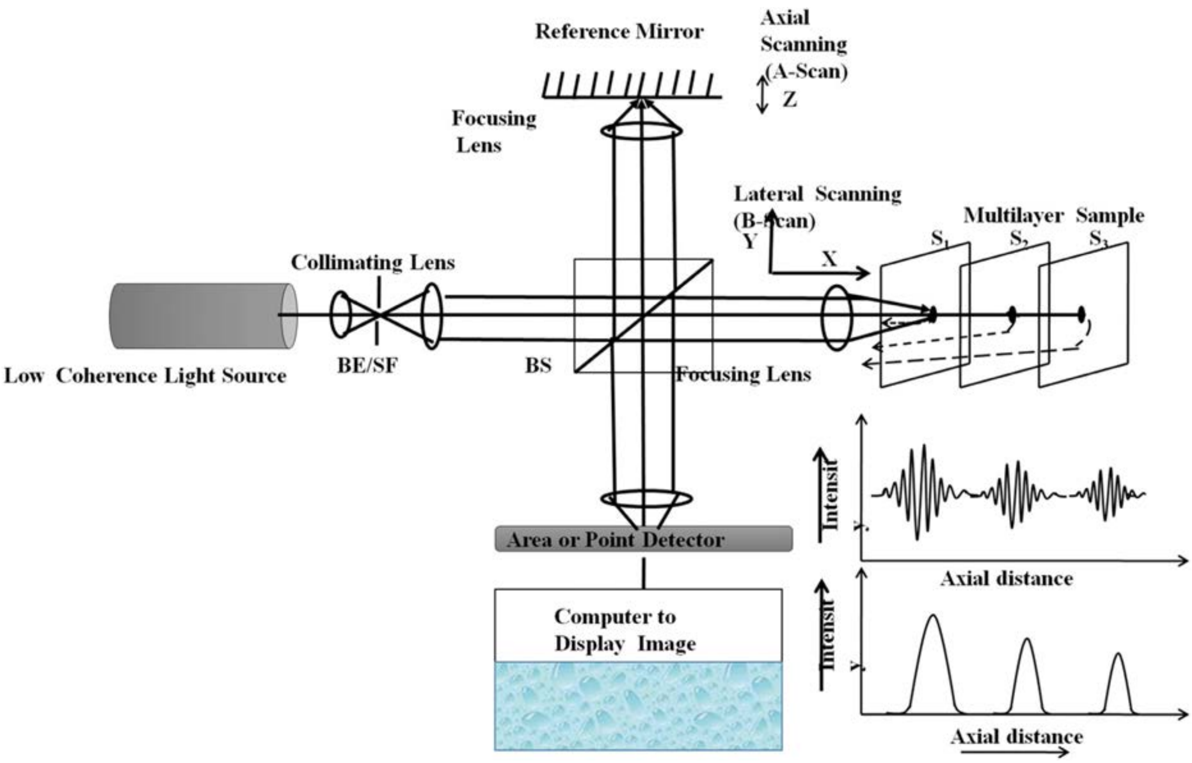
Optical coherence tomography (OCT) represents one of the major imaging technological breakthroughs of our century, owing to its capabilities to noninvasively enable three dimensional (3D) visualization of tissues in living specimens with cellular-level resolution [1]. OCT has become the standard of care in ophthalmology and has been a critical tool for understanding disease mechanism, facilitating their diagnosis, and monitoring their treatment, particularly for blinding diseases such as diabetic retinopathy, age-related macular degeneration (AMD), and glaucoma, affecting hundreds of millions of people worldwide. OCT has also emerged as a critical clinical tool in cardiology, dermatology, endoscopy, gastroenterology, and beyond.

The principle of OCT is analogous to ultrasound imaging, measuring the time of flight of echoes reflecting from different layers of tissues to infer the depth localization of the layers. Owing to the greater speed of light waves compared with ultrasound waves, OCT leverages the unique sensitivity of interferometry techniques to achieve such measurements. Interferometry can be traced back to Thomas Young's double-slit experiment in the 1800s, where two light waves from the same source, passing through two distinct slits, can be recombined coherently. The resulting wave has a maximum energy (i.e., constructive interference) when the difference in distances travelled (i.e., the optical path difference) by the two waves is a multiple of the wavelength (i.e., the waves are in phase) and a lower energy (i.e., destructive interference) when the optical path difference between the two waves is an odd multiple of half the wavelength (i.e., the waves are out of phase). By analysing the repeated pattern (i.e., fringes) of the interference signal, one can inform the distance travelled by one wave relative to the other, with an accuracy below the wavelength of light. The same principle is applied to different variations of interferometry techniques and OCT, with one light path serving as the reference arm and the other path serving as the sample arm.

While several scientific experiments, including Albert Michelson's interferometry in the 1880s and low-coherence interferometry (LCI) by Sir Isaac Newton in the 1980s, have contributed to the working principle of OCT, pioneering experiments carried out by Professor Adolf Fercher's group at The Institute of Medical Physics (IMP), Medical University of Vienna and Professor James Fujimoto's group at Massachusetts Institute of Technology (MIT) were instrumental to the commercial development and clinical utility of OCT. Professor Fercher's group demonstrated the first measurement of the axial length of a living human eye using LCI in 1986 [2], enabling the development of the first commercial ocular biometry system for measuring intraocular distances, which has been critical for the management of cataract. On the other hand, Professor Fujimoto's team advanced the development of femtosecond lasers in medicine, leading to the first demonstration of OCT for imaging the eye in 1991 [1] and the launching of the first commercial OCT system by Zeiss in 1996. Among several prizes, the two teams were jointly awarded the 2017 Russ Prize by the United States National Academy of Engineering for their invention of OCT and its tremendous impact in clinical care, and especially in ophthalmology (Figure 1).

PRINCIPLE OF LOW COHERENCE INTERFEROMETRY AND OPTICAL COHERENCE TOMOGRAPHY

The principle of low coherence interferometry (LCI), from which OCT derives, leverages the fact that for a broadband source with multiple wavelengths, light reflecting from a given layer of the sample interferes constructively (i.e., maximum energy) with light reflecting from the reference mirror at all the wavelengths only when the location of the layer exactly matches that of the reference mirror, forming a strong peak (i.e., the sum of energies at all wavelengths). For any other layers of the sample, the mismatch with the reference mirror causes all the wavelengths to be out of phase with each other, thereby interfering destructively (i.e., cancelling out their energies). The reflectivity profile therefore has a single peak corresponding to the location of the layer. The broader the source, the more define the location of the layer, which characterizes the axial resolution of the OCT system. The same process can be repeated for individual layers of the sample by scanning the location of the reference mirror to match that of individual layers of the sample, as illustrated below.



Principle of Optical Coherence Tomography. Courtesy of Prof. D.S. Metha.

Figure 1. The 2017 Russ Prize honoring the teams of Professors Fujimoto from the Massachusetts Institute of Technology (MIT) and Fercher from the Institute of Medical Physics (IMP), Medical University of Vienna, for their pioneering experiments in OCT. Adapted with permission from The National Academy of Engineering.

Over the three decades that followed, several technologic breakthroughs have significantly contributed to the clinical utility of OCT and its broader adoption in a multitude of medical fields.

Major milestones in the development of OCT

OCT has evolved from its initial inception using the time delay between the reference arm and the sample arm, known as time-domain OCT (TD-OCT), to its advanced approach known as Fourier-domain OCT (FD-OCT) in which the interference between light reflecting from all layers of the sample and the reference arm can be registered separately for individual wavelengths. By combining this information from all wavelengths of the source and performing the Fourier analysis of the spectrum, one can decode the reflectivity strength of individual layers, defined as amplitude scan (A-scan), thereby forming the basis for the 3D image reconstruction in FD-OCT. This concept was first introduced by Fercher *et al.* in 1995 [3] and was later developed into two approaches: the first approach, termed spectral-domain OCT (SD-OCT), using a line-camera to simultaneously register all wavelengths of the source (i.e., the interference spectrum) [4]; and the second approach, termed sweep-source OCT (SS-OCT), in which individual wavelengths are registered sequentially using a point detector and the full interference spectrum is achieved by sweeping across individual wavelengths of the source [5]. It is worth noting that the clinical adoption of TD-OCT systems was challenging (Zeiss, who was the first company to commercialize OCT systems almost abandoned this market segment) until the advantageous imaging sensitivity and speed of FD-OCT over the state-of-the-art TD-OCT was demonstrated by Leitgeb *et al.* in 2003 [6], marking a paradigm shift in the field of OCT and contributing to its broader adoption in clinical care. It is also worth mentioning that while SD-OCT has enabled the finest depth sectioning of tissue by broadening the light source, SS-OCT has enabled the deepest penetration in tissues owing to its primary range of operation within the longer wavelengths as well as the fastest time-delayed based point recording of the interference spectrum. Also, the advanced version of TD-OCT known as full-field OCT (FF-OCT) has enabled the fastest enface visualization of different layers of tissues with a transverse resolution close to that of confocal microscopy.

Figure 2. Comparison between TD-OCT, SD-OCT, and SS-OCT. Adapted with permission from [1]; Rothenbuehler, S. P., Malmqvist, L., Belmouhand, M., Bjerager, J., Maloca, P. M., Larsen, M., & Hamann, S., Comparison of spectral-domain OCT versus swept-source OCT for the detection of deep optic disc Drusen. Diagnostics, 12(10), 2515 (2022); and Nathans, J., Seeing is believing: The development of optical coherence tomography. *Proceedings of the National Academy of Sciences*, 120(39), e2311129120 (2023).

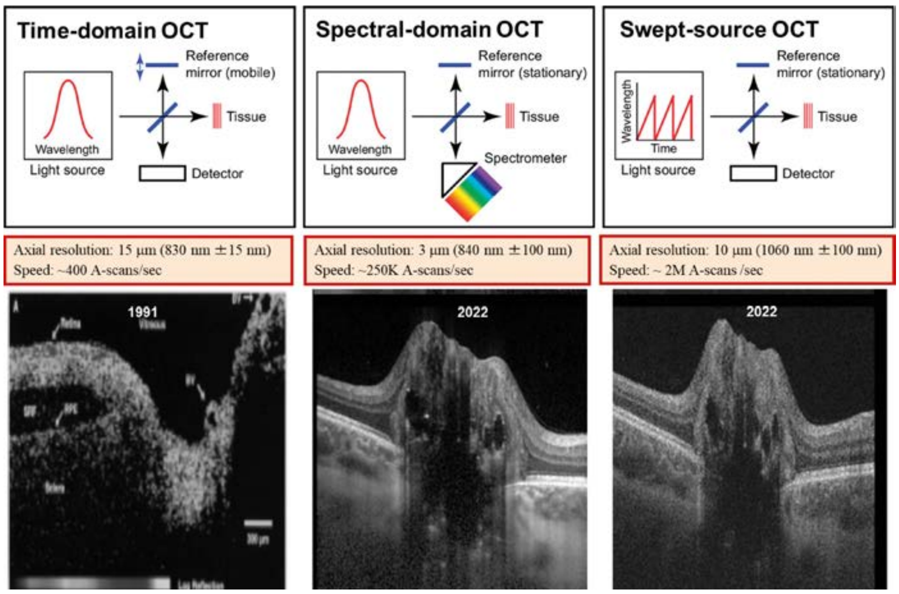


Figure 2 presents the three main configurations of OCT along with illustrations of their imaging capabilities.
Another major milestone in OCT was the introduction of OCT angiography (OCTA) for non-invasive assessment of vasculature in living tissues, which was up to then performed with the traditional invasive fluorescein angiography. While blood flow evaluation was first demonstrated using Doppler TD-OCT, the advanced imaging speed of FD-OCT had made possible fast volumetric imaging of tissues with repeated scans, enabling enface visualization of the vasculature network in the eye and brain [7]. This milestone provided another paradigm shift in the clinical utility of OCT, adding functional imaging capabilities to the structural OCT imaging modality, and enabling to assess disease progression and response to treatments such as anti-vascular endothelial growth factor (anti-VEGF) in a multitude of vascular retinal diseases, including diabetes retinopathy, age-related macular degeneration, and glaucoma.

Contribution of advanced technologies to OCT development

From TD-OCT to SD-OCT and SS-OCT, OCT owes its rapid development and adoption, not only to scientific innovations, but more importantly to advances in technologies such as fiber optic telecommunication, and photonics, including broadband sources, fast tunable sources, and sensitive detectors.

1. The development of single-mode fibers in the 1980s has enabled OCT systems to move from free-space interferometers using bulk optical components to fiber-based interferometers, yielding compact and stable imaging systems while also opening new opportunities for OCT integration into catheters and endoscopes.
2. OCT systems initially relied on ultrafast femtosecond lasers to achieve high axial resolution imaging, making OCT systems expensive and less user-friendly as femtosecond lasers are challenging to operate and maintain. The development of robust broadband superluminescent diode (SLD) light sources has enabled more compact and cost-effective systems, thereby facilitating the broader adoption and clinical utility of OCT.
3. The development of Fourier domain mode locking technologies for tuning SS-OCT sources as well as microelectromechanical systems vertical-cavity surface emitting laser (MEMS-VCSEL) have enabled SS-OCT to reach a multi-megahertz A-scans/sec speed, significantly boosting the development of intraoperative OCT and OCTA and their clinical utility.
4. While initial OCT systems relied on Silicon (Si) based charged couple device (CCD) detectors with limited sensitivity at longer wavelengths, the development and adoption of Indium Gallium Arsenide (InGaAs) based complementary metal-oxide-semiconductor (CMOS) detectors with higher sensitivity at longer wavelengths has enabled the expansion of OCT in imaging highly scattering tissues with improved light penetration and imaging depth.

Clinical Applications of OCT

OCT was initially developed using sources in the optical or first near-infrared (NIR-I) window (~650 – 900 nm) to primarily image the eye, owing to the almost transparent nature of eye tissues within that wavelength range, and making ophthalmology the primary field of application of OCT. OCT has become the standard of care in treating a multitude of eye disease conditions such as diabetic retinopathy, age-related macular degeneration (AMD), and glaucoma. OCT is also used for detecting and monitoring glaucoma progression by evaluating retinal nerve fiber layer thinning and optic nerve damage. In AMD in particular, OCT has played a major role in monitoring the progression and treatment response to intravitreal anti-VEGF therapy. However, highly scattering tissues such as skin were challenging to image owing to the limited penetration of light beyond a couple hundred of micrometers. The later development of broadband sources in the second near-infrared (NIR-II) window (~1000 – 1700 nm), enabling lower tissue scattering and deeper light penetration in highly scattering tissues, together with advanced technologic development in fiber optic telecommunication and photonics, has facilitated the adoption of OCT in other biomedical fields such as dermatology, dentistry, and beyond. Additionally, the integration of OCT into endoscopes and catheter probes has also opened new era of opportunities in endoscopy, cardiology, gastroenterology, urology, and neurology.

Current trends and outlook

Despite the rapid development and adoption of OCT in the past few decades, the technology still holds great potentials with further improvements not only in hardware and software, but also in clinical utilities through multidisciplinary collaborations of engineers, scientists, clinicians, and entrepreneurs. Hardware's improvements will be driven by new integrated technologies and photonics including broader and faster SS-OCT sources, faster and more sensitive detectors, to cite a few. The ongoing integration and adoption of machine learning and artificial intelligence (AI) into the OCT imaging pipeline, especially for processing and analysing data, will dominate the software sector, which will significantly enhance the clinical utility of OCT, allowing to detect diseases in the early stage, improving the diagnosis accuracy, and assisting with automated and real-time diagnostic and decision-making. Other ongoing efforts in OCT development are the integration of more functional imaging capabilities into OCT systems, including OCT elastography for biomechanical evaluation of tissues, polarization-sensitive OCT for evaluating the birefringence of tissues in normal and diseased conditions, OCT optoretinography for assessing light-evoked change in scattering properties and response of photoreceptors, dynamic OCT to enable label-free evaluation of cellular motility, to cite a few. Finally, the development of cost-effective miniaturized and portable OCT systems, including on-a-chip and smartphone-based OCT systems could boost the adoption of home- or community-based OCT systems,facilitating clinical care access to underserved rural areas and reducing patients' burden from frequent follow-up visits to the clinic.

Conclusion

This review provides a short summary of key milestones in the development of OCT that have contributed to its broader adoption in the medical field. The author would like to emphasize that while this review highlighted a few of the pioneering experiments in OCT, these innovations often built upon other scientific contributions, often at the boundaries of fields, which have significantly impacted the development of OCT. It is also important to highlight that the impact of OCT wouldn't be possible without the synergy of multidisciplinary collaborations of scientists, engineers, clinicians, and entrepreneurs, as well as the support of industry and governments. Looking forward, several areas of research and development, including optoretinography, parallel OCT, dynamic OCT, enface OCT, and others are underway and have the potential to expand the capabilities and application fields of OCT. Also, the strategic integration of IA into the OCT imaging pipeline is transforming the workflow in clinical practices.

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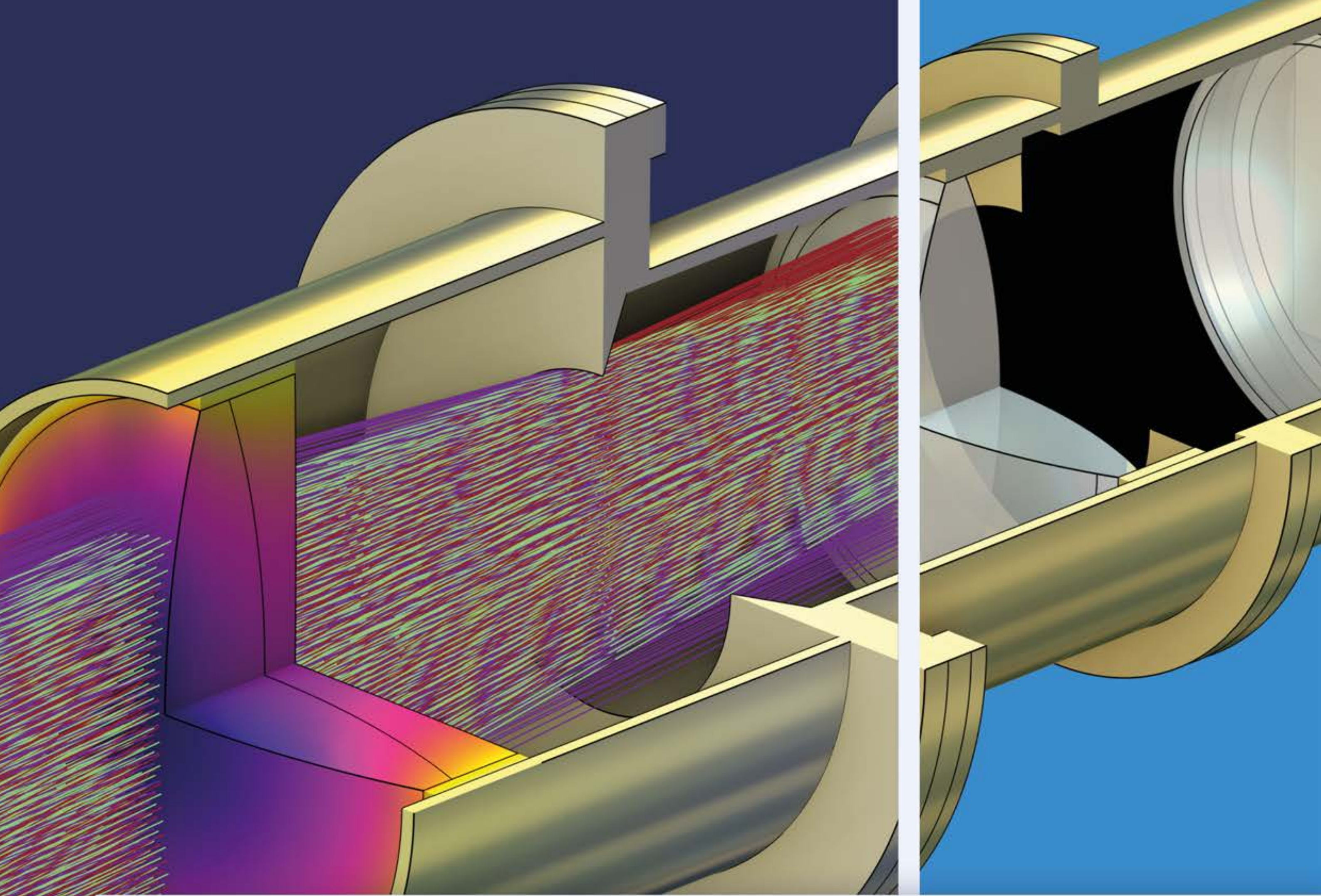

ALL-OPTICAL NEUROPHYSIOLOGY WITH HOLOGRAPHIC LIGHT SHAPING

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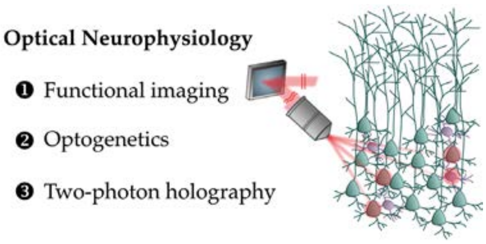

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To unravel how the mammalian brain computes in health and disease, neuroscientists need techniques that can non-invasively interrogate and manipulate neuronal activity with high spatiotemporal precision. In recent years, new approaches have emerged to achieve this goal by combining advanced light-shaping optical methods, two-photon excitation, and genetic tools for calcium, voltage imaging and optogenetics. Here, we provide a brief overview of these approaches, which lay the foundation for fully optical neurophysiology in both head-restrained and freely moving animals.

OPTICAL NEUROPHYSIOLOGY

Understanding brain function requires the investigation of neuronal circuitry across multiple spatiotemporal scales with the goal to map circuit activity and identify the respective behavioral correlates. One fundamental question is how these circuits operate: How are neurons connected within the circuit and to other circuits? Are individual neurons equivalent or do they form hierarchically organized assemblies? Do certain cells act as hubs orchestrating circuit activity and to what extent is a given spatiotemporal firing pattern necessary and unique for a particular behavior?

Answering these questions requires the ability to observe and also manipulate circuit activity with single-cell and single spike precision. Electrophysiological approaches can provide single-cell resolution when using intracellular electrodes, or population-level information when employing multi-electrode arrays and have greatly advanced the understanding of circuit dynamics to date. However, recordings at cellular resolution are low in throughput while population recordings lack single-cell resolution. In general, electrical techniques offer no access to the genetic identity of the recorded cells and are inherently invasive. In the case of intracellular recordings, this contact is even more disruptive and not compatible with longitudinal studies that require stable recordings over extended periods.

To overcome the limitations of electrical recordings, a collaborative effort among molecular biologists, physicists, biophysicists, and chemists has aimed to replace electrodes with light, both to read and manipulate electrical activity non-invasively, holding high potential especially for neuroscience applications. This interdisciplinary effort has given rise to the field of all-optical neurophysiology [1], which combines the genetic specificity of molecular tools with the spatial and temporal precision of optical techniques.

READING NEURONAL ACTIVITY WITH LIGHT

The challenge of reading neuronal activity with light was initially addressed through the development of calcium indicators, and more recently, genetically-encoded calcium indicators (GECIs). GECIs exploit the fact that neuronal activity is accompanied by transient increases in intracellular calcium, which changes its fluorescence in response to calcium binding providing an indirect yet robust optical readout of neuronal activity. As genetic tools GECIs provide both cell-type specificity and compatibility with chronic imaging, making them powerful tools for monitoring population dynamics over extended periods.

The use of wide-field single photon illumination allows calcium activity to be imaged across large brain regions and, combined with confocal detection schemes, enables cellular resolution in superficial layers. However, achieving population imaging with single-cell resolution deep within scattering tissue requires the use of two-photon (2P) microscopy, a technique based on the principle of Ω absorption first predicted by Maria Goeppert Mayer, who was later awarded the Nobel Prize in Physics for her pioneering contributions to quantum mechanics.

While calcium indicators have revolutionized our ability to image neuronal activity, their relatively slow kinetics limit temporal precision, since calcium transients integrate electrical events over hundreds of milliseconds. To overcome this limitation, more recently genetically-encoded voltage indicators (GEVIs) have been developed to directly report membrane potential changes rather than relying on secondary calcium signals. Depending on the molecular design of the GEVI, electrical changes can be read out as variations in fluorescence intensity, emission wavelength, or fluorescence lifetime. When combined with fast optical modalities, like wide field imaging, two-photon random-access scanning, light-sheet, or holographic imaging, GEVIs provide a direct way to monitor the electrical dynamics of neuronal populations at both single-cell and network levels in real time.

Together, calcium and voltage indicators form the foundation of optical neurophysiology, offering a powerful, genetically targetable, and minimally invasive way to observe how neurons communicate and process information across the brain.

CONTROLLING NEURONAL ACTIVITY WITH LIGHT

The ability to manipulate neuronal activity is provided by optogenetics, an emerging field that began with the discovery of genes encoding microbial light-sensitive ion transporters like Channelrhodopsin and Halorhodopsin. Expressed in neuronal cells these opsins directly convert absorbed photons into ionic currents, allowing activation or inhibition of neuronal firing with high spatiotemporal precision. Optogenetics has transformed neuroscience, offering an unprecedented, non-invasive way to perturb and control brain function paving the way to dissect neural circuitry. The majority of todays' optogenetic experiments have used relatively simple illumination methods with visible light used to illuminate large brain regions while genetically restricting expression to certain cell types. Due to that, wide-field illumination can only synchronously activate entire populations of neurons providing rather unphysiological perturbations, while dissecting neural circuitry and contributions of individual neurons requires the development of optical methods capable of illuminating individual or several cells independently.

2P scanning microscopy approaches largely adopted for population calcium imaging cannot be directly translated to single-cell optogenetic stimulation for two main reasons. First, the diffraction-limited focal spot employed in conventional scanning microscopy is too small to illuminate the entire soma and efficiently recruit a sufficient number of opsin molecules to reliably trigger an action potential or maintain inhibition. Second, the temporal constraints imposed by sequential scanning hinder a true-parallel control of multiple target cells simultaneously.

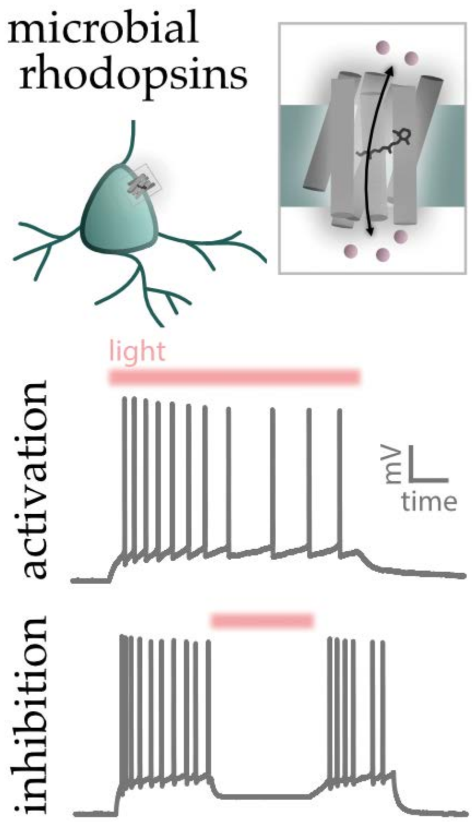

Figure 1. Microbial rhodopsins can be light-activated ion transporters that render ionic fluxes controllable with light. Genetically targeted to neuronal cells they allow control of neuronal activity with the spatiotemporal precision of the respective illuminaiton.

SCANLESS HOLOGRAPHIC ILLUMINATION

Some limitations of point scanning methods can be overcome through the use of holography, an ●●●

optical method originally introduced by Dennis Gabor (Nobel Prize in Physics, 1971). Holography works by modulating the wavefront of a laser beam so that the light field in the focal plane reproduces a user-defined spatial pattern. The modern implementation of this technique, known as Computer-Generated Holography (CGH) [2], relies on Spatial Light Modulators (SLMs) that can dynamically shape the phase of the incident beam. By computing holograms that correspond to specific positions, CGH allows the creation of multiple focal spots or customized illumination patterns within a 3D volume [3], each capable of stimulating individual neurons or neuronal ensembles.

When combined with 2P excitation, high-power pulsed lasers, and targeting strategies that restrict opsin expression preferentially to the neuronal soma, these approaches enable deep-tissue, parallel, and cell-specific optogenetic control, a powerful combination we refer to as circuit *optogenetics* [4].

Using CGH to create larger illumination areas covering the entire soma typically leads to a loss of axial resolution, which scales proportionally with the lateral spot size. To overcome this limitation, CGH can be combined with a technique known as temporal focusing (TF) [5], where ultrashort laser pulses are spectrally dispersed before being recombined at the focal plane. Because the pulse duration, and therefore the photon density, is restored only at the focal plane, excitation remains both temporally and spatially confined and allows the creation of extended excitation discs that uniformly illuminate the entire cell body while maintaining axial resolution comparable to that of a single diffraction-limited spot.

The combination of CGH and TF thus enables precise, parallel, and volumetric stimulation of multiple neurons in three dimensions, with subcellular spatial accuracy and millisecond temporal precision. After the demonstration of the first system for holographic 2P light patterning combined with TF, multiple variants have been developed to further enhance performance. These include approaches to reduce holographic speckle using generalized phase contrast, to extend the generation of temporally focused shapes in 3D, and to project light patterns at kilohertz rates, enabling sub-millisecond control of relative spike timing and increasing the number of targetable cells.

More recently, holographic light shaping has emerged as a key strategy for fast, multi-target 2P voltage imaging, allowing parallel, high-speed recording of voltage signals to detect neuronal activity with high contrast across multiple neurons [6]. This recent achievement underlines that holographic 2P illumination allows both 2P optogenetics and 2P voltage imaging rendering it an ideal illumination modality to set up all-optical neurophysiology approaches.

ALL-OPTICAL NEUROPHYSIOLOGY

To date, most demonstrations of circuits optogenetics have been performed in head-restrained mice, where both imaging and photostimulation beams are delivered through a high–numerical-aperture objective via a cranial window. In these preparations, animals can be either anesthetized or awake allowed to run on a spherical treadmill or a rotating wheel, while their neuronal activity is simultaneously monitored and manipulated.

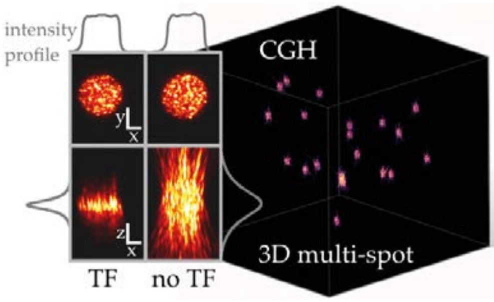

Figure 2. Three dimensional 2P holography for for targeting multiple cells with soma-sized spots. Inset showing intensity profiles of TF *vs.* No-TF spots.

Such experiments have successfully linked the activity of defined neuronal populations to sensory processing, motor control, and decision-making behaviors, providing direct evidence for the causal role of specific cells and circuits in brain function. These studies illustrate that precise spatiotemporal control of neuronal activity, enabled by techniques such as 2P holographic optogenetics, can reproduce physiologically relevant patterns of network activity, allowing researchers not only to observe but also to manipulate the flow of information through brain circuits.

However, many brain circuits, especially those involved in spatial navigation, social interaction, or goal-directed behavior, operate under naturalistic conditions that require freely moving animals. In recent years, 2P miniscopes have emerged as an extremely powerful approach for imaging calcium activity in freely moving mice or rats. In these devices, the scanning head used in conventional 2P microscopy is miniaturized to a size compatible with the animal's head, typically weighing less than 3 grams.

An alternative to miniaturized microscopes is to leave the complexity of the optical system on the optical table and use only a fiber and a focusing element, such as a GRIN lens or a mini-objective, as a relay between the output of the optical system and the animal's head *via* an adapter weighing less than 1 gram. To transmit holographic excitation patterns, the fibers used must belong to the class of fiber bundles composed of 15,000 to 30,000 individual multimode fibers allowing the holographic pattern to be faithfully transmitted to the output, which is then focused onto the brain through the GRIN lens or mini-objective.

Following an initial demonstration of a holographic fiberscope in 2014, which used 1P holographic excitation combined with multi-confocal calcium imaging, a new class of endoscopes, called two-photon 2P-FENDO [7], has been recently developed using 2P excitation. An important property of the fibers used in 2P-FENDO is the inter-core differential delay, designed to reduce inter-core coupling. In the context of 2P excitation, this has the consequence that light injected into multiple cores simultaneously at the fiber entrance emerges at the output with temporal delays on the order of a few picoseconds per meter. As a result, the light produced at the focal plane of the GRIN lens or mini-objective does not form a single, uniform illumination spot. Instead, it appears as a random distribution of small bright points, each corresponding to an individual fiber core. This scattering effectively produces an illumination area equivalent to what would be obtained using a single illuminated core. Because the distribution of these points is sufficiently sparse, the axial resolution remains that of a single core, regardless of the number of cores illuminated providing intrinsic axial confinement without the need for temporal focusing.

Making advantage of this properties 2P-FENDO enable fast calcium imaging and single-cell optogenetic stimulation, enabling all optical experiments in freely moving animals at unprecedented spatiotemporal precision.

CONCLUSION

The convergence of advances in genetically encoded indicators, optogenetic actuators, and holographic light-shaping approaches is making it possible to map, manipulate, and decode neuronal circuits across scales, with cellular resolution and millisecond temporal precision, thereby revealing causal links between activity patterns and behavior and giving rise to the field of all-optical neurophysiology. Recent progress in the development of genetically encoded voltage indicators and illumination methods compatible with two-photon voltage imaging has further enriched the field, enabling the readout of neuronal activity with single-spike resolution. Finally, as developments in fiber-based two-photon systems extend these capabilities to freely moving animals, optical neurophysiology is entering a new era in which complex, naturalistic behaviors can be studied with unprecedented resolution and specificity. Ultimately, these approaches are paving the way toward a mechanistic understanding of how distributed neuronal networks give rise to perception, cognition, and action. ●

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PHOTONIC PATHWAYS TOWARD REAL-TIME TISSUE ASSESSMENT

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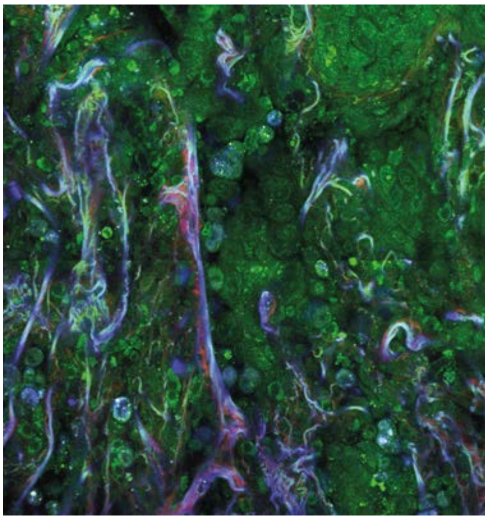

Photonics is transforming pathology by enabling fast, label-free tissue diagnostics. We developed Higher Harmonic Generation Microscopy (HHGM), a compact femtosecond-laser platform combining SHG, THG, and autofluorescence to image unprocessed tissue with submicron resolution. HHGM reproduces histological architecture within minutes, preserves tissue for further analysis, and enables AI-driven, real-time diagnostics across cancer types.

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Photonics has transformed modern medicine. Techniques such as optical coherence tomography (OCT) and white-light endoscopy, now standard tools in ophthalmology and gastroenterology, have brought optical precision to daily clinical practice, with tens of thousands of systems deployed worldwide. These technologies demonstrate the power of photonics to improve diagnostic accuracy, streamline workflows, and reduce patient burden. Yet, despite major advances in lasers, fiber optics, and nonlinear imaging, the full potential of photonics in healthcare remains largely untapped. Many areas of medicine still depend on slow, labor-intensive, or invasive diagnostic procedures. The challenge ahead is to match the rapid evolution of photonic innovation with clearly defined clinical needs, ensuring that solutions are neither overengineered nor underpowered for their purpose.

One such unmet need is the rapid assessment of tissue during surgery or biopsy. This article outlines the diagnostic bottleneck, the photonic principles that could overcome it, and our progress in developing higher harmonic generation microscopy (HHGM) as a fast, label-free alternative to conventional solutions.

THE DIAGNOSTIC BOTTLENECK

Histopathology remains the cornerstone of cancer diagnosis. The technique, developed nearly two centuries ago, involves formalin fixation, paraffin embedding, sectioning, and staining of tissue with hematoxylin and eosin (H&E) to visualize nuclei, cytoplasm, and stroma. Pathologists then assess characteristic features of malignancy in tissue architecture and cellular morphology (such as nuclear enlargement, nuclear pleomorphism, and hyperchromatism), alongside immunohistochemical and molecular markers that guide treatment. The approach is highly reliable but slow: results typically take two to five days.

Biopsies are the main source of diagnostic tissue. When CT or MRI imaging identifies a suspicious lesion, clinicians extract small tissue samples for analysis. However, because it can be difficult to obtain representative material, several samples (often 2–12) must be taken to ensure that diagnostic material is included. If all are non-representative, the biopsy must be repeated. In pulmonology and gastroenterology, rapid on-site evaluation (ROSE) partly mitigates this by allowing cytopathologists to inspect fine-needle aspiration smears within minutes. Yet ROSE assesses only single cells, not histological structure, and reaches predictive values of about 70% (1).

In the operating room, similar challenges arise. Surgeons must decide which tissue to remove or preserve, decisions that can determine the outcome of lung, brain, or endocrine surgery. To aid them, intraoperative frozen section (FS) analysis provides rapid histopathology: tissue is frozen, sectioned, and stained for microscopic examination. FS offers high diagnostic accuracy (95–98%) (2), but the process is slow, technically demanding, and interrupts the operation for at least 25–45 minutes. In many hospitals, especially those without on-site pathology facilities, it is logistically challenging and sometimes even requires transport of the tissue to a larger hospital by a taxi. What surgeons and pathologists need is a fast, reliable, and label-free method to assess tissue morphology and cellularity in real time, ideally within 10–15 minutes, with minimal handling and submicron resolution.

NONLINEAR MICROSCOPY: IMAGING WITHOUT LABELS

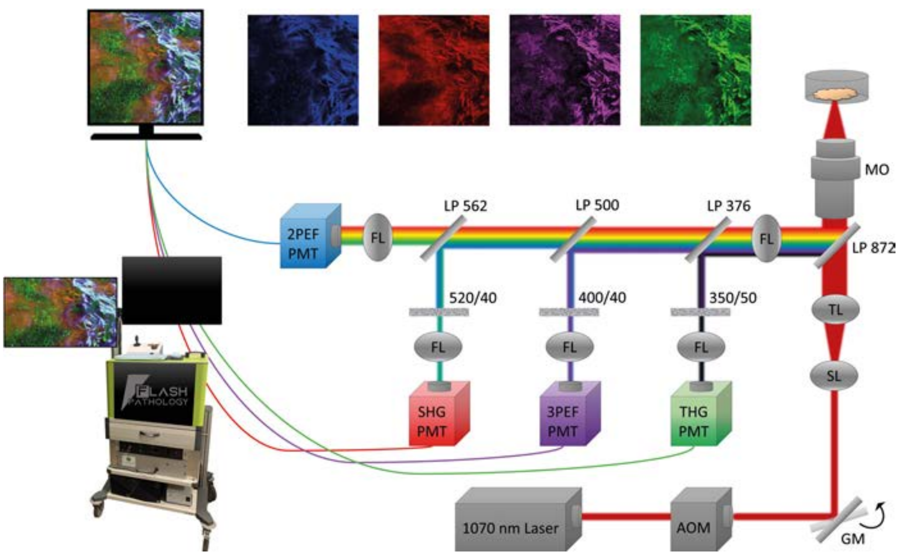
Nonlinear optical microscopy provides a powerful framework for such real-time histology. By using near-infrared photons (>900 nm), light penetrates deeper into tissue while limiting photodamage. Crucially, nonlinear interactions occur only at the focal volume, enabling intrinsic optical slicing and eliminating the need for physical sectioning.

Several nonlinear contrasts can reveal complementary aspects of tissue architecture. Raman-based methods, such as coherent anti-Stokes Raman scattering (CARS) and stimulated Raman scattering (SRS), visualize molecular vibrations and have been translated into stimulated Raman histology (SRH), a computationally rendered, label-free analog of H&E staining pioneered by academic (3) and industrial groups, including LightCore and Invenio. Multiphoton fluorescence microscopy exploits intrinsic chromophores such as NAD(P)H and flavins to visualize cellular metabolism. Second harmonic generation (SHG) highlights ordered, non-centrosymmetric structures like collagen fibers, while third harmonic generation (THG) maps optical interfaces, visualizing cells, nuclei, and extracellular structures, without dyes or labels. Firms like Flash Pathology and Eleuthera Photonics use SHG, THG, and multiphoton autofluorescence to visualize unprocessed tissue in real time. A linear approach towards real-time histology is confocal microscopy combined with rapid fluorescent staining, implemented by Vivascope and SamanTree Medical, providing another route to fast histological imaging. Together, these advances outline a clear translational pathway toward rapid, photonics-based intraoperative pathology.

HIGHER HARMONIC GENERATION MICROSCOPY (HHGM)

Our laboratory focuses on the translation of higher harmonic generation microscopy (HHGM), which integrates SHG, THG, • • •

Figure 1. Schematic of the transportable HHG microscope developed by Flash Pathology BV. A 1070 nm is focused by a high NA objective, resulting in a resolution of 0.4 × 0.4 × 2.7 μm^3. Generated signals are detected in epi-direction and divided into separate channels through dichroic mirrors. Photomultiplier tubes are used to detect the four channels simultaneously. Galvo mirrors (GM) are used to perform a bidirectional raster scan, creating a 2D image with a field of view of around 400 × 400 μm^2. Larger 2D images are created as a mosaic of smaller images by moving the motorized sample stage in x- and y-direction. 3D images are obtained by moving the stage in vertical (z) direction. Fast overview images are generated at a speed of 7.5 s/mm^2, and high resolution images at 1 $minute/mm^2$. On average a biopsy is scanned in 5 minutes.



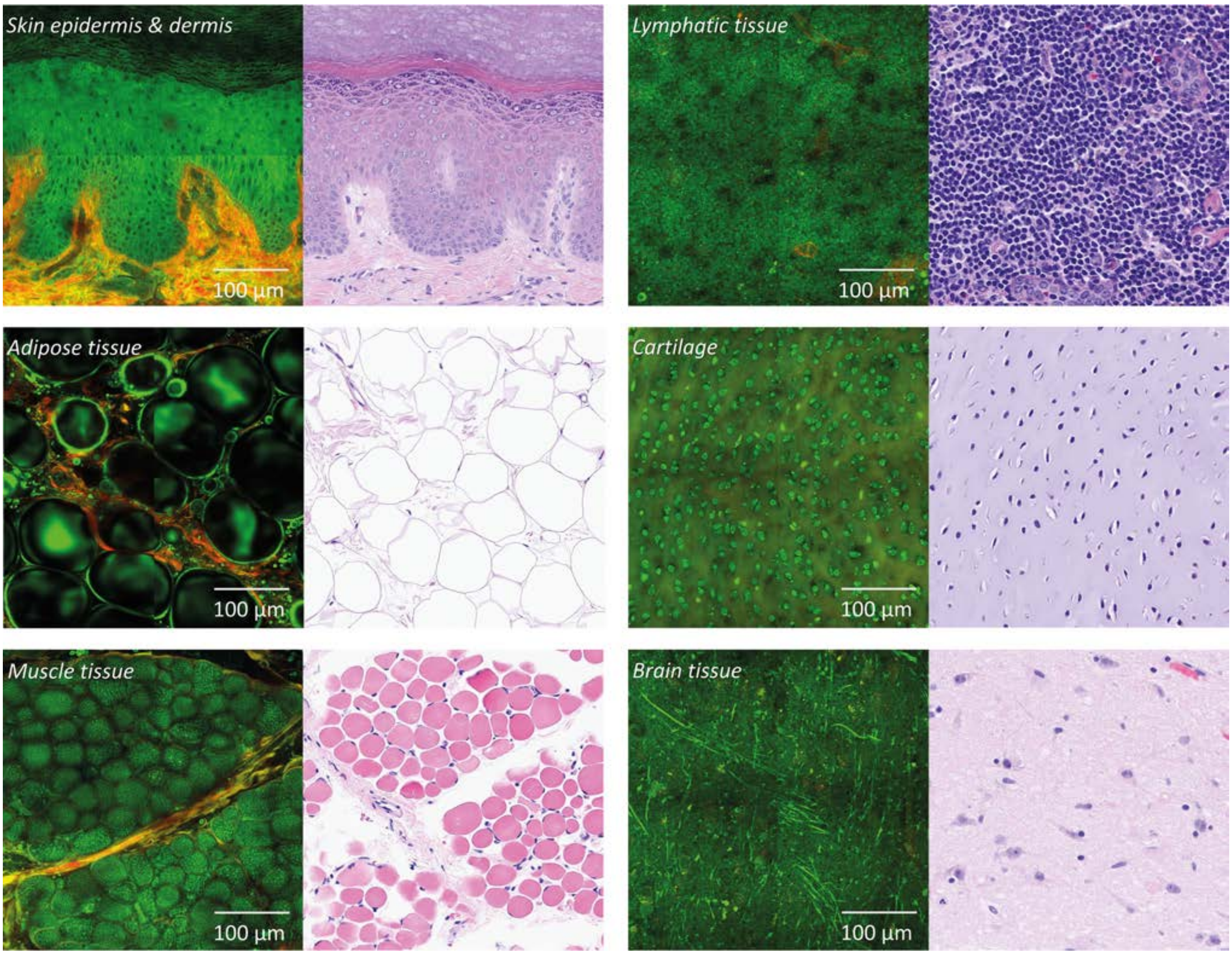
and two- and three-photon excited autofluorescence, to the clinic. In HHGM, two or three photons from the excitation laser combine to form a single photon with twice or thrice the energy. SHG arises in organized, non-centrosymmetric molecules such as collagen, while THG emerges at refractive index discontinuities, interfaces between cell membranes, nuclei, collagen, and elastin fibers. Combined with autofluorescence from NAD(P)H, flavins, retinol, and elastin, these contrasts yield richly detailed, label-free images that resemble histology in architecture, but contains information beyond that.

Generating efficient harmonic signals requires ultrashort femtosecond pulses. To achieve this with minimal tissue heating, Flash Pathology BV, uses a compact fiber-laser microscope operating at 1070 nm combined with pulse-picking technology: the system delivers bursts of five sub-80 fs pulses at 1 MHz, producing strong nonlinear excitation with only 5 mW of average power, well within safe limits for excised tissue. The resulting instrument, measuring $0.6 \times 0.8 \times 1.5\ m^3$ and weighing 40 kg, achieves $0.4 \times 0.4 \times 2.4\ \mu m^3$ resolution and can generate diagnostic images within minutes. See *figure 1* for the layout inside the microscope.

FROM BENCH TO BEDSIDE: TESTING HHGM ACROSS CANCER TYPES

We have validated HHGM across a range of clinical applications, see *e.g.* (4, 5). In HHGM images of renal tumor resections, pathologists correctly identified normal versus tumor tissue in 97% of cases. In lung biopsies from 47 patients (109 samples), high-quality HHGM images were obtained within six minutes of excision, with 97% deemed suitable for diagnostic interpretation and 87% correctly classified by pathologists. In parathyroid tissue, 85% sensitivity and 83% specificity was achieved. Beyond structural imaging, 3D HHGM combined with artificial intelligence enables automated classification of immune cell types in bronchoalveolar lavage samples • • •

Figure 2. HHG (SHG-THG-2PEF) images compared to conventional histology images with hematoxylin and eosin stain (H&E), for healthy tissue: skin, lymphatic, adipose, cartilage, muscle and brain tissue.



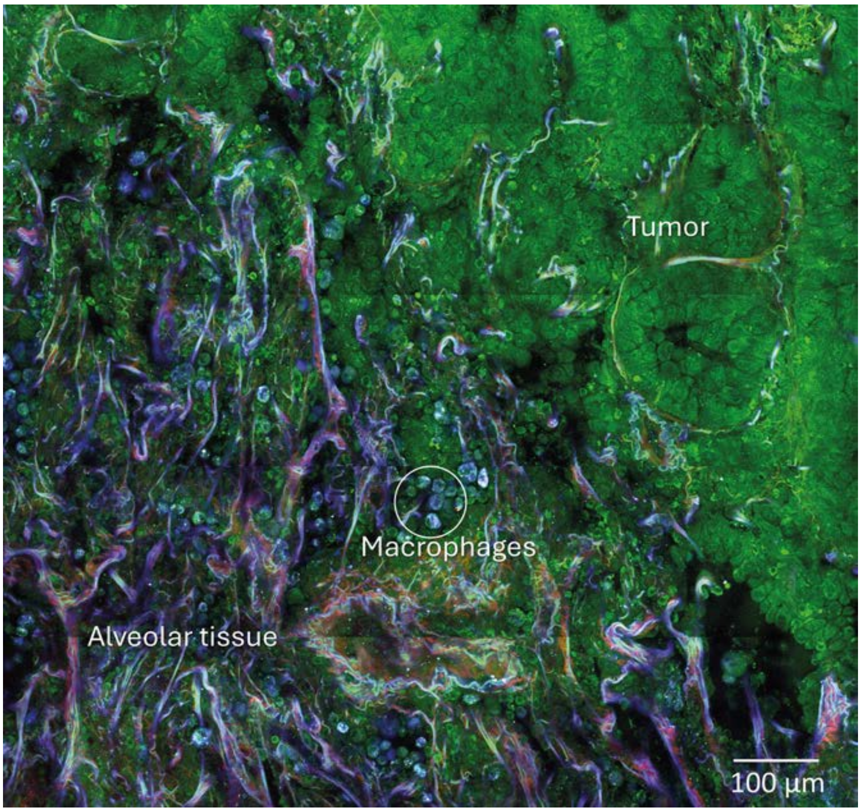
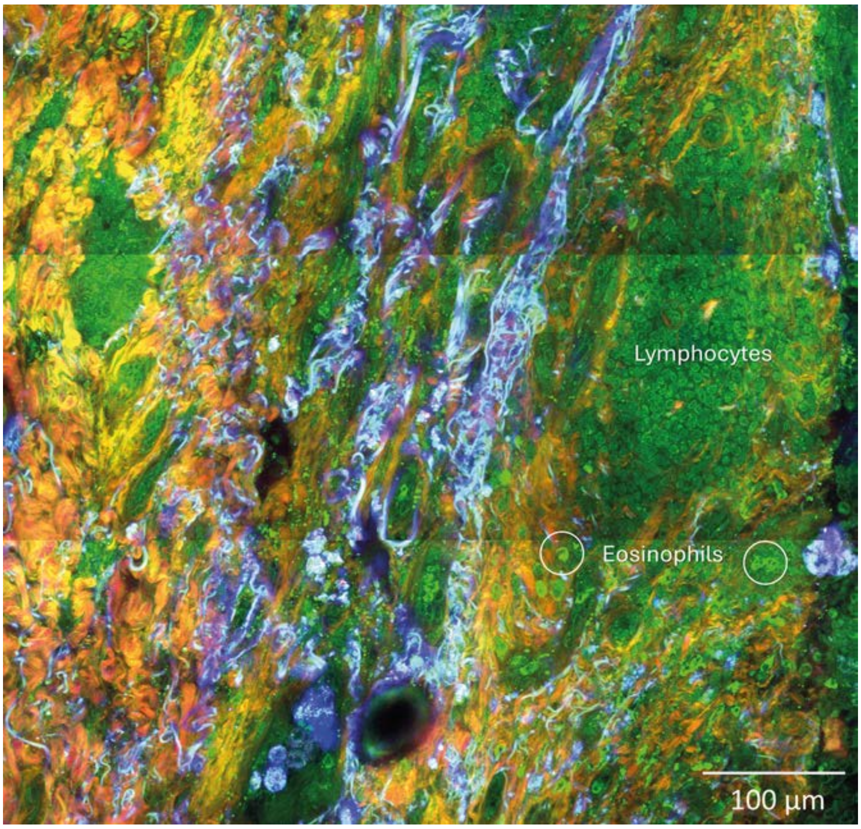


Figure 3. HHG (SHG-THG-2PEF) image of a lung tumor (adenocarcinoma).

Figure 4. Figure 4 HHG (SHG-THG-2PEF) image of a lung biopsy (adenocarcinoma, not visible in this part of the image).



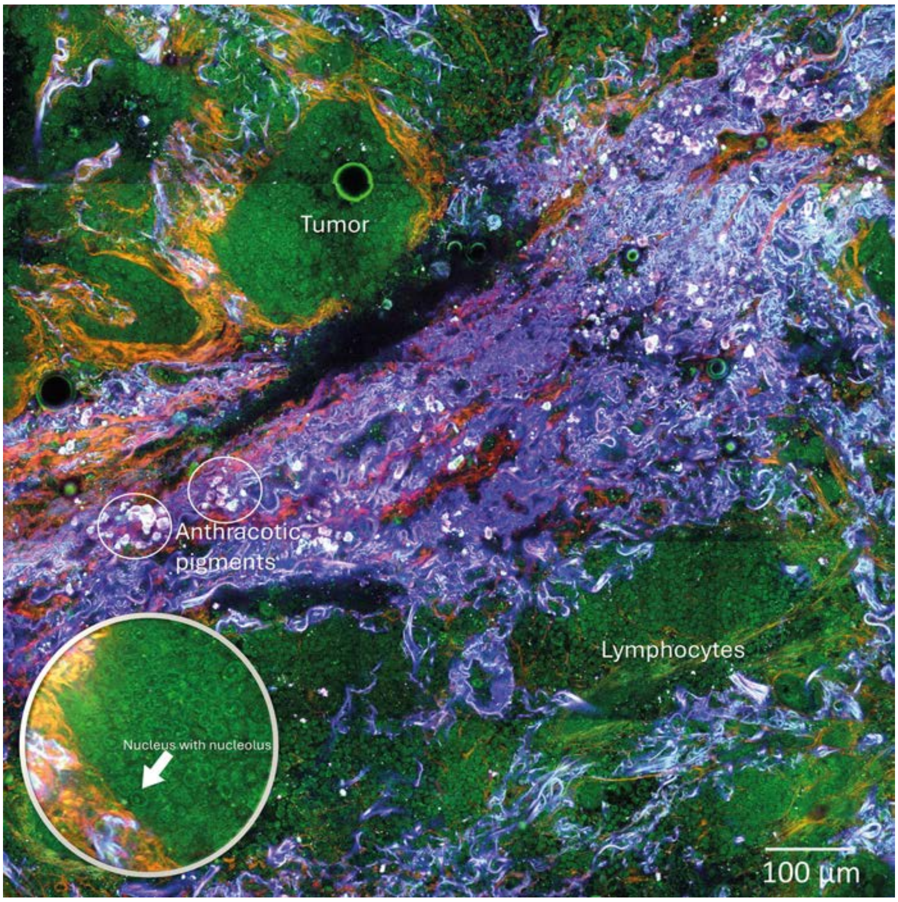


Figure 5. HHG (SHG-THG-2PEF) image of a lung tumor (adenocarcinoma) with close-up of the cellular details of the tumor cells.

and discrimination of tumor and healthy tissue for brain and lung tissue. Our foundation model, CellSAM, trained on HHGM data, achieved near-perfect segmentation of tumor, immune, and stromal cells in brain tissue (precision 99.4%, recall 98.7%) (6).

In the following, we present examples of higher harmonic generation (HHG) microscopy images from various tissue types.

Figure 2 compares HHG microscopy images of healthy tissues with corresponding standard hematoxylin and eosin (H&E) histology images. In HHG microscopy, cellular and most tissue structures are visualized *via* the third harmonic generation (THG) signal (displayed in green), while collagen fibers generate second harmonic generation (SHG) contrast (shown in red). In addition, two-photon excited fluorescence (2PEF), displayed in blue, provides complementary information. For reference, H&E staining uses two dyes to visualize tissue architecture: hematoxylin stains cell nuclei blue to purple, and eosin stains cytoplasmic and extracellular components pink to red. The overall tissue architecture in HHG images closely resembles that seen in H&E histology.

In skin tissue, the distinct epidermal and dermal layers are clearly resolved. In HHG images, nuclei appear as dark voids within the cellular structures. Lymphatic tissue exhibits high cellular density, with small cells containing minimal cytoplasm. Adipose tissue consists of large adipocytes that appear empty in H&E images due to lipid loss during sample processing. Hyaline cartilage shows a homogeneous, glass-like background with embedded chondrocytes. In muscle tissue, the HHG image reveals cross-sections of skeletal muscle fascicles. Finally, brain tissue displays the grey matter region with several identifiable neurons (circled) and a few myelinated axons, visible as bright green linear structures in the HHG image.

Figure 3 shows an HHGM image of a lung tumor biopsy (adenocarcinoma). Collagen fibers appear in red, elastin fibers in blue, and cells in green. In the lower left region, remnants of alveolar tissue are visible, displaying the characteristic fine collagen and elastin network interspersed with macrophages. Toward the upper right, this orderly structure gives way to densely packed, enlarged cells consistent with malignant transformation. HHGM thus readily distinguishes normal from tumor regions within a single field of view. Feedback on the representativity of the biopsy was available to the endoscopist within five minutes after extraction, allowing rapid recognition of tumor type based on cellular morphology and growth pattern.

The composition of the tumor microenvironment (TME) and the types of immune cells it contains are critical determinants of tumor progression, therapeutic response, and clinical outcome. Figures 4 and 5 present HHG microscopy images of adenocarcinoma tissue, illustrating the cellular and extracellular complexity of the TME.

In Figure 4, the second harmonic generation signal highlights collagen fibers, revealing the dense and often disorganized stromal matrix characteristic of epithelial tumors. Elastin fibers contribute additional structural contrast in the two-photon excited fluorescence channel, while the third harmonic generation signal enables label-free visualization of individual cells within the tumor stroma. The image reveals a heterogeneous immune infiltrate consisting of lymphocytes, eosinophils, and macrophages. Lymphocytes appear as small, round cells with minimal cytoplasm, often clustered near stromal interfaces or blood vessels. Eosinophils are identifiable by their bright, granular cytoplasm and lobed nuclei, whereas macrophages are larger, irregularly shaped cells with variable internal contrast.

Figure 5 shows numerous elastin and collagen fibers to form a complex extracellular network interspersed with tumor cells and lymphocytes. The magnified view highlights the detailed cellular morphology of tumor cells: HHG imaging clearly resolves nuclei as ring-shaped structures and nucleoli as bright, dot-like features within them. Between the elastin fibers, white–purple structures correspond to macrophages laden with anthracotic pigment (carbon particles), readily distinguishable by their dark inclusions.

Together, these images demonstrate the capability of HHG microscopy to visualize both structural and immune components of the tumor microenvironment *in situ*, without the need for labeling or staining. This intrinsic contrast provides a powerful means to study tumor–stroma organization and tumor–immune cell interactions at subcellular resolution.

CONCLUSION

The convergence of compact femtosecond lasers, label-free nonlinear imaging, and deep learning is opening a new frontier in digital pathology. Higher Harmonic Generation Microscopy (HHGM) generates information-rich, multicolored images that capture the architectural fidelity of histology with the speed and immediacy of cytology, while enabling fully automated analysis, all without staining or sectioning. HHGM can be seamlessly integrated into clinical workflows, delivering diagnostic feedback within minutes, and importantly, the imaged tissue remains intact for subsequent molecular or histopathological evaluation. The relative simplicity of the technique, requiring, for instance, only a single laser source, renders the machine robust, compact, and cost-effective, facilitating translation to the clinic.

ACKNOWLEDGEMENTS

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SMART ILLUMINATION FOR 3D-IMAGING OF BIOLOGICAL TISSUES

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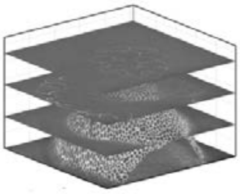
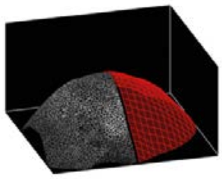

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Three dimensional imaging of living tissues with widefield fluorescence optical microscopy is limited by out-of-focus blur, light dose, and acquisition speed. We discuss recent camera-based strategies that use light more intelligently to improve resolution, sectioning and reduce toxicity when imaging thick biological structures.

The microscope as a scientific instrument for biological discovery emerged in the 17th century. When Robert Hooke examined a thin slice of cork under a microscope, he saw tiny compartments and named them 'cells', thereby helping to establish the idea that living tissues are made up of repeating units. For a long time afterwards, microscopes continued to reveal shapes — membranes, nuclei and filaments — without necessarily showing what those structures were doing.

Over the last two decades, the use of fluorescence has transformed biological imaging. Fluorescence is the process by which a molecule called fluorophore absorbs light at one wavelength, which excites its electronic state, and then de-excites by emitting light at a different wavelength. Using optical filters that only transmit the emitted light allows labelled structures to stand out with high contrast. This revolution was accelerated by the development of fluorescent proteins (FPs), which are genetically encoded tags that can be fused to proteins of interest inside living cells and organisms [1]. Through FPs, a wide variety of tools are available nowadays, including calcium or voltage reporters for neural activity, cytoskeletal markers for force and shape investigation, and stress or programmed cell death probes. Once the necessary genome edits have been introduced, entire organisms can be engineered to express these probes in selected tissues or throughout the body, enabling us to observe cellular behaviour in vivo rather than on an isolated glass slide.

Imaging cells within their host organism poses new technical challenges for the microscopist. It requires 3D imaging with high spatial and temporal resolution deep inside whole organisms, such as Drosophila embryos, zebrafish larvae or organoids. There are three practical hurdles to overcome. Firstly, out-of-focus fluorescence creates a blurred background that obscures details especially for deep observations. Secondly, building a 3D stack slice by slice increases the light dose, bleaching fluorophores and disrupting physiology. Thirdly, acquiring many planes is time-consuming; the dynamics we are interested in can exceed the capabilities of our scanners and cameras.

This article explores strategies that use structured and smart illumination to mitigate these constraints. The goal is simple: keep samples alive, capture events as they happen, and reveal structures that were previously hidden—by using light more intelligently.

3D-MICROSCOPY

Microscopes are inherently asymmetric instruments. Light propagates along a single, privileged direction — the optical axis. Imaging instruments naturally create contrasted images in the transverse (xy) plane,

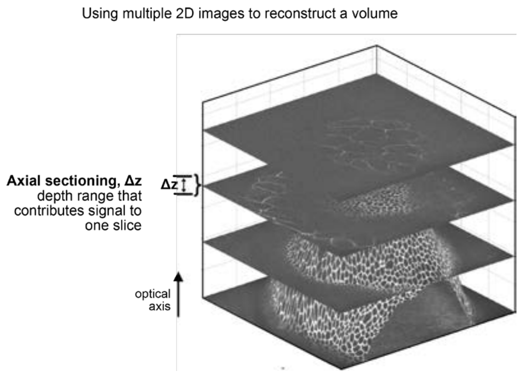


Figure 1. A three-dimensional structure is captured by acquiring a stack of 2D slices at successive positions along the optical (z) axis (4 of ~50 shown). Effective optical sectioning means each slice is sensitive only to a narrow axial thickness, Δz; if Δz is large, out-of-focus fluorescence from neighboring planes blurs the image.

while access to the third dimension (z) is indirect.

To create a 3D image with a conventional microscope, a stack of 2D images must be acquired while translating the sample along the optical axis. In principle, this method should work: each slice samples a different depth, and the stack encodes the volume (see Fig 1).

In practice, however, we encounter the sectioning problem. As the excitation light propagates along the optical axis, it also excites fluorophores above and below the focal plane that is optically conjugated to the camera. These fluorophores emit photons that are not part of the desired image plane; they travel back along the same axis and impinge on the camera as a blurred background. In link with this background, widefield microscopes discriminate objects poorly along the optical axis: a uniform fluorescent layer perpendicular to the optical axis cannot be localized, and two homogeneous layers at different depths are indistinguishable. The thicker the specimen, the stronger this unwanted background becomes.

This is why the confocal microscope, introduced as a solution for optical sectioning, has become such an important tool in biology.

CONFOCAL MICROSCOPY — RESTORING OPTICAL SECTIONING

A confocal microscope forms an image one point at a time (Fig. 2). A tightly focused excitation spot scans the sample. At the image plane conjugated to the focal plane, the in-focus fluorophores excited by the beam focus yield a small intense spot while the out-of-focus fluorophores, excited by the diverging beam, form a large low-intensity smear. By placing a pinhole strictly conjugated to the excitation focus spot, one ensures that most of the light emitted by the in-focus fluorophores is collected while most of the light of the out-of-focus fluorophores is discarded. Emission produced above or below the focus being largely blocked at the pinhole (Fig. 2), the microscope now records a slice with far less out-of-focus background. By repeating the scan at successive depths, a 3D stack is built with far better axial discrimination than the conventional -widefield- microscope.

While this introduces sectioning, it also comes at a price in the form of necessary trade-offs for 3D imaging. The pinhole rejects most of the emitted photons, many of which carry useful information, so the overall throughput is low. In order to maintain the signal, users often have to slow down the scan in order to accumulate more photons per pixel, which reduces the imaging temporal resolution; alternatively, they can open the pinhole, which sacrifices sectioning. Ultimately, the low usable signal per pixel (photon budget) forces the user to increase the excitation power. However, biological tissues can be very sensitive to light exposure. Excited fluorophores can generate reactive oxygen species (ROS) that can alter signalling or trigger cell death. In practice, the cumulative dose increases with the number of planes, dwell time and re-imaging frequency, meaning that 3D confocal imaging imposes stress that scales with volume and time.

In subsequent sections, we •••

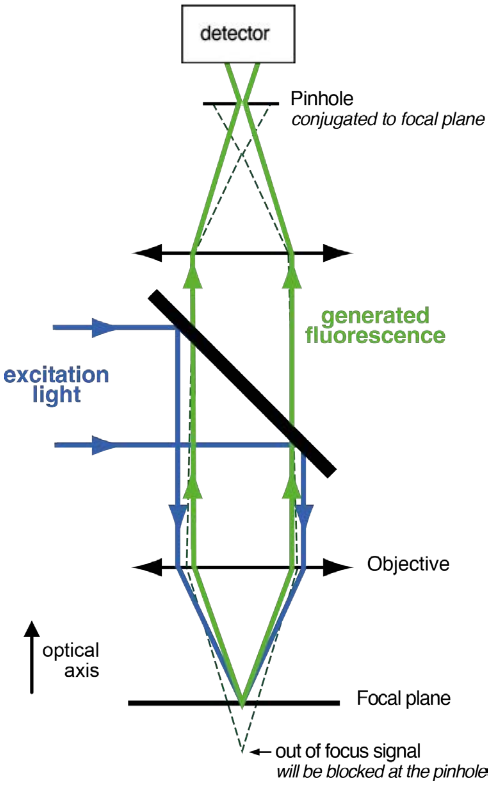


Figure 2. Confocal principle. The excitation light (blue) is focused to a spot that scans the sample. Fluorescence (green) passes through a small pinhole placed in a plane optically conjugate to the focal plane, so emission from above or below focus is blocked (dashed rays), producing a slice with much less out-of-focus background.

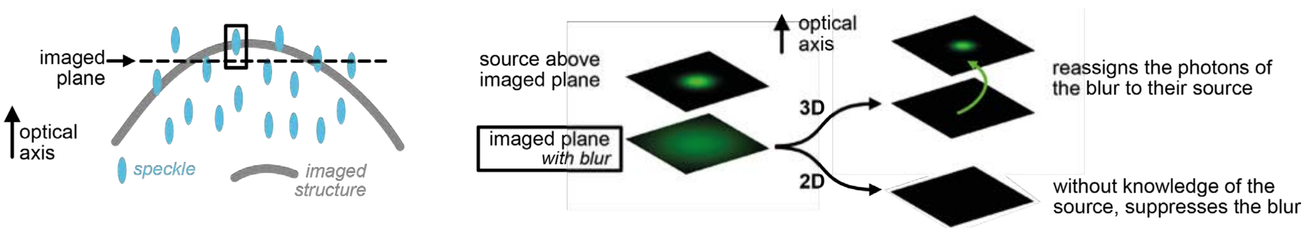
present complementary strategies that address these limits. Firstly, 3D Random Illumination Microscopy (3D-RIM) uses speckled excitation and variance-based reconstruction to recover super-resolved, optically sectioned volumes while reassigning photons to their correct depth. Secondly, an extended-depth-of-field (EDF) mode compresses the volume onto a single exposure to capture fast dynamics with a much lower readout burden. Lastly, smart illumination allows to reduce the light dose impinging on the sample by focusing the illumination patterns only where it is required.

3D-RANDOM ILLUMINATION MICROSCOPY

An alternative to point-scanning is Structured Illumination Microscopy (SIM, [2]): rather than scanning a focus, the whole field is illuminated with periodic patterns and several images are recorded with shifted phases and orientations. The patterned light down-modulates within the microscope's passband the information otherwise beyond the resolution limit. These images are combined numerically to yield a synthetic image with twice better resolution. In 3D-SIM, the pattern is also modulated along z, which improves axial as well as lateral resolution and provides sectioning for 3D imaging. The main drawback of 3D-SIM is that the reconstruction technique requires the knowledge of the illumination patterns inside the specimen. In embryos and other thick, heterogeneous tissues, aberrations and scattering distort the patterns in ways that are hard to measure or predict, so conventional 3D-SIM can produce artifacts or fail at depth.

In recent work [3], we proposed Random Illumination Microscopy (RIM) as an alternative structured illumination microscopy technique that avoids the knowledge of the excitation patterns. The sample is illuminated with a sequence of random speckle patterns and imaged with a camera at gentle intensity. Instead of using the patterns value at each point in the tissue, RIM reconstruction procedure exploits the statistics of the speckle ensemble. It extracts a super-resolved image from the variance of the multiple low-resolution speckled images using a variance matching inversion scheme. The RIM approach requires only the knowledge of the speckle short-range correlation and the observation point spread function. In addition to a two-fold resolution gain which has been mathematically demonstrated and experimentally confirmed [4,5], it provides numerical optical sectioning. The latter can be simply explained by first noting that the speckled illuminations form random bright grains throughout the sample volume. The fluorescence light emitted by the in-focus excited fluorophores yields sharp spots at the image plane, while the light emitted by the out-of-focus fluorophores yields large smears. When the speckled patterns are changed, the fluorescence coming from in-focus structures undergo large intensity fluctuations, whereas the blurred

Figure 3. 3D-RIM. Left: a 3D structure (grey) is imaged with a speckle, which appears as a random distribution of bright spots (blue). The imaged plane appears as a dashed line. We focus on a small region of interest (black box). Right: In that small box, the imaged structure is excited by a speckle grain above the imaged plane, thus contributing a blur in the imaged plane. A 2D approach (confocal or 2D RIM, bottom right) removes this blur because it has no knowledge of the source above the imaged plane. A 3D approach (top right) will reassign the out of focus photons to their source through a deconvolution.



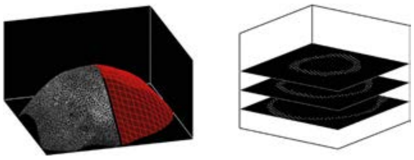


Figure 4. Smart-scanning. Sometimes, the signal of interest occupies a small fraction of the sample volume. Such is the case for example when cells are organized as a curve surface (left). We can then estimate a spatial model of the structure (computed surface in red), and concentrate illumination to a thin shell around this structure of interest (right).

contribution of the out-of-focus regions varies much less. As a result, the variance processing washes out the out-of-focus background.

In both the confocal and RIM procedures, the out-of-focus contributions are discarded physically or numerically: we end up using only the photons thought to originate from sources in the focal plane. This approach is justified if only one slice of the sample is imaged. On the other hand, if one wants to record a volume image of the sample, discarding the photons arriving from fluorophores above and below the focal plane is not a good idea as they carry information on the three-dimensional (3D) structure of the sample. This led us to develop a 3D version of RIM that uses the 3D nature of speckle and 3D data processing to exploit the information carried by these out-of-focus photons (see Fig. 3).

In *3D-RIM*, we sequentially image the volume of the sample while keeping the 3D speckle pattern fixed. Instead of moving the sample, axial scanning is carried out by a remote-focusing unit placed in the detection arm, such that the illumination stays registered and acts as a stable 3D probe. The structuring of the speckle along optical axis can then be used to improve sectioning. See the illustration in Fig. 3: when imaging a given plane, the fluorophores above or below this planes provide out-of-focus photons appearing as smears on the image. If we have knowledge of the 3D stack, however, we can attribute those out-of-focus photons to their source—effectively reassigning them to the proper plane. Thus there is no need to suppress the smears: we use them and put the photons back where they belong. Mathematically, this reassignment is performed through a deconvolution step before computing the 3D variance.

The consequences are that 3D-RIM keeps RIM's robustness in thick, aberrated tissues while adding stronger axial sectioning and better photon budget—fewer photons are thrown away by the variance step. In practice, the same level of detail can be obtained with lower illumination power, making the method gentler for live samples.

EXTENDED DEPTH OF FIELD

While faster than the confocal, structured illumination microscopies, including RIM, are slower than the widefield microscope as they require the acquisition of multiples images of the sample under different illuminations. In addition, thick 3D samples require many sequential slices to reconstruct a volume. Each newly acquired image also comes with a camera "dead time" linked to reading out of the information on the sensor. When biology is fast and the scientific question tolerates a projective view along z, we reasoned that compressing the whole volume into a single exposure becomes a powerful alternative. This can be done through extended depth imaging [6].

During each camera exposure, the focal plane is swept rapidly through the specimen using a tunable element (for example, an electrically tunable lens). The sensor therefore integrates fluorescence from the full axial range, yielding one extended-depth frame. Repeating this with a set of different speckle illuminations provides the data for variance-based reconstruction, which removes the characteristic blurred background that normally mars extended depth images. We could thus retrieve super-resolved details in the projection.

Compared with acquiring a full 3D stack with standard RIM, EDF-RIM reduces the number of readouts and can be about ten times faster, while maintaining lateral resolution. The price to pay is that axial information is compressed into ● ● ●

the projection; when full volumetric reconstruction is required, 3D-RIM remains the method of choice.

We could validate the instrument on biologically relevant thick samples, including mouse intestine tissue, Drosophila embryos, and human cultured cells, illustrating both robustness and live-imaging compatibility.

SMART SCANNING

Camera-based 3D imaging offers speed and high resolution, providing gentler, more distributed illumination than point-scanning confocal systems. However, even with parallel acquisition, very sensitive tissues can be damaged. Background fluorescence also poses a fundamental limitation: the photon noise associated with background can overwhelm the speckle-based variations used for super-resolved reconstruction, undermining the capacity for super-resolution.

To overcome these issues, we have developed a smart microscope that focuses illumination only where necessary, placing the imaging process under algorithmic control and enabling structures of interest to be targeted progressively [7]. Real-time analysis learns from the measurements already acquired and chooses where to probe next, so the illumination converges toward relevant features such as curved embryonic surfaces (Fig. 4). When we have a strong prior knowledge of the structure of interest -as is the case with surfaces, for example - it may take as few as three steps: performing a very sparse pre-scan; estimating a spatial model of the object (in this case, a surface); and scanning the surface. In more complex situations, a longer iterative approach may be required to converge. In our initial study, we focused on cell sheets, which are curved 3D surfaces commonly found in embryos, but the concept is general.

In the future, the detection could also be trained through examples, using machine-learning and artificial intelligence approaches. Temporal continuity is also crucial: information from one time point could inform the next, allowing the acquisition to concentrate on changes and maximize new information per irradiation photon.

The benefits of smart scanning are first in the reduction of the light dose. Because the structures of interest often occupy only a small fraction of the total volume, the illuminated voxels – and thus the total light dose impinging on the sample– can be reduced by up to two orders of magnitude. Lower dose means less phototoxicity and less bleaching, enabling much longer observations of living tissues. At the same time, restricting illumination to the informative regions reduces background and its associated photon noise, which improves reconstruction quality. A last practical side effect is strong data compression: by measuring less but measuring smarter, we store and process only what matters.

PERSPECTIVES

Using light more intelligently can improve contrast, resolution, speed, and sample health in 3D imaging. By placing excitation photons only where they are informative, we extend what live fluorescence microscopy can do without harming the specimen.

As a perspective, crossmodality is the natural next step. We can pair 3D-RIM or EDF-RIM with adaptive illumination patterns that target regions of interest in real time. Cross modality with point scanning microscopy (non-linear point scanning is still the way to go at really great depth), and light sheet microscopy will also be explored.

In all cases, the aim is to maximize information per photon, minimize dose, and go faster when imaging thick tissues.

ACKNOWLEDGEMENTS

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COMPLETE SOLUTIONS FOR QUANTUM APPLICATIONS

How Menlo Systems' Optical Frequency Combs and Ultrastable Lasers Enable the Second Quantum Revolution

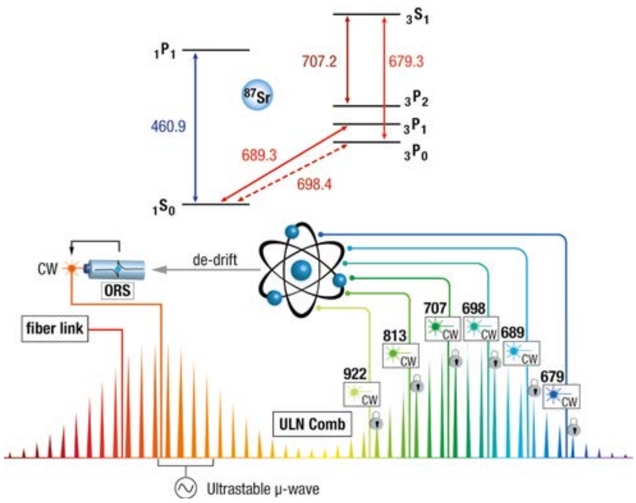
Quantum technologies are driving a new era of innovation by exploiting quantum physics for real-world applications. Their ability to measure, compute, and communicate with unprecedented precision makes them essential for tackling today's most complex scientific and technological challenges. Particularly impactful is quantum sensing, harnessing fragile quantum states of atoms, ions, or photons as ultra-sensitive probes of their environment, enabling breakthroughs in navigation, geodesy, and tests of fundamental physics.

To realize these capabilities, researchers need tools that combine absolute stability, coherence, and reproducibility. From quantum simulators, communication, and computing to atomic sensors and metrology, precisely stabilized light is needed to manipulate atoms and ions, define timing and phase relationships, and establish coherent links between quantum systems.

This is where photonics comes in: optical frequency combs are mode-locked pulsed lasers whose spectrum consists of thousands of evenly spaced, phase-coherent lines. When locked to an ultrastable reference, the combs inherit this stability and transfer spectral purity to other wavelengths at the 10^{-18} level, enabling precise probing of atomic transitions.

Menlo Systems has served the optical community with high-end optical frequency combs for nearly 25 years and provides a fully integrated, commercial solution for quantum and timekeeping applications: the FC1500-Quantum. The system combines an optical reference and an ultrastable frequency comb with several continuous-wave (CW) lasers for atom cooling, repumping, and addressing narrow clock transitions in atoms or ions. Low phase noise of the comb-disciplined lasers ensures the phase coherence required for precise state manipulation. Laser light can be fiber-delivered to the physics package, simplifying integration with vacuum systems and optical setups. Acting both as a reference for all lasers and as the spectral bridge linking optical and microwave domains, frequency combs are the heart of modern quantum laboratories [1].

A showcase example of the FC1500-Quantum in action is Fermilab's MAGIS-100 (Matter-wave Atomic Gradiometer Interferometric Sensor) [2] project, which aims to explore fundamental physics through atom interferometry over a 100-meter vertical baseline. Here, clouds of ultracold strontium atoms are launched in free fall while laser beams, stabilized by the FC1500-Quantum, act as beam splitters and mirrors for matter waves. Several watts of sub-hertz light at 698.4 nm are collimated along the baseline. The system's ultrastable frequency and phase coherence are critical for this quantum sensor, which could probe ultralight dark matter, test the equivalence principle and pave the way for future gravitational wave detectors.



▲ The atomic 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 ultrastable laser transferring its spectral purity onto an optical frequency comb and all other lasers which are also locked to the comb (lower part).

Another example of frequency-comb-aided quantum-enabled precision is found in optical atomic clocks, which are poised to redefine the SI second. Unlike the current standard cesium clocks, which are based on transitions at roughly 9 GHz, optical clocks leverage the stability and accuracy of ultra-narrow atomic transitions in the optical range, typically hundreds of THz. Frequency combs form the core of such systems and act as clockworks, counting trillions of oscillations. These state-of-the-art clocks allow for a precision of 10^{-18} [3], corresponding to an error of 1 s in 15 billion years. With collaborations like MAGIS-100 and the Boulder Atomic Clock Optical Network (BACON) [4], Menlo Systems is pushing the boundaries of quantum sensing and metrology. ●

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Photonics in Sweden

Sweden's photonics ecosystem is anchored by leading academic research, innovative industrial actors, and national coordination through PhotonicSweden. With more than 200 companies and 8,000 employees, Sweden continues to advance cutting-edge photonics technologies across sectors. Close collaboration between universities, research institutes, and industry fosters innovation, talent development, and international engagement—positioning Sweden as one of the key players in the European photonics landscape.

Nobel Light Week in Stockholm.
Photo by Lennart BM Svensson

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Development of Optical Science and Photonics Infrastructure in Sweden

The evolution of optics and photonics in Sweden during the second half of the 20th century was driven by institutional and academic initiatives. A key period began in 1966 with the expansion of optics research at the Royal Institute of Technology (KTH), supported by international collaboration.

At the European level, the formation of the European Optical Society (EOS) in 1991 marked a significant milestone, with active participation from Swedish researchers. That same year, the Swedish Optical Society (SOS) was founded as a non-profit organization uniting academia, industry, and government to advance optics and photonics. Symbolically launched on St. Lucy's Day, the society has been dedicated to knowledge dissemination, interdisciplinary collaboration, and ecosystem development.

One of SOS's key contributions was establishing a recurring national optics conference. Initially biennial, it attracted participants from both academia and industry and has since evolved into an annual tradition organized by PhotonicSweden.

These efforts laid the foundation for Sweden's robust and coherent national infrastructure for optical science, research, and innovation.

Photonics Research and Education in Sweden

Sweden has built a strong ecosystem for photonics research and education, where universities and research institutes work closely with industry to drive technological breakthroughs. These institutions not only provide cutting-edge education to train future photonics specialists but also generate high-impact research that feeds into global innovation networks.

Key Universities and Research Institutes

• KTH Royal Institute of Technology (Stockholm)

KTH plays a pivotal role in Swedish photonics through research and education programs spanning biophotonics, quantum photonics, laser physics, nanophotonics, and integrated photonics. The Division of Micro and Nanosystems and the Department of Applied Physics host several pioneering groups working on photonic chips, optoelectronics, and light–matter interaction. KTH is also active in quantum technology initiatives, contributing to Sweden's position in the European Quantum Flagship program.

• Lund University

Lund has long been recognized as a hub for optics and laser physics. Its Lund Laser Centre (LLC) is one of the largest laser research facilities in Europe, attracting both academic and industrial collaborations. Research covers ultrafast optics, high-power lasers, nanophotonics, optical design, and medical optics. The university also hosts NanoLund, a major interdisciplinary research environment dedicated to nanoscience and nanotechnology, where photonics is a key area.

Professor Anne L'Huillier of Lund University was awarded the Nobel Prize in Physics, together with Pierre Agostini and Ferenc Krausz. The prize was awarded "for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter." This groundbreaking work in ultrafast optics has not only advanced fundamental science but also reinforced Sweden's position at the forefront of global photonics research.

(Read more in the press release from the Royal Swedish Academy of Sciences: https://www.nobelprize.org/prizes/physics/2023/press-release/).

• Chalmers University of Technology(Gothenburg)
Chalmers is internationally known for research in quantum photonics, optoelectronics, nanofabrication, and advanced optical communications. The university is home to the FORCE Center (Fiber Optic Research Center) and is active in bio-nanophotonics and semiconductor photonics. Around 50 researchers are engaged in photonics-related projects, contributing to both fundamental science and industry-oriented solutions. Chalmers has also fostered spin-off companies such as EXFO Sweden AB, exemplifying successful technology transfer from research to market.

• Luleå University of Technology (LTU)
LTU specializes in industrial applications of photonics, particularly in Sweden's mining, forestry, and bioenergy sectors. Research areas include laser manufacturing processes, optical sensing for harsh environments, and environmental diagnostics. LTU collaborates extensively with local industries to implement photonics-based solutions that increase sustainability and efficiency in resource-heavy sectors.

• Umeå University
Umeå conducts research in organic electronics, photonics materials, and optical physics, bridging the gap between fundamental material science and photonics applications. Its interdisciplinary approach links photonics with energy storage, biomedical applications, and sustainable electronics.

• Mid Sweden University
Mid Sweden University is recognized for research in advanced materials for photonics, detector technologies, and optical sensors. Their work often focuses on applied photonics, with strong industry connections in areas such as digital imaging, environmental monitoring, and security systems.

• Uppsala University
At Uppsala, photonics research is integrated across disciplines, particularly in biomedicine, electronics, renewable energy, and nanotechnology. The university is active in microscopy, optical materials, and light-based energy harvesting technologies, contributing to sustainable and medical applications of photonics.

• Stockholm University
The Quantum Photonics Group at Stockholm University is engaged in quantum light generation, entangled photon sources, and quantum dot technologies for applications in quantum communication and quantum sensing. This research supports Sweden's contributions to the emerging quantum technology ecosystem in Europe.

• RISE Research Institutes of Sweden AB
As Sweden's largest independent research institute, RISE bridges academia and industry. It offers applied research capabilities in fiber optics, organic electronics, optical metrology, and semiconductor photonics. With access to state-of-the-art laboratories, clean rooms, and pilot production facilities, RISE plays a key role in scaling up laboratory research into industrial innovation.

• SWERIM AB
SWERIM applies photonics in laser processing, optical measurements, and materials characterization, with a strong focus on industrial manufacturing and materials innovation. Its collaborations with Swedish and European industries enable photonics to be embedded in next-generation production technologies.

Thematic Clusters in Swedish Photonics

Quantum Photonics & Fundamental Light Science
Sweden has strong representation in quantum photonics, ultrafast optics, and light–matter interaction, contributing to Europe's quantum technology initiatives.

- KTH Royal Institute of Technology – quantum photonics, nanophotonics, photonic chips.
- Lund University – ultrafast optics, attosecond science (home of Nobel laureate Anne L'Huillier).
- Stockholm University – quantum photonics group: entangled photons, quantum dots, quantum light sources.
- Chalmers University of Technology – quantum photonics, semiconductor nanostructures, optoelectronics.

Biophotonics, Health & Life Sciences Applications
Photonics is widely used in Swedish biomedical and life sciences research, especially for imaging, sensing, and diagnostics.

- KTH – biophotonics, biomedical optics.
- Lund University – medical optics, ultrafast lasers for bio-imaging.
- Uppsala University – optical microscopy, biomedical photonics.
- Chalmers University of Technology – bio-nanophotonics.
- Industrial & Applied Photonics
- Photonics is directly applied to Swedish key industries, including manufacturing, forestry, mining, and energy.
- Luleå University of Technology (LTU) – laser-based manufacturing, harsh-environment sensing, mining applications.
- SWERIM AB – laser processing, optical metrology, materials analysis.

- Mid Sweden University – photonics for imaging, detector technologies, environmental monitoring.
- RISE – applied photonics for industry: fiber optics, semiconductors, metrology.

Materials, Nanophotonics & Energy Applications
Materials research underpins Sweden's photonics innovation, with a focus on nanostructures, organic electronics, and sustainable energy.
- Lund University / NanoLund – nanophotonics, semiconductor nanostructures.
- Umeå University – organic electronics and photonics, optical physics.
- Uppsala University – photonics in renewable energy and nanomaterials.
- Chalmers University of Technology – wide-bandgap optoelectronics, semiconductor photonics.
- RISE – organic electronics, advanced materials.

Communication, Connectivity & Fiber Optics
- Photonics plays a central role in advancing communication systems, fiber optics, and future internet technologies.
- Chalmers University of Technology – FORCE center: fiber optics, optical communications.
- KTH – photonic integrated circuits for communications.
- RISE – fiber optic technologies and testing facilities.

Summary Insight:
Sweden's photonics ecosystem can be seen as four interconnected pillars:
1. **Quantum & Fundamental Science** (KTH, Lund, Stockholm, Chalmers)
2. **Biomedical & Biophotonics** (KTH, Lund, Uppsala, Chalmers)
3. **Industrial & Applied Photonics** (LTU, SWERIM, Mid Sweden, RISE)
4. **Materials, Energy & Communication** (Lund, Umeå, Uppsala, Chalmers, RISE)

This balance between fundamental breakthroughs (like attosecond science) and real-world industrial impact (laser processing, fiber optics, sensing) makes Sweden highly competitive in the global photonics landscape.

The Swedish Photonics Industry
Photonics, the science and technology of generating, controlling, and detecting photons, underpins many advanced systems in modern society. It is widely regarded as a key enabling technology (KET) because of its cross-cutting impact across multiple sectors, including telecommunications, manufacturing, healthcare, defence, transportation, and environmental monitoring. Despite its critical role, photonics often remains embedded and "hidden" within end-user products, making its presence less visible to the general public while being indispensable for technological progress.

Sweden stands out as a significant hub for photonics innovation in Europe, hosting a dynamic ecosystem of companies that develop and commercialize cutting-edge photonic components, systems, and integrated solutions. These companies range from specialized SMEs to globally recognized industrial leaders, addressing applications from biophotonics and quantum technologies to LiDAR and precision manufacturing. The sector's strength lies in its high-value engineering expertise, advanced manufacturing capabilities, and strong integration with global supply chains.

Key Swedish Photonics Companies and Their Core Contributions
Sweden's photonics industry is highly diversified, with companies spanning defence, healthcare, telecom, industrial automation, and consumer electronics. These firms bridge cutting-edge research with commercial solutions, strengthening Sweden's position as a global hub for photonics innovation.

Defence, Security & Imaging
- Aimpoint AB – Global pioneer in red dot reflex sights, widely used by hunters, law enforcement, and armed forces worldwide. Known for robust, energy-efficient, and high-precision optical systems, Aimpoint's technology has become a standard in modern targeting solutions.
- FLIR Systems AB (Teledyne FLIR) – Leader in infrared (IR) imaging and thermal sensing for defense, industrial inspection, and predictive maintenance. Swedish R&D has contributed to miniaturized IR cameras and drone-mounted sensors, critical for both civilian and military use.
- SAAB AB – Integrates advanced optoelectronics and photonics in defense systems, including surveillance radars, optical targeting systems, and communication technologies. Photonics enables SAAB's leadership in next-generation situational awareness and electronic warfare.
- Ir-Nova AB – Specializes in infrared detector modules used in demanding environments, supporting FLIR, SAAB, and international defense applications.
- Spectrogon AB – Produces optical filters, holographic gratings, and thin-film coatings essential for spectroscopy, laser systems, and IR imaging. Its high-precision filters are deployed in military, aerospace, and industrial monitoring systems.

Lasers, Optics & Industrial Photonics
- Cobolt AB (HÜBNER Photonics) – Internationally recognized for single-frequency, ultra-stable CW to fs lasers with superior beam quality. Applications span life sciences, quantum optics, materials processing, and terahertz research.
- Excillum AB – Developer of the brightest X-ray sources in the world, using proprietary metal-jet anode technology. These sources enable breakthroughs in semiconductor metrology, non-destructive testing, and biomedical imaging.
- Optoskand AB (Coherent) – Provides fiber-optic beam delivery systems for industrial lasers used in cutting, welding, and additive manufacturing. Its technology enables precision and reliability in heavy-duty laser machining.

- Latronix AB – Builds laser-based measurement systems for railway monitoring and industrial quality control, ensuring high safety and efficiency in transport and manufacturing.
- Optronic Partner AB – A contract developer specializing in custom optical measurement solutions, from prototyping to full-scale production, serving industrial automation, medical devices, and environmental sensing.
- TYRI Sweden AB – Focuses on advanced photonic lighting systems for off-road vehicles, mining, and construction machinery, enhancing visibility, safety, and energy efficiency in harsh environments.

Telecom, Optical Networks & Fiber Technologies

- Finisar Sweden AB (Coherent) – Designs tunable lasers and photonic integrated circuits (PICs) for ultra-high-speed optical communications. Expertise in InP wafer processes enables 100+ Gbit/s optical transceivers, crucial for data centers and 5G/6G backbone networks.
- NOKIA (former Infinera AB) – Develops optical networking solutions and photonic semiconductors for scalable, high-capacity fiber networks. Swedish operations contribute to global deployments of coherent transmission technologies.
- Nyfors Teknologi AB – Produces precision fiber-optic processing equipment, critical for splicing, coating, and preparing fibers in telecom networks and photonics sensing applications.
- Proximion AB – Specialist in Fiber Bragg Gratings (FBGs), enabling telecom signal processing, structural health monitoring, and harsh-environment sensing (e.g., oil & gas pipelines, aerospace).

Automotive & Consumer Photonics

- Magna Electronics Sweden AB – Designs LiDAR, vision sensors, and advanced driver-assistance systems (ADAS) for the automotive industry. Plays a crucial role in enabling autonomous and semi-autonomous driving technologies.
- Tobii AB – World leader in eye-tracking technologies, with applications in assistive technologies, medical diagnostics, gaming, and AR/VR. Tobii's solutions combine AI and photonics-based sensing for real-time gaze detection.
- Trimble AB – Provides high-precision geospatial solutions, including 3D laser scanning, GNSS, and robotic total stations for construction, surveying, and agriculture.

Advanced Materials, MEMS & Components

- Mycronic AB – Global leader in photolithography and precision dispensing equipment for electronics and flat-panel display manufacturing. Its systems are critical in producing semiconductors and advanced displays.
- Silex Microsystems AB – World-leading MEMS foundry, integrating microfabricated optical and photonic structures into sensors for consumer electronics, automotive, and healthcare.
- SiTek Electro Optics AB – Produces position sensing detectors (PSDs) used in beam alignment, radiation detection, and precision metrology.

- Thorlabs Sweden AB – Supplies a wide range of optomechanical components, lasers, detectors, and integrated photonic systems, supporting both research and industrial photonics globally.

Summary Insight:

Sweden's photonics industry is globally competitive across several sectors:

1. **Defence & Security**
(SAAB, FLIR, Aimpoint, Ir-Nova, Spectrogon)
2. **Lasers & Industrial Photonics**
(Cobolt, Excillum, Optoskand, Latronix, TYRI, Optronic)
3. **Telecom & Networks**
(Finisar, Nokia, Nyfors, Proximion)
4. **Automotive & Consumer**
(Magna, Tobii, Trimble)
5. **Materials & Components**
(Mycronic, Silex, SiTek, Thorlabs)

Together, these firms complement Sweden's academic and research ecosystem, forming a strong photonics value chain from fundamental science to global market leadership.

Strategic Importance and Global Impact

The Swedish photonics industry is deeply interconnected with global markets, supplying critical components and systems to sectors such as semiconductors, automotive, aerospace, healthcare, and communications. By investing in laser technologies, imaging systems, optical sensors, and photonic integration, Sweden contributes significantly to Industry 4.0, smart mobility, and the digital transformation.

Moreover, photonics plays an increasingly vital role in addressing societal challenges, including energy efficiency, environmental monitoring, and healthcare diagnostics, aligning with the European Green Deal and sustainable development goals (SDGs).

Sweden's Photonics Ecosystem, Global Networks, and Activities

Sweden has developed a well-connected and innovation-driven photonics ecosystem, where research, industry, and policy converge to support technological advancement and international competitiveness. This ecosystem is anchored by PhotonicSweden, the national technology platform, and reinforced by active participation in European and global networks.

PhotonicSweden – The National Platform

Founded in 2011, PhotonicSweden serves as the primary coordination and networking body for photonics in Sweden. PS was created through the merger of Swedoptronics, a network of photonics companies, and the outreach and networking activities of the Swedish Optical Society.

- **Membership:** Over **50 organizations** (SMEs, large companies, research institutes, universities) and numerous individual members.
- **Core functions:**
  - **Innovation Support** – Helping companies, especially SMEs, to accelerate the commercialization of photonic technologies.
  - **Networking** – Creating strong connections across academia, industry, and government to promote collaboration.
  - **Policy Engagement** – Acting as Sweden's voice in European and international photonics initiatives, ensuring alignment with EU research and industrial strategies.
  - **Knowledge Exchange** – Organizing workshops, conferences, and training programs that bring together stakeholders across sectors.

EU and International Engagement

Sweden plays an active role in shaping the European photonics agenda.

- **EU-funded projects:** PhotonicSweden participated in 13 EU projects under FP7, Horizon 2020, and Horizon Europe, covering areas such as biophotonics, quantum technologies, smart manufacturing, and optical communications.
- **Photonics21:** Sweden is an active contributor to Photonics21, the European Technology Platform for photonics, which defines Europe's Strategic Research and Innovation Agenda (SRIA) and influences EU funding priorities. Swedish representatives are involved in several Photonics21 working groups (including quantum, life sciences, and manufacturing).
- **Nordic Collaboration:** Strong ties exist with neighboring Nordic countries (Denmark, Finland, Norway) through joint research programs, conferences, and industry partnerships. These collaborations leverage regional strengths in optics, imaging, and telecommunications.

The Optics & Photonics Conference: Sweden's Annual Gathering

Originally initiated by the Swedish Optical Society, the Optics & Photonics Conference has become PhotonicSweden's flagship event. This two-day conference includes academic and industrial sessions, exhibitions, poster presentations, and pitch talks for exhibitors. This event attracts not only attendees and exhibitors from the Nordic countries but also participants from across Europe.

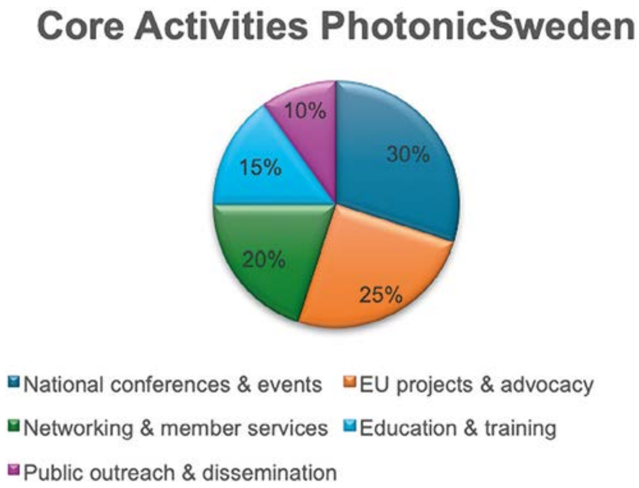
A key addition is the Nordic Photonics Forum, held the day before the conference. This half-day session highlights regional collaboration and funding opportunities across the Nordic countries.

The conference serves as a central meeting point for Sweden's photonics stakeholders and a catalyst for new partnerships and projects.

Optopubs: Informal Networking and Knowledge Sharing

Optopubs are informal seminar sessions that combine technical talks with social interaction. Typically featuring one academic and one industry speaker, they offer a relaxed setting for learning and networking over food and drinks.

Held regularly in Stockholm, Gothenburg, Lund, and Hudiksvall, these events attract 25–70 participants and are hosted by local companies, offering varied perspectives and fostering community engagement.



Key Facts: The Swedish Photonics Industry at a Glance

- **200+** active photonics companies
- **8,000+** professionals employed nationwide
- Estimated annual turnover: **€2–3 billion**
- All major universities engaged in photonics research and education
- Strong international presence and EU project participation
- Semicon Sweden – A new initiative co-funded by the European Union to strengthen the ecosystem and Sweden's position in semiconductors, launched in February 2025, Semicon Sweden is a national effort led by the Swedish Electronics Association with backing from agencies like Vinnova, RISE, Lund University, and PhotonicSweden. The goal is to strengthen Sweden's semiconductor and photonics ecosystem, improve national coordination, and position Sweden as a key European player—especially as part of the EU Chips Joint Undertaking (Chips JU).
- Most Swedish companies involved in photonics primarily identify as part of the broader electronics industry. The Swedish electronics sector directly employs approximately 66,000 individuals and generates an annual turnover of nearly €20 billion. However, when including companies whose products and services critically depend on both electronics and photonics technologies—such as those in telecommunications, automation, medical technology, and advanced manufacturing, the industry's scale expands significantly. This broader category comprises an estimated 8,000 companies, employing around 260,000 people and contributing to a combined turnover of approximately €90 billion annually. These figures underscore the extensive integration and economic impact of photonics as an enabling technology within Sweden's high-tech industrial landscape.

GRAVITATIONAL-WAVE ASTRONOMY: A CENTURY AFTER EINSTEIN, AND TEN YEARS AFTER THE FIRST DETECTION

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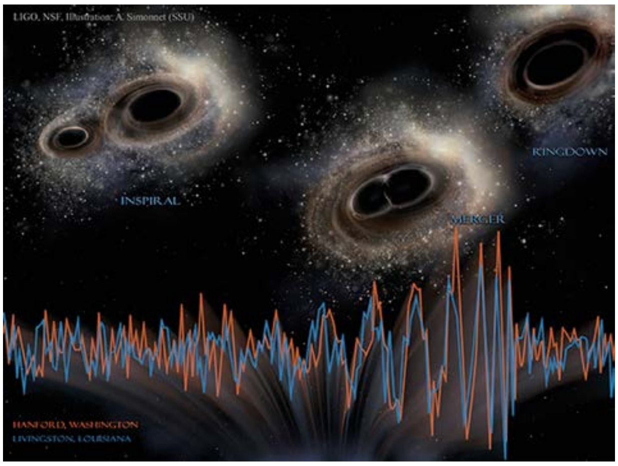


Since Einstein's 1916 prediction, gravitational-wave astronomy has evolved into a mature observational science. After early conceptual debates and bar-detector attempts, kilometer-scale laser interferometers LIGO achieved the first detection in 2015 (GW150914), opening a new window for astronomy and enabling new tests of general relativity.

https://doi.org/10.1051/photon/202513448

With Virgo joining in 2017, the LIGO and Virgo detectors and about 70 telescopes all around the world allowed the first multi-messenger event (GW170817), tightly constraining the speed of gravity, revealing r-process nucleosynthesis in a kilonova, and introducing "standard siren" cosmology. By September 2025 the network, including now also the Japanese KAGRA, has reported nearly 300 candidate gravitational-wave sources (more than 200 published), enabling population studies of black-hole masses and spins, evidences of intermediate-mass black holes, and mixed systems. Here we review the historical developments, key technological milestones, and science highlights.

On September 14, 2025, we have celebrated the tenth anniversary of the first detection of gravitational waves (the event called GW150914). Predicted by Albert Einstein in 1916 through the linearization of his general relativity field equations, these waves are oscillations of spacetime geometry that propagate at the speed of light and are emitted by the acceleration of asymmetric compact systems—such as a binary black hole system. Gravitational waves had a difficult beginning: Einstein himself, in his 1916 article, wrote that in all possible situations, their amplitude would be practically zero [1]. He was clearly aware of the challenge of deforming spacetime, a medium that is elastic yet extremely rigid, and even more, of making it vibrate. Of course, in 1916 the existence of compact objects like black holes and neutron stars was not yet known, and the idea of massive bodies like the Sun rotating near the speed of light with the density of atomic nuclei would have seemed like fantasy. In 1936, Einstein denied the existence of gravitational waves, unable to identify them as exact solutions to his equations. Fortunately, the article, written with Nathan Rosen, known for both the EPR paradox and the *Einstein–Rosen bridges*, was never published, since a reviewer identified an inconsistency. Shortly thereafter, Einstein and Rosen corrected the error and published a different conclusion [2]. Yet, a fundamental question remained: even if such waves exist mathematically, can they be detected? Do they possess a physical reality? Can they deposit energy in a detector? This dilemma persisted until 1957, at the famous Chapel Hill conference, where some of the leading researchers in relativity concluded that the passage of gravitational waves would indeed modify the distance between free-falling test masses, and that if these masses were coupled to a dissipative element, the passage of the wave would generate heat [3].

From Weber's bars to interferometry

At the beginning of the 1960s, the experimental quest began. The first attempt to detect gravitational waves was carried out by the American physicist Joseph Weber, who introduced resonant bars: metallic cylinders designed to oscillate at their resonant frequency when traversed by a gravitational wave. In 1969, Weber went as far as to claim the detection of several signals, which might have originated from galactic supernovae [4]. However, it soon became clear that the recorded signals were too intense to be attributed to gravitational waves. Despite this, Weber had the merit of launching

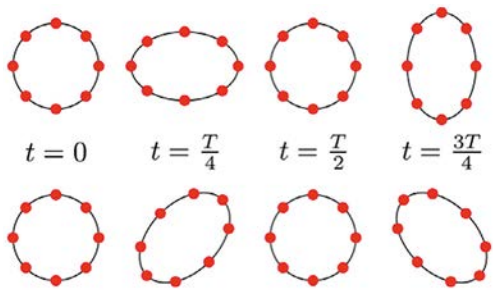
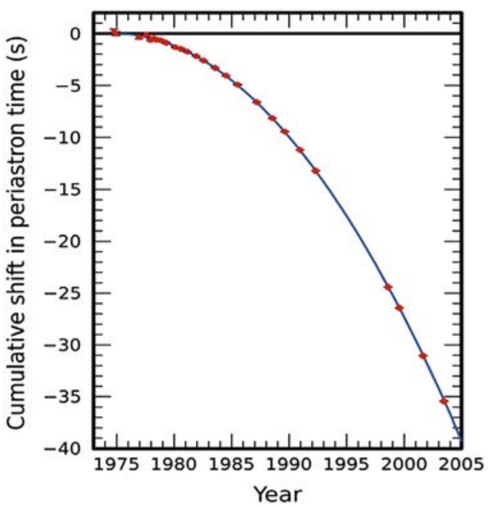


Figure 1. a system of freely falling masses when a gravitational-waves passes through the plan of the page.

the experimental efforts and introducing a fundamental idea: that of coincident detection using instruments separated by large distances, in order to exclude local noise sources, such as seismic activity, electrical glitches, or transient mechanical or electronic disturbances specific to individual instruments. During the same period, two Russian physicists, M. E. Gertsenshtein and V. I. Pustovoit, understood that the Michelson interferometer, the same instrument for which Albert Abraham Michelson received the Nobel Prize in 1907, had the right characteristics for detecting gravitational waves. In 1972, Rainer Weiss, a young physics professor at MIT in Boston, conducted a detailed analysis of the noise sources limiting the sensitivity of such an instrument, and proposed a conceptual scheme for a gravitational-wave detector. This would become one of the foundational ideas that led to LIGO and Virgo. The document, about thirty pages long, was not formally published at the time, but remained an internal MIT report [5]. Also for this work, Weiss would later be awarded the Nobel Prize in Physics, together with Kip Thorne and Barry Barish, for their decisive contributions to LIGO. In parallel, neutron stars were being discovered in the form of pulsars, by Jocelyn Bell Burnell. At the same time, the first black hole candidates began to emerge from X-ray astronomy. The invention of the laser in 1960 opened the way for the first prototypes of laser interferometers. One of the earliest was developed by Robert Forward in Malibu: although its sensitivity was ten orders of magnitude worse than that of today's LIGO and Virgo, it represented a crucial first step toward interferometric detection of gravitational waves [6].

Figure 2. Evidence of orbital decay of PSR B1913+16 Source : https://en.wikipedia.org/wiki/Hulse–Taylor_pulsar



Binary pulsars and the proof of the gravitational-wave existence

In 1974, two American radio astronomers, Russell Hulse and Joseph Taylor, discovered the binary pulsar PSR B1913+16, a system composed of two compact objects, one of which is a pulsar. The presence of the pulsar - a highly precise cosmic clock - allowed for extremely accurate orbital measurements and made it possible to test general relativity in strong-field conditions. This discovery earned the two scientists the 1993 Nobel Prize in Physics. Observations of the system over several years showed that the orbital period was decreasing over time, in spectacular agreement with •••

the theoretical predictions of gravitational-wave emission. This provided the first confirmation of the existence of gravitational waves, as predicted by Einstein's theory [7].

The birth of large interferometers

In the 1980s, large-scale projects were proposed: two detectors in the United States (to enable coincidence detection), which would become LIGO, and a third near Pisa (Italy), Virgo, the result of a Franco-Italian collaboration that has since grown into a broader European effort. Meanwhile, other experimental prototypes and key technological developments emerged: vibration isolation systems to isolate the test masses from the seismic noise and create an almost "free fall" condition in the frequency region of interest, improvements in lasers, mirror coatings and a deeper understanding of fundamental noise sources. Particular attention was devoted to quantum noise (including *squeezing*, following the early works of Carlton Caves in the 1980s [8] and Brownian thermal noise, studied by Peter Saulson [9] and others). France played a crucial role in several of these technological developments, especially in laser stabilization, mirror coatings, optical metrology, and interferometric simulations, contributions that remain essential today.

The commissioning and the "single machine"

At the beginning of the new millennium, LIGO and Virgo were "switched on", and the long and arduous *commissioning* phase began: the period between the end of detector integration and the start of scientific data-taking. The goal was to bring the detector into its operational regime and begin the systematic identification and mitigation of noise sources. Although theoretical models had driven the design of these instruments, their originality - and the extreme displacement sensitivity required, of the order of 10^{-18} meters - meant that several noise sources, their coupling mechanisms, and their mitigation strategy had to be studied experimentally and *in situ*. Furthermore, their target sensitivity lies in a frequency range around 100 Hz, a region relatively new for precision metrology, where a dense "forest" of noise sources, including environmental, technical, and control-related noise, makes detection even more challenging. The first-generation versions of LIGO and Virgo did not succeed in detecting gravitational waves. Around 2011, both detectors were upgraded to their second-generation configurations: *Advanced Virgo* and *Advanced LIGO* [10,11]. This meant replacing mirrors, lasers, suspending optical benches and improving vibration isolation. Meanwhile, an important political development had occurred: LIGO and Virgo had signed a data-sharing and joint-publication agreement. Since 2007, they have effectively operated as a single global observatory, a "single machine", capable of triangulating and localizing sources. In fact, unlike telescopes, LIGO and Virgo are non-directional: they observe the entire sky, continuously. In order to pinpoint a source, one must compare the arrival times of the gravitational-wave signal at least of three detectors. Beyond being a great scientific and technical adventure, the detection of gravitational waves has also proven to be a visionary exercise in international cooperation.

GW150914: The Birth of Gravitational-Wave Astronomy

In 2015, the first observing run of LIGO began. Virgo, due to a two-year historical delay from the time of its funding, was not yet ready. Just two days after the start of the data taking, LIGO observed a signal, lasting a fraction of a second, in coincidence between its two detectors. The event was interpreted as the merger of two black holes, each of approximately 30 solar masses, located at a distance of about 1.3 billion light-years. The signal was unmistakable, although for reasons of caution, it took the scientific community five months to finalize the analysis and announce the discovery.

Figure 3. LIGO Hanford interferometer. Source : https://www.ligo.caltech.edu/image/ligo20150731er

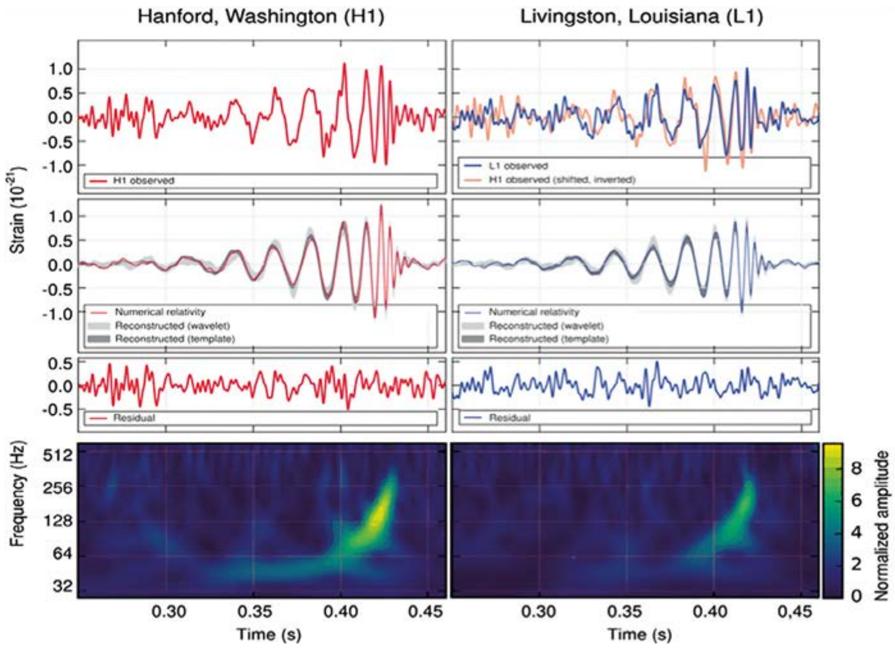


Figure 4. GW150914, the first gravitational-wave detection
Source : https://en.wikipedia.org/wiki/First_observation_of_gravitational_waves

The detection was published by the LIGO and Virgo Collaborations, comprising more than a thousand scientists. With that detection (GW150914) gravitational-wave astronomy officially began [12]. This first signal not only enabled the first direct detection of gravitational waves, but also demonstrated that black holes can exist in binary systems and can merge within the age of the Universe. Moreover, general relativity was tested in a completely new regime: that of strong gravitational fields. The detected waveform was compared to a combination of analytical models (valid especially during the inspiral phase) and numerical simulations (necessary during the merger and ringdown phases). If general relativity had been incorrect, the orbital dynamics of the objects, and therefore the emitted waveform, would have differed. But the match was remarkably precise.

Virgo joins LIGO: The era of multi-messenger astronomy

In 2017, Virgo officially joined LIGO in the second observing run (O2). On August 14, the first triple detection - with signals observed by both LIGO detectors and Virgo - was recorded: a binary black hole merger (GW170814) [13]. This event marked a fundamental step forward, demonstrating the power of triangulation in improving the sky localization of gravitational-wave sources. Just three days later, on August 17, the gravitational-wave community observed a truly historic event: GW170817, the first detection of a binary neutron star merger [14]. The gravitational-wave signal was emitted first, followed 1.7 seconds later by a short gamma-ray burst detected by NASA's *Fermi* and ESA's INTEGRAL satellites. The combined observation enabled an extremely precise •••

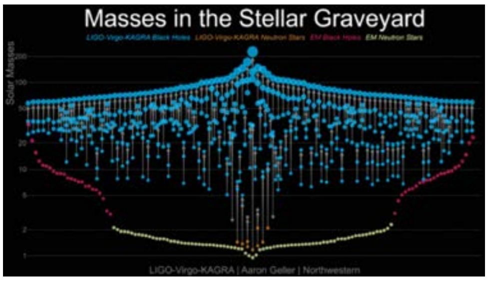


Figure 6. Gravitational-wave sources detected by the LIGO-Virgo-KAGRA (GWTC4.0 catalog) Source: https://www.ligo.caltech.edu/news/ligo20250826

measurement of the speed of gravitational waves: their velocity matches that of light to within one part in 10^{15}, ruling out a wide class of modified gravity theories that had been proposed to explain dark energy. Thanks to the localization capabilities of the Virgo-LIGO network, about 70 telescopes around the globe, spanning almost the entire electromagnetic spectrum, were able to quickly point toward the source, located in the galaxy NGC 4993, about 130 million light-years away. Among them was the Hubble Space Telescope. This coordinated effort led to the discovery of an optical transient, the so-called *kilonova*, produced by nuclear reactions following the merger of the two neutron stars. The spectral and photometric analysis of the kilonova light confirmed the presence of heavy elements (such as gold, platinum, and lanthanides), thus validating the long-standing hypothesis that such mergers are key sites for r-process nucleosynthesis [15]. Moreover, this joint detection enabled a new method to measure the Hubble constant, by combining the gravitational-wave luminosity distance with the electromagnetic redshift of the host galaxy. This so called *standard-siren* approach provides a completely independent way from those using Type Ia supernovae or the cosmic microwave background, and is therefore essential in addressing the ongoing Hubble tension [16].

Technological advancements and the rise of compact objects population studies

Around 2018, one of the most significant upgrades was introduced into the detectors: the implementation of squeezed vacuum states of light. This technique, originally theorized in the early 1980s by Carlton Caves, reduces quantum noise, particularly at high frequencies, by manipulating vacuum fluctuations. The application of squeezed light marked the beginning of a new generation of quantum-enhanced gravitational-wave detectors [17]. In 2019, data-taking resumed for the third observing run (O3). Between 2019 and early 2020, before the interruption caused by the COVID pandemic, nearly 100 gravitational-wave sources were detected. This volume of events allowed the community not only to highlight exceptional signals, but also to begin conducting population studies. By combining the properties of multiple sources, researchers could derive statistical distributions of mass and spin for observed black holes and begin investigating whether these distributions are consistent with theoretical predictions. For example, the third gravitational-wave transient catalog (GWTC-3), published in 2021, revealed an excess of black-hole with masses near 35 solar masses, raising questions about their mechanism of formation [18]. These studies opened the door to a statistical astronomy of compact objects, no longer focused solely on rare or spectacular events, but on the global structure and demographics of the gravitational-wave sky.

Toward a global network: new detectors, KAGRA and the O4 data taking

After 2020, the detectors underwent further changes. In particular, LIGO managed to increase its power and implemented a specific form of squeezing, called *frequency-dependent squeezing*. Virgo introduced the so-called *signal recycling* mirror (already present in LIGO), with the aim of enhancing the detector's bandwidth, and the optimization of this configuration is still underway. Meanwhile, in 2023, data collection resumed with a fourth observing run (O4) involving the international network of terrestrial interferometric detectors, currently known as LVK (LIGO–Virgo–KAGRA), and soon to be called IGWN,

Figure 5. Virgo, source: https://www.ligo.caltech.edu/image/ligo20170927b

the *International Gravitational-Wave Network*. Virgo joined the the data taking in 2024 and the Japanese detector KAGRA, located underground and designed to operate at cryogenic temperatures, joined the run despite a sensitivity still insufficient for full scientific contribution. However, it continues to make steady progress, and will become the first cryogenic interferometer once fully operational. A fifth detector, LIGO-India, is currently under construction as a collaboration between the United States (providing instrumentation) and India (providing infrastructure such as the vacuum tubes and site). Once completed, it will significantly improve the localization accuracy of the network. Since the beginning of O4, more than 200 candidate events have been identified (by rapid search algorithms), mainly binary black hole mergers, with a detection rate of approximately 2–3 per week. The full analyses are forthcoming, but some "exceptional" systems have already been identified, including a merger that produced a final black hole of about 200 solar masses, in the intermediate-mass black hole region. These events are of great interest, not only because they expand the *taxonomy* of astrophysical objects, but also because they challenge formation theories. In particular, at least one of the black holes observed in the GW231113 event (23 November 2023) appears to lie within the "mass gap" between 60 and 130 solar masses, where no black hole remnants are expected due to pair-instability supernova.

Ten Years of Gravitational-Wave Astronomy

Ten years after the first detection (GW150914), the global detector network has observed nearly 300 candidates gravitational-wave sources, including about 200 published events at the time of writing (September 2025, see [19]). This corresponds to mainly black holes mergers, while two confirmed neutron star mergers and a few mixed events (black hole + neutron star) have been identified.

Thanks to the LIGO–Virgo–KAGRA collaboration, new astrophysical windows have been opened. Gravitational-waves allow us to:

- Perform tests of general relativity
- Address key cosmological questions such as the value of the Hubble constant
- Explore the mass distribution and formation pathways of black holes
- Probe the interior structure of neutron stars
- Localize transient for rapid electromagnetic follow-up

While advanced data analysis techniques, play a crucial role in improving detection efficiency, the future of gravitational-wave science fundamentally depends mainly on instrumental progress: better mirrors, more powerful lasers, improved isolation systems, more sophisticated squeezing schemes—and crucially, sensitivity at lower frequencies (down to 10 Hz or even below), where technical and environmental noise sources are most challenging. Many R&D efforts around the world are now focused on preparing upgrades to LIGO and Virgo in the 2030s, and on the next-generation observatories: the Einstein Telescope (ET) in Europe and Cosmic Explorer (CE) in the United States. These facilities, currently under study, are designed to have much longer arms and are therefore far more sensitive.

So, happy 10th birthday GW150914, and happy birthday to LIGO, Virgo, and KAGRA. Looking forward to new surprises and to a new sky made by spacetime vibrations.

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Using quantum correlations to study black holes: squeezing techniques for quantum noise reduction in gravitational wave detectors

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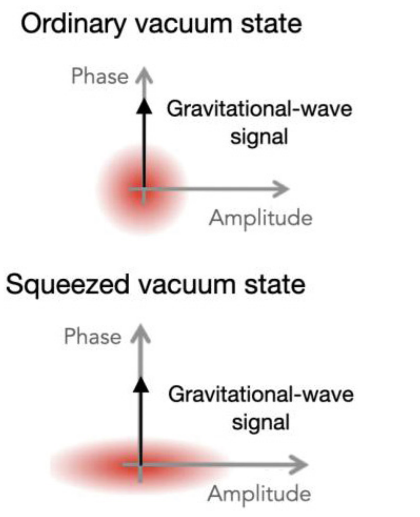

"Experimenters might then be forced to learn how to very gently squeeze the vacuum before it can contaminate the light in the interferometer."

Carlton Caves, 1981

Since 2015, the gravitational-wave detectors LIGO and Virgo have opened a new window on the universe, detecting hundreds of signals and launching a new era of astronomy with profound impact on relativity, astrophysics, and cosmology. To listen deeper into the cosmos, detectors must become increasingly sensitive. One of the main limitations is quantum noise, ultimately arising from vacuum fluctuations entering the instrument. By "squeezing" this vacuum, i.e. manipulating its noise properties, LIGO and Virgo have already extended their reach by up to 65%, revealing events that would otherwise remain hidden. This article provides an overview of squeezing techniques for gravitational-wave detectors, from their origins to the most recent advances.

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In April 2019, the gravitational-wave detectors LIGO and Virgo switched on for their 3rd observation run (O3) after a period of upgrade which allowed them to consistently increase their astrophysical reach. Among the many actions taken during the break, the most remarkable was the injection of a specially prepared quantum state, known as squeezed vacuum. Thanks to this technique, quantum noise, which is the primary factor limiting the instrument's sensitivity, was significantly reduced, allowing the detectors to observe over 50% more black hole mergers. In other words, out of every 10 black holes detected, 3 are observable specifically because of vacuum injection. Although counterintuitive, squeezing injection is arguably the most impactful application of quantum vacuum fluctuations developed to date. An unconventional economist might even venture to quantify, in millions of euros, the value of the vacuum itself.

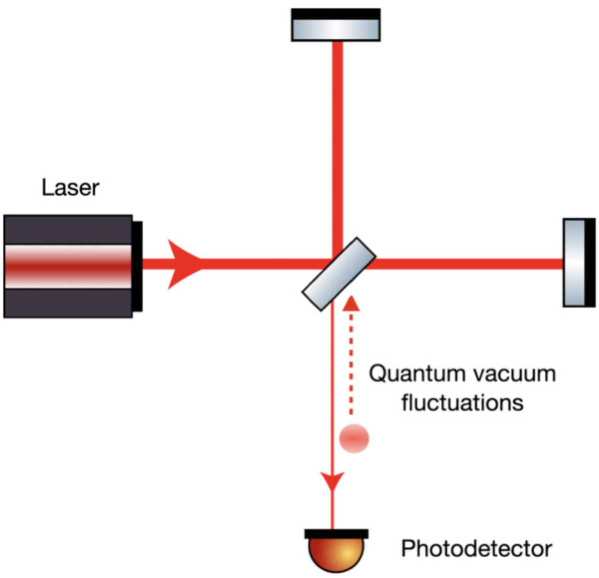
The technique relies on manipulating quantum fluctuations to redistribute uncertainty between the quadratures of the optical field. To understand how vacuum allows us to observe more distant gravitational wave sources, we need to take a step back and address the two theories that revolutionized physics in the 20th century: general relativity and quantum mechanics. Let's begin with the first.
In 1915, Albert Einstein, predicted that spacetime is curved, revolutionizing our

understanding of physics' most fundamental concepts. Einstein showed that Newton's theory of universal gravitation, in which gravity is an instantaneous force between masses, is actually an approximation of a more general theory.

The new theory of general relativity became the framework through which we study the universe at large scale, stars, and new, exotic objects discovered in the 20th century, such as pulsars, black holes, and neutron stars. Soon after publishing his famous equations relating energy and matter to spacetime curvature (the field equations of general relativity), Einstein discovered that a specific solution to these equations involved waves. In other words, the curvature of spacetime, produced by violent phenomena in the universe, can propagate through space, just as electromagnetic waves do. When an extremely energetic phenomenon shakes spacetime, it vibrates, such ripples of the spacetime, called gravitational waves spread throughout the universe.

However, spacetime is extremely rigid and the distortion produced by gravitational waves is incredibly small. We now know that the most powerful sources observed by LIGO and Virgo produced a change in the detector baseline (which is a few km) smaller than the size of an atomic nucleus. Such extremely precise measurement has been done for the first time by LIGO in 2015 [1], and then jointly by LIGO and Virgo in 2017 and it was possible after more than 50 years of experimental development of interferometric detectors. These instruments, known as Michelson interferometers, operate on a simple principle: a laser beam is split into two by a beam splitter and the two paths travel along two perpendicular arms, each several kilometers long. At the

Figure 1. Simplified schematic of a gravitational-wave detector showing the entry points of vacuum fluctuations that give rise to shot noise.



ends of the arms, mirrors reflect the beams back toward the beam splitter. The returning beams recombine at the interferometer output, producing interference. The output power depends on the difference in the arms' lengths. A passing gravitational wave induces a differential change in the arm lengths, altering the interference condition and causing a measurable power variation at the detector output.

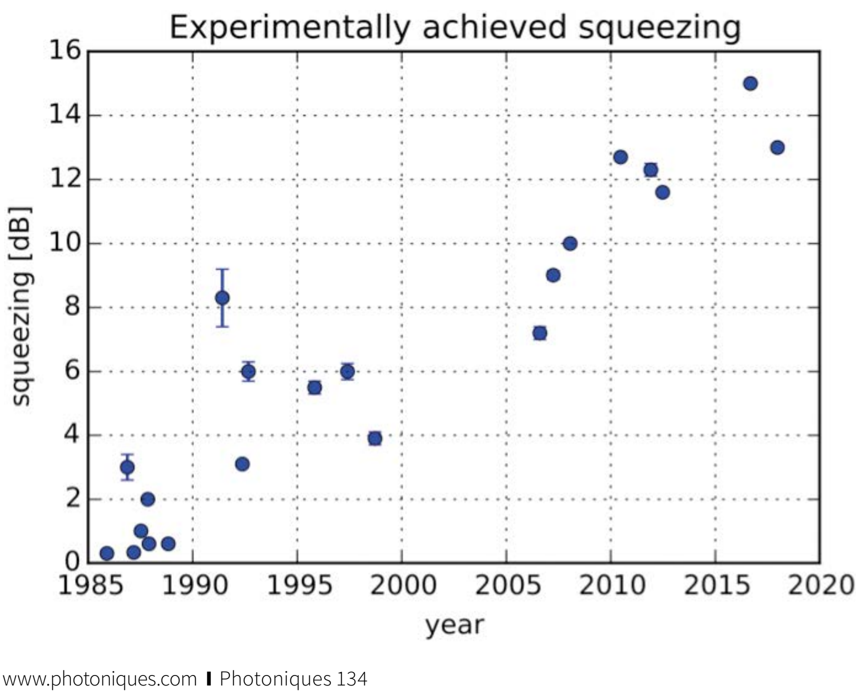
The challenge in these measurements lies in reducing every possible source of noise that could mask the tiny variations caused by gravitational waves (of the order of 10^{-19} m over 3 km). Over the past 10 years since the first detection, more than 300 gravitational wave events have been measured from merging compact objects, especially binary black hole systems. This new form of astronomy has already unveiled a new cosmos: previously unobserved binary black hole systems and a new population of more massive black holes. They have also enabled new measurements of the universe's expansion rate, contributing to a major scientific debate that may lead to a crisis in modern cosmology. Over the next decade, gravitational waves will provide even more insight into cosmology, nuclear physics, and astrophysics—and may even offer clues to a quantum theory of gravity, *the holy grail* of theoretical physics.

To push this scientific program forward, detectors must increase their sensitivity more and more. This is a challenging task, as lowering the noise level becomes increasingly difficult when approaching the fundamental limits of the instruments. The main limiting factor is quantum noise, which constrains the detector sensitivity across much of its frequency band (10 Hz to a few kHz). In a semi-classical view, quantum noise arises because light consists of photons. The photon arrival rate in a laser beam follows a Poissonian distribution, meaning the power on a photodiode fluctuates around a mean value. This results in the so-called "shot noise," which limits the precision with which changes in the interferometer's output power can be measured. Reducing shot noise can be achieved by increasing the laser power, as fluctuations scale more slowly than the photon flux. This strategy has been employed and additional power enhancements are planned in upcoming instrument upgrades. Nonetheless, it presents two notable limitations: on one hand, it increases radiation pressure, a random force arising from fluctuations in the arrival times of photons on the interferometer's test masses (i.e., the mirrors), which causes random motion of the mirrors masking the effect of gravitational waves. Moreover, elevated laser power induces thermal effects that deform the interferometer mirrors, introducing optical aberrations which substantially degrade sensitivity and may compromise detector operation.

But light is not just particles; it is also a wave. When we apply quantum mechanics to light, by quantizing the electromagnetic field, we get a different and powerful view of quantum noise. This insight came from the physicist Carlton Caves in the 1980s. While investigating how laser radiation pressure affected detectors, Caves developed a fully quantum picture of quantum noise in the interferometer and realized that it actually comes from the vacuum fluctuations [2]. Such fluctuations, also known as "zero-point fluctuations" allow virtual particles (like photons) to be created and destroyed temporarily, due to Heisenberg's uncertainty principle. They are also responsible for laser spontaneous emission, the Lamb shift, and the Casimir effect (a force between two metal plates in vacuum).

In a fully quantum picture, laser light can be described by a coherent state. Such a state is characterized by the fact that its phase and its amplitude (which are two canonically conjugate variables) have the minimum possible uncertainty allowed by the Heisenberg principle. This laser state can be represented in the phase–amplitude plane as a circle displaced from the origin by an amount corresponding to the laser's amplitude. A vacuum state is also a coherent state, a state with minimum uncertainty, with zero amplitude and its representation in the phase-amplitude plane is a circle cantered in the origin (See Fig. 3 left panel). The key point to keep in mind is that laser and vacuum are much alike when it comes to considering their fluctuations; the only difference is that these fluctuations occur around a given amplitude for the laser and around zero

Figure 2. Timeline of experimentally achieved squeezed-light levels since the first demonstration in 1985, showing steady improvements in noise reduction over time.
From wikipedia: https://commons.wikimedia.org/wiki/File:Squeezed-light-timeline.svg



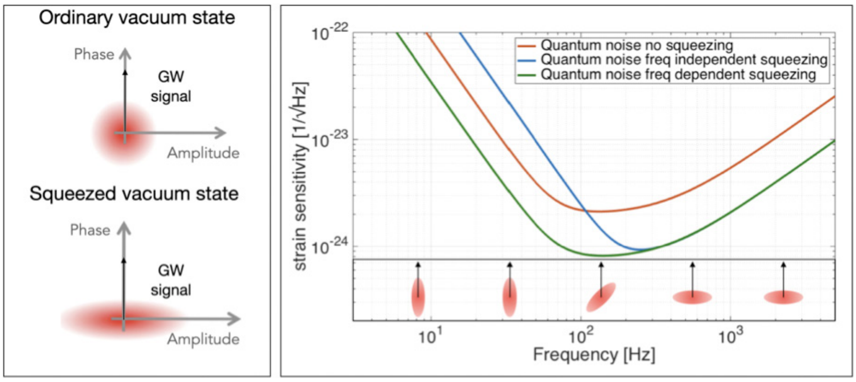


Figure 3. Left panel: Phase–amplitude quadrature representation of a coherent vacuum state (top) and a squeezed vacuum state (bottom). In the coherent case, uncertainties are equal in both quadratures, while in the squeezed case noise is reduced in one quadrature and increased in the other. Right panel (top): Quantum noise reduction achieved by injecting frequency-independent phase squeezing (blue) versus frequency-dependent squeezing (green). Frequency-independent squeezing reduces noise only at high frequencies, increasing it at low frequencies, while frequency-dependent squeezing provides broadband noise suppression. Right panel (bottom): Rotation of the squeezing angle by 90° across the frequency spectrum, caused by optomechanical coupling with the interferometer's suspended test masses. This rotation misaligns the low-noise quadrature with the gravitational-wave signal when only frequency-independent squeezing is used.

for the vacuum. Since such fluctuations are responsible for quantum noise, we cannot limit ourselves to consider those that enter the interferometer with the laser from the bright port but we should also take into account those entering with the vacuum from the output port. Surprisingly enough, while the fluctuations from the laser cancel out when the two beams interfere at the beam splitter, those entering from the output port do not, they recombine with the laser power in the arms and become the ultimate responsible for the quantum noise (See Fig. 1).

This insightful picture of interferometer quantum noise also enabled Caves to propose a fascinating solution: we should manipulate the vacuum fluctuations entering through the output port to "reshape" them and reduce their harmful effects.

We have to say "reshape" and not just "reduce" because in a coherent state, amplitude and phase fluctuations cannot be arbitrarily reduced. In fact, the Heisenberg principle dictates that the product of the uncertainty for two conjugate quadratures (as phase and amplitude in this case) cannot be lower than a given amount. What we can do is to reduce the fluctuation in one quadrature at the expenses of the other. Such a manipulated state, known as squeezed state, has uneven fluctuation in the two quadratures, and can be represented by an ellipse instead of that of a circle (See Fig 3, left panel). It is important to notice that since the interferometer measures phase changes, the uncertainty circle must be squeezed along the appropriate direction to reduce noise. In 1981, Caves proposed this groundbreaking approach to reduce quantum noise without increasing the laser power. In his paper, *"Quantum-Mechanical Noise in an Interferometer"*, he wrote:

"Experimenters might then be forced to learn how to very gently squeeze the vacuum before it can contaminate the light in the interferometer."

It took nearly 40 years of experimental development before squeezing began to be routinely used in LIGO and Virgo. This squeezing is generated using an Optical Parametric Oscillator (OPO), which consists of a nonlinear crystal inside an optical cavity, pumped by a laser at twice the frequency of the light used for the interferometric detection. In the case of LIGO and Virgo, which operate in the near infrared at 1064 nm, the pump laser for the OPO is a green light at 532 nm. The OPO is operated below threshold (meaning the pump power is too low to generate a bright output beam) and the nonlinear crystal inside it enables a process called parametric down-conversion, where energy from the pump can virtually split into pairs of lower-frequency photons. Although no real light is emitted, this interaction modifies the quantum fluctuations of the vacuum field exiting the OPO. The result is a squeezed vacuum state, where noise is reduced in one quadrature (e.g. the phase) and increased in the other one [3].

It sounds simple, but it is much more challenging in practice. Over the years, researchers have progressively increased the level of squeezing produced, that is the ratio between the reduced fluctuations and those of standard vacuum, usually expressed in dB (see Fig.2). However, achieving a significant reduction of quantum noise in the detectors is made difficult by several reasons.

One is that squeezed states are extremely fragile: any optical loss encountered by the squeezed beam reduces its squeezing level. In fact, quantum mechanics tells us that losses cause the squeezed vacuum to recombine with ordinary vacuum, degrading the effect proportionally to the importance of the loss. Optical losses occur everywhere in the interferometer: from transmission through Faraday isolators and anti-reflective mirror coatings, to scattering caused by surface imperfections, and the light picked off for extracting control signals. Minimizing these sources of loss as much as possible is essential to fully exploit the beneficial effect of squeezing on quantum noise. To give an idea, achieving high levels of quantum noise reduction (around 10 dB) requires keeping total optical losses below 8% along the entire optical path.

Another challenge concerns frequency. Virgo and LIGO operate at low frequencies (10 Hz–10 kHz), a range dominated by various disturbances such as electronic, acoustic, and laser frequency noise. Squeezing is far much easier to achieve at MHz frequencies, where these •••

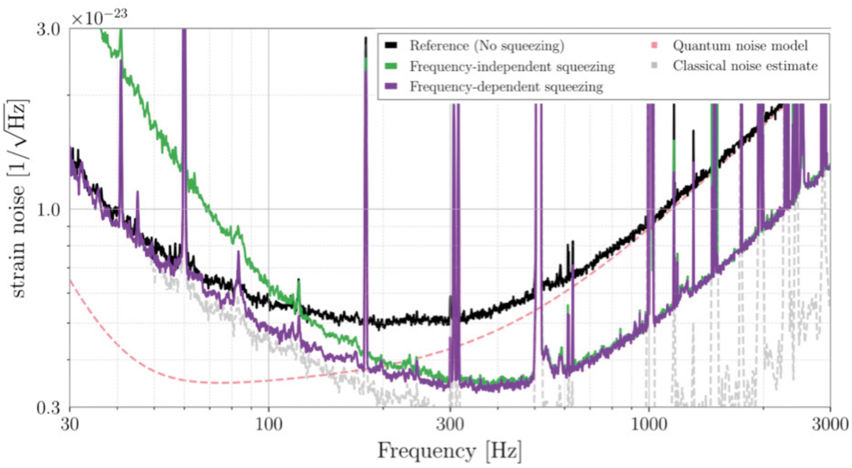


Figure 4. Observation of frequency-dependent squeezing in the LIGO Livingston detector. Noise spectra without squeezing (black) are compared to measurements with frequency-independent (green) and frequency-dependent (purple) squeezing. Frequency-independent squeezing reduces shot noise by 5.8 dB near 1 kHz but increases radiation pressure noise at low frequencies. While, frequency-dependent squeezing yields a 1–2 dB broadband noise reduction from ~60 Hz to 1 kHz, enhancing sensitivity across the whole band. Figure from [8].

disturbances are far less significant. The world is much quieter in the MHz region, with respect to the forest of disturbances in the Virgo-LIGO operation bandwidth. It took, then, decades to learn how to produce a high level of squeezing in the frequency band relevant for gravitational-wave detectors. Finally in April 2019, after months of prototyping and commissioning, squeezed vacuum is injected into Virgo and LIGO. Quantum noise drops by 3 dB: the same effect as doubling laser power. This increases detection rate by up to 50% for the LIGO–Virgo network. It is a great experimental success [4,5].

However, a closer look at the sensitivity below 50 Hz reveals a slight increase in noise when squeezing is injected. The reason is subtle: the reduced-noise quadrature (the minor axis of the squeezing ellipse), which is aligned with the phase quadrature to match the gravitational-wave signal, undergoes a 90-degree rotation at low frequencies due to the opto-mechanical interaction with the suspended test masses.

This means that, at low frequencies, the fluctuations (i.e., the noise) are actually amplified compared to the case where standard vacuum is injected. In practice, the effect is similar to that of a power increase, though without the drawbacks of mirror heating and other issues discussed above. Although the sensitivity degradation induced at low frequency because of this effect was barely observable during Observation Run 3 due mainly to the presence of technical noises, it is expected to become more and more detrimental as the detectors approach their design sensitivity.

Fortunately, a solution was found to enable broadband quantum noise reduction: the injection of frequency-dependent squeezed (FDS) vacuum, in which the squeezing ellipse rotates as a function of frequency to compensate for the rotation induced by the interferometer (see Fig.3, right panel). Such rotation of the squeezing ellipse can be obtained reflecting the frequency independent squeezed states by an optical cavity (known as filter cavity) operated slightly out of its resonant condition. In practice this rotation is produced by the cavity's asymmetric reflection of the upper and lower sidebands of the vacuum field. A detailed explanation and quantitative discussion can be found in [6]. Squeezing angle rotation in the region of interest for gravitational wave detectors has been demonstrated with a full-scale filter cavity prototype in 2020 [7].

For the next observation run (O4), started in May 2023, these frequency-dependent squeezed states have been produced combining the frequency independent squeezed state previously used in Virgo and LIGO with 300 m long suspended filter cavities. LIGO is currently injecting frequency dependent squeezing, obtaining an impressive broadband quantum noise reduction (See Fig. 4) reaching up to 5.8 dB at high frequency and producing an increase in the detection rate of 65%. [8]. As for Virgo, despite the successful construction of the frequency dependent squeezing source [9], it is not yet

Figure 5. View inside the Virgo tunnel showing the filter cavity vacuum pipe running alongside the north arm of the interferometer.

injected into the interferometer, as the low-frequency sensitivity is not yet good enough to take advantage of it. Squeezing will be a key technology also for future detectors. Over the coming years, Virgo, LIGO, KAGRA, and third-generation detectors like the Einstein Telescope will continue improving the squeezing performances aiming to push squeezing levels up to 10 dB, corresponding to a noise reduction by a factor of three. To this purpose ongoing R&D efforts are focusing on reducing losses and adapting squeezing states to different detector configurations. Moreover, the community is investigating alternative quantum noise reduction techniques such as speed-meters, conditional frequency-dependent squeezing, white-light-cavity based schemes or quantum teleportation [10,11].

In conclusion, although quantum principles impose fundamental constraints on the sensitivity of gravitational wave detectors, they also enable strategies to circumvent the Heisenberg limit (of course without violating it!) through the implementation of squeezing techniques. What is truly fascinating is that by exploiting the principles of quantum mechanics at microscopic scales, we can significantly enhance our capacity to investigate the universe at a much larger scale. ●

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SAILING TO THE STARS WITH PHOTONICS

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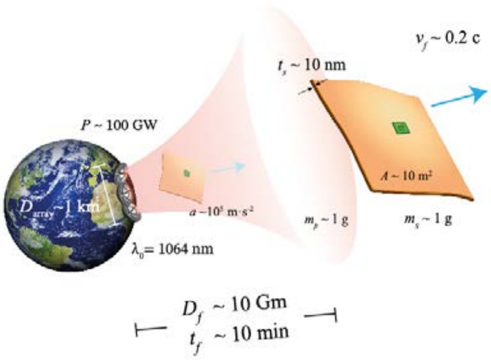

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Probing nearby star systems would take thousands of years for today's spacecrafts due to the immense distances between us and our stellar neighbours. In recent years, lightsails have gained interest as physically realistic interstellar vehicles. Lightsails are envisaged to be thin, highly reflective and lightweight membranes accelerated by high-power lasers up to substantial fractions of the speed of light. This ambitious endeavour entails substantial challenges, the solutions of which are rooted in photonics.

About 4.2 light years away, our nearest stellar neighbour, Proxima Centauri, harbours a planet in an orbit compatible with the existence of liquid water. Could it be home to life? From our own solar system, we can only gather indirect evidence that often raises more questions than it answers. Sending an exploratory probe would only make sense if it could send information back within one or perhaps a few human lifetimes. This would require speeds exceeding 10% of the speed of light, which simply cannot be attained by standard rocketry or by any spacecraft that carries its own source of energy and reactive mass. To reach relativistic speeds, an external source of momentum is needed.

From the beginning of electrodynamical theory, light was predicted to carry momentum, which could be transferred to matter upon absorption or reflection. The magnitude of this radiation pressure is small for everyday light intensities, and it is only with the advent of lasers and their extreme intensities that the effect could be exploited for applications on small length scales like optical tweezers and in fields of study like cavity optomechanics. On a larger scale, solar sails composed of highly reflective thin films can take advantage of the freely available light from the sun and its associated momentum. While its intensity at realistic distances is modest compared to lasers, the small radiation pressure can accumulate over long times to provide attitude and orbit control within the solar system. Several solar sail demonstrations have been successful, with a growing presence in the space community as a cheaper alternative for interplanetary exploration.

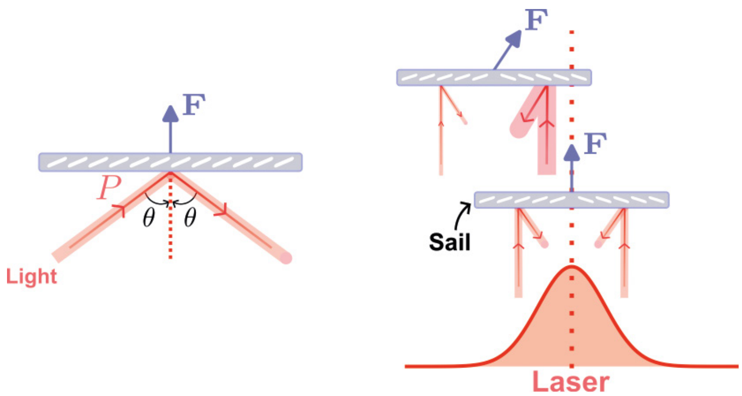
To go further, beyond our own solar system, the sun's intensity provides insufficient acceleration. The idea of *lightsails*, in contrast to solar sails, is that propulsion is provided by lasers with much higher intensities than that of the sun, enabling relativistic speeds. While first proposals became literally the work of science fiction [1], recent technological progress and "Moore's law" for lasers are bringing lightsails and interstellar exploration within reach.

Every aspect of an interstellar lightsail mission represents an extreme engineering challenge, but all are possible within known laws of physics [2]. Project designs envisage an extremely low mass sail (10 m^2 in area but less than 10 grams total), carrying a chip-like payload containing imaging or spectroscopic equipment and a communication laser [3]. A massive, kilometre-sized Earth-based laser array with a mind-boggling 100 GW of power accelerates the sail to 20% of the speed of light over ten or so minutes (see abstract graphic). The lightsail then cruises to Proxima Centauri over 20 years, takes a few pictures of its exoplanet and sends them back to Earth one photon at a time. It may sound farfetched, but an increasing number of scientists believe the many challenges of this mission can be overcome over the next several decades.

SENDING AND RECEIVING: THE LASER AND COMMUNICATIONS

The primary obstacle to the mission is the laser array, with the main concern being not only its power, but its size: the laser must be capable of focusing onto the small sail area until it reaches its target velocity. The sail acceleration, limited by material strength, leads to a predicted acceleration distance of order 10^{10} m, almost 10% of the distance to the Sun, while the laws of diffraction impose a laser-aperture diameter on Earth of order one kilometre. The entire array must be coherent with phase control to compensate for atmospheric turbulence and be able to compensate for the rotation of the Earth. Researchers have proposed hierarchical modular fibre-laser arrays, which work with internal phase sensing, or could be adapted with orbiting lasers for a coherent phase reference compensating the atmospheric fluctuations. To minimise atmospheric absorption, the laser wavelength is proposed to be in the near-infrared (NIR, *e.g.* 1064 nm—1550 nm). With current fibre-laser technology, the cost of such a laser would exceed one trillion • • •

The fundamental principle enabling solar sails and lightsails is radiation pressure. Light incident upon a perfectly reflecting mirror at an angle θ experiences a radiation pressure force $F = 2P\cos^2\theta\hat{n}/c$, where P is the power intercepted by the mirror and $\hat{n}$ is the normal to the mirror surface. This equation holds in the ray-optics regime, where the characteristic size of features on the sail is much larger than the light wavelength. For more general scattering, wave optics can be applied to calculate the radiation pressure force. This often applies to sail structures, such as metasurfaces, that scatter light non-specularly, i.e. with components transverse to the incident light propagation. Transverse scattering is necessary for lightsails to remain centred within a propelling laser beam, maximizing propulsion and ensuring accurate transport to the sail destination. Indeed, the sail's scattering profile and laser beam's intensity profile can be designed in tandem such that small displacements from the beam's propagation axis change the proportion of power intercepted on sections of the sail [4]. This affects the light scattering in the transverse plane, enabling the sail to restore itself to the beam centre.



dollars. However, "Moore's law for lasers" predicts the same power laser would be up to three orders of magnitude cheaper within thirty years, becoming comparable to the budget of other large-scale science projects. Solar-cell farms can now fill areas in excess of one square kilometre – could phase-controlled, coherent, large-surface photonic crystal semiconductor lasers one day do the same [5]?

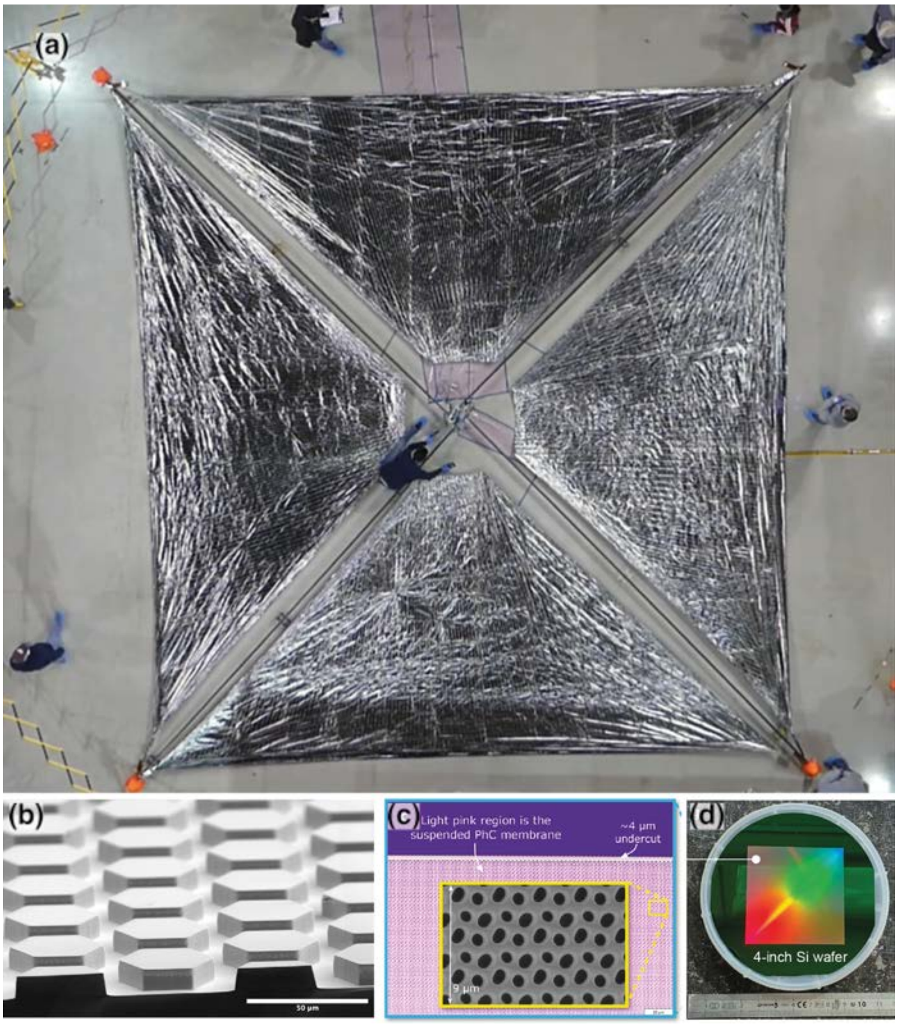
Once the sail reaches Alpha Centauri, it must send data back to Earth. The best bet is using an onboard laser, ideally repurposing the sail itself as a reflective mirror and using the immense aperture of the Earth-based accelerating laser as a detector. Powering the transmitter, pointing its beam towards Earth and isolating transmitter photons from those of the vastly brighter Proxima Centauri in proximity will be very challenging. No concrete engineering solutions have been proposed yet, but estimates of photon counts and possible modulation schemes have been analysed. Again, no laws of physics need to be violated, but this area will need much further study.

SAIL DESIGN AND MATERIAL SELECTION

If the sheer scale of the laser seems daunting, the constraints on the sail make it at least equally challenging: the sail must be extremely light, highly reflective, capable of withstanding tremendous accelerations in excess of 10,000g, and must remain taut and stable within the beam. All while surviving irradiation by the 100 GW laser beam.

To avoid overheating, the sail must be minimally absorptive at NIR wavelengths, where the laser is likely to operate, which precludes any metallic reflective coatings commonly used in solar sails, instead favouring dielectric reflectors [6]. Bragg reflectors come to mind as highly reflective dielectric-only structures, but the reflectivity benefit of additional layers is rapidly offset by the mass they add. Instead, single-layer, thin, high-index dielectrics are often optimal in terms of acceleration. Photonic crystals and metasurfaces have emerged as better solutions to optimise acceleration: properly designed photonic crystals based on arrays of holes have lower mass than dielectric slabs (e.g. Figure 1c), all while having increased reflectivity. In addition, non-specular reflections from photonic crystals, and phase shift from metasurfaces, can provide transverse forces needed for stabilising the sail in the beam (see below and the insert). An important design aspect to consider when designing the photonic properties of sails is that, for a 0.2c mission, the laser wavelength shifts by up to 22% due to the Doppler effect. Photonic

Figure 1. Experimental lightsail structures. (a) NASA's Advanced Composite Solar Sail System, a solar sail launched in 2024. The size of the sail is roughly that envisioned for a laser-driven mission. Reproduced from [https://www.nasa.gov/smallspacecraft/what-is-acs3/]. Copyright 2024 NASA. (b) Scanning electron micrograph (SEM) of a hexagonally corrugated lattice trilayer (Al_2O_3-MoS_2-Al_2O_3, scale bar 50 micron), a highly reflective lightsail candidate. Image kindly provided by M. Campbell as part of the work [M. Campbell *et al.*, arXiv:2508.05035 (2025)]. (c) SEM of a pentagonal-lattice photonic crystal with numerically optimized hole shapes. The entire fabricated structure is 60 mm × 60 mm. Adapted from [7] under a CC BY 4.0 licence. Copyright 2025 Springer Nature. (d) Fabricated Si3N4 circular-hole photonic crystal on a Si wafer, possessing enhanced broadband reflection. Adapted from [J. Chang *et al.*, Nano Lett. **24**, 6689–6695 (2024)] under a CC BY 4.0 licence. Copyright 2024 American Chemical Society.



solutions must thus be relatively broad band. Greater than 50% reflectivity averaged over the full Doppler band has been demonstrated in the lab on fabricated Al_2O_3-MoS_2-Al_2O_3 photonic crystals that are less than 200-nm-thick (Figure 1b), while other groups have developed membranes as large as 60 mm × 60 mm [7] (Figure 1c), a substantial step towards metre-scale lightsails.

Even minimal absorption in the sail leads to heating, which must be re-radiated into the vacuum of space, requiring high emissivity at mid-infrared (MIR) wavelengths. Materials like silicon that have high refractive index, and thus strong reflection, can be marred by excessive absorption without providing sufficient emissivity in the MIR. To prevent the temperature reaching material limits, the simplest solution is to add a highly MIR-emissive layer such as silica on the space-facing side. An even more promising strategy for simultaneous propulsion and thermal regulation comes from nanopatterning. Photonic crystals can be patterned at the NIR length scale, achieving high reflectivity, but further structured at the larger MIR length scale to resonantly enhance the sail emissivity. Alternatively, more advanced active photonic cooling mechanisms have been proposed, such as rare-earth-ion doping in the sail as used in solid state laser cooling. The most likely sail material candidates are thus dielectrics with high tensile strength to withstand the acceleration, high refractive index, low NIR absorption and crucially, the ability to be manufactured as large scale patterned freestanding films.

An area that requires more investigation is the sail's spatial temperature distribution and evolution. Dust particles are anticipated to be a significant source of heating, both from impact on the sail and, if they attach to the membrane, as a localised absorption site. Strategies to mitigate dust impacts (e.g. through detaching locally heated segments or shielding) are needed. In comprehensive thermodynamic simulations of sail-temperature evolution, a silicon nitride sail was shown to be effective at staying below its melting point over the full extent of the simulation, however, the simulation time was limited to just a few seconds due to computational costs (in comparison to the several-minutes-long acceleration phase).

STABILITY DESIGN

One of the biggest challenges with the lightsail mission is the sail's dynamical stability. The sail should intercept as much beam power as possible and stay on course to its target, so it must be confined within the laser beam for the entire acceleration phase lasting several minutes. Stability is nontrivial given continuous perturbations from, for example, atmospheric beam distortions or laser noise. There is no mass budget available for traditional stabilisers like thrusters, and the round-trip time of photons back to the laser is too long for closed-loop stabilisation. Stabilisation must thus be achieved locally on the sail, and be passive, ideally stemming from the radiation-pressure profile itself [2].

In essence, two mechanisms are required: restoring forces/torques and damping forces/torques. The restoring forces and torques trap the sail within the laser beam area, whereas damping forces and torques diminish the amplitudes of oscillations excited by perturbations. Passively generating restoring and damping can be done using the incoming laser momentum. However, this presents an inherent trade-off: laser momentum that is otherwise reflected specularly, thus providing maximum propulsion, must be partly scattered perpendicularly to the beam propagation to create transverse forces and torques (see the insert).

Restoring forces act like a spring, growing in magnitude with the distance between the sail centre and the laser-beam axis, guiding the sail back to the beam centre. In practice, this would be achieved by the sail scattering light in the same direction as the displacement from the laser-beam axis, thus repositioning towards the beam centre by conservation of momentum [4]. Restoring torques are similar, relying on changes in scattering with changes in angle relative to the ideal orientation. The simplest designs that exhibit such restoring properties are ● ● ●

geometrically shaped mirrors, such as an inverted cone flying apex-down in a parabolic-intensity beam. Yet, photonic crystals and metasurfaces have emerged as superior candidates with restoring mechanisms because they can provide stability with a planar geometry (having better beam interception efficiency for a given mass) in a Gaussian beam, and can come with the enhanced scattering dispersion needed for torques and damping forces.

Restoring forces alone under continuous excitation by perturbations lead to oscillations with growing amplitude, with the sail eventually leaving the beam and shooting off course. To keep these in check, damping forces and torques are required, which oppose velocities away from the beam axis and oppose destabilising angular velocities. Damping in the vacuum of space is tricky. One way to achieve it is by altering the magnitude of restoring forces and torques over time through parametric or adiabatic damping. This can be done through active feedback by periodically switching the laser off, or more naturally, through the sail's dispersive scattering response and slow change of wavelength (Doppler shift) over the course of acceleration. More promising suggestions involve explicitly velocity-dependent forces, such as adding an internal damped degree of freedom into the sail (like earthquake dampeners in skyscrapers) or using relativistic optical effects (e.g. the relativistic Doppler effect, used in fields of study like cavity optomechanics). For instance, damping the rotational motion of a lightsail is possible using the Doppler redshift and blueshift of light on the portions of the sail rotating away from and towards the laser, respectively. The advantage of photonic structures like gratings is apparent for these methods, as they can dramatically enhance any change in scattering due to minute changes in wavelength – but taking advantage of this dispersion over the full Doppler shifted band is challenging.

The best way to stabilize sails is still an active topic of theoretical investigation, and we don't yet have the technology to make finely structured thin membranes on the scales required for interstellar missions. However, increasingly large, high-quality membrane photonic crystals have been fabricated in the lab (Figure 1c, d). Researchers have measured non-specular scattering from fabricated gratings and found consistency with the requirements of self-stabilizing lightsail motion. Moreover, direct radiation pressure measurements of restoring forces using a torsional pendulum apparatus or tethered membranes have been successful.

CONCLUSION

Lightsails are the most promising spacecrafts for reaching near-relativistic speeds, opening highways into new star systems, and providing answers to the fundamental question of our place in the universe. While not entirely realistic with today's technology, based on current pace of progress in laser and fabrication technology, many researchers believe an interstellar mission could be launched within a few decades.

Many challenges, such as large-scale lasers and nanofabrication, will find progress driven by other industries and scientific endeavours including telecoms, semiconductor manufacturing, defence, and fusion research. We expect that once these technologies mature enough for the price tag of the required lasers to be within grasp of large-scale science projects such as LIGO or the LHC, the prospect of an interstellar mission will encourage more targeted research into practical implementations of lightsail missions, which in turn will spur technological advances across scientific fields. The comparison with LIGO is one that often appears among lightsail researchers. To us, lightsails are where LIGO was fifty years ago, when the detection of gravitational waves, requiring the resolution of shifts less than the width of a nucleus over 4 km interferometric arms, seemed to be farfetched science fiction. Many technical challenges were posed without obvious solutions. But with the resolve of visionary scientists, gravitational wave astronomy is now a reality, and perhaps in another fifty years, incentivised by progress in photonic technologies, interstellar probes will be too.

ACKNOWLEDGEMENTS

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COMPUTING WITH FIBER-OPTICS SOLITONS

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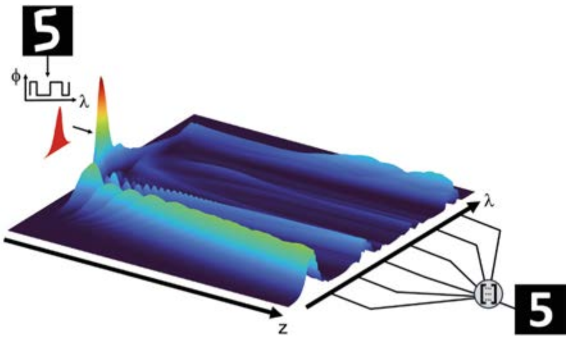

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Optical solitons, discovered in optical fibers fifty years ago, have long been celebrated as robust manifestations of nonlinear wave physics. Initially conceived as candidates for long-haul communications, their role has since evolved toward a broader landscape of nonlinear dynamics and ultrafast photonics. In one of their most recent applications, they have emerged as computational blocks for optical machine learning. Nonlinear fiber dynamics naturally generate high-dimensional feature spaces, robust nonlinear transformations, and femtosecond-scale processing speeds, properties that electronics cannot match.

In this perspective, we focus on soliton-inspired optical computing, with particular emphasis on fiber-based extreme learning machines (ELMs). We highlight recent experimental demonstrations and numerical modeling that establish soliton propagation as a potential powerful computational substrate. We also discuss opportunities and challenges for taking advantage of nonlinear fiber dynamics in machine learning, from multimode soliton processors to hybrid integrated systems, and argue that solitons may enable the next generation of ultrafast, energy-efficient, and noise-resilient computing.

The discovery of optical solitons in fiber optics in the early 1970s marked a milestone in nonlinear science [1]. Solitons, formed from the balance of Kerr nonlinearity and chromatic dispersion, represent self-organized states of light propagating without distortion over long distances. Fiber solitons were first extensively studied in the context of high-capacity telecommunications systems, driving many advances in the design of modern optical systems. More recently, they have had major impact in the development of broadband supercontinuum light sources, where soliton dynamics play a central role in driving the spectral broadening. Beyond these applications, solitons have influenced diverse areas of physics and served as a versatile testbed for nonlinear wave theory. Today, solitons are again finding a new application, this time as computational primitives for optical computing. As electronics approach fundamental speed and energy limits, nonlinear photonics provides an attractive route to achieve ultrafast, energy-efficient information processing. Solitons, with their robustness, dynamics, and compatibility with ultrafast lasers, provide a natural basis for optical machine learning hardware.

FIBER-OPTICS SOLITONS AS COMPUTATIONAL PLATFORM

The benefit of optical computing lies in harnessing the intrinsic properties of light: massive parallelism, ultrahigh bandwidth, and the ability to harness its nonlinear response. Within the different photonic computing approaches, extreme •••

learning machines (ELMs) have emerged as particularly well suited to implementation in optical systems due to their simplicity. In contrast to deep neural networks, ELMs avoid iterative training of hidden layers: the input weights are fixed by the physics of the medium, while only the output weights are optimized in a linear step. This approach maps naturally onto nonlinear fiber propagation, where data encoded on ultrashort pulses evolves under the nonlinear Schrödinger equation, producing a complex and high-dimensional representation of the input in a single pass. Essentially, the fiber acts as a physical "kernel generator," projecting input data into a rich feature space that can then be linearly processed for learning or classification tasks.

Soliton dynamics provide particularly powerful routes for this kind of dimensionality expansion. Indeed, processes such as soliton fission, dispersive wave generation, and Raman-induced frequency shifts diversify the temporal and spectral content of the light field in a highly nonlinear yet deterministic manner. These mechanisms effectively create a broad set of nonlinear kernels, where the resulting spectral (and temporal) patterns are both high dimensional and sensitive to the encoded input. Such features directly correspond with the requirements of machine learning, providing natural bases for classification, regression, and other data-driven tasks. In this way, soliton-induced dynamics transform optical fibers into functional learning machines, bridging nonlinear wave physics with modern computational standards.

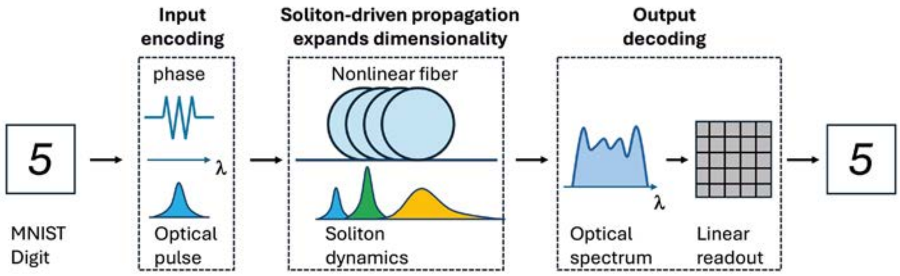

Figure 1. Concept of soliton-based optical computing. Input data encoded onto ultrashort pulses propagates through a nonlinear fiber where soliton dynamics expand the dimensionality of the signal. The resulting high-dimensional spectral features are processed by a linear readout enabling machine learning tasks such as digit classification.

IMPLEMENTATION

Recent advances by several groups have provided both experimental and numerical evidence that soliton dynamics can serve as the basis for optical machine learning. In our own recent experimental study [2], highly nonlinear fibers were used to implement an extreme learning machine, where input data encoded onto the spectral phase of femtosecond pulses was transformed through nonlinear propagation (see Figure 1 for a concept illustration). Task-independent analysis based on principal component analysis (PCA) showed that the effective computational dimensionality depends strongly on fiber length, dispersion regime, and input power, with up to 100 independent components generated under optimal conditions. These intrinsic metrics highlight how nonlinear propagation enriches the feature space, even though maximal spectral broadening does not necessarily correspond to maximal dimensionality. Task-dependent evaluation, using the MNIST digit recognition benchmark, confirmed that performance is optimum at intermediate power levels where dimensionality expansion is balanced by output consistency. The MNIST database is a widely used machine learning dataset consisting of 70,000 images of handwritten digits 0–9. Using this task, the system achieved a classification accuracy of 88% exceeding the linear baseline 82% when encoding 40 PCA and demonstrating that reliable computational features emerge before the onset of nonlinear instabilities.

Complementary numerical simulations [3], based on the generalized nonlinear Schrödinger equation, provided further insight. A realistic numerical model of a fiber-ELM reproduced classification accuracies exceeding 90% and showed how parameters such as dispersion profile, encoding strategy, and readout bandwidth shape performance. The simulations also studied the role of intrinsic noise, with anomalous-dispersion soliton fission suffering more from noise penalties, while normal-dispersion operation proved more robust.

Similar conclusions were reached in other recent demonstrations of neuromorphic computing based on soliton dynamics [4] where the coherent cascade of nonlinear dynamics enabled digital operations such as XOR, efficient classification of benchmark datasets, and even real-world tasks such as COVID-19 diagnosis in a compact fiber platform. More broadly, supercontinuum generation has been benchmarked as an analog computing element [5] with detailed parameter scans showing that the rich spectral diversity of the continuum acts as a universal function approximator and improves neural tasks such as autoencoding. The concept of nonlinear inference capacity was also recently introduced in fiber-optical extreme learning machines [6], showing that increasing optical nonlinearity can scale the computational depth to a level that can compete with deep neural networks.

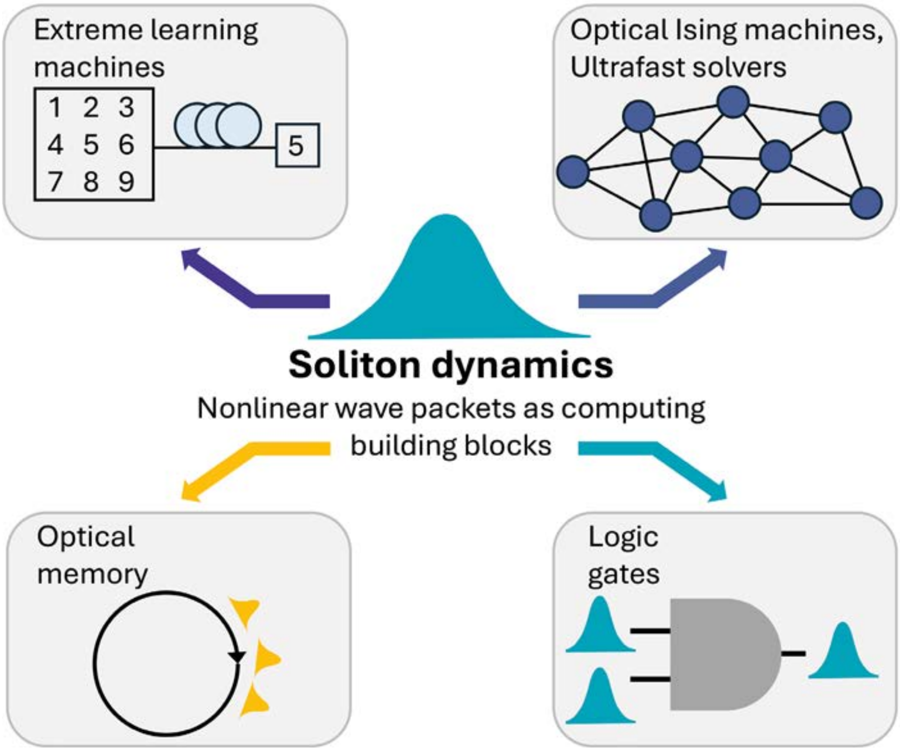

Figure 2. Applications of solitons as computational building blocks. Soliton dynamics provide a versatile platform for optical computing. Their robustness and nonlinear interactions enable a range of applications, including extreme learning machines for data classification, optical Ising machines and ultrafast solvers for optimization, optical memory based on circulating solitons, and logic gates constructed from soliton collisions and interactions.

Together, these results highlight a key distinction from electronic machine learning hardware. In electronics, nonlinear mappings are explicitly programmed into layered architectures, and dimensionality is expanded through iterative matrix operations. In contrast, soliton-driven fiber propagation physically generates a high-dimensional feature space in a single ultrafast pass, with dynamics governed by well-understood nonlinear physics rather than algorithmic construction. This makes the fiber itself a tunable kernel generator, inherently parallel, ultrafast, and energy efficient. In this sense, soliton dynamics provide not just an optical analog of electronic accelerators, but a new computational substrate well suited for machine learning.

FUTURE DIRECTIONS

Looking ahead, soliton-based computing opens several promising directions. Using multimode fibers would allow spatiotemporal solitons, orbital angular momentum states, and intermodal interactions to provide additional computational degrees of freedom, effectively expanding the dimensionality. Integration with metasurfaces, silicon photonics, or 2D materials may yield compact, tunable processors that combine the richness of fiber dynamics with the scalability of integrated platforms. Beyond ELMs, soliton physics offers opportunities to implement optical Ising machines [7], ultrafast optimization solvers, and neuromorphic processors operating at femtosecond timescales (see Figure 2 for a concept illustration). The broadband character of soliton interactions could make them attractive for edge AI in optical communication networks, where computation could be embedded directly into the transmission medium. Furthermore, soliton chaos and noise-resilient states may enable entirely new computing architectures such as stochastic optical processors.

CONCLUSION

Solitons have been a cornerstone of nonlinear optics for five decades. Today, they are re-emerging not only as a subject of fundamental study but as a resource for computing. By bridging nonlinear wave physics with artificial intelligence, soliton-based computing opens a path toward ultrafast, energy-efficient, and noise-robust photonic processors. From long-haul communications to learning machines, solitons continue to find new applications in photonics. ●

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QUANTUM SENSORS AND THEIR LIMITS

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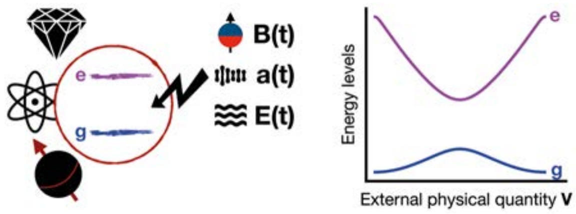

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A fundamental aspect of quantum systems lies in their extreme sensitivity to external perturbations. This characteristic, which generally represents a considerable challenge for physicists seeking to isolate these systems in order to observe their quantum properties, can actually be transformed into an advantage. Indeed, this intrinsic sensitivity makes quantum systems ideal candidates for high-precision metrology. Quantum sensors exploit this susceptibility to measure physical quantities with precision difficult to match with classical approaches.

To illustrate how quantum system and their interaction with the environment can be tuned for a given application, it is interesting to consider the example of the single-Cooper-pair box. Composed of a small superconducting electrode connected to a reservoir via a Josephson junction, the Cooper-pair-box constitutes an artificial two-level system that can be used as a qubit: the charge qubit. By controlling the exact configuration, particularly the ratio of Josephson energy to charging energy, this type of superconducting circuit can be made sensitive or unsensitive to charges, a characteristic directly observable in the transition energy spectrum as a function of the effective charge offset (see Fig. 1). While quantum information processing demands systems that are highly isolated from environmental noise to preserve quantum coherence, quantum sensors deliberately exploit their interaction with the environment.

In this context, it is interesting to precisely identify the important properties required for a quantum sensor. Quantum sensors constitute a specific class of measurement devices that exploit the properties of quantum mechanics to detect and quantify physical quantities. Inspired by DiVincenzo's criteria for quantum computers, Degen *et al.* [1] proposed that a quantum sensor is distinguished by four essential characteristics:

- (i) The system must possess discrete energy levels, a fundamental characteristic of quantum systems.
- (ii) It must be possible to initialize the system in a well-defined quantum state, generally the ground state or a specific superposition state.
- (iii) The system must be able to be manipulated coherently, thus allowing controlled quantum operations.
- (iv) The quantum system must interact with the physical quantity of interest V(t), and this interaction must modify the transition energy of the system, generally in a linear or quadratic manner.

These criteria define a conceptual framework that encompasses a wide variety of physical systems - from cold atoms to nitrogen-vacancy color centers in diamond, to Josephson junctions and superconducting qubits. It also becomes apparent that what distinguishes quantum sensors from their classical counterparts is not so much their size or microscopic nature, but rather the exploitation of fundamental principles of quantum mechanics in the measurement process itself.

QUANTUM ADVANTAGES IN METROLOGY

Quantum sensors do not merely exploit the properties of microscopic systems; they take advantage of the very principles of quantum mechanics to achieve superior performance. Several fundamental advantages can be identified [1]:

- The quantization of energy levels offers an absolute reference for measurements, unlike classical systems that often require external calibration. Although not a sensor in the strict sense of the term, atomic clocks exploit the transition frequency between two energy levels of an atom, thus providing a time reference of remarkable stability. This is actually a quantum technology that we use daily since it is an integral part of the satellite positioning system.
- Quantum superposition allows for simultaneously exploring multiple configurations of the system. This superposition enables the implementation of quantum measurement algorithms, such as the quantum phase algorithm, which offer algorithmic advantages over classical approaches.
- Quantum entanglement allows for non-classical correlations between different parts of the measurement system, enabling the surpassing of precision limits accessible to classical strategies. This approach notably allows for surpassing the standard quantum limit.

Finally, the discrete nature of quantum interactions (for example, the absorption or emission of individual photons) allows in some cases ultimate sensitivity to extremely weak signals, up to the detection of single events.

FUNDAMENTAL LIMITS OF QUANTUM METROLOGY

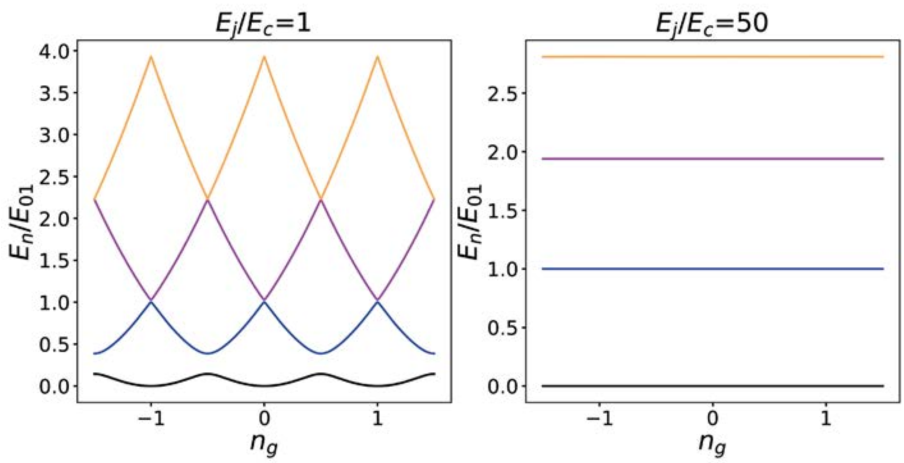
From a formal point of view, the precision of estimation of a parameter ϕ is bounded by the quantum Cramér-Rao inequality [2] by $\Delta\phi \geq 1/\sqrt{(n\,FQ)}$, where n is the number of independent measurements and FQ is the quantum Fisher information, which quantifies the maximum sensitivity achievable for a given quantum state. Due to the additivity of quantum Fisher information, an important fundamental limit follows directly from this inequality: the standard quantum limit (SQL) with a dependence on $1/\sqrt{n}$. This limit, known as shot noise in quantum optics, assumes nothing more than classical statistical correlations between different measurements. It therefore does not allow for fully exploiting the quantum nature of the system and probes. An obvious strategy to exceed this limit is therefore to use quantum effects such as entanglement to introduce correlations. Nevertheless, quantum mechanics still sets ultimate precision limits through Heisenberg-type uncertainty relations, which are sometimes referred to as Heisenberg bounds with a dependence on $1/n$.

An emblematic example of the application of these concepts is the Advanced LIGO gravitational interferometer, designed for the detection of gravitational waves. In its initial configuration, this instrument operated at the standard quantum limit. The use of squeezed states of light allowed for redistributing the quantum noise between different complementary observables, thus reducing the noise in the quadrature of interest and allowing for crossing the SQL barrier over a wide frequency range [3].

ADVANCED QUANTUM STATES FOR METROLOGY

While the coherent state -- considered as the most classical-like quantum state -- present equal fluctuations for phase and intensity, squeezed states on the other hand can have much smaller fluctuation for one of the quadrature to the expense of the other (see Fig. 2). This reduction of the fluctuation is essential to overcome the SQL as it allows to greatly reduce the uncertainty for a well-chosen observable. Yet, while quantum squeezing allows for exceeding the SQL, other more sophisticated quantum states are better suited to approach the ultimate Heisenberg limit. ● ● ●

Figure 1. Transition energies for the first 4 levels as a function of the charge offset n_g, normalized to the 0 → 1 transition n_g=0 (E_{01}). The left panel illustrates the case when the charging and Josephson energies are equal, and the right panel illustrates the case when the Josephson energy is 50 times larger than the charging energy (transmon regime).



Among these, N00N states represent a particularly interesting example [4]. A N00N state corresponds to a quantum superposition of the form |N,0⟩ + |0,N⟩, where N particles (typically photons) are simultaneously in one or the other of two possible modes. The metrological interest of these states lies in their increased sensitivity to perturbations: a N00N state accumulates a phase N times faster than a classical state containing the same number of particles.

To illustrate this phenomenon, let us consider an entangled two-photon state |2,0⟩ + |0,2⟩ passing through a medium inducing a phase shift ϕ. While a classical two-photon state would acquire a global phase of 2Δϕ, the entangled state develops a phase of 4Δϕ, thus doubling the sensitivity of the measurement [5]. More generally, for an incident N00N state, the probability of finding the state |N,0⟩ + exp(iNϕ)|0,N⟩ is given by $q(\phi)=\cos^2(N\phi/2)$. The error on the phase is then obtained by $\Delta\phi=\Delta q/(\partial q/\partial\phi)=1/N$, the Heisenberg limit. This amplification of sensitivity constitutes the very signature of the quantum advantage in metrology.

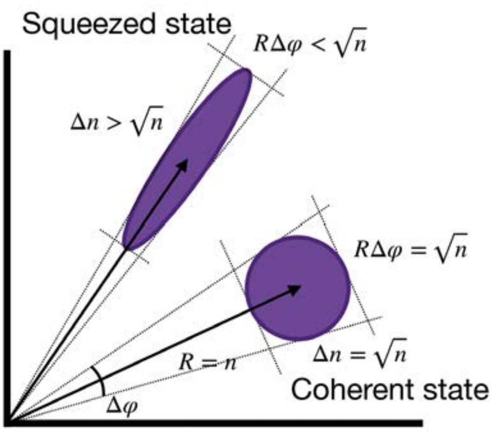


Figure 2. Phase-space diagram depicting the fluctuations, in photon number Δ*n* and phase Δϕ, of coherent and squeezed states. While the coherent state has equal fluctuations in intensity and phase, the squeezed state can present decreased phase fluctuations at the expense of increased intensity fluctuations.

PERSPECTIVES: CIRCUIT QUANTUM ELECTRODYNAMICS

A particularly promising platform for the development of advanced quantum sensors is circuit quantum electrodynamics (cQED) [6]. This approach, which transposes the concepts of traditional quantum electrodynamics to superconducting circuits, allows for extraordinarily strong and controllable light-matter interactions. In these systems, superconducting qubits play the role of artificial atoms, while superconducting resonators replace optical cavities. The decisive advantage of this architecture lies in the extreme confinement of electromagnetic fields, leading to couplings several orders of magnitude greater than in conventional optical systems.

These strong interactions facilitate the preparation and manipulation of non-classical quantum states, including squeezed states, large-photon-number Fock states, and even more complex states such as Gottesman-Kitaev-Preskill (GKP) states [7]. This ability to generate advanced quantum resources paves the way for a new generation of quantum sensors capable of operating at the fundamental Heisenberg limit. Recent work has demonstrated the use of displaced cat states, more robust than squeezed states or Fock states, with a sensitivity for phase and amplitude estimation very close to the Heisenberg limit [8]. Looking forward, GKP states are extremely promising in the context of quantum sensors as they are inherently resilient to photon loss. Furthermore, these states have been at the centre of important effort in quantum computing for their application in quantum error correction and protocols have already been successfully implemented experimentally. For quantum sensing, quantum error correction opens an interesting avenue as it would allow for maintaining complex quantum states that can approach the Heisenberg limit.

THE PRACTICAL DILEMMA: COMPLEX QUANTUM STATES VERSUS MULTIPLICATION OF CLASSICAL SENSORS

Examining only the fundamental limits of quantum metrology seems to suggest that the use of quantum sensors constitutes the best way to improve sensitivity. However, the fundamental question faced by experimenters is that of the compromise between complexity and the real cost-benefit of advanced quantum approaches. On one hand, theory clearly demonstrates that a sensor using N resources in an optimal quantum state can achieve a precision proportional to 1/N, surpassing the classical limit of 1/√N. On the other hand, this theoretical improvement must be weighted by the considerable technical challenges associated with the preparation and maintenance of these quantum states, which are often extremely fragile. The N00N state is a perfect example: although it does indeed allow reaching the Heisenberg limit, this type of state is particularly sensitive to losses, making its practical use very difficult. In general, the production of large non-classical states requires sophisticated experimental setups (indistinguishable photon sources, low-loss optical elements, cryogenic environments) and generally suffers from a success probability that decreases exponentially with N. In parallel, a classical approach simply consisting of multiplying the number of independent sensors by a factor of N^2 would effectively achieve the same metrological precision as an optimal quantum sensor using N resources. This brute force strategy has the advantage of being technically simpler to implement and of increased robustness to noise. In many current practical cases, the distributed classical approach remains competitive, even superior, due to its technological maturity. However, in contexts where resources are inherently limited (spatial, energy, or material availability constraints), or when quantum correlations offer unique capabilities (such as interaction-free detection), the quantum approach retains a decisive advantage that justifies the considerable efforts to prepare, control, and maintain quantum states. Furthermore, integrating quantum error correction would provide more robust quantum resources for sensors operating at the Heisenberg limit. With recent advances in research laboratories, the frontier of this competition is gradually shifting towards quantum solutions that clearly surpass their classical counterparts.

CONCLUSION

Quantum sensors represent an exciting frontier at the intersection of fundamental physics and precision technologies. On one hand, the use of a system with discrete energy levels allows for developing absolute sensors, which therefore do not require calibration. This aspect is at the center of important efforts to determine more precisely the base units of the International System of Units. On the other hand, the laws of quantum mechanics allow for controlling correlations in such a way as to surpass the standard quantum limit, thus offering an enormous gain in sensitivity. The development of quantum sensors could consequently greatly impact fields as diverse as gravitational wave detection, medical imaging, inertial navigation, or geological prospecting. Recent advances in the generation and manipulation of non-classical quantum states, particularly in platforms such as circuit quantum electrodynamics, also suggest metrological applications operating at the fundamental limits allowed by physics. The main challenge, however, remains preserving the fragile quantum properties in the face of decoherence while maintaining the necessary interaction with the quantities to be measured. Meeting this challenge requires interdisciplinary approaches, combining quantum physics, materials science, and precision engineering. ●

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NEXT-GEN PHOTONICS INSTRUMENTS FOR BIOIMAGING AND SPECTROSCOPY

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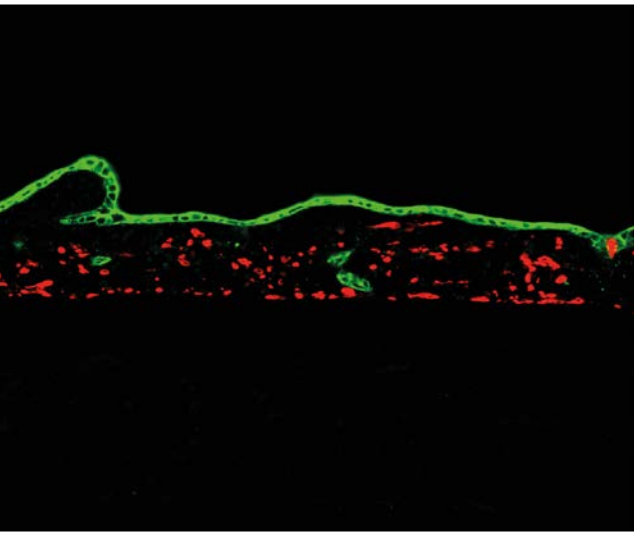

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Photonics has revolutionized the life sciences by providing powerful, non-invasive tools for observing, measuring, and manipulating biological systems with exceptional precision and sensitivity. Imaging techniques such as optical microscopy, fluorescence imaging or optical coherence tomography enable researchers and clinicians to study cells, tissues, and molecular interactions in real time and in their natural environments. And spectroscopy of biological samples enables the non-invasive investigation of molecular composition, structure, and dynamics within cells, tissues, and biofluids. These technologies are essential for early disease diagnosis, drug development, neuroscience, genomics, and personalized medicine.

Recent advances in photonics are pushing the boundaries of what's possible in bioimaging and spectroscopic analysis of biological samples. New developments in light sources and detectors are opening exciting frontiers in sensitivity, speed, and spectral coverage. The latest LEDs technologies bring greater flexibility, brightness, and depth performance to bioimaging and spectroscopic tools, enabling new capabilities in noninvasive diagnostics, functional imaging, and real-time molecular sensing. Quantum dots detectors, along with enhanced readout electronics and integrated multiplexing, are and exciting development which enables the next-generation of imaging systems to capture weak signals and resolve fast dynamics. And the most recent optical components are being tailored to biological samples and to optimize the illumination and the performance of the imaging systems.

NEW DEVELOPMENTS IN FLUORESCENCE MICROSCOPY

Fluorescence microscopy is a cornerstone of modern biological and biomedical research. This technology offers unparalleled sensitivity and specificity for visualizing structures and processes within cells and tissues. By tagging molecules with fluorescent markers, researchers can observe the localization, dynamics, and interactions of proteins, nucleic acids, and other biomolecules in real time, often at the single-molecule level. This ability to illuminate specific components within complex biological systems has transformed our understanding of cellular function, disease mechanisms, and developmental biology.

Light sources are a critical component of fluorescence microscopy, as they provide the excitation energy required to stimulate fluorophores and generate the emitted fluorescence signal. The choice of light source directly influences the brightness, resolution, and sensitivity of the imaging system. Modern fluorescence microscopes increasingly use LEDs as light sources due to their long lifetimes, low power consumption, and rapid switching between wavelengths, making them ideal for routine and multi-color imaging. Compared to mercury and metal halide lamps traditionally used for widefield fluorescence, LEDs offer many advantages for automated systems.

The UK based company CoolLED designs and manufactures cutting-edge LED illumination systems for these applications. They have developed powerful, stable and customisable multi-spectral solutions for manufacturers of automated fluorescence systems. Their ultra-bright illumination with high-speed TTL triggering increases imaging speed, boosting throughput which is especially valuable for high-content screening. Slide scanning also benefits where homogeneous illumination is critical for high-quality image stitching, so image acquisition is both fast and high quality.

The need for deeper tissue penetration, reduced background autofluorescence and improved photostability has driven the development of fluorescent dyes in the red to nearinfrared (NIR) spectral region. Some examples are the stabilized boreniumion dye, which emits in the red/NIR region and remains stable in air, or the optimized redabsorbing rhodamine derivatives, which can improve brightness and spectral tuning in the red region. For these new dyes, the wavelengths range 340-850 nm of the CoolLED's solutions allows them to cover the full range of fluorophore needs.

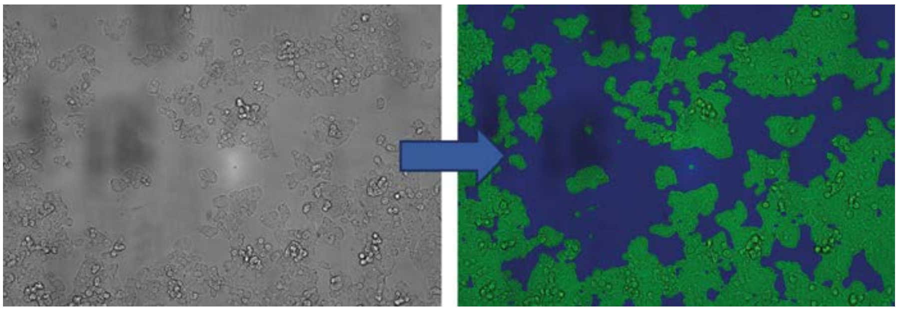


Figure 1: Cell confluence measurement. Left, raw image from the incubator; right, AI processed false color image (Source: Opto GmbH).

THE ROLE OF CALIBRATION TARGETS

High-end fluorescence microscopes often require the use of calibration targets for reproducible x/y/z positioning and sensitivity. They are essential tools for ensuring the accuracy, consistency, and reproducibility of imaging data across different instruments and serve as reference standards to assess key imaging parameters such as spatial resolution, intensity uniformity, spectral alignment, and chromatic aberration. As fluorescence microscopy becomes more complex, reliable calibration becomes increasingly critical for validating results and meeting rigorous standards in different biomedical applications.

Figure 2: LED source for fluorescence microscopy (Source: CoolLED).©

Calibration targets traditionally consisted of reservoirs of fluorescent liquids, doped specialty glass or colored beads. The recent developments in broadband photoluminescent coatings have shown very interesting advantages. These engineered thin-film or substrate-embedded materials are particularly valuable for validating system performance, because a single target can generate a stable, broad-range fluorescence output under multiple excitation wavelengths. The company IMT Masken und Teilungen AG, with extensive experience in building sub-micron patterning processes, has developed cost-effective solutions to meet specific users' requirements for photoluminescent patterns on glass. In collaboration with the Swiss Federal Laboratories for Materials Science and Technology (Empa), broadband photo-luminescent coatings have been developed and optimized for use in various application scenarios. These include plasma-deposited inorganic thin-film coatings with high resistance to radiative degradation for high-power illumination, as well as bright photoluminescent organic-based coatings. The susceptibility of the coatings to bleaching has been further reduced by applying additional layers of heat dissipating material. IMT has optimized the processes for depositing photoluminescent layers as well as the nanopatterning processes, to coat arbitrary and large area structures.

A MODULAR APPROACH

Nowadays, imaging modules offer several key advantages, especially in modern, integrated or automated life science and biomedical systems. These modules combine optics, illumination, filters and cameras into a compact unit, reducing footprint and allowing seamless integration into other systems. They can be pre-aligned, pre-calibrated and/or optimized for specific fluorescence applications, which simplifies the design and use processes. And they also allow users to customize them by selecting or upgrading excitation wavelengths, emission filters, detectors or control software to match specific fluorophores or assays.

Within this approach, the German company Opto GmbH is a specialist in advanced imaging and vision systems, offering modular, plug and play digital microscopes, imaging modules, and job-specific vision modules. The company develops optomechatronic components and systems tailored to markets such as biomedical imaging or microfluidics. One interesting example are the Opto's epifluorescence microscopes, which are capable of handling from a single fluorescence channel up to 12 or 16 fluorescence channels in just a few seconds. These fluorescence microscopes are designed for automation and integration into more complex imaging platforms, such as microfluidic screening systems and cell analysis workflows. They include multi-wavelength LED excitation, synchronized to rapid filter switching, and motorized filter wheels for fast spectral channel selection. Some interesting applications are high-throughput screening, DNA/RNA sequencing, microfluidics, and lab-on-chip devices, where fast, multi-color fluorescence imaging is critical.

COST-EFFECTIVE LONG-RANGE IMAGING OCT

Optical Coherence Tomography (OCT) is a powerful, non-invasive imaging technique widely used in biological and biomedical research for capturing high-resolution, cross-sectional images of tissue microstructures. Based on low-coherence interferometry, OCT provides depth-resolved information with micrometer-scale resolution and millimeter-scale penetration, making it ideal for studying layered biological tissues such as skin, retina, cornea, and blood vessels. Unlike traditional histology, OCT allows real-time imaging of living tissues without the need for staining or physical sectioning.

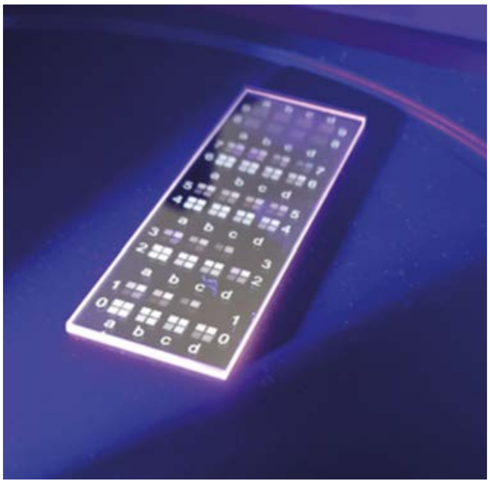
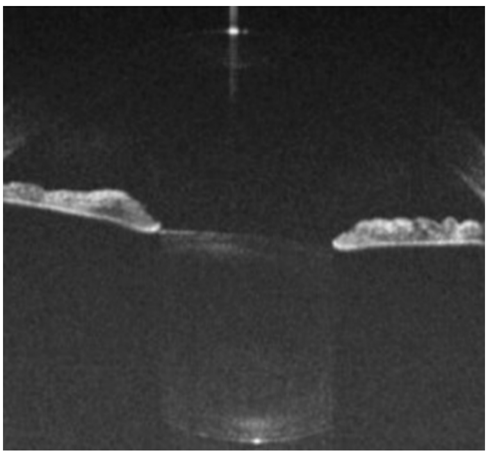


Figure 3: Calibration target for fluorescence microscopy: structured metal coating backlighted with a broadband fluorescent layer (Source: IMT Masken und Teilungen AG,).

Figure 4: Image of the eye, anterior chamber, and lens taken by the new Cobra-S long-range imaging spectrometer, CS800-831/28 (Source: Wasatch Photonics).



Long-range imaging Optical Coherence Tomography is an advanced form of this technology designed to capture high-resolution, depth-resolved images over extended axial ranges. It is very beneficial in different biomedical fields. In ophthalmology, for example, long-range imaging is beneficial for examination of the full anterior chamber, from cornea to crystalline lens, as it permits a more complete image of the eye to be acquired in less time for assessment of eye health. It also facilitates wide-field imaging of the retina, the curvature of which requires a greater range of imaging depth, particularly in clinical settings where the patient is unlikely to remain static. In general medicine, long-range OCT can be of great benefit for lumen imaging in intravascular and gastrointestinal applications. In such scenarios the structures of interest may be more than a few millimeters from the imaging catheter and therefore fall outside the typical OCT imaging window. A long imaging depth can account for such variability in distance between the imaging probe and area of interest, facilitating better imaging outcomes.

Imaging range in SD-OCT depends on both the center wavelength and on the bandwidth of the light source. So, longer wavelengths have been traditionally required in order to probe depths greater than a few millimeters in a single scan. 1300 nm has been the preferred wavelength when imaging depths of >5 mm are needed. But the use of this wavelength requires InGaAs cameras, which are significantly more expensive than the detectors used in other regions of the spectra. In order to offer a cost-effective solution which can extend the use of long-range imaging OCT, the company Wasatch Photonics has developed an ultra-high resolution optical spectrometer that can achieve imaging depths of up to 14 mm using an 800 nm OCT. With this new design, they have translated the benefits of long-range imaging to 800 nm SD-OCT. The model CS800-841/28 is capable of 0.015 nm resolution over a 28 nm bandwidth centered at 841 nm. It has been designed to minimize roll-off with diffraction-limited optics and a low-crosstalk detector. Roll-off at 10 mm imaging depth is <12 dB, ensuring high clarity images even at extended depths. Due to the shorter center wavelength of the Cobra-S long-range imaging model, scatter in tissue will be higher, though absorption in water will be lower. This may change the contrast of structures slightly, and in some cases offer improvements in differentiation, *i.e.*, for some inner retinal structures such as ganglion cells.

QUANTUM DOTS FOR THE FUTURE OF BIOSENSING

Quantum dot–based NIR semiconductor sensors are an exciting and rapidly advancing technology for biological and biomedical applications. These sensors exploit the size-tunable bandgap of quantum dots to detect or emit light in the NIR/SWIR region, roughly from 700 nm up to 1700 nm or beyond, which is highly attractive for bioimaging and sensing due to reduced tissue absorption, lower autofluorescence, and deeper penetration. Recent research has explored NIR quantum dots as fluorescent probes in vivo, as contrast agents for imaging, and in biosensing modalities.

In sensor form, quantum dot–based detectors can be engineered for spectroscopic readout, photodetection, and multiplexed sensing of biological analytes. The company Serino, spinoff from the LMU University Munich, is focused on making near infrared spectroscopy more accessible through quantum dot–based NIR semiconductor sensors. Their platform aims to reduce the cost of spectroscopy by up to 90% while increasing pixel density to deliver higher precision and sharper imaging. Serino offers customized multi-pixel detectors tailored to match the unique infrared fingerprint of a target material, thereby optimizing sensitivity and specificity. With higher pixel densities and advanced quantum NIR materials, their goal is offering a spectral system with great performance and a much lower cost point, opening spectroscopy to broader adoption in precision agriculture, recycling, pharma…

CONCLUSION

Photonics continues to revolutionize the fields of bioimaging and spectroscopy, providing researchers and clinicians with powerful tools for noninvasive, high-resolution analysis of biological systems. The transition from traditional light sources to advanced LEDs for fluorescence microscopy has significantly enhanced stability, energy efficiency, and spectral control. In parallel, photo-luminescent coatings used as calibration targets ensure consistent performance across fluorescence systems, supporting standardization and quantitative imaging workflows. Emerging quantum dot–based sensors offer a new generation of compact, wavelength-selective detectors for spectroscopy, combining high sensitivity with customizable spectral response tailored to specific analytes or biological signatures. Additionally, the developments of spectrometers for long-range imaging Optical Coherence Tomography (OCT) at lower wavelengths will allow the manufacturing of cost-effective systems to obtain deeper tissue imaging at high speed and resolution. They will expand the range of applications of this technology. Finally, modular imaging modules are increasingly adopted in biomedical instrumentation, offering plug-and-play solutions that integrate optics, detectors, and illumination into compact units. OEMs and embedded bioanalysis platforms will benefit for the new developments in this field. Together, these photonic technologies are converging to form highly integrated, precise, and scalable solutions that will shape the future of biomedical diagnostics, monitoring, and research.

HIGH-PRECISION GRAYSCALE LITHOGRAPHY FOR MICRO-OPTICS

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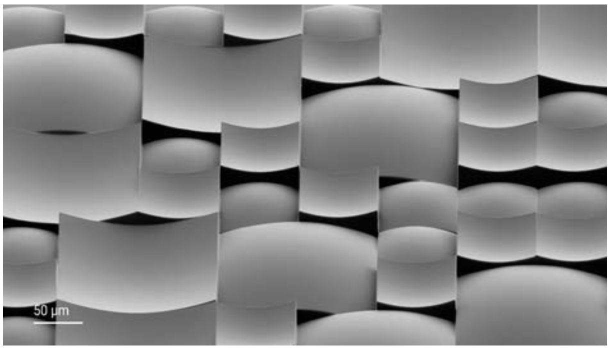

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Micro-optics are key components in a wide range of applications, including advanced imaging, sensing, and display systems. These applications require optical elements that combine a minimal form factor with outstanding optical performance. Two-Photon Grayscale Lithography, based on Two-Photon Polymerization, enables additive manufacturing of 2.5D microoptics with submicron resolution, high shape accuracy and broad design flexibility, making it a powerful technology for next-generation optical components.

Fast and versatile microfabrication technologies are driving the development of miniaturized optical elements that are essential to modern optical and photonic systems. Applications such as 3D sensing, display technologies, imaging systems, and AR/VR devices rely on optical components with increasingly smaller dimensions and ever-higher precision. As the trend toward miniaturization continues, the fabrication of microscopic optical structures presents growing challenges in nano- and microfabrication.
Two-Photon Grayscale Lithography (2GL®) addresses these challenges by enabling the rapid and precise fabrication of 2.5D micro-optical elements with freeform geometries, submicron resolution, and ultra-smooth surfaces. Based on Two-Photon Polymerization (2PP), 2GL combines the design freedom of additive manufacturing with the outstanding grayscale printing performance, known for its surface quality and shape accuracy required for advanced optics.
The Quantum X litho system implements this approach in a maskless lithography platform optimized for optics manufacturing. It enables the fabrication of refractive (figure 1), diffractive, and hybrid micro-optics with a shape accuracy of $S_a \leq 200$ nm (ISO 25178) and surface roughness below $R_a < 5$ nm. These characteristics make the system suitable for applications ranging from rapid prototyping and master template fabrication to wafer-level patterning for industrial manufacturing.

TWO-PHOTON POLYMERIZATION: PRINCIPLE AND APPLICATIONS

Two-Photon Polymerization (2PP) relies on the physical effect of two-photon absorption, where an atom or molecule absorbs two photons simultaneously to reach a higher energy state. Typically, this involves a photosensitive liquid resin that normally cures under UV light but is instead solidified by near-infrared (NIR) laser light when two photons are absorbed at once. This effect is confined to the laser's focal volume, where the light intensity is sufficiently high, enabling localized polymerization with submicron precision.

2PP is widely used for fabricating microoptics with high spatial resolution, optical-quality surfaces, and high shape accuracy. However, the printing process requires splitting of the structure design into numerous closely spaced layers to avoid staircasing effects and achieve smooth surfaces. As a result, fabricating micro-optical elements often implies long print times.

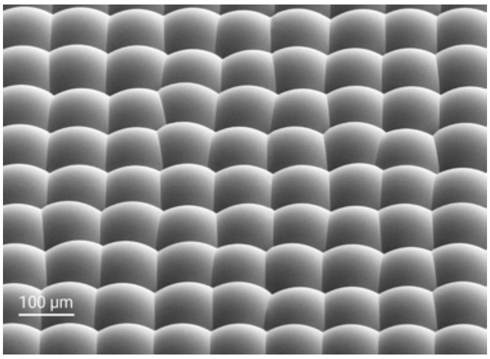


Figure 1: Densely packed microoptics in random microlens array for diffuser applications. The microlens array was fabricated by Two-Photon Grayscale Lithography and features a fill factor of 100%.

TWO-PHOTON GRAYSCALE LITHOGRAPHY: COMBINING PRECISION AND PRINT PERFORMANCE

Two-Photon Grayscale Lithography builds on the established principle of two-photon polymerization (2PP), extending it with dynamic voxel size control to significantly improve printing speed.

Unlike conventional layer-by-layer fabrication, 2GL continuously modulates the laser power during exposure to produce spatially varying voxel heights within a single scanning plane. A grayscale image serves as the input, translating into spatial variations in exposure dose. This allows 2.5D structures to be printed in one step, drastically reducing the number of layers and substantially shortening overall fabrication time by up to two orders of magnitude.

2GL offers broad design flexibility for freeform micro-optics, enabling the fabrication of complex refractive elements, sharp-edged geometries, and hybrid components that combine refractive and diffractive elements. The process produces smooth surfaces without slicing artifacts or voxel-induced distortions, making it well-suited for high-precision optical applications.

2GL provides a means to iterate and produce functional prototypes with optical-grade quality much faster than conventional Two-Photon Polymerization, and without the need for time-intensive mask fabrication. The combination of speed, submicron resolution, and design flexibility makes 2GL a practical approach for both rapid development and scalable manufacturing of advanced microoptical components. In addition, the ability to fabricate 2.5D nano- and microstructured patterns supports wafer-level production and the creation of master templates for subsequent ●●●

replication processes.

ALTERNATIVE MICROFABRICATION TECHNOLOGIES

Various microfabrication technologies are used to fabricate 2D and 2.5D micro-optical structures. This section presents an overview of lithography-based methods, both mask-based and maskless, and compares their capabilities and limitations with those of Two-Photon Grayscale Lithography.

2D UV LITHOGRAPHY

One-photon absorption underpins conventional photolithography, where light transfers geometric patterns from a photomask to a photosensitive material. In contrast, maskless technologies use direct laser writing to pattern structures without the need for masks.

Microlens arrays are commonly fabricated using a UV lithography combined with photoresist reflow. In this process, a photoresist is exposed to UV light to fabricate 2D microstructures, which are then thermally reflowed to create hemispherical or aspherical surface profiles. While this process is well-suited for large-scale production of simple microlens designs, it is limited in design complexity and in achieving high fill factors up to 100%. The design flexibility can be enhanced by transferring patterns into the substrate using reactive ion etching (RIE), although this adds process complexity and cost.

GRAYSCALE LITHOGRAPHY

Grayscale lithography extends binary photolithography by enabling fabrication of complex 2.5D microstructures with continuous height profiles. This capability is essential for producing advanced micro-optics such as those used in mobile devices, diffractive optical elements, hologram optics and structured surfaces.

Two main approaches exist in grayscale lithography: photomask-based lithography and direct laser writing, each suited to different applications.

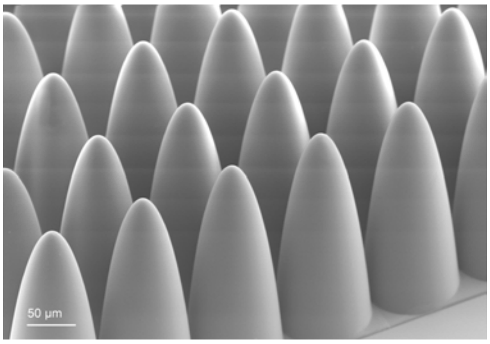


Figure 2: High aspect ratio microlens array fabricated using Two-Photon Grayscale Lithography, showcasing submicron shape accuracy and optical-grade surface quality.

While photomask-based lithography offers high throughput for large-area fabrication and high-volume production, direct laser writing enables fast iteration cycles for rapid prototyping.

MASK-BASED 2.5D GRAYSCALE UV LITHOGRAPHY

Photomask-based grayscale lithography uses specific masks to modulate exposure doses across a photosensitive resist, creating the desired topography after UV light exposure and development. The resulting 2.5D structures can then be transferred into the substrate via etching or replicated by thermal or UV molding.

Although this method allows rapid exposure of large substrates for high-volume production, it requires costly grayscale masks precisely tailored to resist characteristics. These masks are time-consuming and expensive to produce and iterate, which can take days or weeks. This limits their use in projects requiring rapid design iteration cycles.

MASKLESS 2.5D GRAYSCALE UV LITHOGRAPHY

Maskless grayscale lithography systems, such as those offered by Heidelberg Instruments, provide flexible fabrication of intricate 2.5D microstructures without the need for expensive masks. In this direct laser writing approach, spatially modulated UV light directly writes into a positive photoresist, with exposure dose variations encoding the desired structure depths. After development, the resulting 2.5D surface topographies are revealed. These patterns can then be transferred into optically relevant materials using replication techniques such as UV molding.

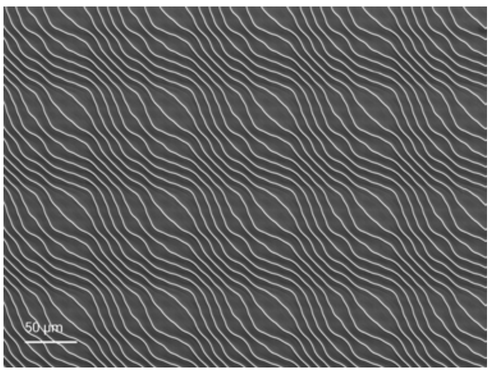
Unlike mask-based grayscale lithography, the maskless approach offers precise exposure control to compensate for nonlinear resist responses and batch-to-batch variations. However, achievable structure heights remain limited by the resist thickness, typically up to 60 µm. Recent studies using newly developed photoresists have demonstrated structure heights exceeding 160 µm, expanding the range of possible applications.

THE ROLE OF MATERIALS IN NANO- AND MICROFABRICATION

Printing material selection influences resolution, surface roughness, transparency, mechanical stability and long-term durability under varying environmental conditions. These properties are particularly critical in photonics and optics manufacturing, where optical performance is paramount.

Recent material innovations have introduced photopolymers with high transmission across the visible

Figure 3: Freeform diffractive optical elements with highest shape accuracy for high optical performance. Design by LightTrans International, print by Nanoscribe.



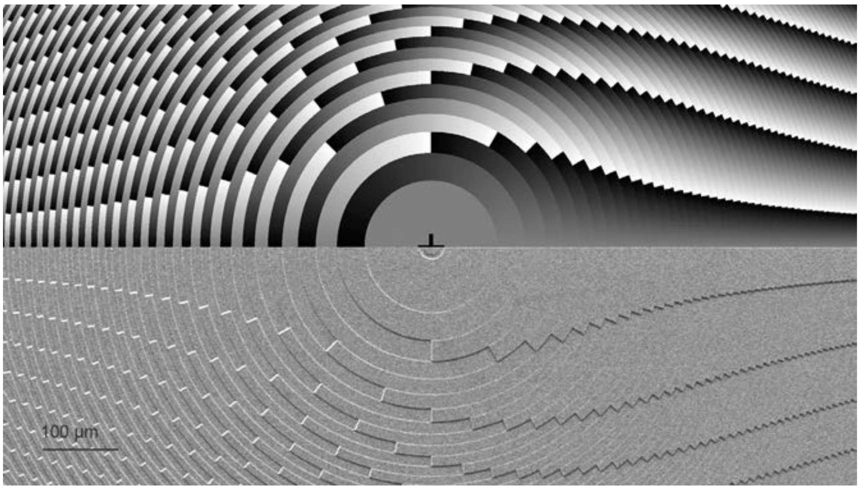


Figure 4: Grayscale design (top) and print of a Moiré lens (bottom). These diffractive lenses can be used to adjust the focus length.

spectrum and extending into the near-infrared and ultraviolet ranges, as well as photopolymers with different refractive indices and Abbe numbers. Both Two-Photon Polymerization and Two-Photon Grayscale Lithography support a wide range of such resins, enabling fabrication of micro-optical components precisely matched to diverse application requirements.

Two-Photon Grayscale Lithography utilizes liquid negative-tone resins, thus overcoming the height limitations imposed by Beer's law in one-photon grayscale lithography, where film thicknesses of positive resists typically restrict structure heights to around 60 µm. In contrast, 2GL enables fabrication of 2.5D microstructures with heights up to 1 mm and with high aspect ratios as exemplified by a 3D-printed microlens array in figure 2. Furthermore, the photoresists used in one-photon grayscale lithography are often highly sensitive to environmental factors, such as humidity and temperature, which can significantly affect process stability. Two-Photon Grayscale Lithography, however, offers robust processing conditions during preparation, printing, and development. In most cases, neither spin-coating nor pre- or post-processing steps are required.

Thanks to its robust process and the low proximity effect, 2GL does not require additional proximity correction tools, which helps reduce process complexity and simplifies data preparation workflows.

MARKETS AND APPLICATIONS

REFRACTIVE 2.5D MICRO-OPTICS

Two-Photon Grayscale Lithography expands design possibilities beyond classical optical geometries while maintaining submicron resolution. Applications include beam shaping, collimation, light homogenization, illumination, and imaging. The 2GL technology enables fabrication of almost any 2.5D shape, including spherical, aspherical, sharp-edged and freeform refractive optics. Both regular microlens arrays and random lens arrangements can be printed with fill factors up to 100% and high aspect ratios are also possible.

DIFFRACTIVE OPTICAL ELEMENTS

Diffractive optical elements (DOEs) are nanostructured surfaces that manipulate light based on the principle of diffraction (figure 3). By encoding spatial phase profiles into subwavelength or micron-scale surface reliefs, they can shape light to produce precise far-field intensity distributions, such as spot arrays, gratings and complex intensity or phase images. DOEs are used in applications that require precise beam shaping, such as holographic projection, laser beam homogenization, beam splitting in •••

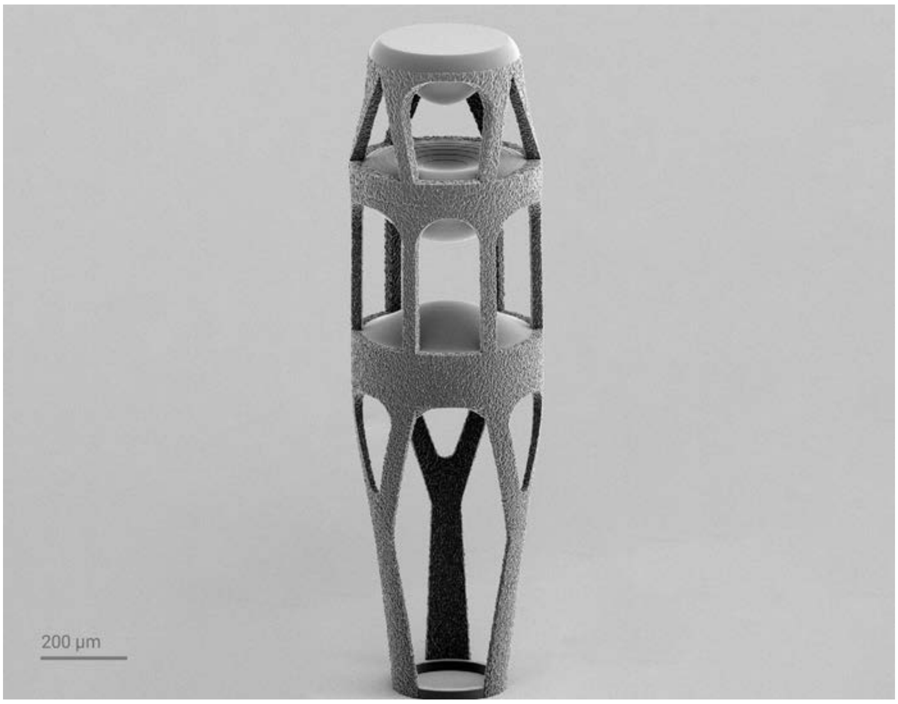


Figure 5: High-precision optics developed for a miniature endomicroscope. The stacked freeform lenses are 3D-printed by Two-Photon Grayscale Lithography. The three lenses are supported by a textured scaffold avoiding back-reflexes. All three freeform lenses have optical-grade surfaces on the top and bottom, integrating diffractive and refractive elements into one optical system and are printed in one pass. Lens design by Printoptix, manufacturing by Nanoscribe.

material processing, and structured light generation for 3D sensing. Their compact form factor and design flexibility make them especially valuable in systems where conventional refractive optics are limited by size, weight, or complexity.

Two-Photon Grayscale Lithography is well suited for the fabrication of multi-level and quasi-continuous DOEs, which require precise 2.5D surface topographies to encode phase functions. The technology offers the lateral and axial resolution needed to create DOE features with submicron precision and offers high shape accuracy and printing performance to print DOEs in reasonable time.

One example is a 256-level Moiré lens fabricated by 2GL with a lateral pixel size of 500 nm. Complex freeform DOEs, such as quasi-continuous DOEs shown in figure 4, further demonstrate 2GL's capability to produce highly accurate surface profiles that are essential for ensuring optical performance in far-field beam shaping or phase control applications.

HYBRID OPTICS

2GL enables the fabrication of hybrid micro-optics that combine refractive and diffractive features into one, continuous topography. This is particularly relevant for applications where complex wavefront shaping or chromatic aberration correction is required. While refractive elements offer high focusing efficiency, diffractive structures can compensate for dispersion or introduce precise phase control. Thus, combining both allows for compact, highly functional optical components.

2GL supports the direct fabrication of such hybrid elements with its ability to produce freeform 2.5D topographies at submicron resolution without multiple lithography or alignment steps. For example, hybrid microlenses designed for aberration-corrected imaging can be printed in a single printing step from grayscale input data, preserving design fidelity and ensuring high surface accuracy.

CONCLUSION AND OUTLOOK

Two-Photon Grayscale Lithography builds on the principle of Two-Photon Polymerization by enabling the fabrication of high-precision 2.5D micro-optics. Through dynamic voxel size modulation, 2GL produces freeform surfaces with optical-grade smoothness and submicron resolution, ideal for beam shaping, imaging, and light modulation applications.

The 2GL process integrates seamlessly into microfabrication workflows: from rapid design iteration based on grayscale input data to high-precision printing. Furthermore, 2GL can be combined with subsequent replication via nanoimprint lithography, hot embossing, or injection molding. This makes 2GL a viable bridge between prototyping and scalable manufacturing.

Looking forward, the optimization of printing material properties is enabling the development of photoresins tailored for specific applications. This advancement will continue to enhance the functionality of printed structures and improve their stability, both during integration into optical modules and throughout their operational lifetime. In addition, automated processes will further increase throughput and improve process repeatability.

While originally developed for 2.5D structures, the underlying grayscale modulation principle also enables the fabrication of complex 3D micro-optics. Three-dimensional geometries, such as stacked freeform lenses for microendoscopy (figure 5) illustrate how 2GL has evolved toward fully 3D optical components for next-generation applications in sensing, communications, displays, and integrated photonics.

Comb-locked cw-terahertz platform

The TeraScan ultra platform from TOPTICA Photonics provides a tunable, phase-stable continuous-wave THz source using frequency-comb locking. Two diode lasers locked to a single optical comb generate a beat note that a photomixer converts into a tunable monochromatic THz wave. The system offers 1 Hz spectral resolution and supports photonic vector network analysis up to 5 THz.
https://www.toptica.com/products/terahertz-systems/customized-solutions/terascan-ultra#header-5

CONFOCAL LASER SCANNING MICROSCOPE

The new FLUOVIEW™ FV5000 confocal laser scanning microscope from Evident incorporates SilVIR™ photon-counting detectors, allowing quantitative signal detection at the single-photon level. A newly designed scanning control system supports both 2K resonant scanning and 8K galvanometric scanning, enabling high-speed imaging of dynamic processes while maintaining spatial resolution, ideal for live-cell imaging, high-content analysis, and quantitative fluorescence microscopy.
https://evidentscientific.com/fr/products/confocal/fv5000

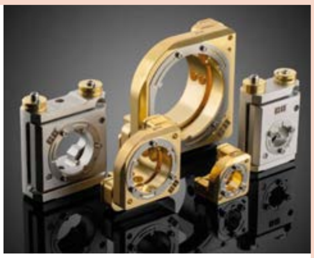
3D Multisensor Metrology

Optical Gaging Products (OGP®) has introduced the SmartScope® M130, a new addition to its 3D multisensor metrology series designed for high-precision measurement of large and heavy industrial components. At the core of the instrument is the IntelliCentric-M Optical System, a patented design featuring fixed optics, a 20-megapixel camera, and OGP's proprietary VIRTUAL ZOOM™ technology. This optical configuration provides instantaneous magnification changes across the same range as a conventional mechanical zoom system, reducing measurement time and maintenance requirements.
https://www.ogpnet.com/products/metrology-systems/multisensor-metrology-systems/smartscope-video-multisensor-systems/smartscope-m-series/smartscope-m130/

ER:YB OPTICAL FIBER

Scaling fiber lasers to high powers around 1.5 µm requires maintaining beam quality and efficiency while mitigating nonlinear effects, thermal load, parasitic 1 µm emission, and long-term material degradation. Exail has recently introduced a new double-clad Er/Yb-doped fiber to address these challenges. With a 10 µm core and a 12.5 µm mode field diameter, the fiber ensures stable beam quality and high efficiency while minimizing photodarkening effects.
https://www.exail.com/product/erbium-ytterbium-doped-fibers-photonics

Kinematic Mounts



Designed to minimize wavefront distortion and preserve optical flatness, these new series of Ultraprecision Kinematic Mounts by Edmund Optics provide accurate and repeatable adjustment in demanding optical setups. Each mount incorporates two hex-driven fine adjustment screws (100 TPI), which can be locked to secure alignment against shock, vibration, or temperature gradients.
https://www.edmundoptics.eu/f/ultraprecision-kinematic-mounts/40063/?utm_source=press_release&utm_medium=print&utm_campaign=mp_4474_ultra_kin_mounts_25&utm_content=landingpage_eu&utm_term=marketplace#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